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Option : Geology of Sedimentary Basins.

- Academic Thesis-

The microfacies of the Upper Cretaceous carbonates from Ghardaïa region (Algerian north Sahara).

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Dedication

This work is a first step, after several years of work has been taken, and others will follow, God willing.

I dedicate it

to my dearest parents, my sister and my little brother….

to my fiancée.

Acknowledgments

First and foremost, I thank God, the Almighty, for granting me the strength, patience, and determination to complete this master's thesis. My deepest and most sincere gratitude goes to my supervisors, Mr. Amine CHERIF and Ms. Khaldia ZOUIT. Thank you for your invaluable guidance, your patience, and the continuous support you provided throughout this research. Your expertise and encouragement were the driving force behind the success of this project.

I would like to express my profound respect and thanks to all my teachers at Kasdi Merbah University.

I also extend my sincere appreciation to the Laboratory Managers and the entire team of geology department. Your practical expertise, time, and assistance were essential to the technical foundation of this work.

To my soulmate, Maouia. Thank you for being my constant source of light, patience, and inspiration. Your unwavering belief in me, your poetic soul, and your beautiful presence made even the most overwhelming days feel manageable. This achievement is as much yours as it is mine.

Finally, To my closest friends and all my classmates in the Geology of Sedimentary Basins program—thank you for the shared memories, the teamwork, and the mutual support over these past years. I am proud to have shared this journey with you.

Content.

Figures table.

Abstract.

The Upper Cretaceous carbonate platforms of the Ghardaïa region (northern Algerian Sahara) record critical paleoenvironmental shifts associated with the Upper cretaceous transition. This study presents a detailed sedimentological and paleoenvironmental analysis of three key stratigraphic sections: Mansoura, Oued Nachou, and Berriane. A primary challenge in interpreting this region is the intense, pervasive dolomitization that frequently obscures original sedimentary textures and biological assemblages. Therefore, the main objectives of this research are to conduct reliable paleoenvironmental reconstructions using surviving microfossil and microfacies assemblages. Through integrated lithostratigraphic logging, analysis of washed residues, and carbonate petrography, including the detailed examination of thin sections to characterize microfacies and diagenetic features, this study tracks the evolution of the platform from restricted argillaceous-evaporitic environments to open-marine carbonate build-ups. Ultimately, this work seeks to clarify the local sedimentary signature of the global Cenomanian-Turonian marine transgression within the heavily diagenetically altered Chebka du M’zab.

Résumé.

Les plates-formes carbonatées du Crétacé supérieur de la région de Ghardaïa (nord du Sahara algérien) enregistrent des changements paléoenvironnementaux critiques associés à la transition du Crétacé supérieur. Cette étude présente une analyse sédimentologique et paléoenvironnementale détaillée de trois coupes stratigraphiques clés : Mansoura, Oued Nachou et Berriane. Un défi majeur dans l'interprétation de cette région est la dolomitisation intense et omniprésente qui masque fréquemment les textures sédimentaires originales et les assemblages biologiques. Par conséquent, les principaux objectifs de cette recherche sont de réaliser des reconstructions paléoenvironnementales fiables en utilisant les assemblages de microfossiles et de microfaciès survivants. Grâce à l'intégration des levés lithostratigraphiques,

de l'analyse des résidus de lavage et de la pétrographie des carbonates y compris l'examen détaillé des lames minces pour caractériser les microfaciès et les caractéristiques diagénétiques, cette étude retrace l'évolution de la plate-forme, passant d'environnements argilo-évaporitiques restreints à des édifices carbonatés marins ouverts. En fin de compte, ce travail cherche à clarifier la signature sédimentaire locale de la transgression marine globale du Cénomano-Turonien au sein de la Chebka du M'zab, fortement altérée par la diagenèse.

General Introduction.

The Upper Cretaceous period represents one of the most significant periods of global marine transgression and paleoenvironmental change in the Mesozoic era. In the northern Algerian Sahara, particularly within the Ghardaïa region (Chebka du M'zab), this transition is recorded as a complex geological event driven by a global marine eustatic drowning of the Saharan Platform (Grosheny et al., 2013). Unlike neighboring regions, such as the Monts des Ksour and Ouarsenis, where fossil-rich sedimentary layers clearly mark this boundary, the M'zab platform is defined by intense, pervasive dolomitization. This extensive chemical transformation has frequently recrystallized the original carbonate rocks, erasing the primary biological traces and delicate sedimentary structures that geologists traditionally rely on for biostratigraphic dating and paleoenvironmental interpretation.

As a result, while this period was globally marked by major eustatic sea-level rises and Oceanic Anoxic Event 2 (OAE 2) and also documented in the Ouled Naïl Mounts its precise local signature in the Ghardaïa region remains a subject of ongoing scientific debate. The regional stratigraphic succession typically manifests as a transgressive sequence: the "Argiles d'El Goléa," comprising restricted alternating marls and dolomitic limestones, overlain by the massive carbonates of the "Barre Turonienne" (Grosheny et al., 2013). Although recrystallization severely limits the fossil record, understanding this shift is critical for reconstructing Tethyan flooding and the paleo-bathymetric deepening of the Saharan Platform (Grosheny et al., 2013).

To address this gap, this study investigates three key stratigraphic sections, Mansoura, Oued Nachou, and Berriane, through integrated field logging, washed residue analysis, and microfacies characterization. The primary objectives of this research are twofold: first, to establish reliable biostratigraphic dating and conduct a comprehensive paleoenvironmental analysis of the three studied sites utilizing surviving microfossil and microfacies assemblages; and second, to define the Cenomanian-Turonian boundary on a microscopic scale despite the heavy diagenetic overprint. By systematically documenting the transition from restricted, evaporite-bearing clays to open-marine carbonate build-ups, this study aims to reconstruct the depositional dynamics and diagenetic history of the Upper Cretaceous Saharan platform, providing clearer insights into this complex regional transition.

CHAPTER I

<u>Generalities</u>

1. Presentation of the Study Area

1.1. Geographical and Geomorphological Framework.

A) Geographical Situation.

The study area is located in the central-northern Saharan Platform (Ghardaïa), between 3°–4° E longitude and 31°–33° N latitude (Fig. 1). This region represents an important paleogeographic domain, acting as the boundary between the distal marine influences of the Tethys to the north and the proximal, continental influences of the African Shield to the south. It is flanked by the Grand Erg Occidental to the west and the massive Tademaït Plateau to the south, making it a focal point for regional stratigraphic correlation.

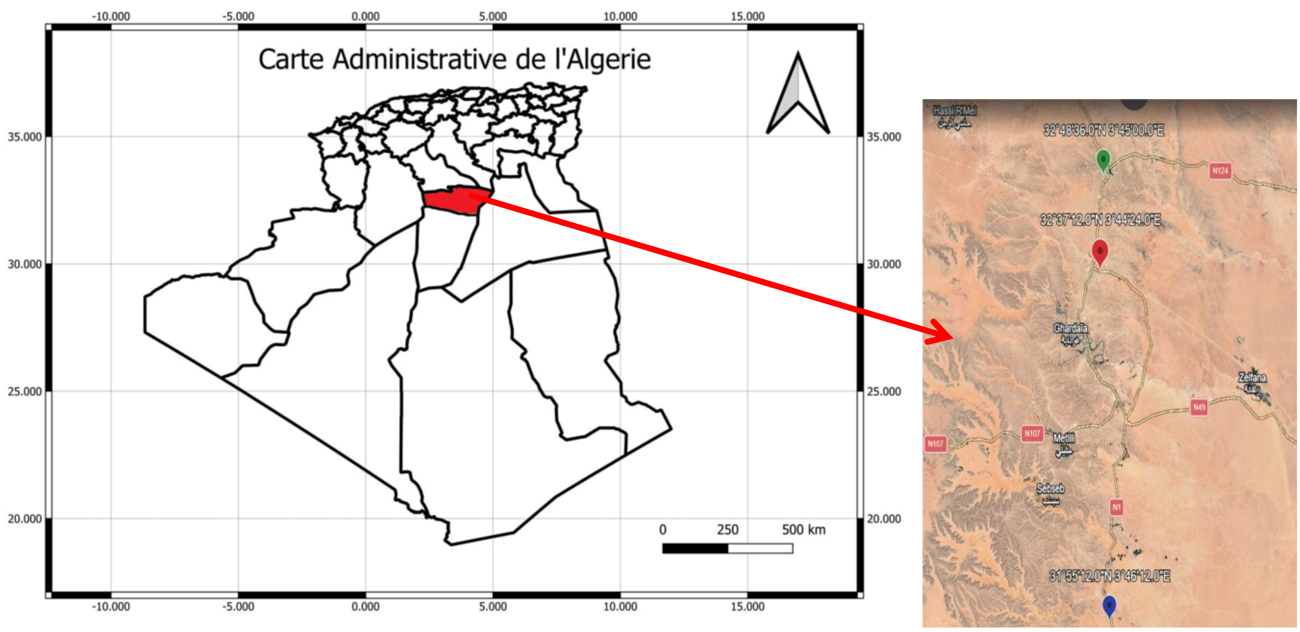


Figure 1 : Geographic location of the study area within the Ghardaïa province.

B) Geomorphological Description

The landscape is dominated by the Chebka du M'zab, a deeply incised hamada.

- <u>The "Chebka" Pattern</u>: This "net-like" morphology is the result of polyphasic erosion. During the Upper Villafranchian (Plio-Pleistocen e), increased humidity triggered intense fluvial incision into the Turonian limestones, creating the characteristic labyrinthine canyon systems (Busson, 1970).

- Cuesta Topography: The region exhibits a differential erosion profile. The resistant Turonian carbonates form a protective "cap rock" (the upper plateau), while the softer Cenomanian marls form the "talus" or receding slopes below.
- Karstology: The "Barre Turonienne" is highly susceptible to karstification. Features such as the Figher and Louss caves indicate a complex history of paleohydrogeology, where dissolution along joint planes created significant secondary porosity (Amard, 1981).
- Hydrographic Control: The drainage (Oued M'zab) is strictly ephemeral and follows a NW-SE trend, which is a surface expression of the gentle (0.2%) regional monoclinal dip (Remini, 2018).

2.2. Geological and Structural Framework.

A) Sedimentary Series.

The lithostratigraphic framework is defined by two main formations representing a transgressive trend:

- Cenomanian Marls (Formation F1 - "Argiles d'El Goléa"): These ~100m thick deposits consist of greenish, clays, gypsum-bearing marls, with thin fossiliferous limestone beds. They represent a low-energy, restricted lagoonal to peri-marine environment. The presence of *Ostreidae* (oysters) and *Thomasinella* suggests fluctuating salinity levels.
- The Turonian Carbonate Bar (Formation F2): Ranging from 50 to 110m, representing a prograding carbonate platform.
- Lower member: Contain Vascoceratidae ammonites, marking the C-T boundary.
- Upper member: Composed of massive, often dolomitized limestones (micrites and biomicrites). This unit represents the high-stand systems tract (HST) of the Cretaceous transgressive cycle.

B) Structural Context.

The structural framework is manifested by (Missoum Herkat and René Guiraud in 2006)

- <u>M'zab Ridge Influence</u>: This NNE-SSW trending anticlinal swell influenced sedimentation by reducing the accommodation space compared to the neighboring Bas-Sahara basin.
- <u>Tectonic Fabric</u>: The plateau is intersected by a system of orthogonal diaclases. These fractures are likely related to the distal effects of the Alpine Orogeny, providing the structural "blueprint" for the rectilinear wadi paths.
- <u>Synsedimentary Tectonics</u>: Variations in the thickness of the "Barre Turonienne" (from 50m to over 100m) suggest fault-controlled subsidence. Reactivation of Hercynian-aged basement faults during the Turonian likely created localized sub-basins, a phenomenon common across the Saharan Platform (Herkat & Guiraud, 2006).

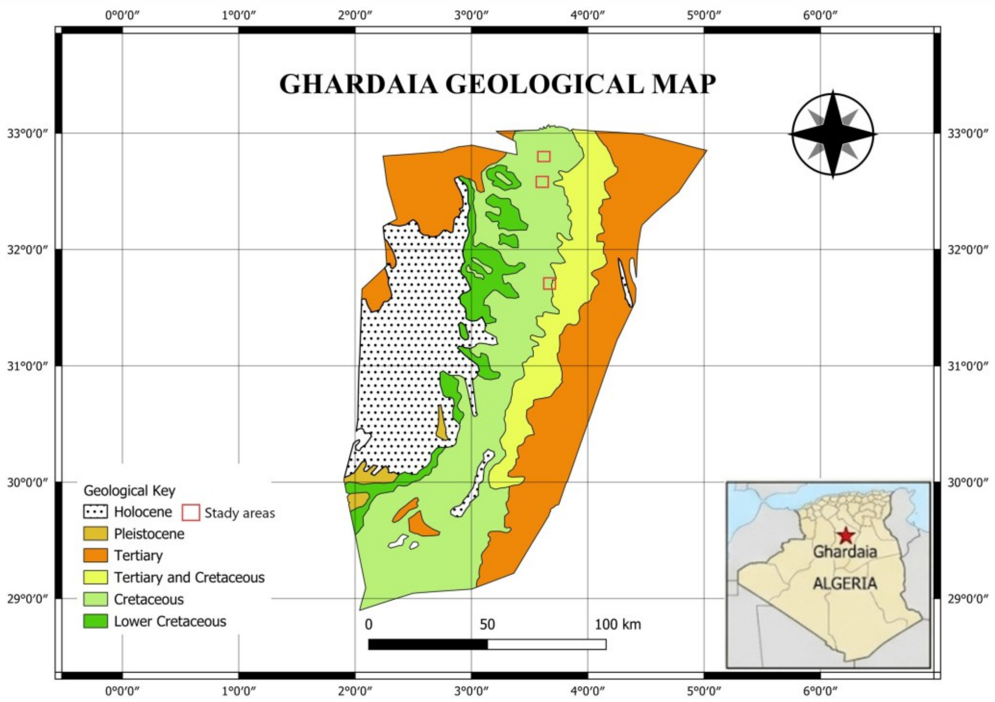


Figure 2: Geological map of Ghardaïa and El Menia.(made by QGIS)

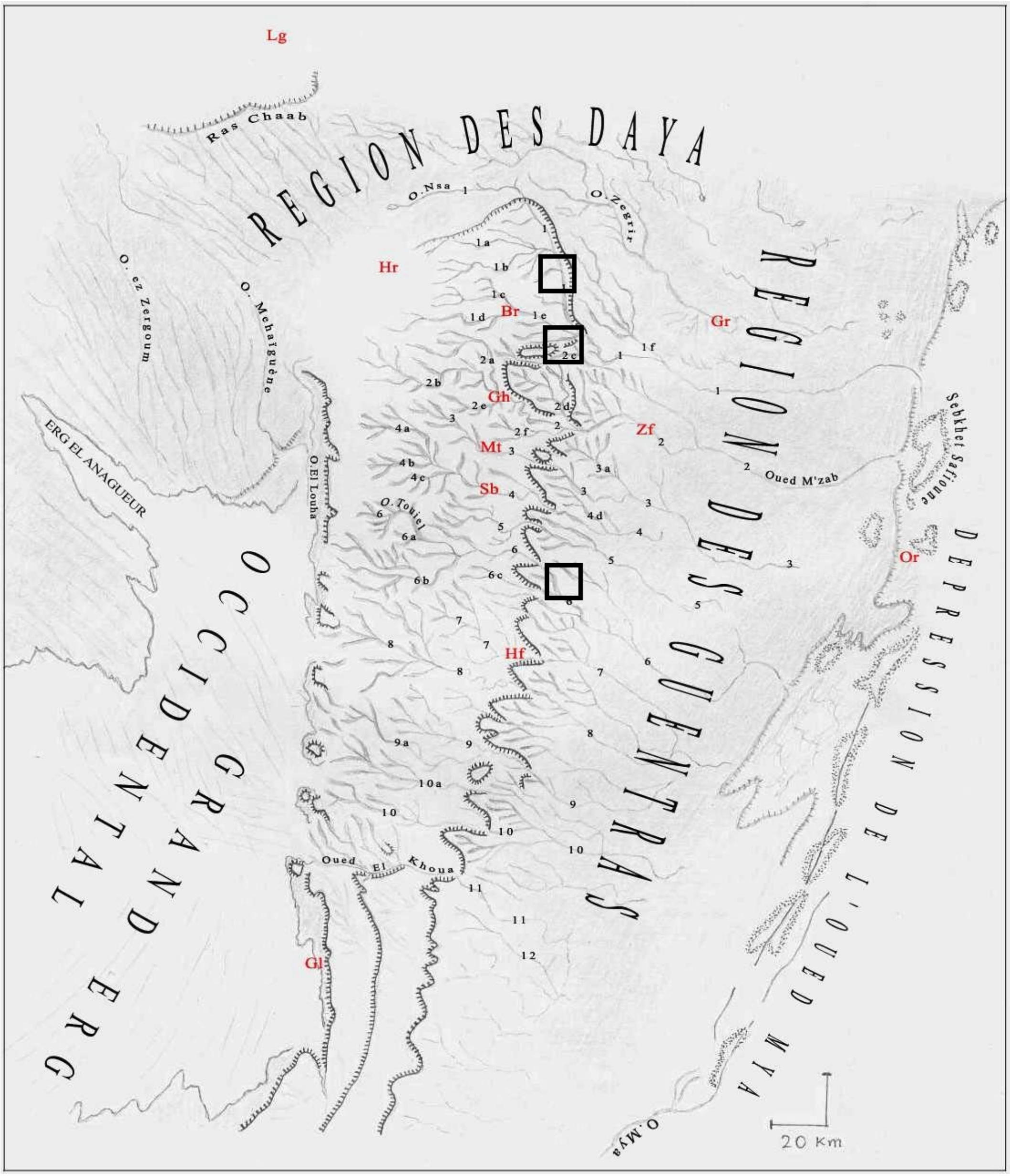


Figure 3: The major geomorphological units of the M’zab and its surroundings (In Banouh 2006).

The study areas

3.Overview on Upper Cretaceous Shallow Marine Carbonates of Northern Algerian Sahara.

The Upper Cretaceous of the Northern Algerian Sahara, particularly in the M’zab and Ghardaïa regions, represents a period of significant marine transgression. This resulted in the deposition of extensive shallow marine carbonate platforms.

3.1. Stratigraphic and Facies Distribution.

The Northern Sahara during the Upper Cretaceous was characterized by a vast epicontinental sea. The depositional environment was dominated by inner to middle shelf carbonates.

The Cenomanian-Turonian Transition marked by the deposition of Carbonate platform (see Fig. 1), the Cretaceous and Lower Cretaceous units form the backbone of the regional lithology. These often consist of bioclastic limestones, dolostones, and occasional marly interbeds.

Lithological Characteristics typically includes:

- Limestones Often rich in microfossils (foraminifera), indicating a warm, shallow, and well-oxygenated marine environment.
- Dolomites Resulting from the diagenetic alteration of original limestones, frequently corresponding to the Turonian strata of the Saharan Platform (Busson, 1972).
- Evaporitic Intercalations covering the top of the sequence (from Coniacian), the interpreted as restricted lagoonal settings, leading to the deposition of gypsum and anhydrite alongside carbonates.

4.Overview on Microfacies Analysis.

The study of microfacies has greatly progressed through three major historical stages:

- **The Descriptive Phase (Early 20th Century):** Early geologists used thin sections primarily for petrography. Steinmann (1925) was the first who employed the term "Microfacies" to describe the microscopic features of sedimentary rocks.
- **The Classification Phase (1950s–1970s):** This period was characterized by the emergency of **Folk (1959)** and **Dunham (1962)** classification. They provided the vocabulary we use today (e.g., *Packstone, Grainstone*) to describe the relationship between grains and matrix, which allows geologists to infer the energy of the depositional environment.

- **The Standard Microfacies (SMF) Phase (1975–Present): Wilson (1975)** and later **Flügel (2004/2010)** introduced the concept of "Standard Microfacies Types" linked to specific positions on a carbonate ramp or platform. This made it possible to compare Algerian Saharan facies with other carbonate systems globally.

4.1The Upper Cretaceous of the Northern Algerian Sahara

In the Northern Sahara (M'zab ridge and Ghardaïa region), the Upper Cretaceous, specifically the **Cenomanian-Turonian (C-T)**, represents a major geological turning point characterized by a vast marine transgression over the African craton.

4.1.1.Regional Geological Framework.

During this time, the Saharan platform was a shallow epicontinental sea. According to **Busson (1972)**, the sedimentation was controlled by the "M'zab Dorsal," which influenced the thickness and type of microfacies deposited.

4.1.2.Key Microfacies Types in the Northern Sahara.

Based on regional studies by **Banouh (2005)** and **Herkat (2006)**, the Upper Cretaceous sequence follows a clear evolutionary path:

1. **Lower Cenomanian (Restricted Facies):**
   - **Microfacies:** Evaporitic mudstones and dolomitic marls.
   - **Environment:** Sabkhas and restricted lagoons.
2. **Middle to Upper Cenomanian (The Transgressive Phase):**
   - **Microfacies:** Bioclastic Wackestones with **Benthic Foraminifera** (e.g., *Prealveolina*, *Ovalveolina*).
   - **Interpretation:** An open inner shelf with moderate energy.
3. **The C-T Boundary (Anoxic Event / OAE2):**
   - **Microfacies:** Laminated black shales or organic-rich Mudstones.
   - **Significance:** This corresponds to a global Oceanic Anoxic Event where oxygen levels dropped, leading to high organic matter preservation (critical for petroleum source rocks).

4. **Lower Turonian (Maximum Flooding):**
   - **Microfacies:** Pelagic Mudstones/Wackestones containing **Planktic Foraminifera** (e.g., *Whiteinella archaeocretacea*).
   - **Environment:** Deepening of the sea, moving toward outer ramp environments.

5. The Dolomitization Concept.

The study of dolomitization, the process by which limestone ($CaCO_3$) is transformed into dolomite ($CaMg(CO_3)_2$) is a cornerstone of sedimentary geology, especially in the context of the Northern Algerian Sahara's reservoir potential.

The "Dolomite Problem" has been one of the most debated topics in sedimentology for over two centuries.

- **The Early Observations (1791–1900s):** The rock was first described by **Déodat de Dolomieu** in 1791. For a long time, geologists struggled to explain why dolomite is so abundant in ancient strata (like the Cretaceous) but rare in modern marine environments.
- **The Model Era (1960s–1980s):** This period saw the birth of classic hydrologic models. **Adams and Rhodes (1960)** proposed the *Reflux Model*, while **Badiozamani (1973)** introduced the *Dorag (Mixed-water) Model*. These allowed geologists to relate crystal textures seen in thin sections to large-scale sea-level changes.
- **The Modern Kinetic Approach (1990s–Present):** Recent research, led by authors like **Purser et al. (1994)** and **Machel (2004)**, focuses on the role of bacteria and high temperatures (hydrothermal dolomitization) in overcoming the kinetic barriers that prevent dolomite from forming in normal seawater.

5.1.Dolomitization in the Upper Cretaceous of the Northern Sahara

In the Northern Algerian Sahara, particularly within the Cenomanian-Turonian "Barre Carbonatée", dolomitization has strongly impacted the chemical components and consequently modifying the rock's microfacies.

5.2.The Saharan Mechanisms

According to the foundational works of **Busson (1972)** and more recent regional analyses by **Ait Itto (2013)**, the dolomitization in the Ghardaïa and M'zab regions follows two primary patterns:

1. **Penecontemporaneous (Early) Dolomitization:** Occurred in supratidal sabkha environments. High evaporation rates concentrated magnesium in the brines, which then seeped into the underlying lime mud.
2. **Burial (Late) Dolomitization:** As the Northern Saharan basins subsided during the Late Cretaceous, increased pressure and temperature allowed for more pervasive dolomitization, often associated with tectonic fractures.

6. Objectif and Methodology.

6.1. Objectif.

To achieve the objectives of this study and reconstruct the paleoenvironmental evolution of the Upper cretaceous in the Ghardaïa region, a systematic analytical approach was adopted.

6.2. Methodology.

Following the macro-structural and lithological observations conducted during fieldwork, the collected samples were subjected to detailed laboratory analyses. The analytical workflow was divided into two primary complementary methods: the micropaleontological study of loose sediments and the petrographic analysis of indurated carbonate rocks.

6.2.1. Treatment and Analysis of Washed Residues.

For the soft, argillaceous, and marly intervals, a standard wet-sieving technique (Fig. 5) was applied to extract and isolate microfossils and diagnostic detrital grains.The raw sediment samples were initially disaggregated and washed thoroughly using water to break down the clay matrix without damaging the biogenic content. The resulting sludge was then washed through a precise column of five geological sieves of decreasing mesh sizes: 500 µm, 250 µm, 125 µm, 90 µm, and 63 µm. Once the retained residues from each sieve were carefully dried, they were examined and sorted under a stereomicroscope (binocular loupe). This step allowed for the morphological identification of benthic and planktonic foraminifera, fossils fragments, as well as the characterization of key mineralogical elements such as well-crystallized quartz varieties, ferruginous elements, and evaporitic gypsum grains.

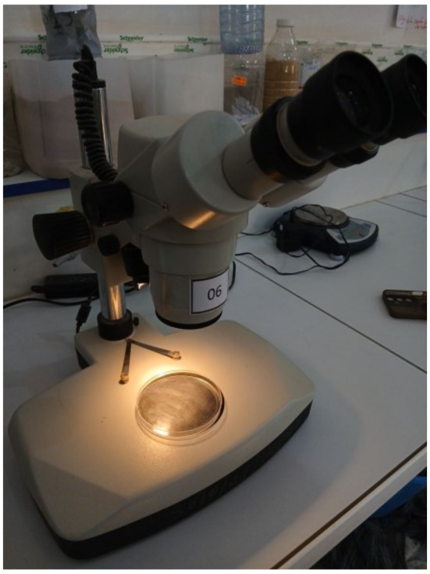


Figure 4 : Principal equipment used for sediment treatment and observation

6.2.2. Preparation and Petrographic Analysis of Thin Sections.

To accurately determine the microfacies, depositional textures, and diagenetic overprints (such as dolomitization and dissolution) of the indurated limestone and dolomite intervals, a detailed thin-section analysis was required.

Due to the precision required in cutting, grinding, and polishing these hard carbonate rocks to a standard optical thickness of 30 µm, the mechanical preparation of the thin sections was entrusted to the specialized laboratories of the National Office of Geological and Mining Research (ORGM).

Once prepared, the thin sections were systematically observed and photographed using a petrographic (polarizing) microscope under both plane-polarized light (PPL) and cross-polarized light (XPL). This optical analysis was fundamental in classifying the carbonate textures (e.g., mudstones to grainstones), identifying matrix-bound microfauna and algal structures, and evaluating the mineralogical transformations that affected the regional platform during and after deposition.

Figure 5 : Petrographic observation and analysis of thin sections utilizing specialized laboratory equipment at the research center(Kasdi Merbah university).

CHAPTER II

The Lithostratigraphy And Micropaleontology Of The Study Areas

1. Introduction.

In this chapter, a detailed description of the various studied stratigraphic sections is presented, based on lithostratigraphic, paleontological, and micropaleontological criteria. The lithostratigraphic study outlines the exact nature of the rocks and their mineralogy across the different units. This is followed by an identification of the macro- and microfaunal assemblages, focusing closely on the microfossils that characterize these layers. These detailed section descriptions serve as the foundational dataset required for interpreting the depositional environments and tracking vertical changes throughout the studied interval.

2. Location of studied areas.

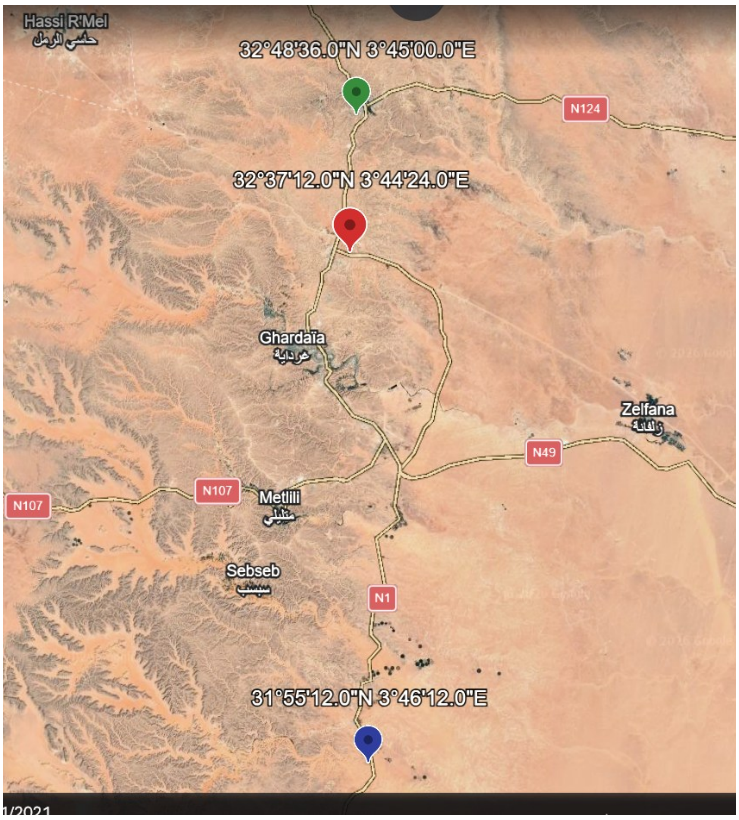


Figure 6 : Satellite view indicating the geographic positioning of the three study areas

The present study focuses on the Ghardaïa region, situated in the northern part of the Algerian Sahara. My Field work were centered on three specific sectors (Fig. 7):

- **The Berriane Section (Green Marker):** Located in the northernmost part of the study area, north of Ghardaïa **(Coordinates: 32°48'36.0"N, 3°45'00.0"E)**. This section represents a highly condensed, diagenetically altered marginal facies, dominated almost entirely by massive dolomites.
- **The Mansoura Section (Red Marker):** Situated closer to the city center, just north of Ghardaïa **(Coordinates: 32°37'12.0"N, 3°44'24.0"E)**. This sector offers a thick, continuous exposure of the transition from basal argillaceous deposits to massive carbonate platform cliffs.
- **The Oued Nachou Section (Blue Marker):** Located in the southern part of the study area, well south of Ghardaïa **(Coordinates: 31°55'12.0"N, 3°46'12.0"E)**. This outcrop provides an excellent record of the more restricted, rhythmically bedded lagoonal environments, heavily featuring intercalated red and green clays alongside evaporites.

3. Lithostratigraphy Description.

3.1. Mansoura Section.

The Mansoura section, (Fig. 7), represents a 38,15 meter-thick continuous exposure located in the Ghardaïa region(Fig. 8). This section provides an excellent record of the sedimentary transition from argillaceous to purely carbonate environments. Based on field observations, lithological successions, and macro-structural variations, the section can be subdivided into two distinct lithostratigraphic units: a basal clay-rich unit and an overlying thick carbonate platform unit.

3.1.1. Basal Clayey Unit (Meters 0 to ~12m; Samples MN1 to MN3)

The lower portion of the Mansoura section reflects a predominantly siliciclastic-dominated phase before the onset of the main carbonate platform.

- **Lithology and Bedding:** This interval consists of thick, relatively soft layers of yellowish to greenish clays and claystones. Interbedded within these clays are thin, sloping grey limestone beds that mark the initial, episodic influx of carbonate deposition.
- **Sedimentary Structures:** The primary internal structures consist of horizontal planar laminations within the claystone intervals, indicating deposition under low-energy, quiet settling conditions.
- **Mineralogical Composition:** The mineralogy is dominated by clay minerals (likely a mix of illite and smectite group minerals common to the basin) with minor detrital quartz grains. The grey limestone interbeds are composed of a fine-grained calcite matrix (micrite) with localized traces of iron oxides, which contribute to the yellowish weathering hue on exposed surfaces.

3.1.2. Upper Carbonate Unit (Meters 12 to 38,15m; Samples MN4 to MN8)

This unit marks a major environmental shift toward a fully developed carbonate platform, characterized by a massive, cliff-forming succession of well-bedded limestones.

- **Lithology and Texture:** The lithology is dominated by massive grey to reddish-brown weathered limestones. Texturally, the beds vary upward from mudstones and wackestones near the transition zone to packstones and localized grainstones/rudstones toward the upper intervals, reflecting a general increase in environmental energy.
- **Sedimentary Structures and Deformations:**
- **Soft-Sediment Deformation (Slumps):** A highly characteristic feature of this unit is the presence of distinct syn-sedimentary slump structures. These features are visible as contorted, folded, and internally deformed

limestone layers sandwiched between undisturbed horizontal strata. These slumps indicate lateral slope instability, paleoslope orientation, or subtle tectonic instability during the depositional phase.

- **Bioturbation:** The limestone beds exhibit highly pronounced bioturbation. The most prominent ichnofossil identified in the field is **Thalassinoides**, which presents as extensive, branching, sub-horizontal cylindrical burrow systems. These trace fossils are typically filled with slightly coarser or mineralogically distinct material compared to the host rock, highlighting a highly active benthic community in a shallow marine setting.
- **Mineralogical Composition:** The mineralogy is overwhelmingly calcitic (dominant calcium carbonate). However, the prominent reddish-orange to dark brown weathering color observed on the outcrop faces indicates a significant presence of iron oxides and hydroxides (such as goethite or hematite). These iron minerals are either disseminated within the micritic matrix or concentrated along bedding planes and burrow linings due to early diagenetic fluid circulation.

3.2. Oued Nachou's section.

The Oued Nachou section(Fig. 9) presents a 13,5 meter-thick continuous stratigraphic. Unlike the massive(Fig. 10), purely carbonate build-ups observed in other localized profiles, this section is distinctive for its rhythmic alternations between argillaceous (clay-rich) deposits and shallow-water restricted carbonates. Based on the stratigraphic log, the sequence is subdivided into four distinct formations that record dynamic environmental shifts, ranging from restricted evaporitic lagoons to shallow algal platforms.

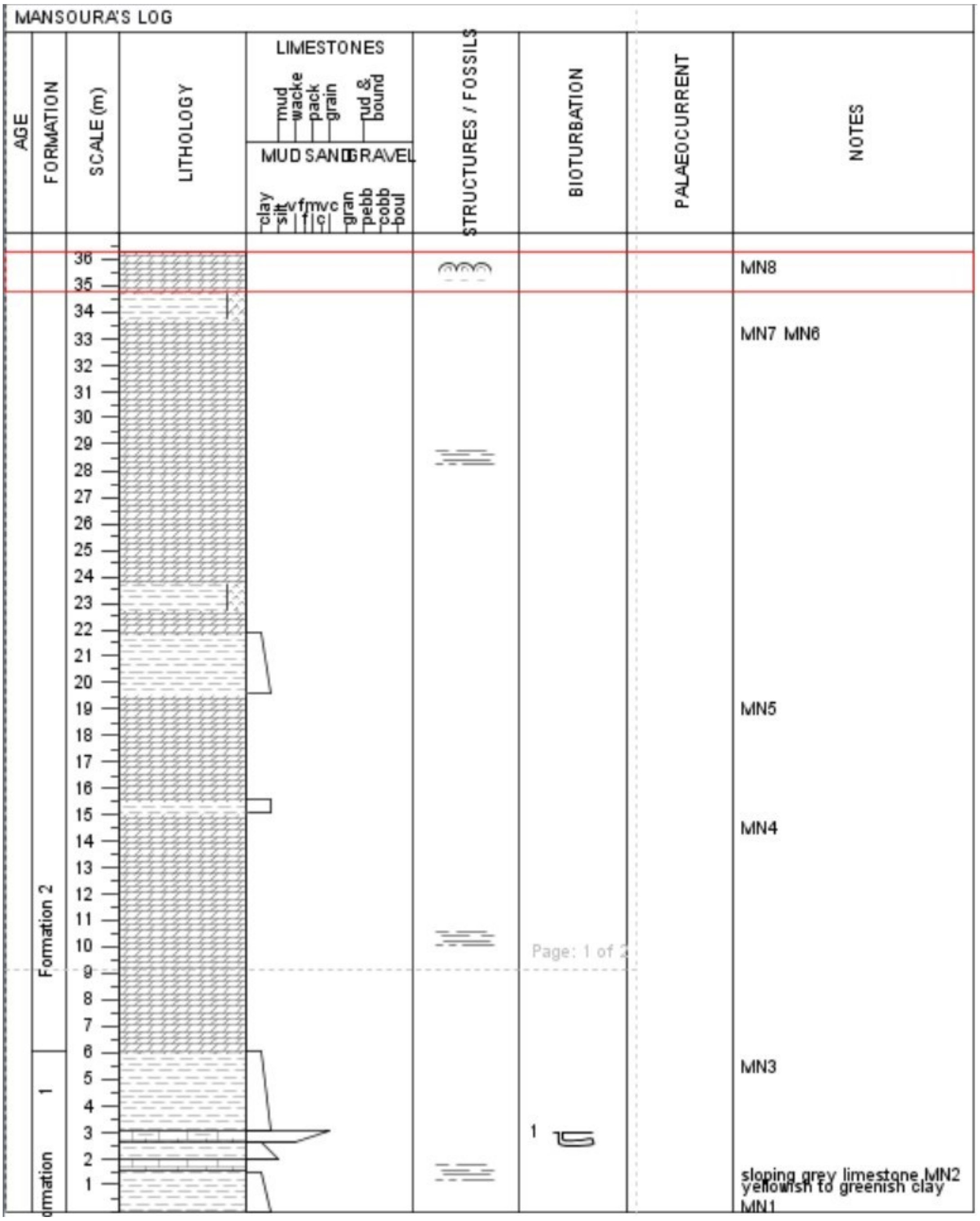
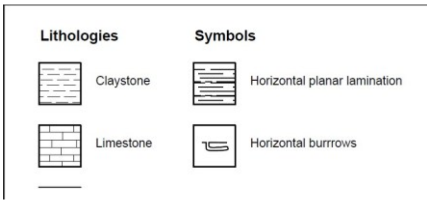


Figure 7 : Lithostratigraphical Column and Sedimentary Structures of the Mansoura Log.



Log's key

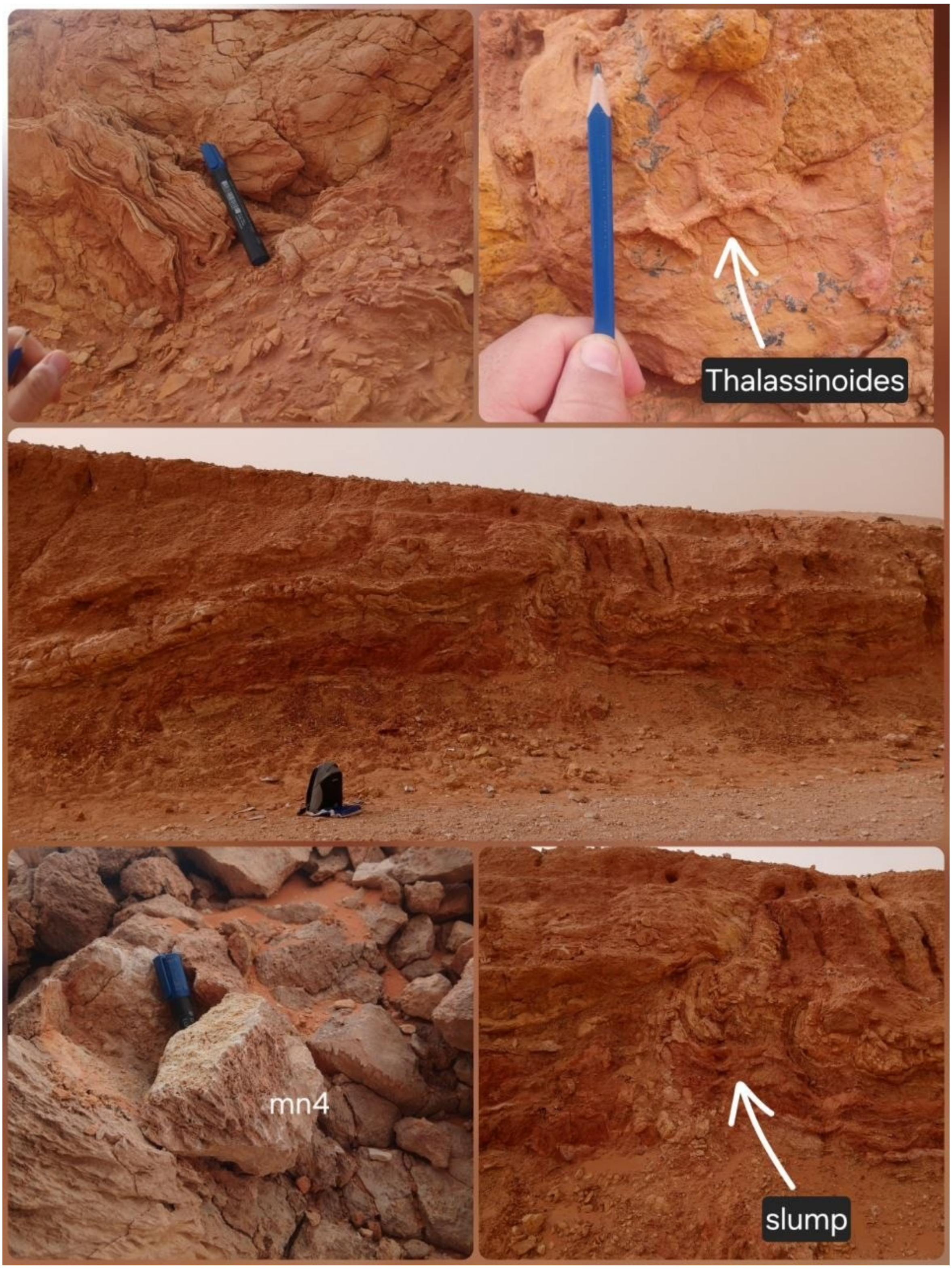


Figure 8*:* Field photograph showing the massive, well-stratified carbonate succession of the upper lithostratigraphic unit in Mansoura.

3.*2*.1. Formation 1: Basal Mixed Unit (Samples ON00 to ON2)

This basal unit rests directly on the substratum with a sharp lower boundary, representing the initial Turonian depositional phase in this area.

- **Lithology and Bedding:** The unit is characterized by alternating beds of limestones (predominantly lime mudstones and wackestones) and intercalations of red clay.
- **Sedimentary Structures:** The dominant internal structure is horizontal planar lamination, indicating periods of low-energy suspension settling in a very shallow or marginal marine setting.
- **Mineralogical Composition:** The mineralogy is a dual system of fine-grained calcite (micrite) and terrestrial clay minerals. The pronounced red coloration of the clays indicates a high concentration of oxidized iron (hematite), pointing to oxidizing conditions and a significant influx of continental detrital material.

3.*2*.2. Formation 2: Lower Carbonate-Evaporite Sequence (Samples ON3 to ON5)

This formation marks an environmental shift toward more restricted, arid, and hypersaline conditions.

- **Lithology and Texture:** The lithology continues as an alternation between red argillaceous horizons and limestone beds (ranging from mud-supported to slightly grain-supported wackestones).
- **Sedimentary Structures:** A critical diagnostic feature of this interval is the presence of **gypsum and anhydrite**. The precipitation of these evaporites strongly points to a restricted, highly evaporitic lagoonal setting where evaporation outpaced marine recharge.
- **Mineralogical Composition:** The rocks are dominantly calcitic but contain significant nodules or lenses of calcium sulfate ($CaSO_4 \cdot 2H_2O$). Iron oxides remain abundant within the interbedded clays, sustaining the red oxidation profile.

3.*2*.3. Formation 3: Argillaceous Transitional Unit (Samples ON6 to ON7).

This unit is visually striking due to a major shift in the color and physical nature of the argillaceous deposits, completely lacking carbonate interbeds.

- **Lithology:** The formation is entirely clay-dominated. It begins with the continuation of the red clays at its base but sharply transitions into a thick, prominent sequence of soft **green clays** toward the top of the unit.
- **Sedimentary Context:** The transition from red to green clays represents a fundamental shift in depositional chemistry. Moving from an oxidizing (red, iron-rich) to a reducing (green) environment signals a potential deepening of the water column, restricted bottom-water circulation, or a cutoff from oxygenated continental runoff.
- **Mineralogical Composition:** Heavily dominated by phyllosilicates (clay minerals). The green hue indicates the presence of unoxidized iron (potentially chlorite or smectite-group clays) rather than hematite.

3.*2*.4. Formation 4: Upper Shallow Algal Platform (Samples ON8 to ON9)

The uppermost formation records the re-establishment of carbonate production in a very shallow, photic marine environment.

- **Lithology and Texture:** This unit sees a return to well-stratified limestones (mudstones to packstones), interbedded with the uppermost layers of green clay.
- **Sedimentary Structures and Biota:** This formation is distinctly characterized by the presence of **stromatolites** and **algae**. The growth of these microbial and algal mats indicates a very shallow, photic, and likely intertidal to shallow subtidal environment with fluctuating salinity. **Vertical burrows** are also heavily present, highlighting the activity of benthic organisms adapting to these shifting, shallow substrates.
- **Mineralogical Composition:** The mineralogy is primarily biogenic and precipitated calcite, with minor argillaceous material trapped within the microbial/stromatolitic laminations.

3.3. Berriane's Section.

The Berriane section represents the third key stratigraphic profile in the study area(Fig. 13), with a precisely measured total thickness of 5.38 meters. While the Mansoura and Oued Nachou sections display distinct alternations of primary limestones and argillaceous deposits, the Berriane profile is uniquely defined by massive, pervasive dolomitization. This succession provides critical insight into the post-depositional diagenetic processes affecting the regional carbonate platform.

Based on the stratigraphic log(Fig. 12) and field observations, the sequence is structurally uniform but can be analyzed through its distinct basal transition and the main platform body.

3.*3*.1. The Basal Contact (Base; Sample BR0).

- **Lithostratigraphic Boundary:** The sequence initiates with a highly distinct, **sharp basal boundary**. This abrupt contact between the underlying substratum and the Turonian carbonate deposits indicates a sudden shift in depositional dynamics, potentially reflecting a rapid marine transgression or a localized depositional hiatus before the establishment of the platform.
- **Significance:** In diagenetically altered profiles, sharp basal contacts often act as critical permeability barriers, concentrating the circulation of magnesium-rich diagenetic fluids that drive the dolomitization of the overlying beds.

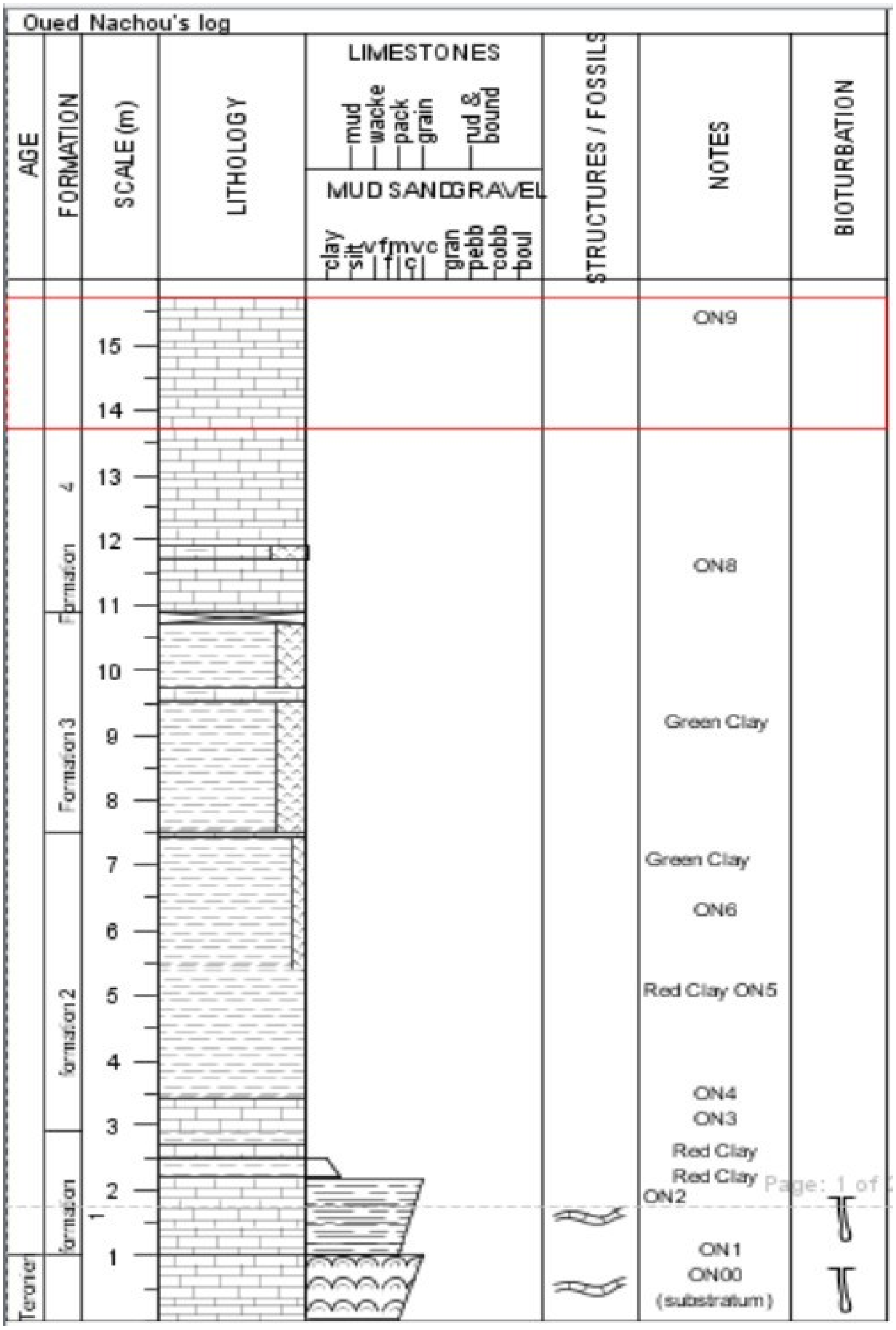
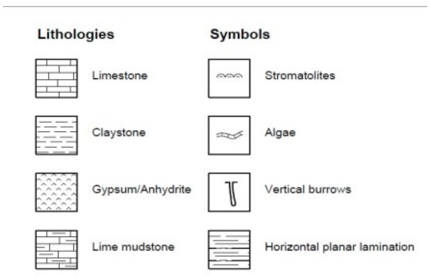


Figure 9 : Stratigraphic log of the Oued Nachou section (created in SedLog).



Log's key

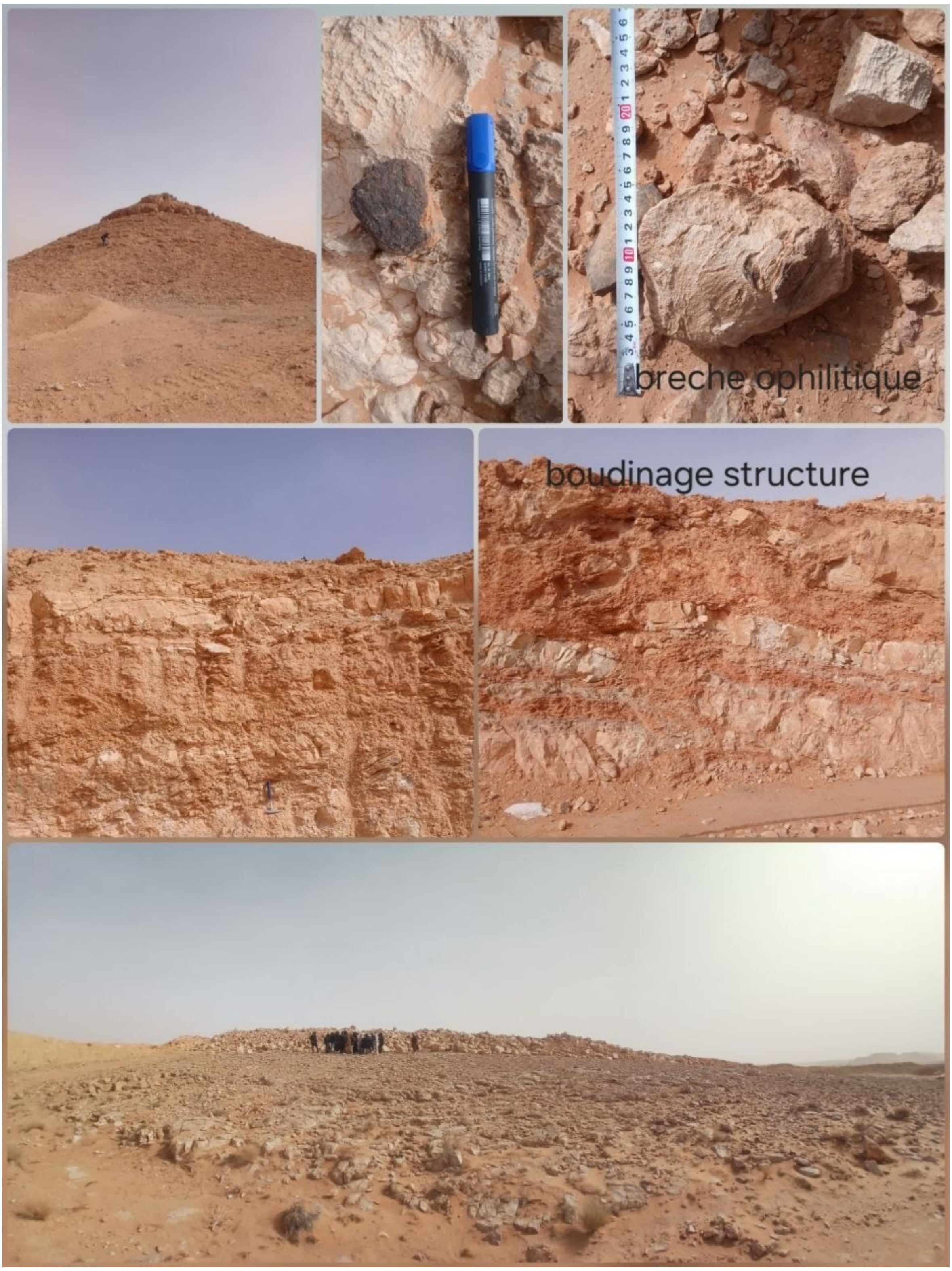


Figure 10: General field view showing the macroscopic structure and stratigraphic continuity of Oued Nachou.

3.*3*.2. The Main Dolomitic Platform (Meters 0 to 5.38m; Samples BR1 to BR6).
Above the sharp basal contact, the entirety of the 5.38-meter section consists of a continuous, massive dolomitic unit.

- **Lithology and Texture:** The lithology is composed exclusively of **Dolomite**. In outcrop, these beds present a rugged, massive, and highly blocky appearance. Because of the intense diagenetic overprint, the primary depositional textures (the original mudstones or grainstones) have been largely obliterated and replaced by a secondary crystalline (sucrosic) texture dominated by the growth of dolomite rhombohedrons.
- **Weathering and Physical Properties:** The exposed outcrop surfaces exhibit characteristic buff, yellowish-brown, and reddish-grey weathering colors. Furthermore, the molecular volume decrease that occurs when calcite converts to dolomite typically enhances secondary porosity (intercrystalline or vuggy porosity), resulting in the highly fractured and rugged outcrop faces visible in the field.
- **Mineralogical Composition:** The mineralogy is overwhelmingly dominated by the carbonate mineral **Dolomite ($CaMg(CO_3)_2$)**. The brownish and reddish weathering hues strongly indicate the presence of iron (either as ferroan dolomite or as late-stage iron oxide precipitates within the secondary pore spaces), which oxidizes upon subaerial exposure.

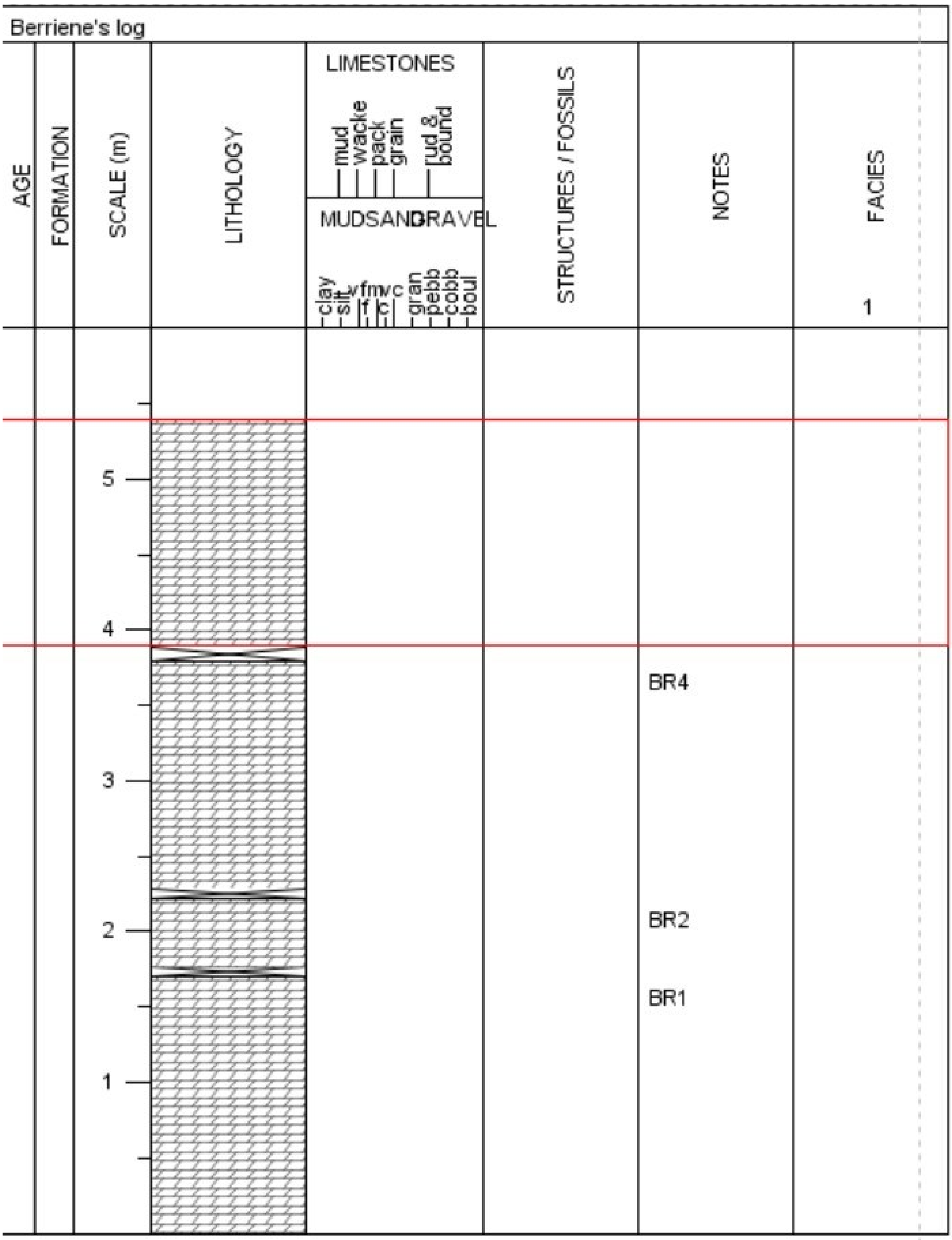
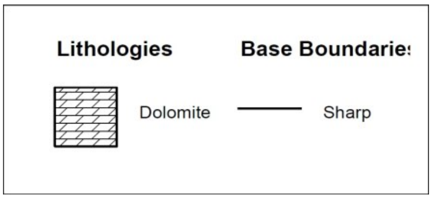


Figure 11 : Stratigraphic log of the Berriane section (created in SedLog).



Log’s key

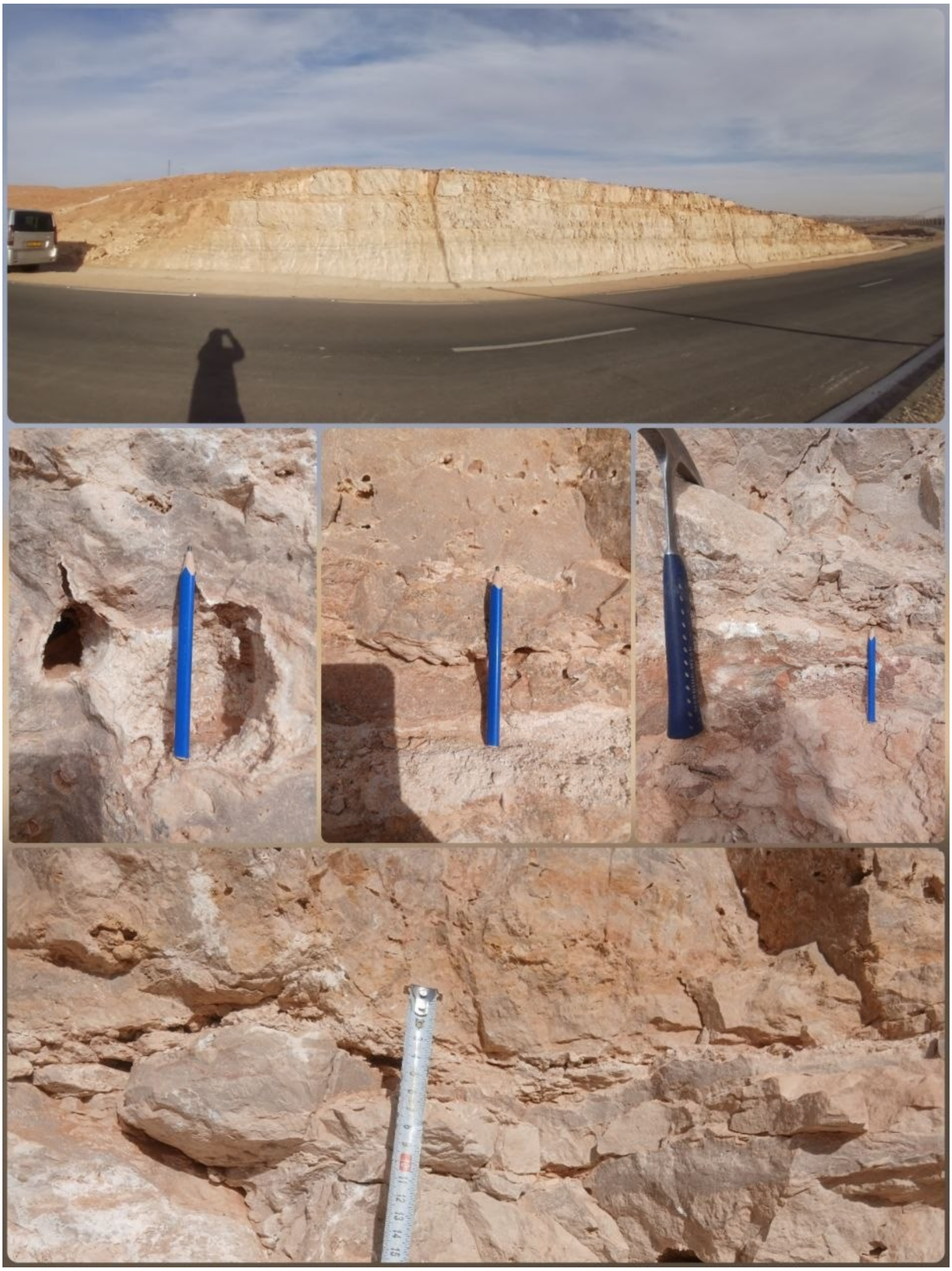


Figure 12 : General field view demonstrating the macroscopic structure and stratigraphic continuity of the exposed sedimentary beds.

4. Micropaleontological and Mineralogical Analysis.

To complement the lithostratigraphic observations, a micropaleontological analysis was conducted on selected marly and clayey samples from the Mansoura and Oued Nachou sections. The objective was to identify the microfaunal assemblages to better constrain the depositional environments.

4.1. Results by Section.

Despite the low yield of intact microfossils, the washed residues provided valuable sedimentological and biological indicators:

Mansoura Section:

- Sample MN1: This basal clay sample yielded the most diverse biological content. In the 125 µm fraction, benthic foraminifera (*Lagena* sp.) were identified alongside ferruginous elements and whitish quartz grains. The finer 63 µm fraction revealed the presence of planktonic foraminifera (*Globigerina* sp.), continuing to show whitish quartz. The 90 µm sieve isolated a small vertebral fragment(Fig. 14). The remaining coarser fractions were barren of fossils, containing only variously colored (predominantly whitish) quartz grains and minor traces of gypsum.
- Sample MN3: Moving upward in the section, the residue (notably in the 250 µm and 125 µm fractions) exhibited a distinct yellow to whitish coloration. Biologically, the yield dropped significantly, containing only highly fragmented, unidentifiable gastropod remains in the 125 µm fraction. Mineralogically, there was a marked increase in the presence of gypsum compared to sample MN1.

Oued Nachou Section:

- Sample ON4: This sample is characterized by a high concentration of well-crystallized silica alongside a specific benthic microfauna. The 250 µm fraction contained well-formed, hexagonal pink and white quartz crystals, along with notable quantities of gypsum. The 125 µm fraction contained similar rose, white, and transparent quartz varieties, though less sorted. Importantly, in the finer 90 µm fraction(Fig. 15), benthic foraminifera (*Dorothia* sp.) were successfully identified among the detrital grains.

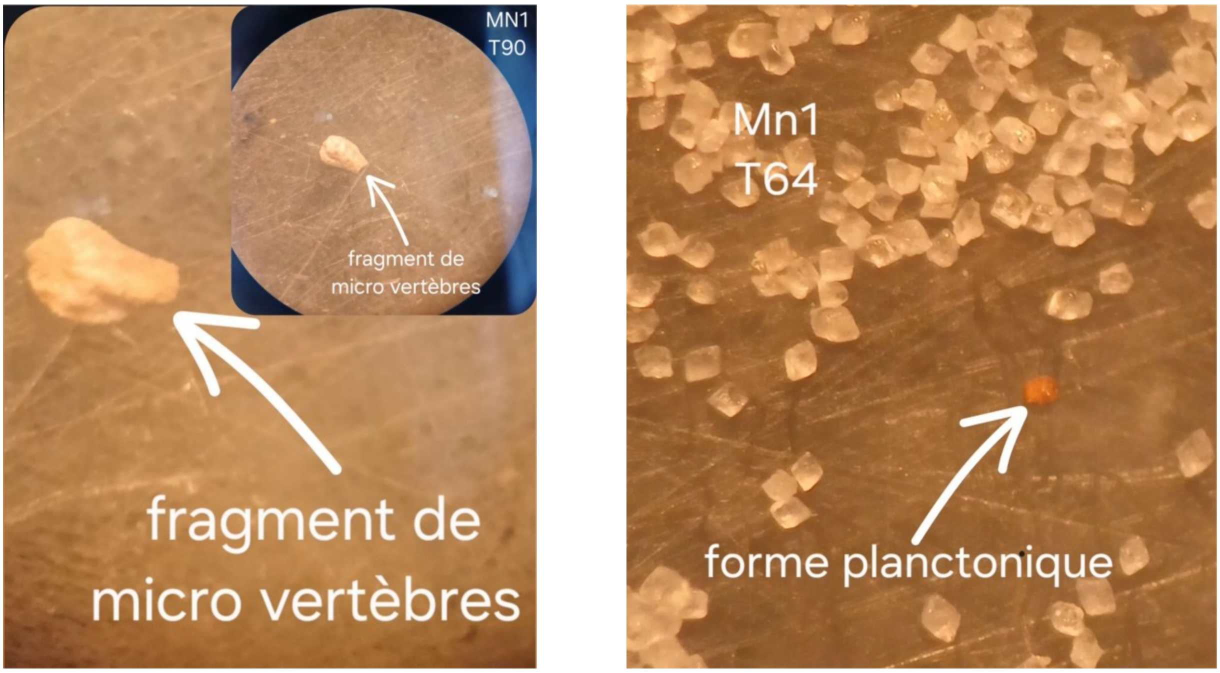


Figure 13 : Microfossil Assemblage of Sample MN1

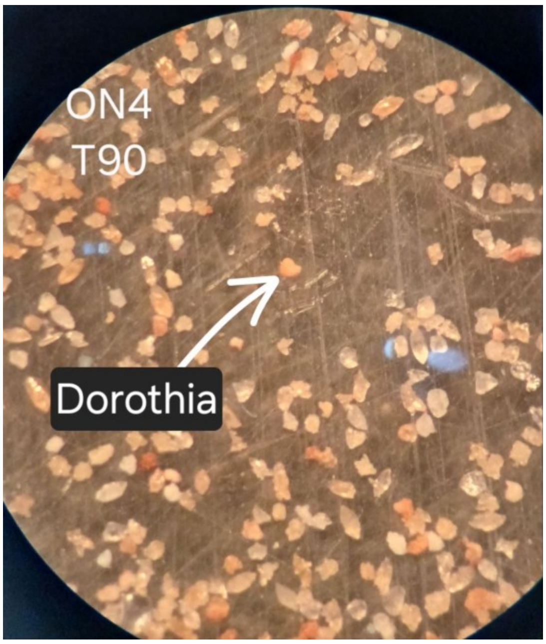


Figure 14 : Identification of benthic foraminifera (Dorothia sp.) in the 90 µm washed residue fraction.

- <u>Sample ON6:</u> The coarser fractions (500 µm and 250 µm) consisted exclusively of detrital quartz. The 125 µm fraction(Fig. 16), however, revealed high concentrations of white and red ferruginous quartz, abundant gypsum grains, and numerous unidentifiable, heavily ferruginized fossil fragments.

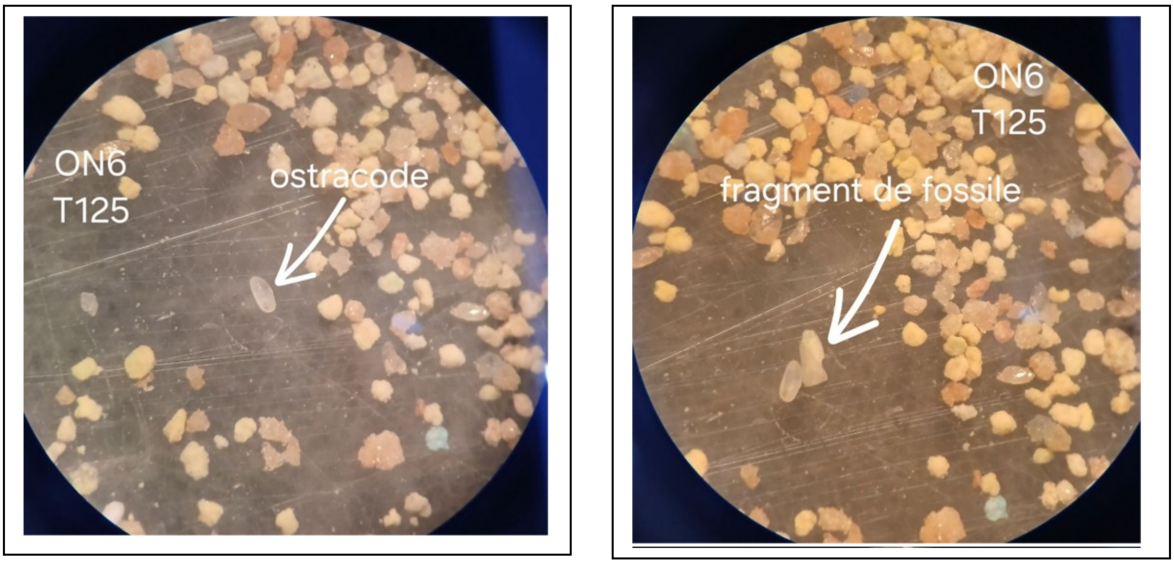


Figure 15 : Microfauna of Sample ON6 (125 µm fraction).

4.3. Discussion and Paleoenvironmental Interpretation.

Despite the physical constraints of the washed residues and the poor preservation of the microfauna, the combined sedimentological and micropaleontological data yield crucial insights into the paleoenvironmental evolution of the study area during the Cenomanian-Turonian transition. The analysis of these residues highlights three distinct paleoenvironmental dynamics:

- <u>Initial Marine Connectivity:</u> The basal clay intervals in both sections (MN1 and ON4) record an initial phase of marine flooding. The presence of planktonic foraminifera (*Globigerina* sp.) in MN1 confirms a definitive, albeit perhaps temporary, connection to open marine waters, allowing for the incursion of pelagic fauna. This is supported by the co-occurrence of benthic foraminifera (*Lagena* sp. in MN1 and *Dorothia* sp. in ON4), which indicates a submerged, oxygenated seafloor capable of supporting normal marine biological communities during the early stages of deposition.

- <u>Progressive Environmental Restriction and Aridity:</u> A critical sequence-stratigraphic trend is observed moving upward through both the Mansoura and Oued Nachou successions. The vertical transition from the basal clays (MN1, ON4) to the upper samples (MN3, ON6) is marked by the complete disappearance of marine foraminifera and their replacement by fragmented gastropod remains. Crucially, this biological impoverishment coincides with a marked increase in the abundance of evaporitic minerals (gypsum). This dual biological and mineralogical shift is characteristic of a shallowing-upward sequence. It strongly suggests a regression or a transition from an open marine setting to a highly restricted, hypersaline marginal environment—such as a coastal lagoon or sabkha—driven by increased aridity and isolation from the open ocean.

- <u>High-Energy Detrital Influx:</u> Throughout both sections, the residues are dominated by a continuous supply of varied continental quartz (whitish, well-crystallized hexagonal pink, and red ferruginous varieties). This high concentration of detrital material highlights close proximity to the paleoshoreline and a sustained terrigenous influx into the basin. Furthermore, the intense fragmentation of the gastropod shells and the heavy ferruginization of the surviving fossil elements (particularly in sample ON6) point to deposition in a dynamic, high-energy marginal setting. The fauna was likely subjected to significant mechanical agitation by waves or currents, and subsequently exposed to oxidizing conditions, before final burial.

ChAPTER III

Microfacies and paleoenvironment

1. Introduction.

In this chapter, the focus shifts from the macroscopic field descriptions established previously to a detailed microscopic analysis of the studied carbonate facies. While the lithostratigraphic framework provides the foundational geometry of the Cenomanian-Turonian platform, a comprehensive petrographic study is essential to fully understand its depositional environments and subsequent post-depositional alterations.

This chapter presents a systematic microfacies analysis, utilizing both Plane Polarized Light (PPL) and Cross Polarized Light (XPL) optical microscopy. The carbonate rocks are first characterized and categorized according to the Dunham classification system to define their original depositional textures. Following this, a major emphasis is placed on the diagenetic overprint, specifically the pervasive dolomitization that has extensively modified the primary sedimentary fabrics.

The fundamental objective of this chapter is to reconstruct the complete paragenetic sequence by systematically detailing dolomite crystal characteristics, replacement relationships, and the quantitative degree of dolomitization. Ultimately, the synthesis of these petrographic observations will drive a robust discussion on the diagenetic mechanisms—such as the potential influence of meteoric fluids—and the overall post-depositional history that shaped this section of the regional platform.

2. Rock Classification.

To categorize the carbonate rocks across our three study areas, we primarily apply the Dunham (1962) classification for depositional textures, which distinguishes rocks based on their grain-to-matrix ratios (e.g., mudstones, wackestones, and packstones). Following the identification of specific microfossils in our samples, we now explicitly incorporate this biological content—such as planktonic and benthic foraminifera—into our classification to highlight open-marine influences (e.g., bioclastic wackestones).

Furthermore, in areas where intense diagenetic alteration has completely obscured these primary bioclastic fabrics, we utilize the Sibley and Gregg (1987) classification to describe the resulting dolomitic textures, specifically identifying non-mimetic (sucrosic) fabrics.

Based on the microscopic analysis of thin sections from our study areas, the classification is as follows:

- Mansoura Section.

- **MN6 & MN7:** With the identification of microfossils, MN6 is reclassified from a simple mudstone to a **Bioclastic Wackestone**. While it contains a fine micritic matrix indicating low energy, it is distinctly populated by planktonic (*Globigerina*) and benthic (*Textularia*) foraminifera.

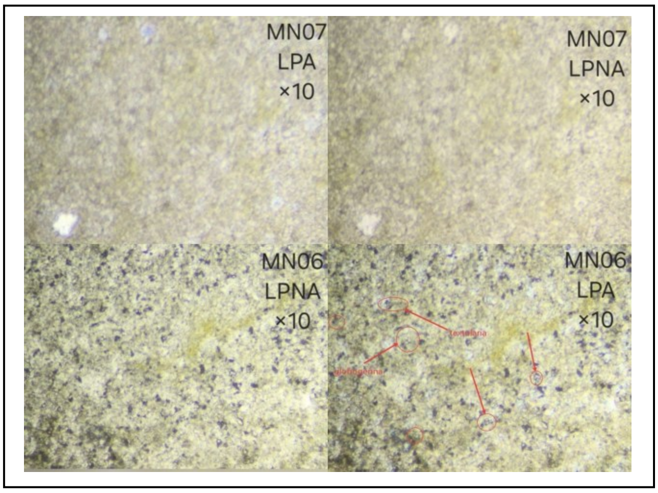


Figure 17 : Thin-section views of samples MN07 and MN06 highlighting microfossils under polarized light.

- **MN8:** Classified as a **Wackestone grading into a Packstone**. It shows a fine-grained matrix with patchy variations and a higher concentration of material, representing a transition to slightly higher energy.

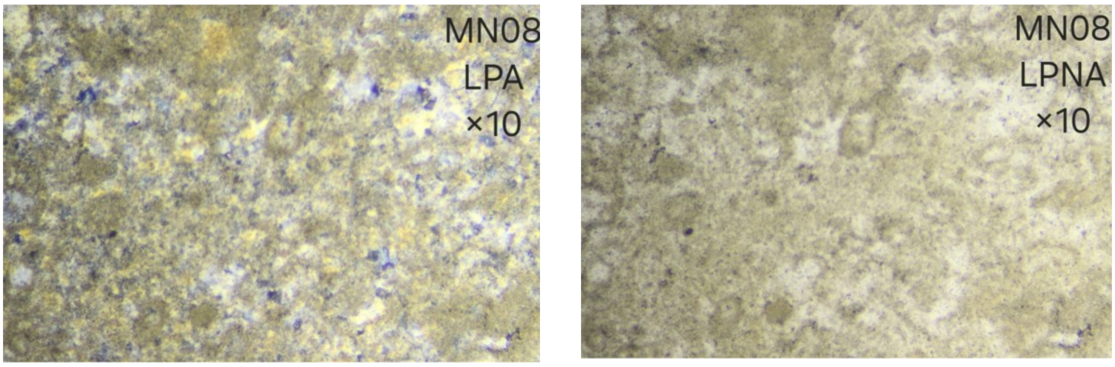


Figure 18 : Microfacies of sample MN08 in LPA and LPNA (×10).

- **MN4:** Classified as a diagenetically altered **Bioclastic Wackestone/Packstone**. The primary texture clearly contains *Globigerina* tests, although the fabric is disrupted by significant moldic porosity and secondary mineralization.

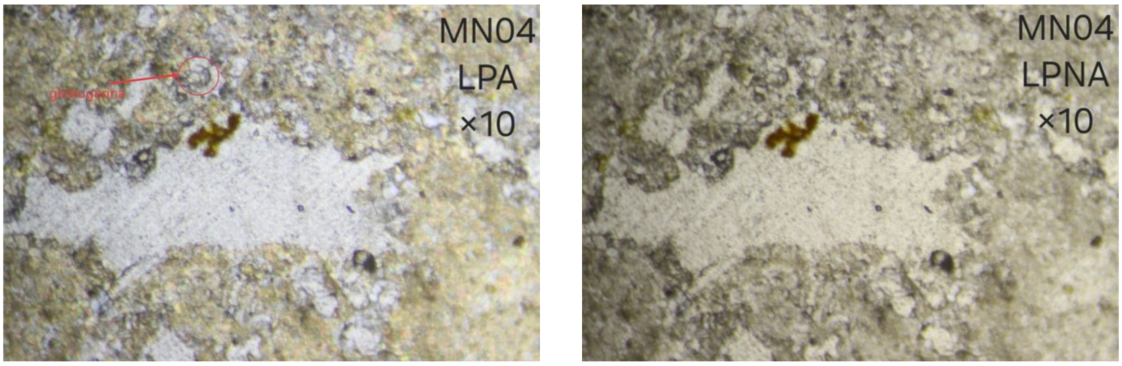


Figure 19 : Thin-section view of sample MN04 in LPA and LPNA (×10).

- **MN2 & MN5:** Previously, the primary texture appeared completely obliterated by recrystallization. However, MN2 preserves ghost structures of microfossils. Therefore, it is classified as a **Diagenetically altered Bioclastic Wackestone**, where the matrix has recrystallized into a crystalline carbonate mosaic, but primary pelagic bioclasts remain identifiable

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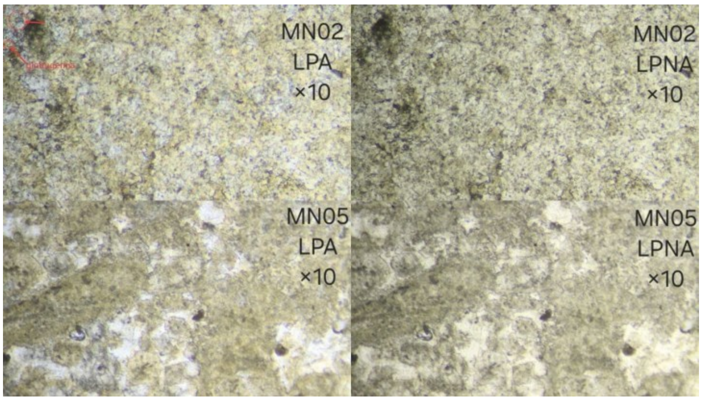

Figure 20 : Thin-section views of samples MN02 and MN05 in LPA and LPNA (×10).

- Oued Nachou Section.(Fig. 19)

- **ON00:** Reclassified from a simple mudstone to a **Bioclastic Wackestone** undergoing patchy recrystallization into sparite. The presence of planktonic foraminifera (*Globigerina*) indicates that the original micritic mud was deposited under open-marine or pelagic conditions before diagenesis occurred.

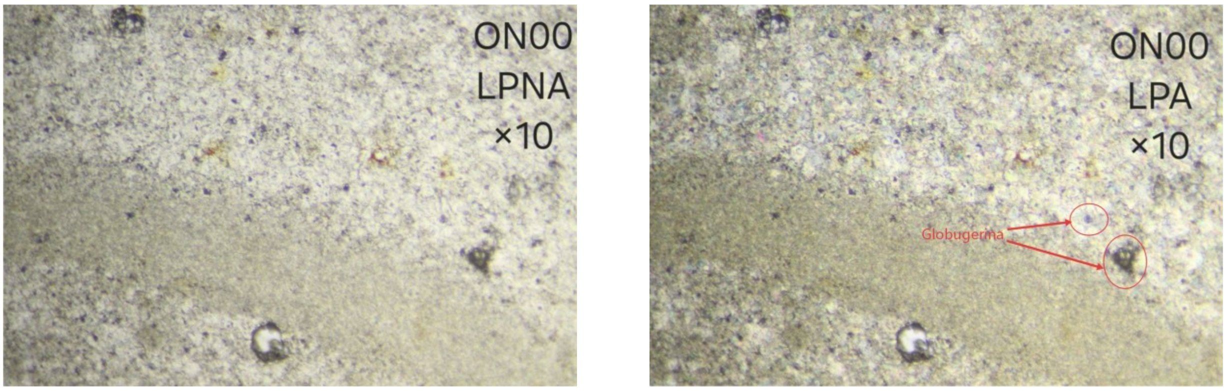

Figure 21 : Thin-section view of sample ON00 in LPNA and LPA highlighting Globigerina (×10).

- **ON1:** Classified as a **Diagenetically altered Bioclastic Wackestone** . While the original depositional mud and grains have been heavily replaced by an interlocking crystalline mosaic due to pervasive neomorphism, the ghostly outlines of marine bioclasts are still visible.

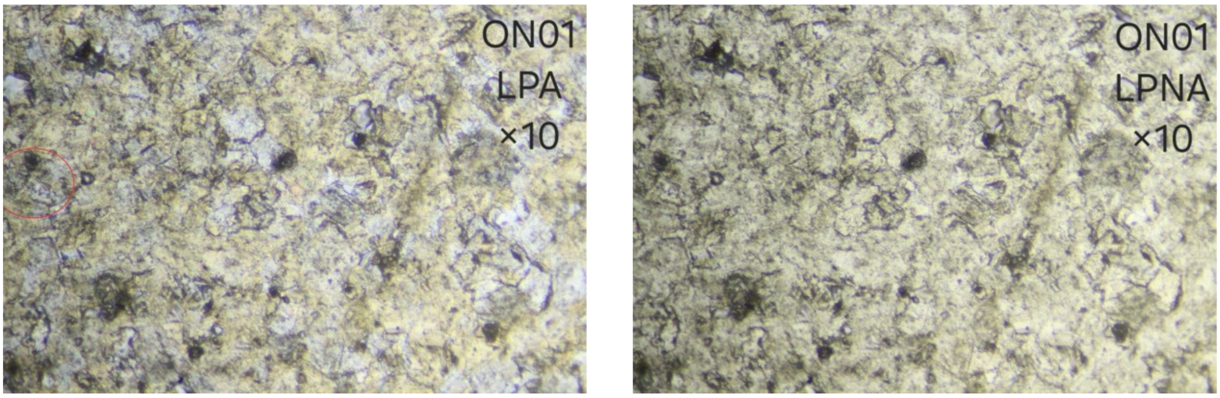

Figure 22 : Thin-section observation of sample ON01 under LPA and LPNA.

- **ON3:** Reclassified as a **Bioclastic Laminated Wackestone**

(or Boundstone). It features wavy microbial or algal laminations, but the inclusion of *Globigerina* means open-marine pelagic material was being washed into this shallow environment and trapped.

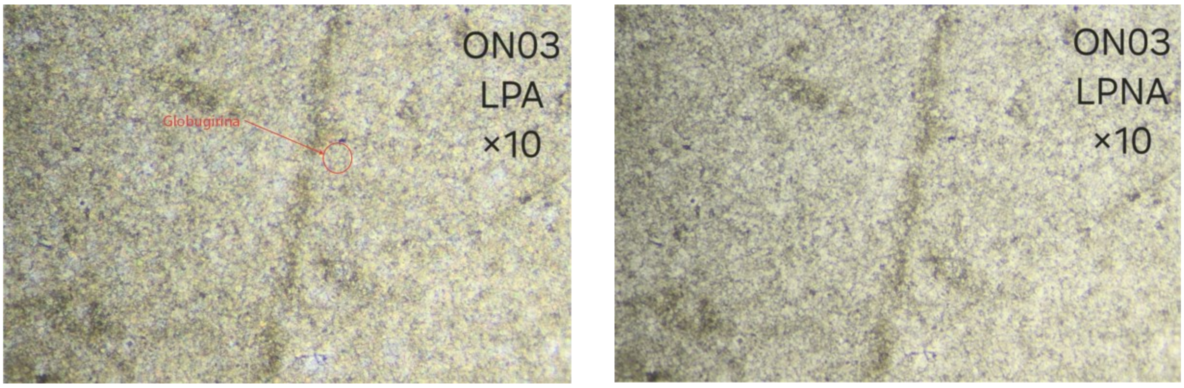

Figure 23 : Thin-section view of sample ON03 showing planktonic foraminifera under LPA and LPNA.

- **ON2 & ON8:** Classified as evaporite-bearing**Wackestones/Packstones**.

These specific samples are defined by secondary vuggy porosity and evaporitic mineral casts, representing periods where the environment became highly restricted and hypersaline.

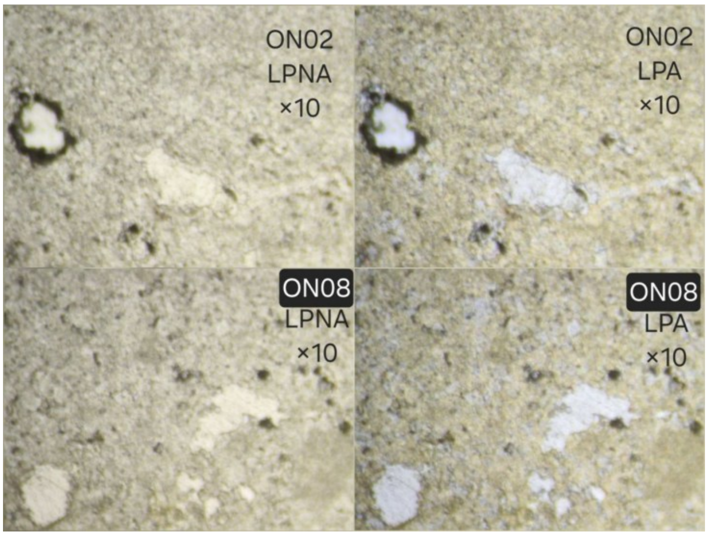

Figure 24 : Thin-section views of samples ON02 and ON08 under LPNA and LPA.

- **ON9:** Classified as **Crystalline Carbonate**. The primary matrix is completely lost to an intensely recrystallized, cloudy microsparitic fabric.

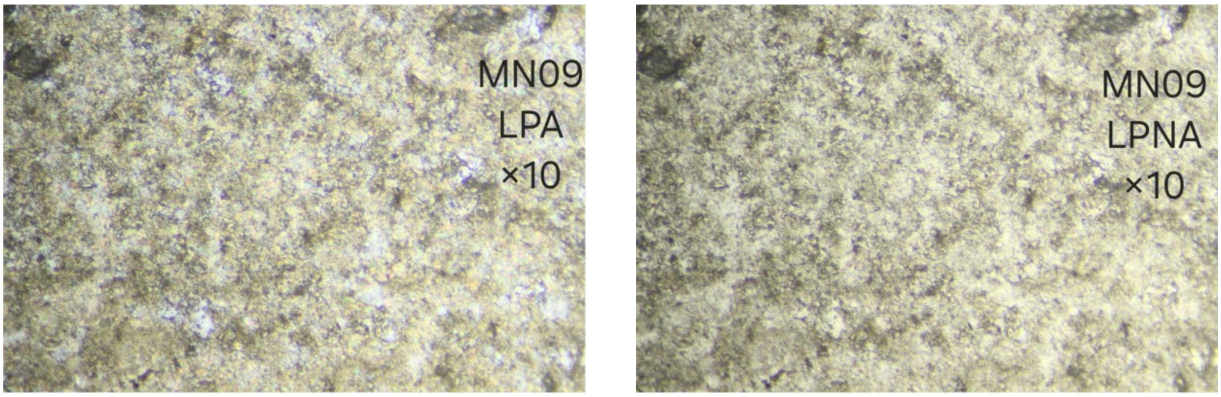

Figure 25 : Microfacies of sample MN09 in LPA and LPNA (×10).

- Berriane Section

- BR1, BR2, BR3, & BR4(Fig. 20): All samples from this profile are classified as Non-mimetic (Sucrosic) Dolomites under the Sibley and Gregg system. The original limestone fabrics (whether mud-supported or grain-supported) have been 100% replaced by dolomite crystals, meaning a primary Dunham classification can no longer be applied.

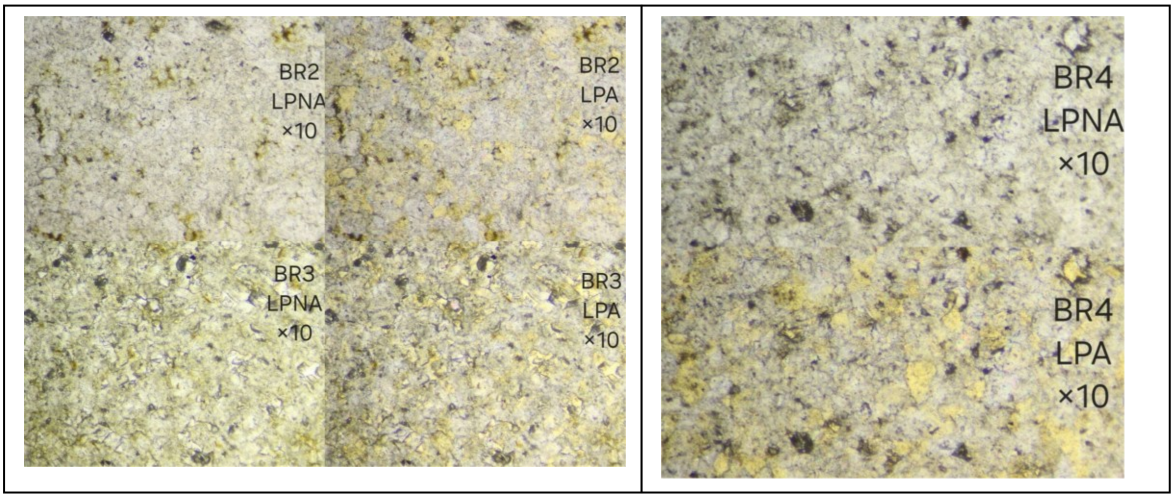

Figure 26 : Thin-section photomicrographs of samples Br02 to Br04 under cross-polarized (LPA) and plane-polarized (LPNA) light.

3. Petrographic Observations.

Microscopic examination of these specific thin sections allows us to see the exact diagenetic overprints and textural changes down to the micrometer scale.

- Mansoura Section.

- **Micrite and Marine Bioclasts:** Mansoura section sample(MN6) on

PPL reveals a major primary feature: a micritic matrix containing a distinct assemblage of microfossils. The presence of *Globigerina* (planktonic) and *Textularia* (benthic) foraminifera is highly diagnostic. This indicates an open-marine or pelagic influence rather than a completely restricted, isolated low-energy environment.

- **Recrystallization with Preserved Relicts:** Mansoura section
- sample(MN2) on PPL shows that despite the intense neomorphism creating a tight crystalline mosaic, the original outlines of *Globigerina* chambers survived the alteration. This allows us to trace the original open-marine fabric even after heavy diagenesis has altered the surrounding mud into microspar.

- **Porosity & Bioclasts:** "mansoura section sample(MN4) on PPL highlights the interaction between primary deposition and secondary alteration. Distinct *Globigerina* tests are preserved right next to an elongated, spar-filled moldic void, which is bordered by a cluster of opaque, reddish-brown iron oxides.

- Oued Nachou Section.

- **Primary Marine Bioclasts & Textural Contrast:** OUED NACHOU section sample(ON00) on PPL captures a sharp boundary between preserved dark micrite and a coarse, altered sparite mosaic. Crucially, the preserved micritic zones contain distinct *Globigerina* tests. This is strong evidence of open-marine incursions, contrasting with the purely restricted lagoonal interpretation.
- **Recrystallization with Preserved Relicts:** OUED NACHOU section sample(ON1) on PPL shows that despite intense neomorphism transforming the rock into a tight crystalline mosaic, the circular ghost structures of bioclasts (likely *Globigerina*) survived the alteration process. This proves the original sediment was fossiliferous before diagenesis.
- **Bioclasts in Laminated Fabrics:** OUED NACHOU section sample(ON3) on PPL shows *Globigerina* tests embedded directly within the dark, wavy laminated fabric. This suggests that while microbial mats or pressure solution seams (stylolites) were forming, the environment was still receiving pelagic microfossils from the open sea.
- **Evaporites & Vugs:** As noted in other samples from this section, bright, localized crystalline patches and distinct vuggy pores indicate periods of high evaporation and secondary dissolution, showing that the Oued Nachou environment fluctuated between open-marine incursions and restricted hypersaline conditions.

- Berriane Section.

- Sucrosic Dolomite Mosaic: Berriane section sample(BR1)on PPL and XPL, Berriane section sample(BR2) on PPL and XPL display a classic sucrosic texture made entirely of interlocking subhedral to euhedral dolomite rhombohedrons.
- Intercrystalline Porosity & Mineralization: Berriane section sample(BR3) on PPL and XPL, Berriane section sample(BR4) on PPL, and XPL highlight the excellent secondary intercrystalline porosity created by the volume reduction during dolomitization. Scattered opaque iron oxides are clearly visible trapped within these pore spaces.

4. Dolomite Characteristics.

Dolomitization is a major diagenetic feature in our study area, particularly within the Berriane section where the primary carbonate matrix has been intensely replaced. Examining these thin sections under plane-polarized and cross-polarized light (at ×10 magnification) allows us to define the specific microscopic characteristics of this dolomite phase.

- **Crystal type: Euhedral-subhedral rhombs:** The dolomite predominantly consists of well-formed euhedral to subhedral rhombohedrons. As observed in the Berriane samples Berriane section sample(BR1)on PPL, Berriane section sample(BR2) on XPL, etc.), these rhombs create a classic non-mimetic, sucrosic texture. The original depositional fabric of the limestone has been entirely destroyed and replaced by these distinct geometric crystals.
- **Crystal size:** Under the ×10 objective, the dolomite falls into the fine to medium crystalline range. The crystal size is relatively uniform across the Berriane thin sections, with the rhombs having grown large enough to completely overprint the original micrite and bioclastic grains of the precursor rock.
- **Crystal boundary:** The crystals display interlocking planar boundaries,

forming a dense crystalline mosaic. However, because the chemical conversion from calcite to dolomite involves a reduction in molecular volume, these boundaries are not completely tight. There is significant secondary intercrystalline porosity developed directly along the crystal margins. These boundaries also acted as pathways for late-stage fluids, which is why we observe opaque, reddish-brown iron oxides concentrated along the edges of the rhombs in samples like "Berriane section sample(BR3) on PPL.jpg" and "Berriane section sample(BR4) on XPL.jpg".

- **Dolomite abundance:** The abundance of dolomite varies drastically depending on the stratigraphic location. In the **Berriane section**, the dolomite abundance is pervasive, representing a near 100% replacement of the primary rock (forming a massive dolostone). In contrast, within the **Mansoura and Oued Nachou sections**, the abundance of true dolomite is much lower, with diagenesis mostly restricted to patchy neomorphic recrystallization (microspar) or isolated evaporitic replacements rather than massive dolomitization.

4.1. Interpretation :

The dolomitization observed in the Berriane section is a late-stage burial process that completely replaced the original limestone with uniform dolomite crystals. This chemical replacement caused a reduction in rock volume, which created significant intercrystalline porosity. Because these newly formed pore spaces stayed open, later oxidizing fluids were able to circulate through the rock and deposit the iron oxides we see in the thin sections. Finally, because this intense alteration is isolated to the Berriane profile and essentially missing from Mansoura and Oued Nachou, it is highly likely that the Mg-rich diagenetic fluids did not cover the whole region. Instead, their flow was controlled by local structural pathways, such as specific faults or fracture networks.

5. Replacement Relationships.

In our thin sections, the diagenetic alteration of the primary carbonate rocks shows clear replacement features, revealing how secondary fluids interacted with the original sedimentary textures. Evidence for replacement includes:

- **Dolomite rhombs replacing micrite:** This is most obvious in the Berriane section (samples BR1, BR2, BR3, and BR4), where the original fine-grained micritic mud has been completely obliterated. It is replaced by a dense, pervasive mosaic of euhedral to subhedral dolomite rhombs, transforming the rock into a sucrosic dolomite. We also catch this replacement process frozen in time in the Oued Nachou section (ON00), where patchy crystalline recrystallization is actively consuming the darker primary micrite.
- **Fossil outlines preserved but internally dolomitised:** Despite the intense diagenetic alteration in some areas, the primary open-marine biological signatures are not always fully destroyed. In sample MN2 (Mansoura) and sample ON1 (Oued Nachou), the rocks have been heavily altered into a tight crystalline mosaic. However, the circular ghost structures of planktonic *Globigerina* bioclasts clearly survived. The original internal material of the tests has been chemically replaced and filled by the secondary crystalline mosaic, but their external morphological outlines remain preserved.
- **Dolomite crystals cross-cut original matrix boundaries:** The chemical replacement process does not respect the original depositional structures or grain boundaries. In sample ON00, the thin section captures a sharp diagenetic front where coarse, newly formed secondary crystals grow directly into and cross-cut the edges of the preserved dark micritic patches. Similarly, in the massive dolomites of the Berriane profile, the interlocking dolomite rhombs have grown so pervasively that any original sedimentary matrix boundaries or bioclastic edges have been completely cross-cut, overprinted, and destroyed by the geometric faces of the new crystals.

5.1. Interpretation.

The observed replacement relationships indicate that diagenetic alteration occurred during late-stage burial, as evidenced by secondary crystals actively cross-cutting primary depositional boundaries. This transformation was driven by gradual neomorphism, allowing the delicate morphological outlines of pelagic bioclasts, such as *Globigerina*, to survive as "ghost" structures even as their internal chemistry and the surrounding micrite were completely replaced. Furthermore, the stark contrast between the pervasive, structure-obliterating dolomitization in the Berriane section and the localized, patchy recrystallization in the Mansoura and Oued Nachou profiles points to strong structural control over fluid migration. Mg-rich diagenetic brines likely exploited specific fault or fracture networks in the Berriane area, while the other regions remained relatively isolated from these main conduits, preserving more of their original open-marine to restricted sedimentary signals.

6. Degree of Dolomitisation.

The degree of dolomitization across our study area is highly variable. By visually estimating the mineral and porosity percentages from the thin sections, we can clearly separate the primary limestones from the diagenetically altered massive dolostones.

- Mansoura Section.

- Calcite: Strong presence
- Dolomite: Weak presence
- Pores: Weak presence

This section shows some significant of dolomitization. The mineralogy is overwhelmingly dominated by the primary calcitic micrite and the preserved bioclastic grains (like the *Globigerina* tests). The porosity is strictly localized as spar-filled moldic voids or fractures (as seen in sample MN4), rather than a widespread diagenetic pore network.

- Oued Nachou Section

- Calcite: Strong presence
- Dolomite: Weak presence
- Pores: Average presence

Similar to the Mansoura profile, the primary mineralogy here remains calcitic. While there is intense patchy recrystallization (converting micrite to sparite) and evidence of evaporitic nodules, this is neomorphism and dissolution, not dolomitization. The slightly higher porosity reflects the distinct vuggy and moldic pores developed during restricted, hypersaline periods.

- Berriane Section

- Dolomite: Strong presence
- Calcite: presence almost zero (Trace amounts)
- Pores: Average presence

This section represents a total replacement of the precursor limestone, making it a pure dolostone. The original calcite matrix and grains have been entirely consumed to form the interlocking sucrosic dolomite rhombs. The high porosity percentage directly reflects the excellent intercrystalline pore space created by the molecular volume reduction during this intense dolomitization process, with some of these pores now hosting iron oxide mineralization.

6.1. Interpretation.

The contrasting percentages of dolomite across our sections suggest that diagenetic fluids affected the Ghardaïa region unevenly, largely due to local structural controls. Because we see a minor but undeniable presence of dolomite (~5-10%) in the Mansoura and Oued Nachou profiles, it is clear that magnesium-rich brines did manage to diffuse across the broader carbonate platform, causing partial, incipient alteration of the original micrite. However, this background diffusion is minimal compared to the near-total replacement (~80-85%) observed in the Berriane section. This massive concentration implies that Berriane acted as a major structural conduit, such as a localized fracture zone or fault network, which channeled the bulk of the diagenetic fluids. As a result, only Berriane experienced enough continuous fluid flow to create the extensive intercrystalline porosity associated with volume reduction, while the other two areas remained mostly calcitic and petrophysically tighter.

7. Paragenetic Sequence.

By synthesizing all our petrographic observations from the three study areas, we can reconstruct the chronological order of the diagenetic events that shaped the rocks in the Ghardaïa region. This paragenetic sequence outlines the journey from the initial sea floor to the final burial stages:

- **Deposition of carbonate sediment:** The sequence begins during the Cenomanian-Turonian with the accumulation of fine carbonate mud along with pelagic and benthic microfossils (such as *Globigerina* and *Textularia*). Depending on the specific location, the depositional environment fluctuated between open-marine incursions and shallow, restricted lagoons where early evaporites occasionally formed.
- **Lithification and micrite formation:** During early burial, the primary sediment underwent compaction and lithification. The original carbonate mud stabilized into a dense micritic matrix. This early hardening was crucial because it helped preserve the fragile, circular outlines of the embedded bioclasts before later chemical fluids could completely destroy them.
- **Partial replacement by dolomite:** As the rock packages were buried deeper, magnesium-rich brines began migrating through the regional formations. The intensity of this step was heavily controlled by local structures. In Mansoura and Oued Nachou, the fluids only caused partial, incipient replacement (~5-10% dolomite) and patchy neomorphic recrystallization. However, in the Berriane section, major structural conduits allowed for intense, pervasive replacement that completely consumed the primary micrite.

- **Development of intercrystalline porosity:** Directly linked to the dolomitization process, this step drastically altered the rock's petrophysical properties. Because the newly formed dolomite crystals have a smaller molecular volume than the original calcite, the replacement process created empty space. In the heavily altered Berriane rocks, this resulted in an excellent, highly interconnected intercrystalline pore network between the newly grown sucrosic rhombs.
- **Minor calcite cementation:** In the latest stages of diagenesis, the remaining pore spaces, vugs, and fractures acted as pathways for late-stage fluids (likely meteoric waters during uplift or fracturing). This led to minor, localized calcite cementation filling some of the moldic voids. This final fluid circulation phase is also responsible for precipitating the reddish-brown iron oxides that we now observe trapped within the intercrystalline pores and along the dolomite crystal boundaries.

8. Discussion.

This discussion synthesizes the lithostratigraphic, micropaleontological, and petrographic data collected from the Mansoura, Oued Nachou, and Berriane sections. By integrating these findings, we can accurately reconstruct the paleoenvironmental dynamics and the complex post-depositional diagenetic history of the Cenomanian-Turonian transition within the Ghardaïa region.

Paleoenvironmental Evolution and Platform Dynamics.

The sequence records a major transition from a siliciclastic-influenced margin to a fully developed carbonate platform. The basal clay-rich units in both the Mansoura and Oued Nachou sections capture the initial phases of marine flooding. The identification of planktonic *Globigerina* alongside benthic *Lagena* and *Dorothia* within these basal residues confirms that the platform had a definitive connection to open-marine waters early in its depositional history. However, the sedimentary record proves that this environment was highly dynamic rather than uniform. As the sequence progressed, the Oued Nachou sector experienced pronounced periods of restriction and aridity. The vertical shift to red clays, abundant gypsum nodules, and stromatolitic laminations indicates a regression toward a shallow, hypersaline lagoon or sabkha setting. In contrast, the Mansoura sector evolved into a more stable, moderate-energy marine environment, evidenced by thick successions of wackestones grading into packstones, heavily bioturbated by *Thalassinoides*, and featuring syn-sedimentary slumps indicative of localized slope instability.

Structurally Controlled Dolomitization

Following deposition and early lithification, a crucial step that stabilized the micrite and preserved the delicate "ghost" outlines of pelagic microfossils, the region was subjected to significant burial diagenesis. The most critical finding of this study is the extreme spatial variation in the degree of dolomitization.

The Mansoura and Oued Nachou sections exhibit only minor, incipient dolomitization (approximately 5-10%), preserving much of their primary calcitic mineralogy and open-marine bioclastic textures. In stark contrast, the Berriane section is characterized by a massive, near-total replacement (80-85% dolomite), completely destroying the original fabric to form a non-mimetic, sucrosic dolomite. This dramatic difference confirms that dolomitization was not a regional, blanket-like syndepositional event. Instead, it was highly structurally controlled. Magnesium-rich burial brines likely migrated through specific, highly permeable conduits—such as localized fault zones or fracture networks—that heavily intersected the Berriane area. This concentrated fluid flow drove the pervasive chemical replacement at Berriane and significantly enhanced its reservoir quality by creating extensive intercrystalline porosity through volume reduction.

Late-Stage Meteoric Alteration

The final stages of the paragenetic sequence were shaped by a distinct shift in fluid chemistry. Following the main dolomitization phase, the Ghardaïa region likely experienced tectonic uplift or subaerial exposure. This allowed fresh, oxygenated meteoric waters to infiltrate the carbonate formations.

These acidic meteoric fluids circulated through the newly established pore networks and structural fractures. In the largely calcitic Mansoura and Oued Nachou sections, this circulation drove localized dissolution, resulting in the distinct vuggy and moldic porosity observed in the thin sections. Meanwhile, in the heavily altered Berriane section, these oxygen-rich waters reacted with the surrounding rock to precipitate the prominent reddish-brown iron oxides that we now see concentrated along the boundaries of the dolomite rhombs and trapped within the intercrystalline pore spaces. Ultimately, the current petrophysical state of these Upper Cretaceous carbonates is the combined result of early structurally-guided marine brines and late-stage meteoric weathering.

9. Conclusion.

This study set out to reconstruct the paleoenvironmental dynamics and the complex diagenetic history of the Upper Cretaceous carbonates in the Ghardaïa region of the northern Algerian Sahara. By integrating macroscopic field lithostratigraphy with detailed microscopic petrography across three distinct sections, Mansoura, Oued Nachou, and Berriane, this thesis provides a comprehensive evolutionary model for this segment of the Saharan carbonate platform.

The sedimentary and micro-paleontological record reveals that the region evolved from an initial siliciclastic-influenced margin into a dynamic shallow-marine carbonate platform. The discovery of pelagic microfossils, specifically *Globigerina*, alongside benthic foraminifera like *Textularia*, confirms that this platform experienced significant open-marine incursions. However, the depositional environment was highly variable. While the Mansoura sector maintained a relatively stable, moderate-energy marine setting (characterized by bioclastic wackestones and packstones), the Oued Nachou sector was subject to pronounced periods of restriction, evolving periodically into a hypersaline lagoon or sabkha environment, as evidenced by evaporitic casts and microbial laminations.

Following deposition and early lithification, the carbonate platform was heavily modified by burial diagenesis. The most significant finding of this petrographic study is the highly localized, structurally controlled nature of the dolomitization process. The Mansoura and Oued Nachou sections remained largely shielded from these altering fluids, preserving their primary calcitic mineralogy and delicate bioclastic textures with only minor (~5-10%) incipient alteration. In sharp contrast, the Berriane section acted as a major structural conduit for magnesium-rich burial brines. This active fluid circulation resulted in pervasive dolomitization (~80-85% replacement), completely transforming the original limestone into a massive, non-mimetic sucrosic dolostone. This chemical replacement fundamentally upgraded the rock's petrophysical properties by generating a highly interconnected intercrystalline pore network through volume reduction.

Finally, the paragenetic sequence was capped by a phase of late-stage meteoric diagenesis. Tectonic uplift and subsequent subaerial exposure allowed fresh, oxygenated meteoric waters to infiltrate the newly created structural fractures and pore networks. This late-stage circulation drove localized dissolution (creating moldic and vuggy porosity in the calcitic sections) and precipitated the characteristic reddish-brown iron oxides observed primarily within the intercrystalline pores of the Berriane dolomite.

In conclusion, the Upper Cretaceous carbonates of the Ghardaïa region are not the product of a single, uniform geological event. Instead, their current architecture, mineralogy, and reservoir potential are the result of a complex interplay between fluctuating depositional environments, structurally focused marine brines, and late-stage meteoric weathering.

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