

Glacial Evidence of Neoproterozoic Carbonate Deposits from Firgoun Area, Southeastern Border of Gourma Basin (Western Niger)

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Abstract

The Firgoun area sedimentary deposits are located on the eastern edge of the West African Craton, precisely in the western part of Niger. They are related to the basal deposits of the Ydouban Group (Gourma basin) considered as Neoproterozoic in age. In the Firgoun area, the uppermost deposits include successively interbedded diamictites, carbonates and cherts (silexites), which are assimilated to the triad, a potential stratigraphic marker that characterized the Neoproterozoic glacial event in West Africa. So, the carbonate sediments associated with the Neoproterozoic glacial deposits are regarded as a useful tool to understand the stratigraphy of Neoproterozoic basins. Previous investigations on the deposits of the Firgoun region regarding the stratigraphy are fragmentary. The age of these deposits is still debated. In this paper sedimentological and preliminary geochemistry analyses were carried out in order: to characterize the uppermost deposits of the Firgoun area, identify the carbonate rocks and correlate them to the cap carbonates neoproterozoic deposits of the West Africa Craton. Two kinds of carbonate rocks lithofacies were identified in the Firgoun area: 1) unmetamorphosed brown dolomitic limestones exhibiting a cavernous appearance and 2) massive marbles with milky white to pinkish colors. These carbonate rocks are mainly composed of calcite, dolomite and accessory minerals such as quartz, oxides and clays. Geochemical analyses of major elements highlight the mixed (humid and arid climates) paleoclimatic characteristics for the Firgoun upper deposits. Isotopic data (negative values $\delta^{13}\text{C}$ (-7.1‰) and $\delta^{18}\text{O}$ (-15.6‰)) enable the correlation of the Firgoun carbonate rocks to the West African Craton Cap carbonates.

Keywords

Cap Carbonates, Neoproterozoic Glacial Deposits, Firgoun Area, West Africa,

1. Introduction

Neoproterozoic glacial deposits are systematically followed by enigmatic carbonate deposits well identified on several continents including Africa (Affaton, 1990; Porter et al., 2004; Font, 2005; Deynoux et al., 2006; Shields et al., 2007a; Álvaro et al., 2023). During this period, glacial sediments (tillites, diamictites), were widely distributed at the scale of the Earth's surface. According to Kirschvink (1992), the extent of these glaciations was such that ice covered the entire planet at that time. This hypothesis, better known as "Snowball Earth" (Harland, 1964; Kirschvink, 1992), evokes the most extreme climate changes known on planet Earth. The carbonated deposits that capped glacial sediments are regarded as important keys for understanding the glacial events. At least three glacial episodes are known during the Neoproterozoic era: the Sturtian (750 - 700 Ma), the Marinoan (635 Ma, Kennedy, 1996) and the Gaskiers (580 Ma, Bowring et al., 2003) glaciations. The Sturtian and the Marinoan glaciations occurred respectively during the Early and Late Cryogenian whereas the Gaskiers one corresponds to the Ediacarian. The West Africa basins (Taoudenni, Volta and Gourma) contain Late Cryogenian glacial deposits (635 Ma, Kennedy, 1996) overlaid by carbonate sequences that have been assimilated to the post-glacial cap carbonates.

According to the interpretation of Harland (1964), Kirschvink (1992), and Hoffman et al. (1998), this succession of glacial deposits (Tillites/Diamictites) and cap carbonates, suggesting a transition from glacial conditions (*Ice-house* = glacial deposits) to deglacial conditions (*Green-house* = cap carbonate deposits), would be at the origin of the most severe global climate changes that affected the Earth during the Neoproterozoic.

Neoproterozoic cap carbonates are very often defined by a succession of two sequences (Font, 2005; Le Hir, 2007; Fabre, 2010b; Young, 2013): a basal unit, essentially dolomitic ($\text{CaMg}(\text{CO}_3)_2$) and a thicker upper unit composed essentially of limestone (CaCO_3) with occasional clays. The dolomitic basal levels are thin, rarely reaching 20m in thickness (Font, 2005; Fabre, 2010b), while the upper levels are relatively thicker.

According to Kennedy (1996), Hoffman et al. (1998), Corkeron & George (2001), James et al. (2001), Hoffman & Schrag (2002), Eyles & Januszczyk (2004), Neoproterozoic Cap carbonates are characterized by the presence of flat or undulating biolaminations, sometimes with hummocky cross stratification (HCS) (Hoffman & Schrag, 2002; Halverson et al., 2004).

Vertical tubules, attributed to microbial constructions (stromatolites), have also been observed (Cloud et al., 1974; Hoffman et al., 1998; Kennedy et al., 2001; Hoffman & Schrag, 2002). The top of the Cap carbonate sequence is characterized by the presence of "tepees", which structures correspond to megarids created by a

regime dominated by waves induced by strong winds (up to 20 m/s) (Allen & Hoffman, 2005).

In West Africa, Neoproterozoic carbonates have been related to the “tillites-carbonates-silexites” triad, characteristic of the Neoproterozoic Taoudenni (Trompette, 1973; Deynoux et al., 2006; Villeneuve, 2008), Gourma (Miningou et al., 2010) and Volta (Porter et al., 2004; Couëffé & Vecoli, 2011) basins. This famous triad, considered a major stratigraphic marker, has also been described in the Firgoun region (Western Niger, Konaté et al., 2018; Alzouma Amadou et al., 2020) where the carbonate sequences are the subject of the present study.

However, previous studies of these presumed Neoproterozoic deposits in the Firgoun region have been limited to sporadic sedimentological and stratigraphic descriptions. The age of these deposits remains controversial. Unlike their equivalents in the Béli sub-basin (SE of the Gourma basin, Burkina Faso, Miningou et al., 2010), which show stromatolitic structures, no trace of fossils has yet been found in the carbonates of the Firgoun region. This makes stratigraphic correlations difficult.

The aim of this study is firstly to investigate the geochemical characteristics of the Firgoun uppermost deposits (Béli-Garous Formation) that include carbonate sediments, secondly to identify carbonate sediments and to correlate them to those found in the Taoudenni and Volta basins. In objective of refining the stratigraphic position of these deposits, a multidisciplinary approach integrating sedimentology, geochemistry and stable isotopes analysis was implemented. The sedimentological characteristics combined with geochemistry (major and trace elements analysis) have made it possible to characterize the paleoclimatic environments of the Firgoun upper sediments. Isotopic data of carbonates allow correlations between the carbonates of Firgoun and those found in the Taoudenni and Volta basins.

2. Geological Setting

The study area includes two major units (Figure 1): 1) the Paleoproterozoic (Birimian, Soumaila et al., 2008; Garba Saley et al., 2024) basement of the Liptako and 2) the sedimentary cover (Neoproterozoic, Machens, 1973; Reichelt, 1972; Konaté et al., 2018; Alzouma Amadou et al., 2020) that contains the Firgoun carbonates, subject of this study.

2.1. Paleoproterozoic Basement

The basement of West African Craton is made up of Archean and Paleoproterozoic formations mainly observed in two separated domains: the Réguibat Shield in the North and the Man Shield in the South (Figure 1). In Western Niger the basement essentially Paleoproterozoic, is represented by the Birimian formations of Niger Liptako province. These latter outcropping along the eastern edge of the Man Shield, are affected by the Eburnean orogeny (2.4 to 1.8 Ga according to Plumb, 1991). They are consisted of alternating greenstone belts (Gorouol, Dar-

gorou-Darbani, Sirba and Makalondi sectors) and granitoid massifs oriented generally NE-SW (**Figure 1**). These granitoid plutons expose in the following sectors: Dargol-Gothèye, Torodi and Téra-Ayorou.

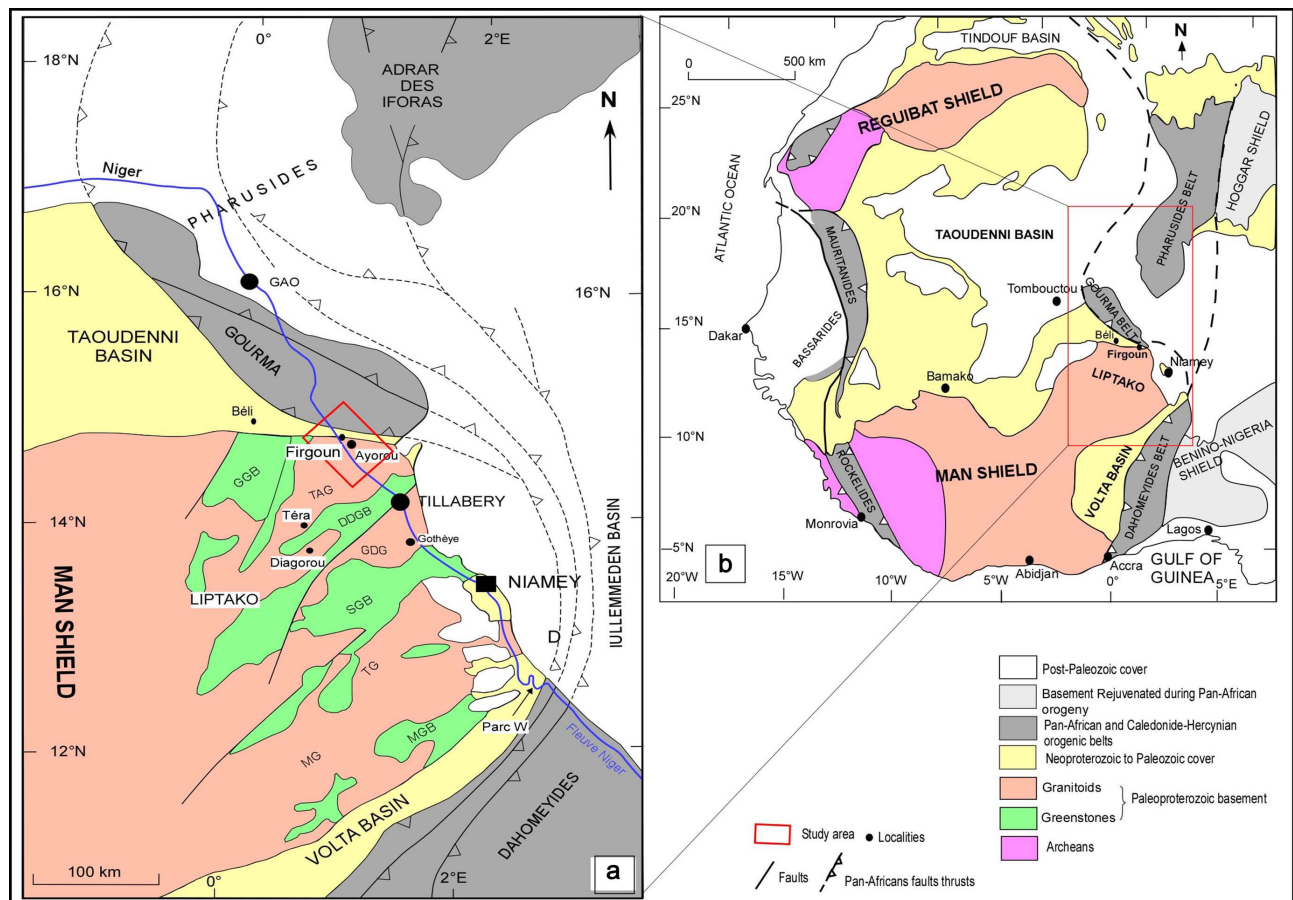


Figure 1. (a) Simplified geological map of West Africa (modified from Deynoux et al., 2006). (b) Geological map of the northeastern border of the Man Shield (modified from Affaton et al., 2000). G.G.B: Gorouol Greenstone Belt; T.A.G: Téra Ayorou Granitoid; D.D.G.B: Diagourou Darbani Greenstone Belt; D.G.G: Dargol Gothèye Granitoid; S.G.B: Sirba Greenstone Belt; T.G: Torodi Granitoid; M.G.B: Makalondi Greenstone Belt; M.G: Mossipaga Granitoid.

The greenstone belts are mainly composed of metavolcano-sediments, phyl-ladesof sedimentary origin, metagrawackes, metabasites and meta-ultrabasites (Soumaila et al., 2008; Garba Saley et al., 2024). Whereas, the granitoid plutons are made of tonalites, trondhjemites and granodiorites (TTG), diorites, quartz diorites, monzonites and locally syenites. In the study area the Paleoproterozoic basement is characterized Birimian granitoids of Téra-Ayorou which are affected by dykes doleritic (Soumaila et al., 2008; Garba Saley et al., 2024).

2.2. Neoproterozoic Sedimentary Cover

The Neoproterozoic sedimentary cover of West African Craton is mainly represented by the huge intracratonic Basin of Taoudenni (**Figure 1**). The sedimentary infilling of this basin began with the Supergroup 1 (coarse sandstones, limestones,

stromatolite dolostones, clays and silts) at approximately 1000 Ma (Deynoux et al., 2006). The Supergroup 1 is successively overlain by the Supergroup 2 and the Supergroup 3. The Supergroup 2 is characterized at its base by the triad “Tillites-carbonates-silexites”, related to glacial deposits occurred during the Late Cryogenian (Shields et al., 2007a; Miningou et al., 2010). While the base of Supergroup 3 corresponds to the Late Ordovician glacial deposits which marked the upper bounded of the Neoproterozoic (Miningou et al., 2010, 2017).

The Neoproterozoic cover outcrops in the peripheral basins of Gourma and Volta which correspond to the southeastern part of the Taoudenni Basin (Figure 1).

The subsiding basin of Gourma with 8000 m thickness is affected to the East by Pan African Orogeny, characterized by the thrusting of the nappes of the Gourma folded belt (Deynoux et al., 2006; Reichelt, 1972; Affaton et al., 2000). This basin, in continuity with the Taoudenni basin, is mainly characterized in his southeastern border by the sedimentary deposits of Ydouban group which poorly outcrop in Béli (Burkina Faso) and Firgoun (Niger) areas (Figure 1) (Miningou et al., 2010; Konaté et al., 2018). According to Machens (1973), Reichelt (1972) and Bertrand-Sarfati et al. (1987), this Ydouban group composed of variable rocks includes from bottom to top: conglomerates and quartzite sandstones (basal Formation of “*Firgoun sandstones*”), coarse sandstones with conglomerates and shale intercalations (Formation I), shales (Formation II), carbonates with intercalations of shales and sandstones (Formation III), quartzite with intercalations of shales (Formation IV) a siliceous formation (cherts and jasper) and carbonates with shales and siltstones (Formation V).

2.3. Stratigraphic Framework of the Study Area

The Neoproterozoic sedimentary deposits of Firgoun outcropping sporadically on both sides of the Niger River are located to the North of Niger Liptako province (eastern border of the West African Craton) approximately 200 km to North-west of Niamey (Figure 1, Figure 2). These rocks related to the basal Neoproterozoic deposits of Ydouban group (Gourma Basin) rest unconformably on the Northeastern border of the Paleoproterozoic basement of Man Shield (granitoids Birimian of Téra-Ayorou) in the Liptako (Figure 1, Figure 2). They are considered equivalent to the lower deposits of the Taoudenni Basin (Supergroup 1 and Supergroup 2) in the North and Volta Basin (Bombouaka and Oti supergroups) in the South (Porter et al., 2004; Trompette, 1973; Alzouma Amadou et al., 2020; Konaté et al., 2018).

According to these authors (Reichelt, 1972; Machens, 1973) the study area litho-stratigraphic succession presents two units or formations: 1) the basal “*Firgoun Sandstone*” Formation, overlain by 2) the “*Béli-Garous*” Formation (more detailed in Reichelt, 1972).

The “*Firgoun Sandstone*” Formation, which is essentially detrital, is made of conglomeratic to microconglomeratic sandstones, quartzite sandstones and silt-

clay sandstones (Alzouma Amadou et al., 2020; Konaté et al., 2018). According to the recent study of Konaté et al. (2018) based on U-Pb zircon detrital measurements, the sediments of “*Firgoun Sandstone*” Formation yield about 1800 Ma age.

The “*Béli-Garous*” Formation, also known as “*Faciès de bordure*” (Reichelt, 1972), is composed of variable rocks (Figure 2): quartzite sandstones, silt-clay sandstones, conglomerates, alternating clayey shales and carbonates, mudstones, cherts or silexites. In this formation, the shale horizons have provided a Pan-African age of 600 Ma, obtained by the Rb-Sr method (Reichelt, 1972). These latter in alternating with carbonates deposits overlie the silicoclastic sediments (quartzite sandstones, silt-clay sandstones, conglomerates).

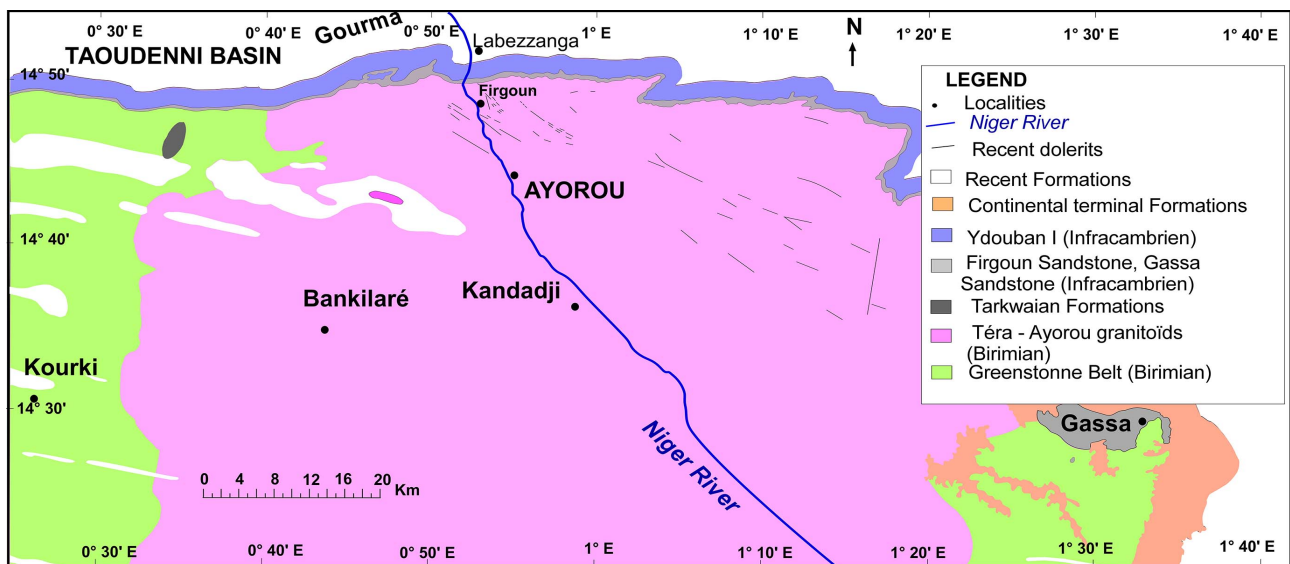


Figure 2. Location of the study area on a simplified geological map of Liptako (extract from Machens, 1973).

3. Sampling and Analytical Methods

A multidisciplinary approach integrating a sedimentological study and geochemical analyses was implemented during this study. During the fieldwork, four (4) lithostratigraphic sections were surveyed and thirty (34) samples were collected. Twenty-four (28) among of these samples were selected for sedimentological study and six (6) others for geochemical analyses. The sedimentological study consisted of macroscopic descriptions of the outcrops in the field and microscopic observations of the carbonate samples at the laboratory. The field investigations are based on several criteria, such as bed thickness, lithology, color, and sedimentary structures.

Thin sections of the 24 samples collected were prepared at the Laboratory of the Ecole des Mines de l'Industrie et de la Géologie (Niamey, Niger). Polished sections of 4 samples are prepared at the laboratory of the “Centre de Recherche Géologique et Minière” (CRGM) in Niamey. In order to determine the petrographic and minerals characteristics of the carbonate facies, the thin and polished sections were described using an optical microscope (OPTICA and LEICA) at the laboratory of

the Department of Geology (Abdou Moumouni University of Niamey, Niger).

Two types of geochemical investigations (geochemical analyses on whole rock and stable isotope analyses) were carried out as part of this study. The samples collected for the geochemical analyses of major and trace elements are made up of variable rocks: cataclased quartzitic sandstones, filled with oxides (FI11), shales (FI3), silicites (FI7), variegated carbonates (FI7) and dolomitic marbles (FI12). All these samples, previously crushed and pulverized, and analyzed using the ICP-MS (Inductively Coupled Plasma Mass Spectrometry) method at the Actlabs Ontario laboratory (Canada).

C and O isotopic analyses specific to carbonate deposits (sample FIR3) were also carried out at the Actlabs Ontario laboratory (Canada). The sample, previously crushed and pulverized, was analyzed using the IRMS (Isotope Ratio Mass Spectrometer) method.

The results of geochemical analyses for major and trace elements were processed using software such as GCDKit and IBM SPSS Statistics 20. To assess the paleoclimatic conditions of the sediments, the major element results were plotted into the [Suttner & Dutta \(1986\)](#) diagram using the above-mentioned software.

The isotopic compositions of carbon and oxygen of a sample were respectively denoted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. The method involves reacting carbonate powder with phosphoric acid (H_3PO_4) at 70°C to extract carbon dioxide (CO_2). The CO_2 gas extracted was analyzed at Actlabs Ontario laboratory (Canada) using an isotope ratio mass spectrometer (IRMS). Results for both carbon and oxygen were reported in conventional notation in per mil (‰) relative to the V-PDB (Pee Dee Belemnites, [Tahata et al., 2015](#)) international standard. The precisions of isotope measurements were 0.2‰ for both carbon and oxygen.

4. Results

4.1. Sedimentological Study

4.1.1. Lithostratigraphic Sections Description

On the basis of the sedimentological analysis four lithostratigraphic sections (C1, C2, C3a and C3b) have been realized in the Firgoun region.

Lithostratigraphic section C1, with approximately 15 m thickness ([Figure 3](#)), was taken from outcrops along the main Ayorou-Gao road ($\text{N}14^\circ 49'55''$ - $\text{E}0^\circ 53'7.6''$).

With an extension of around 3 km, this section, slightly oriented SE-NW, appears to be the most representative. During our field observations, 7 lithofacies were identified ([Figure 3](#)). These are from bottom to top:

- coarse quartzite sandstones, conglomeratic to microconglomeratic (lithofacies Fr1), resting unconformably on the more or less metamorphosed granites of the Birimian basement;
- quartzite sandstones with intercalations of silt-clay sandstone beds (lithofacies Fr2);
- more or less fine silt-clay sandstones (lithofacies Fr3);

- dark quartzite sandstones, with fine to medium grains (lithofacies Fr4);
- fine to medium sandstones with silt-clay interlayers (lithofacies Fr5);
- manganese-rich quartzite sandstones (lithofacies Fr6), associated with intermediate conglomeratic levels;
- and slates (lithofacies Fr7) with dolomitic marble interlayers.

Lithostratigraphic section C2 (Figure 3), about 3 m thickness, was made at outcrops along the Niger River border (N14°49'4"-E0°51'59" (North Bramé)). This SW-NE trending section is over 2 km long. Two types of lithofacies have been identified (Figure 3): at the bottom, quartzite sandstones identical to those described in section C1 (lithofacies Fr6) and, at the top, greenish-grey shales topped by sporadic deposits of carbonates (lithofacies Fr7).

Lithostratigraphic section C3a (Figure 3) realized south of Donkolo (N14°50'48"-E0°52'55.8"), is surveyed over a distance of more than 3 km, in a SE-NW direction. Four types of lithofacies are distinguished (Figure 3):

- more or less fine quartzite sandstones, dark gray in color (upper term of lithofacies Fr6);
- shales overlain by milky-white marbles (lithofacies Fr7);
- shales (pelitic shales, slates, clay shales) gradually evolving into silexites; (lithofacies Fr8);
- and shales of varying color (lithofacies Fr9).

Lithostratigraphic section C3b, about 4 m thick (Figure 3), was surveyed south-east of Donkolo (N14°50'57.5"-E0°53'34.9"). This section was surveyed over a distance of more than 4 km, in a SE-NW direction. Three types of lithofacies were identified (Figure 3):

- fine quartzite sandstones (upper term of lithofacies Fr6);
- shales evolving vertically to milky-white marbles (lithofacies Fr7);
- and banded cherts or silexites (lithofacies Fr8).

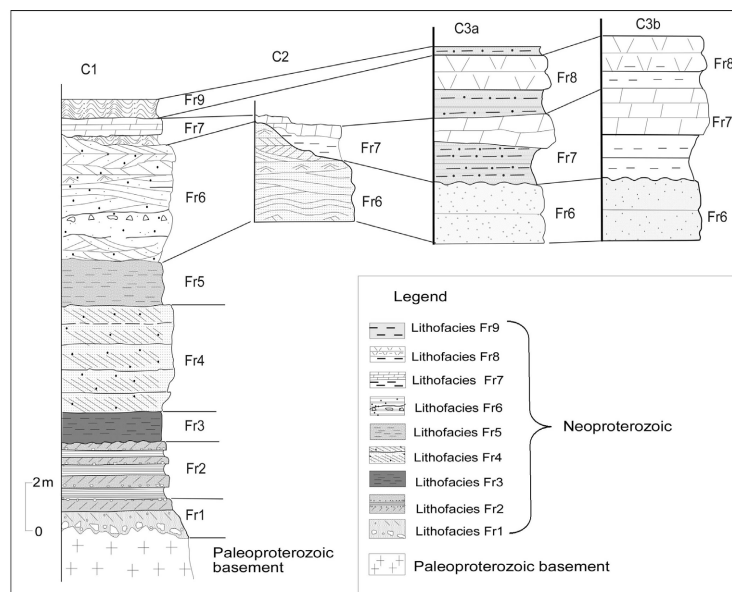


Figure 3. Lithostratigraphic sections C1, C2, C3a and C3b of the studied area.

4.1.2. Lithostratigraphic Correlation

Correlation between different lithostratigraphic sections (C1, C2, C3a and C3b) of Firgoun area (**Figure 3**) has enabled to establish a synthetic lithostratigraphic column (**Figure 4**), including from bottom to top, 9 lithofacies, named Fr1 to Fr9. The lower siliciclastic unit (lithofacies Fr1 to Fr3) is assigned to the “Firgoun Sandstone” basal Formation. While the upper deposits (Fr4 to Fr9) have been linked to the “*Béli-Garous*” Formation.

Lower unit “Firgoun Sandstone” Formation

The “*Firgoun Sandstone*” Formation essentially detrital begins with conglomeratic to microconglomeratic basal sandstones (lithofaciès Fr1, about 1 m thickness) which rest unconformably on the Paleoproterozoic basement of Liptako (**Figure 4**). The presence in this lithofacies of poorly sorted “matrix-supported” conglomerates, consisting of subrounded, blunty quartz granules and pebbles (size varying from 2 to 4 cm) indicates a fluvial influence of sedimentation. This lithofacies evolves towards the top to relatively finer deposits presenting in places ripple marks and oblique bedding (**Figure 4**).

The lithofacies Fr2, with a total thickness of 3.5 m, is represented by alternating quartzite sandstone beds and silt-clay sandstone levels, attributed to a turbiditic sequence (**Figure 4**). The finely bedded silt-clay sandstone levels become increasingly coarse and thick towards the top. Quartzite sandstone horizons become increasingly finer towards the top. It is characterized by the presence of oblique bedding, sometimes associated with asymmetrical and symmetrical ripples with erosive surfaces. Oblique beddings occur both in quartzite sandstone beds and in silt-clay sandstone interlayers (**Figure 4**).

The lithofacies Fr3, made up of relatively fine deposits, outcrops over a maximum thickness of around 1.5 m. These clayey-silty sandstone beds mark the end of the “Firgoun Sandstone” Formation. The main sedimentary structures observed in this lithofacies are hummocky cross stratifications (HCS), oblique bedding associated with asymmetrical and symmetrical ripples (**Figure 4**).

Upper unit “Béli-Garous” Formation

Unlike the previous deposits, which are essentially detrital, those of the “*Béli-Garous*” formation are made up of a diversity of rocks: conglomerates, quartzite sandstones, silt-clay sandstones, shales, silexites and more or less metamorphosed carbonates (limestones and dolomites) (**Figure 4**).

The “*Béli-Garous*” Formation begins with shallow sedimentation (lithofacies Fr4), about 4 m thick. The lithofacies Fr4 is made of blackish-brown quartzitic sandstones (**Figure 4**). Asymmetric to symmetric ripples sometimes associated with oblique bedding were observed at the top of the beds.

The lithofacies Fr5 corresponds to fine to medium sandstone beds with brownish silt-clay intercalations which overlined the precedent lithofacies. Asymmetric to symmetric ripples sometimes associated with oblique bedding were observed at the top of the beds (**Figure 4**).

Lithofacies Fr6 outcrops over a thickness of approximately 5 m. it is represented by quartzitic sandstone beds, more or less manganese-bearing (**Figure 4** and **Fig-**

ure 5). This type of lithofacies is characterized in the intermediate levels by the presence of faceted pebble conglomerates (Figure 5) attributed to occurrences of diamictites. These are poorly sorted deposits (unclassified), composed of more or less floating pebbles in a sandstone matrix. Furthermore, it is also worth mentioning the notable presence in this lithofacies of sedimentary features such as oscillation ripples, interference ripples, herringbone bedding, and hummocky cross stratifications (HCS) (Figure 5).

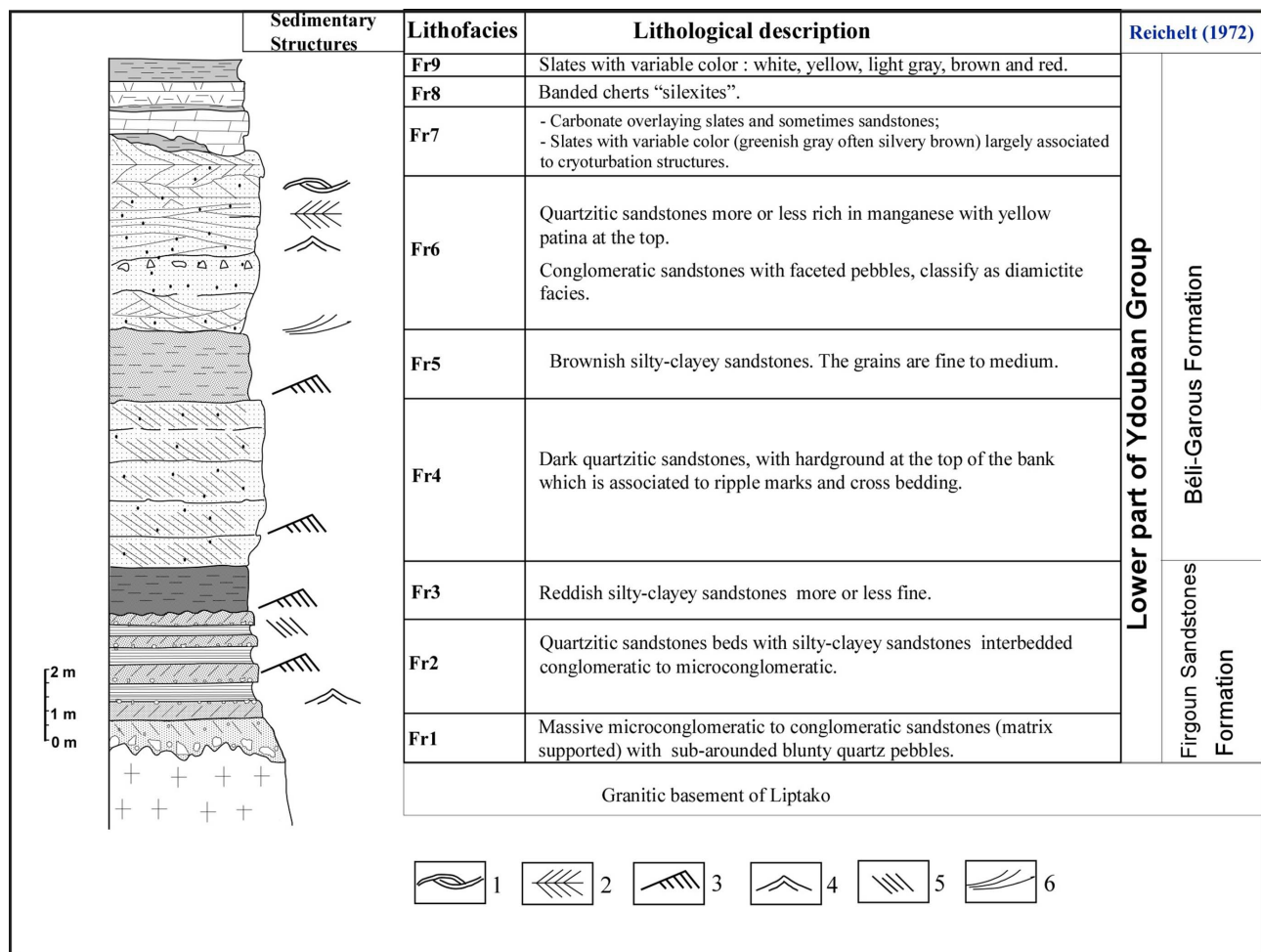


Figure 4. Synthetic lithostratigraphic column of the Firgoun area. 1, Hummocky cross-stratifications (HSC); 2, herring bones; 3, current ripples; 4, wave ripples; 5, planar cross-bedding; 6, planar cross tangential at the bottom (modified from Konaté et al., 2018; Alzouma Amadou et al., 2020).

The lithofacies Fr7, locally overlying the preceding deposits, is composed of slates, with intercalations of carbonate horizons. Particular sedimentary structures, notably "cryoturbation figures", are frequently associated with slates (Figure 5).

Carbonate deposits are poorly exposed (approx. 0.5 m). These carbonate deposits sandwiched between the diamictites of lithofacies Fr6 and the silexites of lithofacies Fr8, represent the upper part of the "Béli-Garous" Formation.

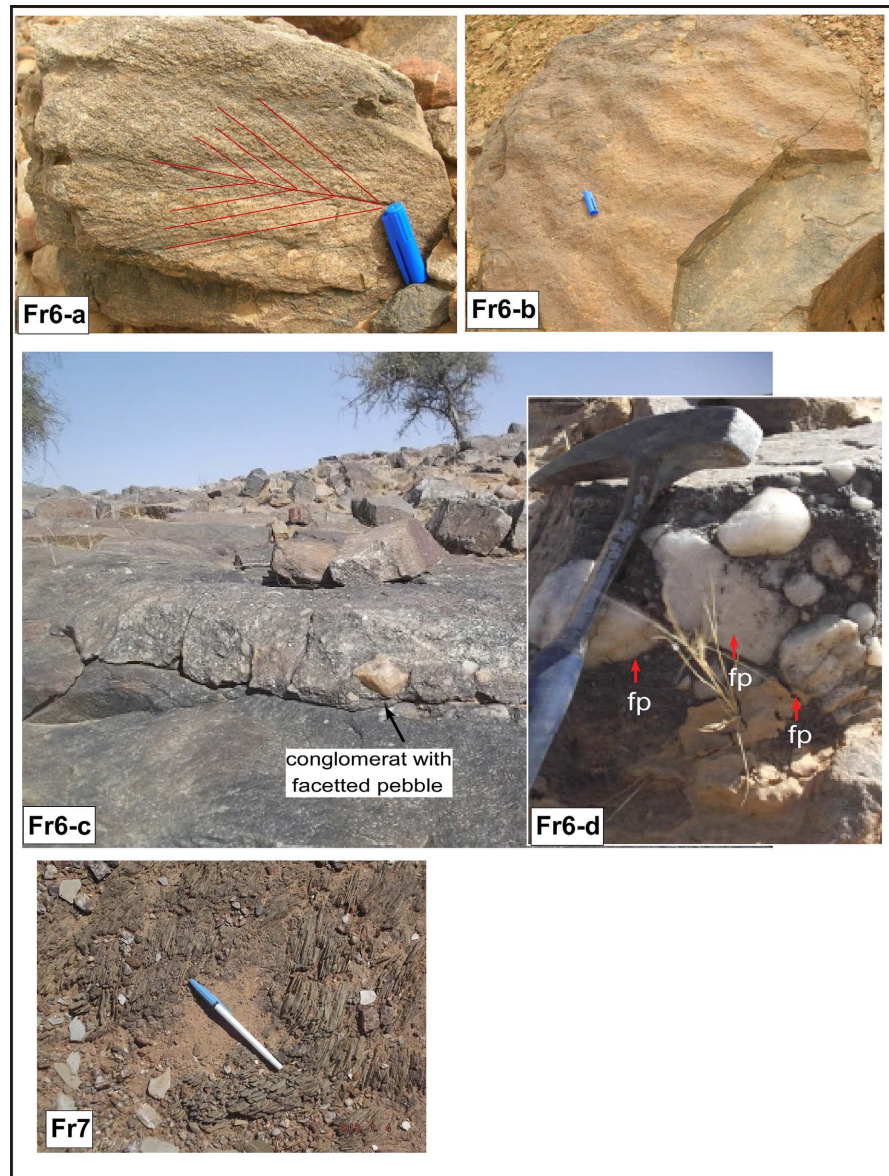


Figure 5. Deposits of glacial lithofacies Fr6 and slates of lithofacies Fr7 presenting cryoturbation features. Herringbones (Fr6-a), current ripples (Fr6-b) structures observed in the lithofacies Fr6. Occurrence of diamictite marked by facettet pebbles (fp) in the lithofacies Fr6.

Two types of carbonate have been founded in the Firgoun region (**Figure 6**): 1) dolomitic limestones (variegated carbonates), unmetamorphosed, and 2) massive marbles, milky white to purplish pink in color. The variegated carbonates (dolomitic limestones) are soft rocks of varied color (whitish, yellow, purple, brownish) presenting centimetric cavities (**Figure 6(a)**).

The discontinuous marble layer is around 0.5 m thick. It is affected by a dense network of fractures (**Figure 6(b)**). Laminar structures identical to diagenetic stylolithes (**Figure 6(c)**) have been observed in pink, slightly metamorphosed dolomitic marbles. They have blackish brown fillings, attributed to barite concretions

(**Figure 6(d)**). According to [Chamley & Deconinck \(2011\)](#), diagenetic stylolites commonly develop in limestone horizons, along stratification planes or at the boundary between limestones and clays (in the case of nodular limestones).

Microscopic observation of dolomitic marbles indicates the presence of rhombohedral crystals of dolomite in a calcitic matrix (**Figure 7(a)**, **Figure 7(b)**). Although dolomite can also exist in the form of cement. In this case it could be a secondary replacement mineral.



Figure 6. Carbonate deposits: (a) Variegated carbonates with a cavernous appearance (dissolution figures), (b) White marbles showing a dense network of microfractures with secondary siliceous or calcitic filling. The pen point indicates a North orientation, (c) and (d) Purplish pink marbles showing diagenetic stylolites (sty) and barite in concretions (Ba).

Microscopic observation in dolomitic limestones (variegated carbonates) shows microsparite cement with a reddish pigment. This latter is due to the presence of oxides (**Figure 7(c)**). Small fragments of dolomite recrystallize within the microsparitic cement.

Indice of copper minerals have been observed in the dolomitic marbles in places (**Figure 7(d)**). Microscopic observation of these marbles indicates minerals such as chalcopryrite and azurite (**Figure 7(e)**, **Figure 7(f)**).

Lithofacies Fr8 corresponds to massive or banded, greenish-black silexites (**Figure 5**). These are silexites with a conchoidal fracture. The gradual transition from the shales of the preceding lithofacies Fr7 to the silexites of lithofacies Fr8 is remarkable in some places.

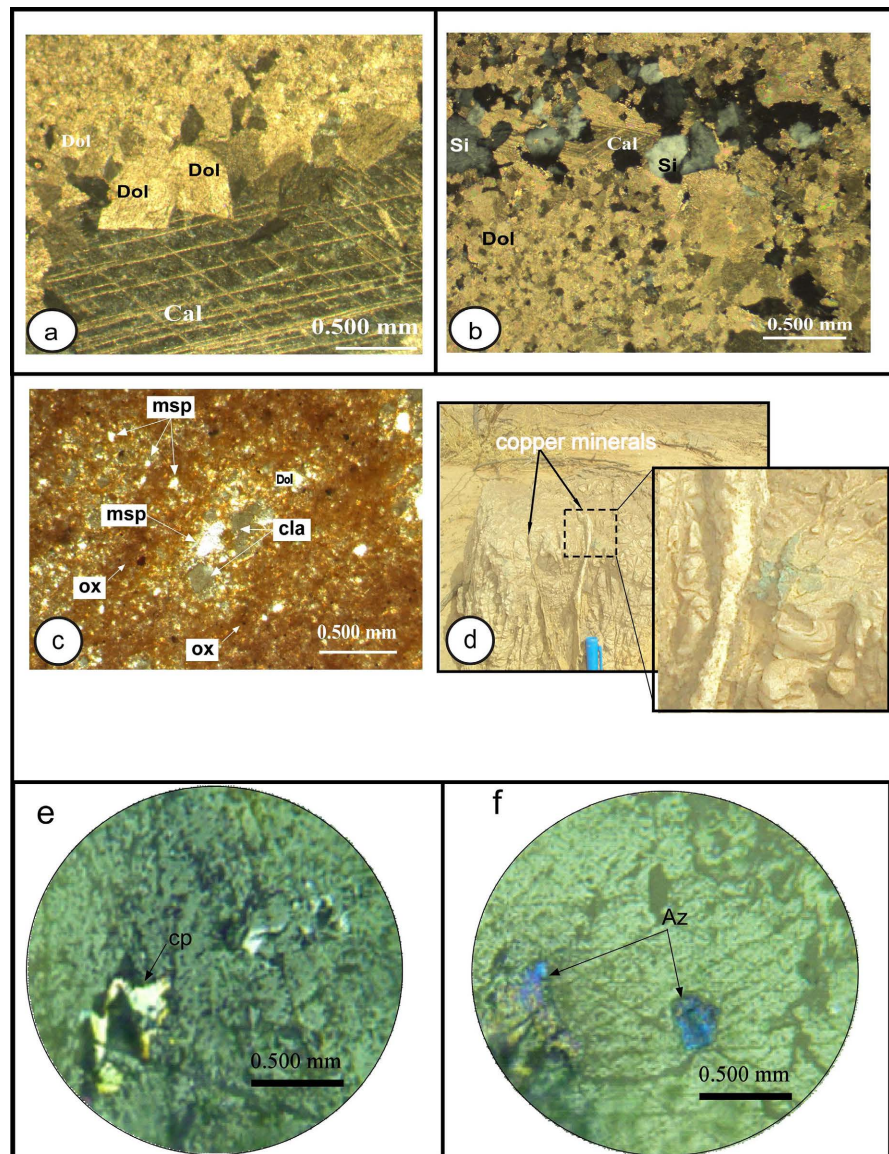


Figure 7. Photomicrograph in the carbonate deposits of lithofacies Fr7. (a) and (b): Thin section in of dolomite marbles observed in reflected light; (c): thin section in variegated carbonates observed in reflected light. Cal: calcite, Dol: dolomite, Si: silica; msp: micro-sparite, cla: clay, Ox: oxides. (d): indice of copper minerals in dolomitic marbles, (e), (f): polished sections showing the presence of azurite (az) and chalcopyrite (cp).

The Fr9 lithofacies, corresponding to marine deposits of the top of “*Béli-Garous*” Formation, is made up of shales, clays and silexites of varying color. These rocks show locally lenses of quartz sandstone (Figure 5).

4.2. Geochemical Characteristics of Uppermost “*Béli-Garous*” Formation

These geochemical analyses are focus on the uppermost “*Béli-Garous*” Formation, which include variable rocks such as cataclased quartzitic sandstones, filled with oxides (FI11), shales (FI3), silexites (FI7), variegated carbonates (FI7) and dolomitic

marbles (FI12).

Major elements

The results of the geochemical analysis of major elements in the sediments sampled as part of this study show high levels of SiO₂ (55.20%), Al₂O₃ (5.50%), Fe₂O₃ (13.94%), CaO (6.15%), MgO (3.69%) and relatively low levels of K₂O (1.59%), Na₂O (0.50%) and MnO (0.82%) (**Table 1**).

Table 1. Geochemical analyses in major elements.

Samples	FI3	FI4	FI7	FI11	FI12
Majors elements (wt%)					
SiO ₂	68.42	69.5	87.84	43.58	6.56
TiO ₂	0.646	0.1	0.131	0.267	0.044
Al ₂ O ₃	12.2	2.28	5.36	6.38	1.32
Fe ₂ O ₃	6.23	25.35	1.26	35.83	1.04
MnO	0.032	0.222	0.522	2.774	0.54
MgO	1.72	0.2	0.15	0.2	16.18
CaO	0.06	0.1	0.08	0.17	30.34
Na ₂ O	0.04	0.04	1.7	0.04	0.72
K ₂ O	9	0.52	0.3	1.16	0.01
P ₂ O ₅	0.04	<0.01	0.02	0.58	0.03
LOI	3.45	1	1.25	8.53	41.64
Total	98.85	99.32	98.6	99.52	98.75

The high SiO₂ content (55.20%) reflects quartz enrichment, while the high Al₂O₃ content (5.50%) is due to the clay mineral content of some of the samples taken at Firgoun, particularly the shales. The Al₂O₃/SiO₂ ratio values are less than 1, confirming the quartz enrichment according to Crook's (1974) classification.

These high SiO₂ and Al₂O₃ values suggest a felsic source for the sediments. The high iron content, 13.94% in average, can be linked to hematite enrichment in the samples studied. The high CaO and MgO values, ranging respectively from 6.15%, and from 3.69%, attest to the carbonate nature of some of the samples studied, particularly the limestone and dolomitic marble samples.

The diagram (Al₂O₃ + K₂O + Na₂O₃ versus SiO₂), commonly used by Suttner & Dutta (1986) to discriminate the climatic conditions of the depositional paleoenvironment, was adopted for the study of the Firgoun sediments.

The different samples, plotted in the Al₂O₃ + K₂O + Na₂O₃ versus SiO₂ diagram, define a field corresponding to either humid or arid conditions (**Figure 8**).

Trace elements

Trace elements analysis shows very high values for Ba (8789 ppm) and Sr (1703 ppm) in the dolomitic marbles (FI12), while for all the samples studied, concentrations are moderate for Rb (1 to 150 ppm) and low for Cs (0.1 to 6.3 ppm).

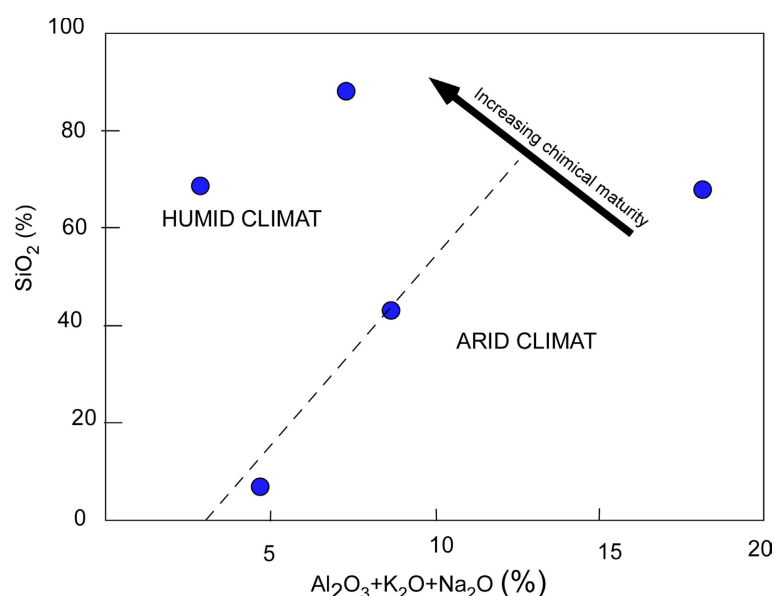


Figure 8. Characterization of the climate of the depositional environment of the Firgoun sediments, deduced from the samples projected in the diagram of [Suttner & Dutta \(1986\)](#).

The trace element profile of the Firgoun samples, normalised to the UCC (Upper Crust Continental, [Taylor & McLennan, 1985](#)), show positive Ba peaks, which are more pronounced in the dolomitic marbles ([Figure 9](#)), suggesting that they are enriched in Ba.

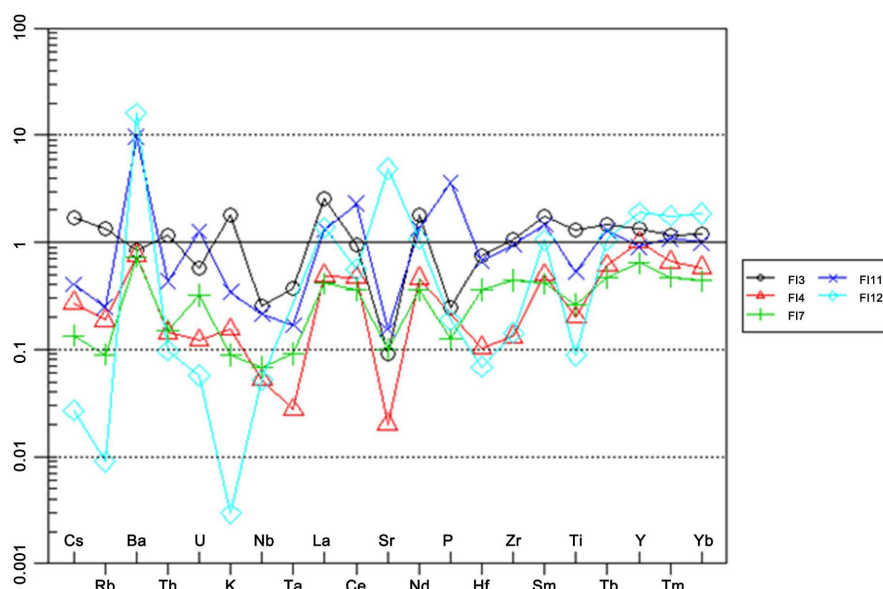


Figure 9. Spectrum of trace elements normalized to UCC values ([Taylor & McLennan, 1985](#)).

The negative peaks in Rb, K and Sr recorded in the trace element spectra of the majority of samples reflect their depletion in the samples investigated. Whereas, the exceptional recording of positive peaks in K and Sr, respectively at the level of

the spectra of schists and dolomitic marbles, suggests their enrichment.

Ba, Rb, K and Cs belong to the LILE (Large Ion Lithophile Elements) group. Due to their highly mobile nature, enrichment in LILE could be the consequence of alteration phenomena (Pelleter, 2007). The variations in LILE elements in the samples taken at Firgoun could be due to weathering. The high Sr content (1703 ppm) recorded in the dolomitic marbles (FI12) and the low Fe/Sr, Mn/Sr and Ca/Sr ratios (<0.01) indicate, according to Frimmel (2009), very limited post-sedimentary alteration.

Geochemical data also indicate low contents of Hf (0.4 to 4.3 ppm), Nb (1.3 to 6.4 ppm), but a high concentration of Zr (205 ppm). These elements belonging to the HFSE group (High Field Strength Elements) have an immobile character.

C and O Isotope Analysis of Carbonates

C and O isotope analyses of the carbonate deposits (sample FIR3) were used to clarify the stratigraphic position of the Firgoun carbonates during the Neoproterozoic glaciations. Given the apparent absence of biostratigraphic markers and the lack of radiometric dating for Neoproterozoic carbonate deposits, the use of C and O isotopes represents an important tool for making stratigraphic correlations for this period.

Indeed, periods of glaciation are generally associated with a strong reduction in organic activity, which drives the fractionation of carbon isotopes (Pelleter, 2007). As a result, C and O isotope compositions can be used to estimate the extent of physico-chemical alterations (diagenesis) that the sediment undergone after its formation.

The results of isotopic analysis on carbonates (sample FIR3 of dolomitic limestone taken from the upper levels of the “Beli-Garous” formation) provided $\delta^{13}\text{C}$ (-7.1‰) and $\delta^{18}\text{O}$ (-15.6‰) values. According to Font (2005), the $\delta^{18}\text{O}$ of meteoric waters is essentially controlled by evaporation/condensation processes (Rayleigh distillation), which depend on geographical latitude and altitude (or depth) and have values ranging from -40‰ to $+5.7\text{‰}$ (mantle: $5.7\text{‰} \pm 0.3\text{‰}$). Therefore, the $\delta^{18}\text{O}$ (-15.6‰) value obtained suggests a probable influence of meteoritic waters on the carbonates. On the other hand, the negative $\delta^{13}\text{C}$ values of the Firgoun carbonates ($\delta^{13}\text{C} = -7.1\text{‰}$) indicate a drastic decrease in organic activity (Hoffman et al., 1998) and testify to a significant period of glaciation in the Firgoun area during the Neoproterozoic.

5. Discussion

5.1. Depositional Environment of “Firgoun Sandstone” Formation

This formation is characterized by marine sedimentation with brief fluvial episodes (Alzouma Amadou et al., 2020). The model of depositional environment could be illustrated in Figure 10.

In fact, the lithofacies Fr1 is characterized by poorly sorted matrix-supported conglomeratic to microconglomeratic horizons at the bottom. The presence of

blunt and subrounded pebbles in the lithofacies Fr1 of Firgoun area points to a fluvial influence (Alzouma Amadou et al., 2020).

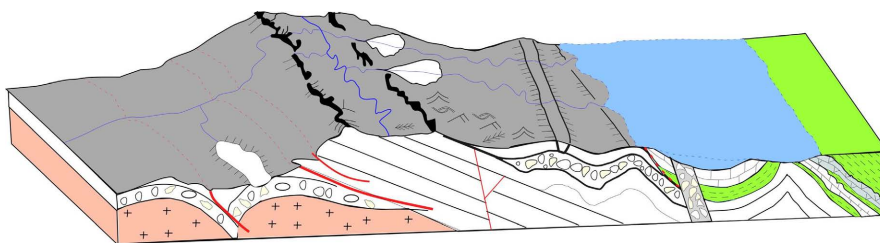


Figure 10. Model of the depositional environment proposed for the Firgoun sediments.

Whereas marine sedimentation is manifested by the presence of a flyschoid-like succession attributed to the Bouma turbiditic sequence in the intermediate deposits (lithofacies Fr2) and the presence of tidal dynamics sedimentary structures characteristic (HCS, oblique bedding associated with symmetrical and asymmetrical ripples) observed in the upper deposits (lithofacies Fr3) of the “Firgoun Sandstone” Formation. Symmetrical or oscillation ripples generally result from bidirectional wave movements (Reineck & Singh, 1973; Alzouma Amadou et al., 2020).

5.2. Depositional Environment of “Béli-Garous” Formation

The “Béli-Garous” formation is characterized by marine sedimentation under glacial influence (Alzouma Amadou et al., 2020) (Figure 10).

The presence of sedimentary structures characteristic of tidal dynamics, notably asymmetrical ripples with rounded or flattened crests, linguoid undulating ripples, sometimes associated with hardgrounds at the tops of benches, herringbone structure (lithofacies Fr4), bundles of intersecting oblique bedding (lithofacies Fr5) and hummocky cross stratifications (lithofacies Fr6) indicate a shallow marine sedimentation. However, the intermediate levels of lithofacies Fr6 are marked by the presence of matrix-supported faceted pebble conglomerates, attributed to glaciogenic deposits (diamictites) (Reineck & Singh, 1973; Campbell, 1967; Collinson & Thompson, 1989). The glacial origin of the diamictites is attested by the presence of faceted pebbles (Le Hir, 2007). The lithofacies Fr6, characterized by occurrences of diamictites associated with marine-type deposits, would have been set up in a mixed glacio-marine environment. In such an environment, the arrival of large boulders seems to be accidental. Only ice rafts, which drop sedimentary material as they melt, can give rise to sedimentation of this type (Konaté et al., 2018).

Marine sedimentation continues in the upper lithofacies, notably in lithofacies Fr7 (slates with intercalated carbonates), lithofacies Fr8 (silexites) and lithofacies Fr9 (shales). The carbonate deposits in the Firgoun region, notably the variegated carbonates and the purplish-pink dolomitic marbles of lithofacies Fr7, often show centimetric cavities interpreted as dissolution figures comparable to the “bird-

eyes limestone” of Nichols (2009). These types of structures generally appear in intertidal environments (Chamley & Deconinck, 2011; Nichols, 2009). According to Chamley & Deconinck (2011), these structures result from trapped air bubbles. Indeed, the abundance of solution cavities and fractures associated to carbonates capping glacial sediments have been described in the Taoudenni basin (Álvaro et al., 2023).

The slates of the lithofacies Fr7 locally display upturned beds or cryoturbation structures (Konaté et al., 2018; Alzouma Amadou et al., 2020). These peculiar structures, attributed to freeze-thaw phenomena, represent an important indicator of periglacial environments (Arbey, 1987; Nichols, 2009). Both, the interbedded diamictites of lithofacies Fr6, the carbonates of lithofacies Fr7 and the silexites of lithofacies Fr8 form the terms of the “Tillites-Carbonates-Silexites” triad, a stratigraphic marker characteristic of the Taoudenni, Gourma and Volta basins. As a result, the interbedded diamictites (lithofacies Fr6) of the Firgoun region have been assimilated to the Neoproterozoic glaciation (probably the Late Cryogenian glaciation, Konaté et al., 2018).

In the Taoudenni basin, the carbonate deposits covering the neoproterozoic glaciogenic sediments have been interpreted as one of the characteristics of the beginning of the postglacial eustatic transgression (Rossi et al., 1984).

5.3. Paleoclimatic Conditions

The result from the projection of the samples in the $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}_3$ versus SiO_2 diagram (Suttner & Dutta, 1986) reveals mixed paleoclimatic conditions (humid and arid) for the sediments of uppermost “Béli-Garous” Formation. According to Nesbitt & Young (1996), intense chemical weathering is strongly associated with a warm, humid climate. The diagram Suttner & Dutta (1986) has been used in order to establish the paleoclimatic conditions on the basis of lithogeochemical characteristics of variable rocks from the “Béli-Garous” sequence. The interpretation of the diagram reveals:

- On the one hand, a humid climate characterized by high chemical maturity, likely due to the high SiO_2 contents (over 65%) in the lower siliciclastic deposits of the Béli-Garous Formation. Furthermore, the low Al_2O_3 , K_2O , and P_2O_5 contents imply a considerable terrigenous input.
- On the other hand, an arid climate characterized by low chemical maturity, which is reflected in high Al_2O_3 , K_2O , and P_2O_5 contents. This characterizes the upper deposits of the Béli-Garous Formation, implying a low terrigenous input, particularly in the carbonates (lithofacies Fr7) deposited in a marine paleoenvironment under arid conditions.

These observations are in agreement with hypothetical boundary or transition between glacial deposits and cap carbonates (Harland, 1964; Kirschvink, 1992; Hoffman et al., 1998). The result is supported by the identification of the carbonate deposits, in particular the marbles and dolomitic limestones (post-glacial carbonate) of lithofacies Fr7 under arid climate condition, which systematically follow

glacial deposits (interbedded diamictites of lithofacies Fr6) under humid climat.

The carbonate rocks of the lithofacies Fr7 overlie in places the interbedded diamictite (lithofacies Fr6) and locally onto slates exhibiting cryoturbation structures. The transition from these slates presenting cryoturbation features to carbonate deposits in the Firgoun region is very similar to the horizon of green pelites intercalated within carbonate beds attributed to the last glacial phase of the Infra-cambrian in the Majâbat region (Taoudenni basin, Fabre, 2010a). This abrupt transition between glacial sediments and carbonates is at the origin of the Neoproterozoic climatic paradox, suggesting a rapid transition from glacial (“*ice-house*”) to tropical (“*green-house*”) conditions (Harland, 1964; Kirschvink, 1992; Hoffman et al., 1998). Therefore, these authors attributed the overlying carbonates to marine warm-water facies (Porter et al., 2004).

5.4. Correlations of Firgoun Carbonate Deposits with West Africa Cap Carbonates

The Firgoun carbonates have been classified as cap carbonates based on field observations, particularly lithological criteria, due to their belonging to the “Neoproterozoic Triad”. They are part of a typical sequence associating tillites/diamictites (glacial formations), carbonates (limestones and dolomites), and silicites/cherts (Konaté et al., 2018).

The carbonate deposits of the Firgoun region, similar to their equivalents deposits in the Neoproterozoic basins of Taoudenni (Shields et al., 2007a), Volta (Affaton, 1990; Porter et al., 2004) and Gourma (Fullgraf et al., 2007; Miningou et al., 2010), are closely associated with “triad” glacial deposits that is considered as an evidence of major stratigraphic marker for Neoproterozoic glaciations in West Africa. The triad has been founded at the base of the Supergroup 2 (Taoudenni basin) and the base of the Oti Supergroup (Volta basin). Indeed, these transgressive carbonate deposits observed in Firgoun region locally overlie shales exhibiting cryoturbation features characteristics of periglacial environment.

Due to the scarcity of radiometric, paleomagnetic and paleontological (traces of stromatolite fossils) data, the stratigraphic position of the cap carbonates is difficult to constrain. In West Africa, the glacial and postglacial succession marking the transition from tillite deposits to cap carbonates was related to the Cryogenian-Ediacaran boundary (Shields et al., 2007a).

A Marionan or late Cryogenian age (ca.635 Ma, Deynoux et al., 2006; Shields et al., 2007a) has been assigned to the Neoproterozoic glacial deposits at the base of the carbonates on the basis of stratigraphic correlations supported by some radiometric, isotopic and paleontological data. Lahondère et al. (2005) reported two U-Pb radiometric ages (609.7 ± 5.5 Ma, U/Pb on zircon and 604 ± 6 Ma, U/Pb SHRIMP) in the volcanic tuffs of the Téniaïgourou formation, which overlies the glacial deposits of the Jbélat formation in Mauritania (Taoudenni basin). In the Volta basin, a Lu-Hf age of 576 ± 13 Ma was also obtained in the phosphorites overlain by cap carbonates and glacial deposits (Barfod et al., 2004). As a result,

the Neoproterozoic glacial deposits overlain by cap carbonates in the Taoudenni and Volta basins were finally correlated with other glacial formations observed elsewhere in the world, in particular the famous Elatina-Ghaub-Nantuo glacial formation (ca. 635 Ma, [Shields et al., 2007a, 2007b](#)).

Compared with their equivalents in the Béli region (Gourma Basin SE border, [Fullgraf et al., 2007](#); [Miningou et al., 2010](#)), which present stromatolitic structures characteristic of tidal environments ([Miningou et al., 2010, 2017](#)), the carbonate deposits in the Firgoun region do not show stromatolites traces. This makes correlations difficult between the carbonates of the Firgoun region and the Cap carbonates of the Taoudenni basin ([Shields et al., 2007a](#)), and Béli region in Gourma ([Miningou et al., 2010, 2017](#); [Fullgraf et al., 2007](#)) considered age late-Cryogenian (ca. 635 Ma, [Shields et al., 2007a](#)).

However, preliminary stable isotope results ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) reveal a probable correlation between carbonates from the Firgoun region and those obtained in Cap carbonates from the Taoudenni ([Shields et al., 2007a](#)), Volta ([Porter et al., 2004](#)) basins and Béli area in the Gourma basin ([Fullgraf et al., 2007](#)). The $\delta^{13}\text{C}$ isotopic signature of the carbonates from the Firgoun region indicates a negative value of -7.1‰ , different with those provided by the post-Marinoan Cap dolomites in the Taoudenni and Volta basins global average around -4‰ ([Porter et al., 2004](#); [Shields et al., 2007a](#)). However, exceptional isotopic value of -8.5‰ is obtained from the Volta basin carbonate sediments ([Porter et al., 2004](#)). In the Taoudenni basin, the rare isotopic values reported from the post-Marinoan carbonates, notably -6.8‰ from the Cliffs (Mauritania) ([Shields et al., 2007b](#)) and Kayes (Mali) ([Álvaro et al., 2023](#)) localities and -6.4‰ in Walidiala valley (Senegal-Guinea, [Shields et al., 2007a](#)) are near to that obtained in the Firgoun carbonates. The Cap dolomites of Jbéliat in the Mauritanian Adrar provided distinct values ($\delta^{13}\text{C}$ values between -3.7‰ and $+1.3\text{‰}$, Taoudenni basin, [Shields et al., 2007b](#)) to those obtained in the Firgoun carbonates.

While the $\delta^{18}\text{O}$ value (-15.6‰) is close to the lowest value provided by the Taoudenni Cap dolomites $\delta^{18}\text{O}$ (-13.4‰ , in the Mauritanian Adrar, [Shields et al., 2007b](#)), but slightly different from those of the Volta Basin Marinoan Cap dolomites ($\delta^{18}\text{O}$ between -9.20‰ and -2.41‰ , [Porter et al., 2004](#)). Isotopic values similar to those of the Firgoun carbonates have also been reported in the Kayes area cap carbonates, Taoudenni basin (-11.8‰ and -5.0‰ , [Álvaro et al., 2023](#)). These observations support probably the Rb-Sr age (600 Ma, [Reichelt, 1972](#)) obtained in shales interbedded with carbonates from the lower part of the Ydouban Group.

6. Conclusion

The carbonate sequences of the Firgoun region show sedimentological similarities with those including in the Late Cryogenian “Tillites-carbonates-silexites” triad ([Shields et al., 2007a](#)), characteristic of the Taoudenni, Gourma (Béli area) and Volta basins ([Affaton, 1990](#); [Porter et al., 2004](#); [Shields et al., 2007a](#); [Miningou et](#)

al., 2010, 2017; Fullgraf et al., 2007).

In the Firgoun region, the carbonate horizons, capped by the silicites deposits of lithofacies Fr8, are underlied by the intermediate diamictites of lithofacies Fr6 at their bottom. These carbonate deposits were deposited in a shallow marine environment.

Despite the lack of fossil evidence, in particular the stromatolites described in the neighbouring Taoudenni and Gourma (Béli area) basins (Shields et al., 2007a; Miningou et al., 2010, 2017; Fullgraf et al., 2007), the variegated carbonates (dolomitic limestones) of Firgoun show centimetric cavities interpreted as dissolution figures similar to the birds eyes limestones (Nichols, 2009) characteristic of tidal environments (Chamley & Deconinck, 2011; Nichols, 2009).

Projection of the major elements from the Firgoun sediment samples in the geochemical diagram ($\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}_3$ versus SiO_2 , Suttner & Dutta, 1986) reveals mixed paleoclimatic characteristics (arid and humid). This observation is compatible with the transition which marks the passage between the intermediate diamictite glacial sediments and the cap carbonates considered to be marine warm-water facies (Porter et al., 2004).

According to several authors, this succession, widely described in Africa and elsewhere in the world, suggests a rapid transition from glacial (“ice-house”) to tropical (“green-house”) conditions (Harland, 1964; Kirschvink, 1992; Hoffman et al., 1998).

The results of the isotopic signatures ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) also show negative values ($\delta^{13}\text{C}$ (−7.1‰) and $\delta^{18}\text{O}$ (−15.6‰)) close to those of the cap dolomites of the Taoudenni and Volta basins. This suggests a possible correlation between the carbonates of the Firgoun region and those of the Taoudenni and Volta basins that cap tillites of the Late-Cryogenian glaciation (ca. 635 Ma, Shields et al., 2007a).

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Conflicts of Interest

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

References

- Affaton, P. (1990). *Le bassin des volta: Une marge passive d’âge protérozoïque supérieur tectonisée au panafricain (600 ±50 Ma)*. Éd. ORSTOM.
- Affaton, P., Gaviglio, P., & Pharisat, A. (2000). Réactivation du craton ouest-africain au Panafricain: Paléocontraintes déduites de la fracturation des grès néoprotérozoïques de Karey Gorou (Niger, Afrique de l’Ouest). *Comptes Rendus de l’Académie des Sciences-Series IIA-Earth and Planetary Science*, 331, 609-614.
[https://doi.org/10.1016/s1251-8050\(00\)01445-2](https://doi.org/10.1016/s1251-8050(00)01445-2)
- Allen, P. A., & Hoffman, P. F. (2005). Extreme Winds and Waves in the Aftermath of a

- Neoproterozoic Glaciation. *Nature*, 433, 123-127. <https://doi.org/10.1038/nature03176>
- Álvaro, J. J., Billström, K., Hallmann, C., Hoshino, Y., & Jorge, A. (2023). Ediacaran Cap Carbonates with Microbial Build-Ups Capping Barite-Bearing Methane Seep Networks in the Kaarta Mountains, Taoudeni Basin, Mali. *Sedimentary Geology*, 455, Article 106481. <https://doi.org/10.1016/j.sedgeo.2023.106481>
- Alzouma Amadou, D., Konaté, M., & Ahmed, Y. (2020). Geodynamic Context of the Proterozoic Deposits of the Firgoun Region (Eastern Border of the West African Craton, West Niger). *Geological Society, London, Special Publications*, 502, 215-236. <https://doi.org/10.1144/sp502-2019-115>
- Arbey, F. (1987). Précisions sur la genèse de figures de gel rencontrées dans les sédiments fini-ordoviciens des monts d'Ougarta (Sahara Algérien). In *Comparaison avec l'Actuel. 112eme Congrès National des Sociétés Savantes, 2e Colloque Géologie Africaine* (pp. 239-264).
- Barfod, G. H., Vervoort, J. D., Montanez, I. P., & Riebold, S. (2004). Lu-Hf Geo-Chronology of Phosphates in Ancient Sediments. In *Goldschmidt Conference Abstract* (pp. 5-11).
- Bertrand-Sarfati, J., Moussine-Pouchkine, A., & Caby, R. (1987). Les corrélations du Protérozoïque au cambrien en afrique de l'Ouest: Nouvelle interprétation géodynamique. *Bulletin de la Société Géologique de France*, 5, 855-865.
- Bowring, S., Myrow, P., Landing, E., Ramezani, J., & Grotzinger, J. (2003). Geo-Chronological Constraints on Terminal Proterozoic Events and the Rise of the Metazoans. *Geology*, 44, 955-958.
- Campbell, C. V. (1967). Lamina, Laminaset, Bed and Bedset. *Sedimentology*, 8, 7-26. <https://doi.org/10.1111/j.1365-3091.1967.tb01301.x>
- Chamley, H., & Deconinck, J-F. (2011). *Bases de sédimentologie* (3e éd.). Dunod.
- Cloud, P., Wright, L. A., Williams, E. G., Diehl, P., & Walter, M. R. (1974). Giant Stromatolites and Associated Vertical Tubes from the Upper Proterozoic Noonday Dolomite, Death Valley Region, Eastern California. *Geological Society of America Bulletin*, 85, 1869-1882. [https://doi.org/10.1130/0016-7606\(1974\)85<1869:gsaavt>2.0.co;2](https://doi.org/10.1130/0016-7606(1974)85<1869:gsaavt>2.0.co;2)
- Collinson, J. D., & Thompson, D. B. (1989). *Sedimentary Structures* (207 p). Chapman & Hall.
- Corkeron, M. L., & George, A. D. (2001). Glacial Incursion on a Neoproterozoic Carbonate Platform in the Kimberley Region, Australia. *Geological Society of America Bulletin*, 113, 1121-1132. [https://doi.org/10.1130/0016-7606\(2001\)113<1121:gioanc>2.0.co;2](https://doi.org/10.1130/0016-7606(2001)113<1121:gioanc>2.0.co;2)
- Couëffé, R., & Vecoli, M. (2011). New Sedimentological and Biostratigraphic Data in the Kwahu Group (Meso- to Neo-Proterozoic), Southern Margin of the Volta Basin, Ghana: Stratigraphic Constraints and Implications on Regional Lithostratigraphic Correlations. *Precambrian Research*, 189, 155-175. <https://doi.org/10.1016/j.precamres.2011.05.009>
- Crook, K. A. W. (1974). Lithogenesis and Geotectonics: The Significance of Compositional Variation in Flysch Arenites (Graywackes). In R. H. Dott, & R. H. Shaver (Eds.), *Modern and Ancient Geosynclinal Sedimentation* (pp. 304-310). SEPM (Society for Sedimentary Geology). <https://doi.org/10.2110/pec.74.19.0304>
- Deynoux, M., Affaton, P., Trompette, R., & Villeneuve, M. (2006). Pan-African Tectonic Evolution and Glacial Events Registered in Neoproterozoic to Cambrian Cratonic and Foreland Basins of West Africa. *Journal of African Earth Sciences*, 46, 397-426. <https://doi.org/10.1016/j.jafrearsci.2006.08.005>
- Eyles, N., & Januszczak, N. (2004). "Zipper-Rift": A Tectonic Model for Neoproterozoic Glaciations during the Breakup of Rodinia after 750 Ma. *Earth-Science Reviews*, 65, 1-73. [https://doi.org/10.1016/s0012-8252\(03\)00080-1](https://doi.org/10.1016/s0012-8252(03)00080-1)

- Fabre, J. (2010a). Evolution du Sahara central et occidental du Précambrien à nos jours. In *1er Colloque International sur la Géologie du Sahara Algérien: Ressources Minérales, Hydrocarbures et Eau* (pp. 44-58).
- Fabre, S. (2010b). *Altération continentale et sédimentation marine au Précambrien: Marqueurs de l'évolution chimique des enveloppes fluides terrestres*. Doctorat de l'Université de Toulouse.
- Font, E. C. (2005). Paléomagnétisme des cap carbonates du Craton Amazonien (Brésil): Implications pour les glaciations du néoproterozoïque/Paleomagnetismo dos carbonatos decapa do Cráton Amazônico (Brasil): Implicações para as glaciações do neoproterozóico. Thèse, Toulouse III, Paul Sabatier (UFR Sciences), Institut de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, USP, 200p.
- Frimmel, H. E. (2009). Trace Element Distribution in Neoproterozoic Carbonates as Palaeo-environmental Indicator. *Chemical Geology*, 258, 338-353.
<https://doi.org/10.1016/j.chemgeo.2008.10.033>
- Fullgraf, T., Savanier, D., Le Metour, J., Lahondere, D., Caby, R., Affaton, P., Tairou, M.S., Camara, M., Traoré, A., Zormé, B., Diarra, B., Sidibé, M., Sanogo, I., Bailly, L., Cocherie, A., Goscombe, B., Tegye, M., & Wemmer, K. (2007). *Notice explicative générale des cartes géologiques à 1/200000*. Ministère des Mines de l'Energie et de l'Eau.
- Garba Saley, H., Konaté, M., & Okunlola, O. A. (2024). Petrographic Study of Mn-Bearing Gondite (Birimian) of Téra Area in the Leo-Man Shield (West African Craton) in Niger. *Economic and Environmental Geology*, 57, 25-39.
<https://doi.org/10.9719/eeg.2024.57.1.25>
- Halverson, G. P., Maloof, A. C., & Hoffman, P. F. (2004). The Marinoan Glaciation (Neoproterozoic) in Northeast Svalbard. *Basin Research*, 16, 297-324.
<https://doi.org/10.1111/j.1365-2117.2004.00234.x>
- Harland, W. B. (1964). *Evidence of late Precambrian Glaciation and Its Significance: Problems in Palaeoclimatology* (A. E. M. Nairn, ed., pp. 119-149). Interscience, John Wiley & Sons.
- Hoffman, P. F., & Schrag, D. P. (2002). The Snowball Earth Hypothesis: Testing the Limits of Global Change. *Terra Nova*, 14, 129-155.
<https://doi.org/10.1046/j.1365-3121.2002.00408.x>
- Hoffman, P. F., Kaufman, A. J., Halverson, G. P., & Schrag, D. P. (1998). A Neoproterozoic Snowball Earth. *Science*, 281, 1342-1346. <https://doi.org/10.1126/science.281.5381.1342>
- James, N. P., Narbonne, G. M., & Kyser, T. K. (2001). Late Neoproterozoic Cap Carbonates: Mackenzie Mountains, Northwestern Canada: Precipitation and Global Glacial Melt-down. *Canadian Journal of Earth Sciences*, 38, 1229-1262.
<https://doi.org/10.1139/e01-046>
- Kennedy, M. J. (1996). Stratigraphy, Sedimentology, and Isotopic Geochemistry of Australian Neoproterozoic Postglacial Cap Dolostones; Deglaciation, Delta 13 C Excursions, and Carbonate Precipitation. *Journal of Sedimentary Research*, 66, 1050-1064.
<https://doi.org/10.2110/jsr.66.1050>
- Kennedy, M. J., Christie-Blick, N., & Sohl, L. E. (2001). Are Proterozoic Cap Carbonates and Isotopic Excursions a Record of Gas Hydrate Destabilization Following Earth's Coldest Intervals? *Geology*, 29, 443-446.
[https://doi.org/10.1130/0091-7613\(2001\)029<0443:apccai>2.0.co;2](https://doi.org/10.1130/0091-7613(2001)029<0443:apccai>2.0.co;2)
- Kirschvink, J. L. (1992). Late Proterozoic Low-Latitude Global Glaciation: The Snowball Earth. In J. W. Schopf, & C. Klein (Eds.), *The Proterozoic Biosphere* (pp. 51-52). Cambridge University Press.
- Konaté, M., Ahmed, Y., Gärtner, A., Alzouma Amadou, D., Ibrahim Maharou, H., Tourba,

- K. et al. (2018). U-Pb Detrital Zircon Ages of Sediments from the Firgoun and Niamey Areas (Eastern Border of West African Craton, West Niger). *Comptes Rendus. Géoscience*, 350, 267-278. <https://doi.org/10.1016/j.crte.2018.06.005>
- Lahondère, D., Roger, J., Le Metour, J., Donzeau, M., Guillocheau, F., Helm, C., Thieblemont, D., Cocherie, A., & Guerrot, C. (2005). *Notice explicative des cartes géologiques à 1/200,000 et 1/500,000 de l'extrême sud de la Mauritanie* (610 p). DMG, Ministère des Mines et de l'Industrie.
- Le Hir, G. (2007). *Comprendre et modéliser les glaciations du néoproterozoïque et les phénomènes associés*. Thèse de l'Université Paris XI ED.
- Machens, E. (1973). *Contribution à l'étude des formations du socle cristallin et de la couverture sédimentaire de l'Ouest de la république du Niger* (167 p). BRGM.
- Miningou, M. Y. W., Affaton, P., Bamba, O., & Lompo M. (2010). Mise en évidence d'une triade glaciaire néoproterozoïque et d'une molasse dans la région du béli, bassin du gourma, nord-est Burkina Faso. *Journal of Sciences*, 10, 55-68.
- Miningou, M. Y. W., Affaton, P., Meunier, J., Blot, A., & Nebie, A. G. (2017). Establishment of a Lithostratigraphic Column in the Béli Area (Northeastern Burkina Faso, West Africa) Based on the Occurrence of a Glacial Triad and a Molassic Sequences in Neoproterozoic Sedimentary Formations. Implications for the Pan-African Orogeny. *Journal of African Earth Sciences*, 131, 80-97. <https://doi.org/10.1016/j.jafrearsci.2017.03.016>
- Nesbitt, H. W., & Young, G. M. (1996). Petrogenesis of Sediments in the Absence of Chemical Weathering: Effects of Abrasion and Sorting on Bulk Composition and Mineralogy. *Sedimentology*, 43, 341-358. <https://doi.org/10.1046/j.1365-3091.1996.d01-12.x>
- Nichols, G. (2009). *Sedimentology and Stratigraphy* (2nd ed.). John Wiley & Sons.
- Pelleter, E. (2007). *Géologie, géochimie et géochronologie du gisement aurifère de Tamlalt-Menhouhou (Haut-Atlas oriental)*. Thèse de Docteur de l'Institut National Polytechnique de Lorraine.
- Plumb, K. A. (1991). New Precambrian Time Scale. *Episodes*, 14, 139-140. <https://doi.org/10.18814/epiiugs/1991/v14i2/005>
- Porter, S. M., Knoll, A. H., & Affaton, P. (2004). Chemostratigraphy of Neoproterozoic Cap Carbonates from the Volta Basin, West Africa. *Precambrian Research*, 130, 99-112. <https://doi.org/10.1016/j.precamres.2003.10.015>
- Reichelt, R. (1972). *Géologie du gourma (Afrique occidentale), un "seuil" et un bassin du précambrien supérieur* (Vol. 53, p. 213). Mémoires du Bureau de Recherches Géologiques et Minières.
- Reineck, H. E., & Singh, I. B. (1973). *Depositional Sedimentary Environments* (439 p). Springer Verlag.
- Rossi, P., Deynoux, M., & Simon, B. (1984). Les formations glaciaires du Précambrien terminal et leur contexte stratigraphique (Formations pré et postglaciaires et dolérites du massif du kaarta) dans le bassin de taoudéni au mali occidental (Afrique de l'Ouest). *Sciences Géologiques. Bulletin*, 37, 91-106. <https://doi.org/10.3406/sgeol.1984.1656>
- Shields, G. A., Deynoux, M., Culver, S. J., Brasier, M. D., Affaton, P., & Vandamme, D. (2007a). Neoproterozoic Glaciomarine and Cap Dolostone Facies of the Southwestern Taoudéni Basin (Walidiala Valley, Senegal/Guinea, NW Africa). *Comptes Rendus. Géoscience*, 339, 186-199. <https://doi.org/10.1016/j.crte.2006.10.002>
- Shields, G. A., Deynoux, M., Strauss, H., Paquet, H., & Nahon, D. (2007b). Barite-Bearing Cap Dolostones of the Taoudéni Basin, Northwest Africa: Sedimentary and Isotopic Evidence for Methane Seepage after a Neoproterozoic Glaciation. *Precambrian Research*, 153, 209-235. <https://doi.org/10.1016/j.precamres.2006.11.011>

- Soumaila, A., Henry, P., Garba, Z., & Rossi, M. (2008). REE Patterns, Nd-Sm and U-Pb Ages of the Metamorphic Rocks of the Diagorou-Darbani Greenstone Belt (Liptako, SW Niger): Implication for Birimian (Palaeoproterozoic) Crustal Genesis. *Geological Society, London, Special Publications*, 297, 19-32. <https://doi.org/10.1144/sp297.2>
- Suttner, L. J., & Dutta, P. K. (1986). Alluvial Sandstone Composition and Paleoclimate; I, Framework Mineralogy. *Journal of Sedimentary Research*, 56, 329-345. <https://doi.org/10.1306/212f8909-2b24-11d7-8648000102c1865d>
- Tahata, M., Sawaki, Y., Yoshiya, K., Nishizawa, M., Komiya, T., Hirata, T. et al. (2015). The Marine Environments Encompassing the Neoproterozoic Glaciations: Evidence from C, Sr and Fe Isotope Ratios in the Hecla Hoek Supergroup in Svalbard. *Precambrian Research*, 263, 19-42. <https://doi.org/10.1016/j.precamres.2015.03.007>
- Taylor, S. R., & McLennan, S. M. (1985). *The Continental Crust: Its Composition and Evolution* (312 p). Blackwell Scientific Publications.
- Trompette, R. (1973). *Le précambrien supérieur et le paléozoïque inférieur de l'adras des mauritanie (Bordure occidentale du bassin de taoudeni, Afrique de l'Ouest). Un exemple de sédimentation de craton. Etude stratigraphique et sédimentologique* (Tomes 1 et 2, 573 p). Travaux du Laboratoire des Sciences de la Terre.
- Villeneuve, M. (2008). Review of the Orogenic Belts on the Western Side of the West African Craton: The Bassarides, Rokelides and Mauritanides. *Geological Society, London, Special Publications*, 297, 169-201. <https://doi.org/10.1144/sp297.8>
- Young, G. M. (2013). Evolution of Earth's Climatic System: Evidence from Ice Ages, Isotopes, and Impacts. *GSA Today*, 23, 4-10. <https://doi.org/10.1130/gsatg183a.1>