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**Late Jurassic coated grains from the Tiaret Mountains (NW Algeria):
Paleoenvironmental reconstruction and seawater-change implications**

Presented and supported by:

Ms. SOUDANI Radja Hind.

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Before the teaching committee composed of:

Mr. BOUZID R.	M.C. A	Oran 2 University	President
Mr. SADJI R.	M.C. A	Oran 2 University	Supervisor
Mr. BOUALEM N.	M.C. A	Oran 2 University	Examinator

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Foreword



Above all, this work would not have been possible without the grace of ALLAH, who granted me the strength, perseverance, and clarity of mind to see this endeavor through its many trials and triumphs.

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“In the name of ALLAH, The Most Gracious, The Most Merciful”

I begin by thanking **Allah** for everything. For the strength to continue when it felt difficult, for the patience to persist through uncertainty, and for the guidance that carried me through this journey.

I would like to express my deepest and most heartfelt gratitude to my beloved **mother** for her endless love, unwavering support, and countless sacrifices. You have always been my source of strength, comfort, and inspiration throughout this journey. Every step I have taken and every achievement I have reached is, in many ways, a reflection of everything you have given me.

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To my beloved **father**, thank you for your prayers and your belief in me. Although if you are no longer here, I feel your love surrounding me, and I carry you with me in everything I do.

To **my grandfather**, thank you for everything you have taught me in this life. Your wisdom, strength, and guidance have stayed with me, shaping how I move through the world.

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Radja hind

Abstract

The Middle–Late Jurassic carbonate deposits of the Bechtout and Bou Rheddou regions, located in the southern Ouarsenis Mountains (northwestern Algeria), constitute a key geological record for understanding the paleoenvironmental evolution of the external Tethyan domain along the southern margin of the Tethys Ocean. This study focuses on the microfacies analysis of coated grains, particularly ooids, oncoids, and cortoids, in order to reconstruct depositional environments and characterize the evolution of Jurassic carbonate systems. The results reveal a significant diversity of coated grains, characterized by distinct morphologies, internal fabrics, and stratigraphic distributions. Oncoids are the most abundant grains and indicate shallow marine conditions within the photic zone under low- to moderate-energy environments, strongly influenced by microbial activity. Ooids, including concentric, radial fibrous, micritic, compound, and pelagic types, reflect hydrodynamic variations ranging from high-energy shoals to quieter depositional settings. Cortoids are interpreted as products of microbial micritization and early diagenetic processes in restricted lagoonal environments. The stratigraphic distribution of these grains records a progressive paleoenvironmental evolution. From shallow transgressive carbonate platforms during the Callovian to more condensed and locally deeper depositional conditions during the Oxfordian–Kimmeridgian, followed by a return to shallow, high-energy carbonate environments in the Tithonian. These changes are interpreted as the result of a combination of tectonic activity, relative sea-level fluctuations, and ecological controls. This study contributes to a better understanding of Jurassic carbonate platform dynamics in the Ouarsenis Mountains and provides new sedimentological and paleoenvironmental data for the southern Tethyan margin.

Keywords: Middle-Late Jurassic, Bechtout, Bou Rheddou, Ouarsenis Mountains, Microfacies, Coated grains.

Résumé

Les dépôts carbonatés du Jurassique moyen-supérieur des régions de Bechtout et Bou Rheddou, situées dans la partie méridionale des Monts de l'Ouarsenis (nord-ouest de l'Algérie), constituent un important enregistrement géologique pour comprendre l'évolution paléoenvironnementale du domaine tellien externe le long de la marge sud de l'océan Téthys. Cette étude se focalise sur l'analyse microfaciologique des grains enrobés notamment les ooïdes, oncoïdes et cortoïdes, afin de reconstituer les environnements de dépôt et de caractériser l'évolution des systèmes carbonatés Jurassiques. Les résultats révèlent une grande diversité de grains enrobés, avec des morphologies, des fabriques internes et des répartitions stratigraphiques variées. Les oncoïdes sont les grains les plus abondants, ils témoignent de conditions marines peu profondes, situées dans la zone photique, sous des régimes hydrodynamiques de faible à moyenne énergie, fortement influencés par l'activité microbienne. Les ooïdes, incluant des types concentriques, fibreux radiaux, micritiques, composites et pélagiques, traduisent des variations hydrodynamiques allant d'un environnement d'eau peu profonde à des hauts-fonds. Les cortoïdes sont interprétés comme le résultat de processus de micritisation microbienne et de diagenèse précoce dans des environnements lagunaires restreints.

La distribution stratigraphique de ces grains enrobés met en évidence une évolution paléoenvironnementale progressive ; au Callovien, plateforme carbonatée peu profonde et transgressive, à des conditions de dépôt plus condensées et localement plus profondes durant l'Oxfordien, au Tithonien, un retour à un environnement carbonaté peu profond et agité. Ces changements sont interprétés comme le résultat combiné de l'activité tectonique, des fluctuations relatives du niveau marin et des contrôles écologiques.

Cette étude contribue à une meilleure compréhension de la dynamique des plateformes carbonatées jurassiques du Monts de l'Ouarsenis et apporte de nouvelles données sédimentologiques et paléoenvironnementales sur la marge sud téthysienne.

Mots-clés : Jurassique moyen-supérieur, Bechtout, Bou Rheddou, Monts de l'Ouarsenis, Microfaciès, Grains enrobés.

المخلص

تمثل الرواسب الكربوناتية للعصر الجوراسي الأوسط-الأعلى في منطقتي بشطوط وبوغدو، الواقعتين في الجزء الجنوبي من جبال الونشريس (شمال غرب الجزائر)، سجلاً جيولوجياً مهماً لفهم التطور الباليوبيئي للمجال التلي الخارجي على طول الحافة الجنوبية لمحيط التيثس. تركز هذه الدراسة على التحليل الميكروفاسيولوجي للحبيبات المغلفة، ولا سيما الأويدات (Ooids)، بهدف إعادة بناء بيئات الترسيب وتحديد تطور (Cortoids)، والكورتويدات (Oncoids)، والأونكويدات (Ooids) الأنظمة الكربوناتية الجوراسية.

أظهرت النتائج تنوعاً كبيراً في الحبيبات المغلفة، من حيث أشكالها وبنيتها الداخلية وتوزيعاتها الطباقية. وتعد الأونكويدات أكثر الحبيبات وفرة، حيث تشير إلى ظروف بحرية ضحلة تقع ضمن المنطقة الضوئية، وتحت تأثير أنظمة هيدروديناميكية منخفضة إلى متوسطة الطاقة، مع تأثير واضح بالنشاط الميكروبي. أما الأويدات، التي تشمل الأنواع متحدة المركز، والليفية الشعاعية، والميكريتية، والمركبة، والبيلاجية، فتشير إلى تباينات في الظروف الهيدروديناميكية، تتراوح من بيئات مائية ضحلة إلى مناطق الحواجز والرواسب الرملية الكربوناتية عالية الطاقة. في حين تُفسر الكورتويدات بأنها ناتجة عن عمليات الميكزّة الميكروبية والتحويلات المبكرة بعد الترسيب، ضمن بيئات لاجونية محدودة.

يُبرز التوزيع الطباقى لهذه الحبيبات المغلفة تطوراً تدريجياً للبيئات القديمة؛ إذ تميز الكالوفيان بوجود منصة كربوناتية ضحلة وذات طابع انتقالي، تلتها خلال الأكسفورديان ظروف ترسيبية أكثر تكتفاً وأعمق محلياً، ثم عودة خلال التيثونيان إلى بيئة كربوناتية ضحلة ونشطة هيدروديناميكياً. وتُفسر هذه التغيرات بالتأثير المشترك للنشاط التكتوني، والتذبذبات النسبية في مستوى سطح البحر، والعوامل البيئية والإيكولوجية المتحكمة في الترسيب.

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الكلمات المفتاحية: الجوراسي الأوسط-الأعلى، بشطوط، بوغدو، جبال الونشريس، الميكروفاسيس، الحبيبات المغلفة.

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First chapter

Generalities



I. Introduction

The study of carbonate sedimentary systems plays a fundamental role in understanding the geological evolution of ancient marine environments. In particular, the Middle–Late Jurassic period represents a key interval marked by significant paleoenvironmental, tectonic, and sea-level changes along the southern margin of the Tethys Ocean. Within this context, the Ouarsenis Mountains, located in northwestern Algeria and belonging to the external Tellian domain, constitutes an important geological archive for reconstructing these processes.

The Bechtout and Bou Rheddou regions, situated in the southern part of the Ouarsenis Mountains, expose well-preserved Upper Jurassic carbonate successions. These deposits, composed mainly of limestones, marls, and characteristic facies such as the Ammonitico Rosso, provide valuable information on sedimentation dynamics, stratigraphic organization, and paleoenvironmental conditions. Previous studies have focused on stratigraphy, paleontology, and regional geology; however, detailed microfacies analyses, particularly of non-skeletal grains, remain essential for refining depositional models.

The present study aims to contribute to this understanding through a detailed microfacies investigation of coated grains (ooids, oncoids, and cortoids) observed in thin sections. By combining bibliographic data with petrographic analysis, this work seeks to characterize the sedimentary environments and reconstruct the evolution of carbonate platforms during the Middle–Late Jurassic. Ultimately, this research provides new insights into the interplay between biological activity, hydrodynamic conditions, and relative sea-level fluctuations that controlled sedimentation within the Tellian domain.

II. Geographic framework

1. General setting

The Ouarsenis Mountains are an integral part of the Tellian domain, a major structural unit of the Alpine orogeny in the North Africa. From a paleogeographic perspective, this domain corresponds to the former southern margin of the Tethys Ocean (Fig1.a). Extending approximately 1,200 km from western Morocco to eastern Tunisia, the Tellian domain is divided into two main geographic zones: the internal zone (Northern Tell) and the external zone (Southern Tell), separated by the median plains. The external zone comprises several mountains, including the Tessala, Béni Chougrane, Ouarsenis, Bibans, and the Numidian chain in the Constantine region.

2. Local setting

The study area, encompassing the Bechtout and Bou Rheddou regions, is located in the southern part of the Ouarsenis Mountains (Fig1.b), within the external zone of the Tellian domain. The Bechtout and Bou Rheddou regions are bounded to the north by the Neogene plains, notably the Chélif plain, and to the south by the Sersou plateau. To the west, it is bordered by the Mina Mountain in the Relizane region, and to the east by the Médéa Mountains (Fig1.c & d). The Ouarsenis Mountains span several administrative provinces (*wilayas*), including Relizane, Chlef, Tiaret, Médéa, and Aïn Defla.

It should be noted that the attribution of the Bechtout and Bou Rheddou regions is subject to some variation in the literature. While some authors consider them part of the Ouarsenis Mountains (Polvêche, 1960; Sadjji *et al.*, 2021, 2022, 2025). According to the National Agency for Water Resources (*Agence Nationale des Ressources Hydrauliques*), the northern part of Tiaret, which includes Bechtout and Bou Rheddou, is definitively considered part of the Ouarsenis Mountains.

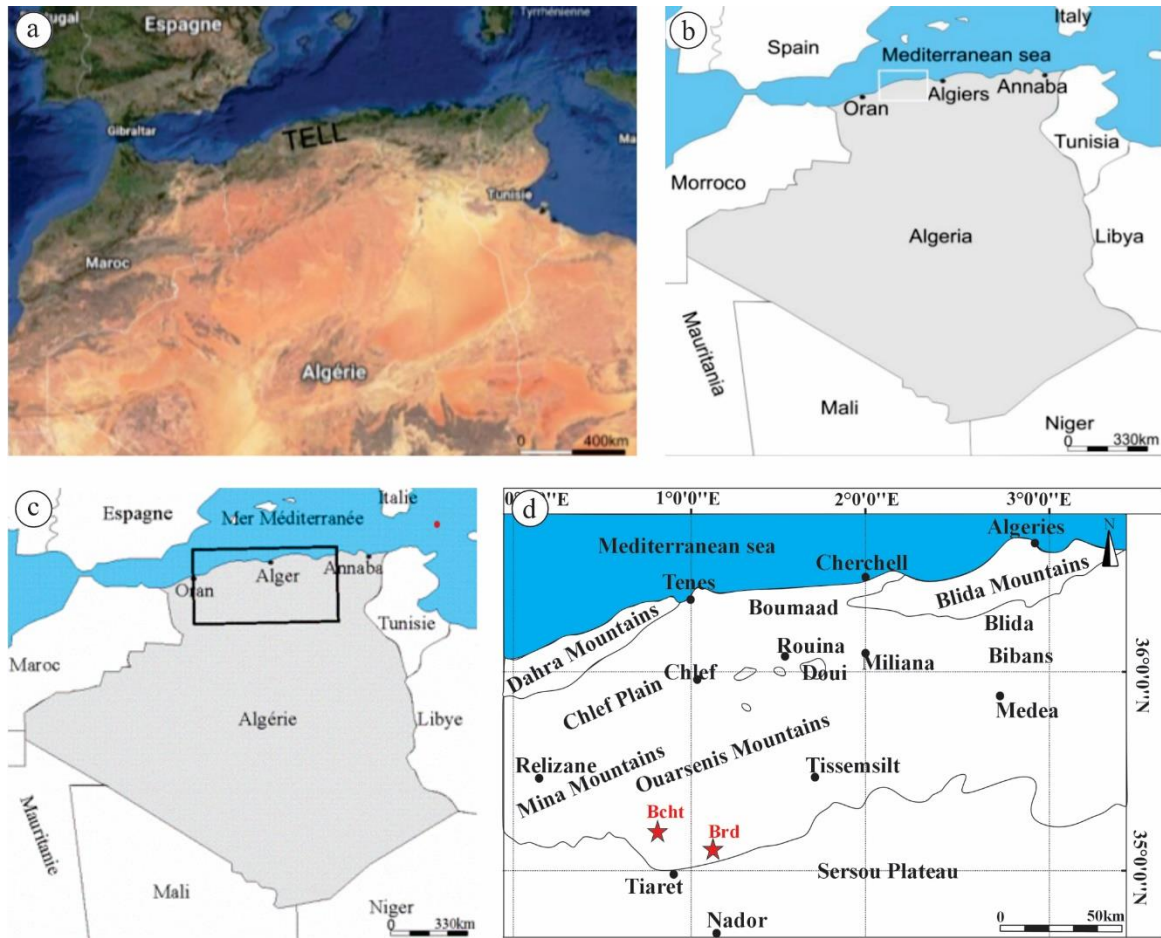


Fig.1: (a) Location of the study region within the Tell domain; (b) Geographic map of Algeria; (c) Geographical delimitation of the Ouarsenis Mountains according to the BNEDR (National Bureau for Rural Development Studies); (a, b, c after [Sadji 2021](#)) (d) Geographical limits of the Ouarsenis Mountains and location of the studied sections; (Bcht) Bechtout, (Brd) Bou Rheddou.

III. Geological framework

In the Ouarsenis Mountains, the Jurassic is characterized by carbonate rocks (dolomites and limestone), sometimes with sandstone intercalations ([Fig. 2](#)). The beginning of the Upper Jurassic is marked by the appearance of the Ammonitico-Rosso facies of middle Oxfordian age. The upper Oxfordian is represented by alternating limestone and red marl. The Kimmeridgian consists of decimeter-thick to micritic, massive beds of a grayish to bluish color alternating with Ammonitico-Rosso layers, while the Tithonian corresponds to alternating limestone and marl with Ammonitico-Rosso interbeds.

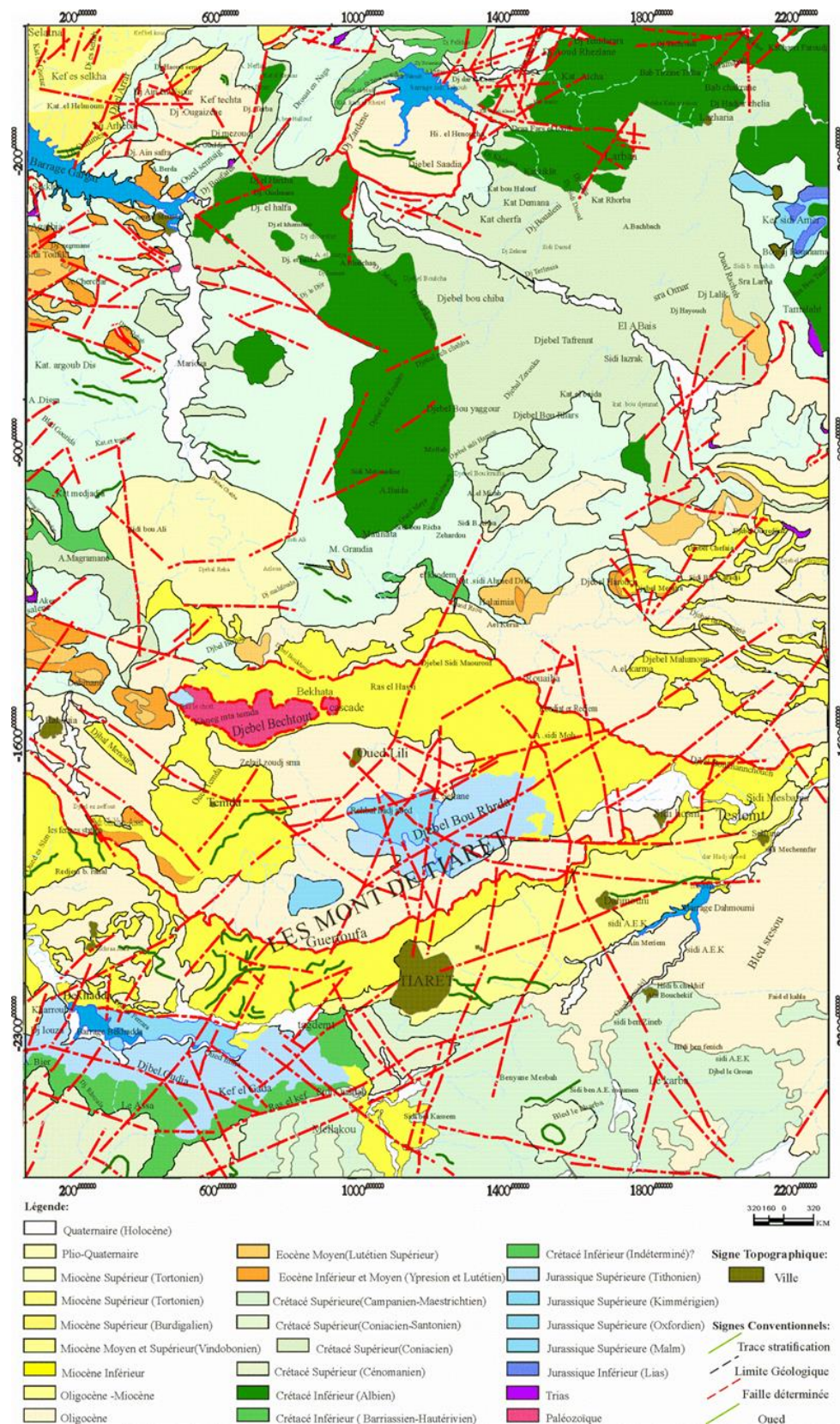


Fig.2: Extract from the interpretative geological map of Tiaret 1/20000 (sheet NI-31-XX), modified, published by the A.N.R.H (National Agency for Hydraulic Resources). After (Touaf, 2022)

IV. The structural framework (Fig3)

The Ouarsenis Mountains exhibit a complex structural and tectonic organization, characterized by anomalous contacts resulting from intra-Miocene movements associated with the paroxysmal tectonic phase (Caire and Mattauer, 1953a and b; Polvêche, 1960). Like much of the Algerian Tell, the Ouarsenis constitutes a thrust sheet domain, reflecting intense tangential tectonics.

Several successive tectonic episodes have affected the region:

1. Paleozoic Movements:

Paleozoic deformations likely occurred in the eastern part of the Ouarsenis (Polvêche, 1960). Evidence for this includes the rhyolitic phase of Bechtout (Lucas, 1952) and the pre-Permian movements described at Tafna (Gentil, 1902). Additionally, an angular unconformity between the Triassic and the Permo-Carboniferous has been observed in the region (Mattauer, 1958), indicating a significant tectono-sedimentary discontinuity.

2. Mesozoic Movements:

These deformations likely correspond to the folding phases that affected the Chelif-Nador region between the Jurassic and Middle Cretaceous. The pre-Neocomian phase, dated to the Early Cretaceous, deformed the coastal massifs (Durand-Delga, 1954), while the Cenomanian phase primarily affected the Chaouala area, followed by a pre-Senonian phase described by (Polvêche, 1960).

3. Tertiary Movements:

During the late Lutetian, a tectonic phase (Deleau, 1938) generated significant tangential movements attributed to the Pyrenean orogeny, which was responsible for major thrust faults within the Ouarsenis Mountains.

The formation of the nappes resulted from horizontal compressive stresses (Fallot, 1952; Goguel, 1952; Polvêche, 1960), reflecting a kinematic regime of north-south-directed sliding and folding (Glangeaud, 1951; Caire and Mattauer, 1953a; Mattauer, 1958).

V. Tectono-stratigraphic units

Several authors have proposed tectono-stratigraphic subdivision models for the Ouarsenis Mountains, notably [Mattaue](#) (1958), [Polvêche](#) (1960), and [Benhamou](#) (1996), the latter having established a structural scheme of the Algerian Tell incorporating the Ouarsenis Mountains ([Fig. 2](#)).

1. *Mattaue's Subdivision (1958)*

Mattaue distinguishes three main structural units:

The autochthonous unit: consists of Paleozoic and Jurassic formations, outcropping mainly in the Théniet El Had, Chlef, and Bechtout–Bou Rheddou regions.

Complex A (autochthonous or parautochthonous): composed primarily of Middle Cretaceous formations that have undergone limited displacement.

complex B: formed of Upper Cretaceous to Lower Miocene formations, including Eocene and Oligocene facies of the Boghari type.

2. *Polvêche Subdivision (1960)*

[Polvêche](#) (1960) identified several major structural units:

The Oligo-Miocene nappe: a thrust sheet composed almost exclusively of Oligo-Miocene sedimentary series.

The Chaouala unit: named after the tribe inhabiting the type region, this unit is composed of Neocomian to Barremian marl-limestone deposits containing a characteristic pyritic fauna. This term has since been adopted for other units of the western Tell, including the Tessala and Tafna Mountains ([Fenet & Magné, 1973](#); [Guardia, 1975](#)).

The Senonian nappe: described in the Relizane region (Mendez), this nappe is composed mainly of Senonian-age materials.

The Albian-Cenomanian unit: represented by Albian-Aptian flysch deposits associated with Cenomanian marl-limestone deposits.

Medjanian unit (Mattaue, 1958): composed of Oligocene deposits of Numidian facies, this nappe extends for approximately 300 km from Sétif in the east to Ammi Moussa (Relizane) in

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the west. It has been extensively described by several authors ([Mattauer, 1958](#); [Polvêche, 1960](#); [Bouillin & Raoul, 1971](#); [Guardia, 1975](#)).

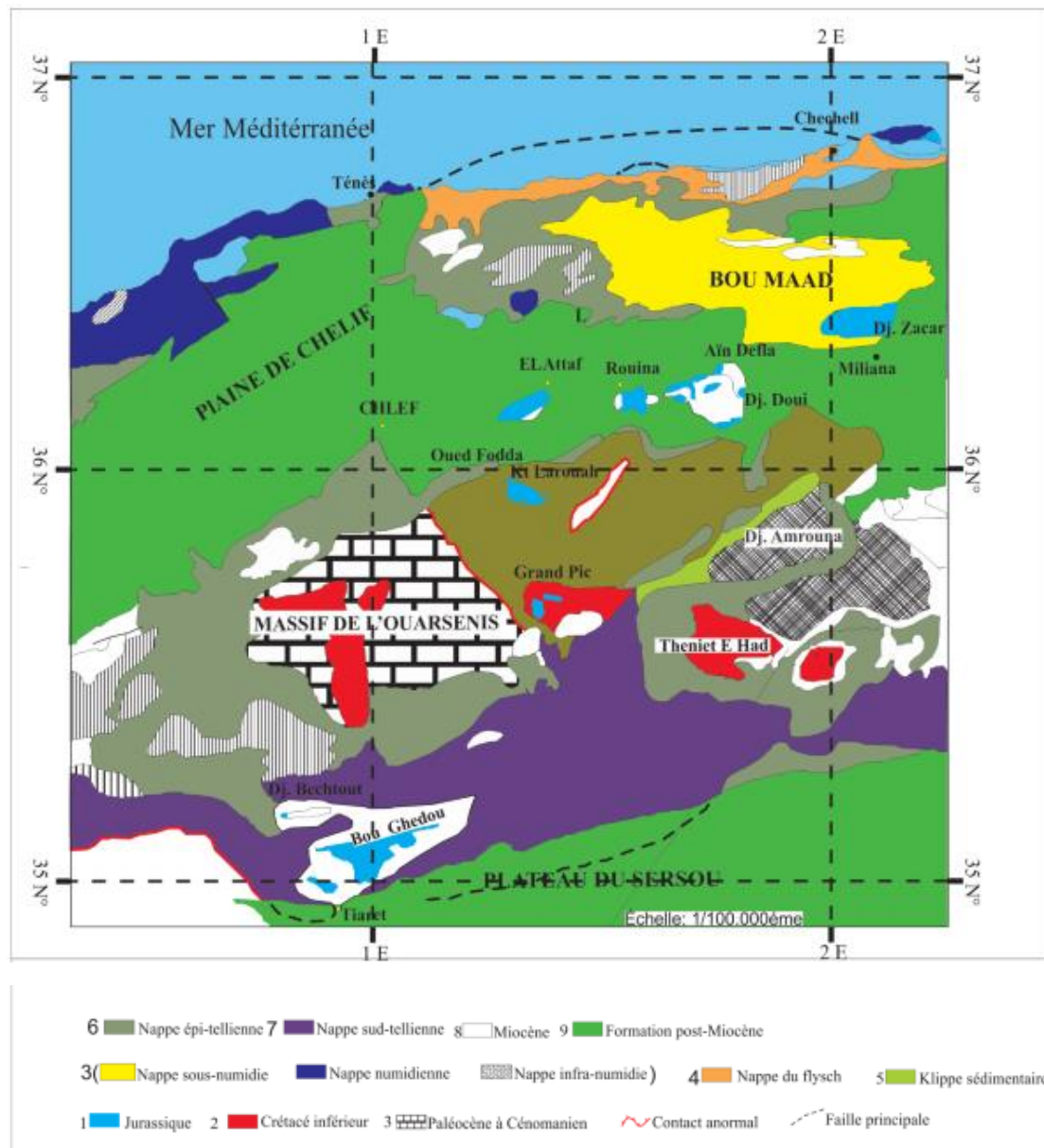


Fig.3: Structural Sketch of the Tell (in. [Benhamou 1996](#), modified by [Sadji 2021](#)).

VI. History of research

1. Initial Field Surveys (1890-1895)

- **Welsch, 1890:** He was the first to outline the succession of the Bechtout and Bou Rheddou regions. He correlated the outcropping facies of the High Plateaus and in the Tell Atlas with those of the French Alps. Based on a rich faunal collection, he established a zonal stratigraphy.

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He also worked on the western region of the Ouarsenis, providing a description of the primary crystalline rocks.

- **Ficheur, 1891**: He presented a stratigraphic model of the Bechtout and Bou Rheddou regions. He also explained certain geological features through the reactivation of vertical faults.

- **Replin, 1895**: He contributed to the understanding of the stratigraphic affinity of the Jurassic.

2. Modern Explorations (1942–present)

- **Ranoux, 1952**: He studied Djebel Bechtout, where he provided additional faunal evidence for the stratigraphic position of the sediments.

- **Polvêche, 1960**: He studied the Lower Cretaceous, which is represented by marl-limestone series in the autochthonous and especially the allochthonous layers, including the Chouala unit.

- **Atrops and Benest, 1986–1994**: They published a series of articles on the lithostratigraphy of the Jurassic, and especially the Upper Jurassic, of the Ouarsenis Mountains. They also worked on the stratigraphy of the Tlemcen and Nador regions. In 1994, they published a synthetic article on the Malm (Upper Jurassic) formations in the Tellian basin, where a lithostratigraphic correlation between Bou Rheddou, the Tlemcen Mountains, Chellala and Nador was established.

- **Benosmane, 1990**: She conducted a stratigraphic and systematic study of the ammonites from Bechtout and Bou Rheddou.

- **Tchoumatchenco, 1992-1995**: Carried out geological surveys and developed and described the geological cross-sections in western Ouarsenis. He also studied the Lower Cretaceous stratigraphy of massif and proposed a structural (geodynamic) model for the overturned Grand Pic series.

- **Chabani, 2020**: Addressed the petrology, petrography, and geochemistry of Visean-age magmatic rocks, referred to as "rhyolites," in the Bechtout region.

- **Sadji, 2021**: In his thesis, addressed multiple aspects, including stratigraphy, chemostratigraphy, paleoclimatology, and sedimentology. From a sedimentological perspective, he reconstructed the sedimentary environments of the Upper Jurassic deposits of Tiaret and Tissemsilt. He also reconstructed the climatic conditions during the Upper Jurassic

using stable oxygen isotopes and finally, investigated the origin of the red nodular facies Ammonitico Rosso.

-Sadji et al., 2025: The authors studied the different episodes of growth and demise of carbonate platform production during the Callovian–Tithonian interval in the Ouarsenis Mountains (Tissemsilt and Tiaret sectors), based on microfacies, macrofacies analysis and carbon stable isotope perturbations throughout this period.

VII. Materials, methods and objectives

This study is based on two complementary approaches: a literature review and, laboratory work.

1. Literature Review

All published research (articles, theses, etc.) concerning the Upper Jurassic of the Ouarsenis Mountains, as well as unpublished doctoral theses, were consulted and reviewed. The primary references adopted are those of [Atrops & Benest \(1986; 1994\)](#); [Sadji \(2021\)](#); and [Sadji et al., \(2021, 2022, 2025\)](#).

2. Laboratory Work

This work involved the preparation of ten thin sections from samples collected in the study area. These samples were prepared and examined under an optical microscope at the teaching laboratory of the University of Oran 2. In addition, more than 50 thin sections were provided by Mr. Sadji Redouane and prepared at the GeoZentrum laboratory (Nordbayern, Erlangen Nuremberg, Germany) as part of his doctoral thesis.

The thin sections were photographed using a digital camera connected to a Zeiss Axiocam 506 microscope in the same laboratory.

VIII. Objective of the Study

The objective of this work is to conduct a detailed microfacies analysis of non-skeletal grains (ooids, oncoids...) from the Upper Jurassic deposits, based on microscopic observations of thin sections, in order to interpret the depositional environment, and to ascribe the different coated grains to a specific environment.



Second chapter

Lithostratigraphy



I. History of geological formations

The Middle to Late Jurassic succession of the Bechtout and Bou Rheddou regions, located in the external Tellian domain, has been the subject of research primarily focused on stratigraphy, with complementary sedimentological and tectonic approaches.

The first systematic studies were conducted in parallel by two teams:

- A Bulgarian team, led by Tchoumatchenco, (1985); Tchoumatchenco *et al.*, (1992; 1995)
- B French team, represented by Atrops & Benest (1986; 1994), in collaboration with Claude Bernard University (Lyon 1), which resulted in several doctoral theses (*e.g.*, Benosmane, 1990)

These two groups worked independently and employed different lithostratigraphic nomenclatures to designate the same units, or occasionally used the same name for distinct geological formations, thereby creating confusion in the scientific literature. This situation was exacerbated by the fact that the publications of the two teams generally did not cite each other's work, making interpretation and correlation difficult.

A significant clarification was provided by Sadji (2021), who conducted a comprehensive comparative study incorporation:

1-Data published by the French and Bulgarian teams;

2-New paleontological (ammonites, benthic foraminifera, *Saccocoma*) and chemostratigraphic data, notably through the analysis of stable carbon isotopes (δC^{13});

3-The recommendations of the International Stratigraphic Guide (Hedberg, 1979).

Based on this synthesis, Sadji (2021) adopted and updated the nomenclature proposed by the French team (Atrops & Benest, 1994), while also introducing modifications based on this own field observations and analyses. These updates notably include:

- Revision of stratigraphic classifications;
- Discovery of benthic foraminifera in formations previously considered sterile;
- Harmonization of the thicknesses of the formations between the northern (Tissemisilt sector) and southern (Tiaret mountains) outcrops, where lithological and terminological discrepancies persisted, particularly for the Tithonian.

Chapter2 Lithostratigraphy

Thus, recent work, notably that of [Sadji \(2021\)](#), now provides a homogeneous and updated view of the lithostratigraphy of the Bechtout and Bou Rheddou regions, resolving previous contradictions and integrating modern tools (biostratigraphy, chemostratigraphy) for a more reliable correlation at both regional and international scale. In the present study we use the lithostratigraphic subdivision adopted by [Sadji \(2021\)](#), [Sadji et al., \(2021, 2025\)](#).

Tab1- The table summarizes the different nomenclatures proposed for the Upper Jurassic period of the Bechtout and Bou Rheddou regions. (In [Sadji, 2021](#))

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Southern sections (Tiaret)												
Atrops & Benest (1986)				Tchoumatchenco et al. (1992)		Atrops & Benest (1994)		Sadji (2021)				
Age		Formation		Age	Formation	Age	Formation	Age	Formation			
Tithonian		Upper	Calcaires et dolomies à silex	Tithonian	Upper	Sedimentary gap		Tithonian	Upper	Bou Rharda Marl limestone		
		Lower	Marno-calcaires supérieur		Lower				Marne de Ain Gnega	Lower	Calcaire de Guelt Halouf	Guelt Halouf Limestone
			Marnes intermédiaires						Marnes de Gratene		Gratene Marl	
Kimmeridgian		Calcaires médians		Kimmeridgian	Calcaire de Slaim « <i>Slaim Limestone</i> »	Kimmeridgian	Calcaires du Bou Rheddou	Kimmeridgian	Bou Rheddou Limestone			
Oxfordian		Upper	Ammonitico Rosso supérieur	Oxfordian	Upper	Calcaire noduleux de Ain el Hamra « <i>Ain el Hamra Nodular Limestone</i> »	Upper	Oxfordian	Upper	Kheneg Red Clay		
		Middle	Grès intermédiaire		Middle		Kheneg Red Clay					
Callovian		Lower	Sedimentary gap	Lower	Calcaire noduleux de Ain el Hamra « <i>Ain el Hamra Nodular Limestone</i> »	Lower	Kheneg Red Clay	Lower	Frid Ammonitico Rosso			
		Middle	Sedimentary gap	Middle	Calcaire noduleux de Ain el Hamra « <i>Ain el Hamra Nodular Limestone</i> »	Middle	Frid Ammonitico Rosso	Middle	Frid Ammonitico Rosso			
Callovian		Upper	Sedimentary gap	Upper	Formation de Nador « <i>Nador formation</i> »	Upper	Sedimentary gap	Upper	Sedimentary gap			
		Lower	Bechtout Limestone	Lower	Formation de Nador « <i>Nador formation</i> »	Lower	Bechtout Limestone	Lower	Bechtout Limestone			

II. Lithostratigraphic description

1. Bechtout Limestone Formation

The Bechtout Limestone Formation, defined by [Atrops & Benest \(1994\)](#), consists of bluish to grayish limestone. This formation rests on a rhyolitic magmatic basement of Viséan age, which is not exposed in the Bou Rheddou region. The lithological succession of the Bechtout Limestone Formation begins with conglomerates (breccias) at Bechtout and with dolomites at Bou Rheddou. The dolomites are massive, yellowish, and are devoid of fauna and flora.

The Bechtout Limestone Formation ([Fig4.a](#)), of Callovian age, outcrop in the Bechtout and Bou Rheddou regions, with thicknesses of 25 m and 55 m, respectively. The succession begins with a carbonate breccia, exposed only at Bechtout. This breccia is composed of angular rhyolitic clasts ([Fig4.b](#)) ranging in size from millimeters to centimeters, embedded in a fine-grained dolomite matrix ([Fig4.e](#)), and is overlain by an oncolitic limestone with spherical oncoids ([Fig4.d](#)). An alternation of breccia layers and oncoid-rich layers is also observed ([Fig4.c](#)). Above, the formation consists of a bluish limestone containing benthic foraminifera, oncoids, green algae, bioclasts, quartz, and lithoclasts, as well as a yellowish dolomite ([Fig4.g](#)). This is followed by a medium- to thick-bedded micritic limestone ([Fig4.h](#)) containing gastropods, benthic foraminifera, and green algae. The succession ends with lithoclasts bearing spiculites with peloids, micritized ooids, and bipyramidal quartz crystals. ([Fig4.f](#)).

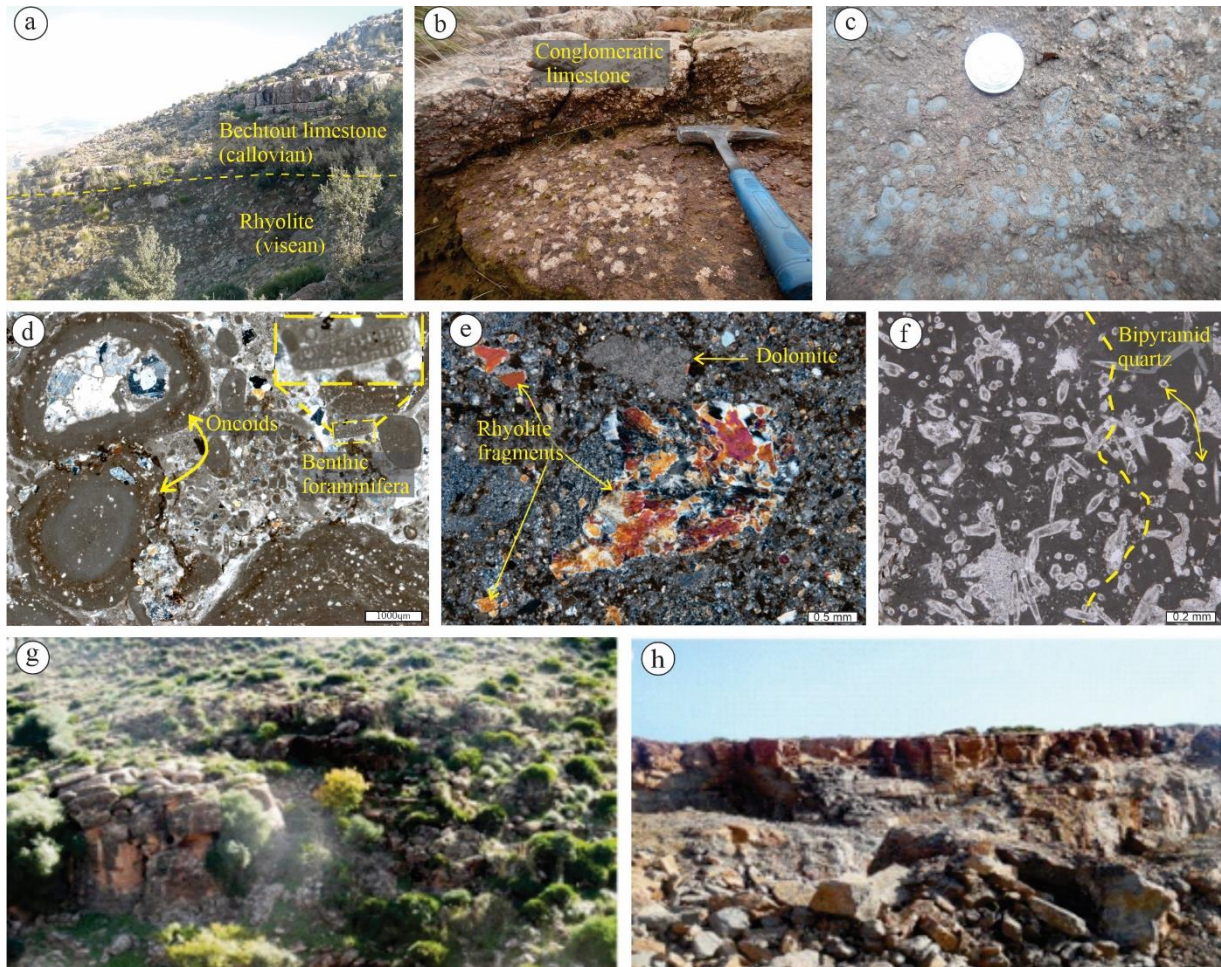


Fig.4: Callovian (Bechtout Limestone Formation); **(a)** The contact between the Visean (Paleozoic) rhyolite and the Callovian limestone (panoramic view) ; **(b)** Transgressive conglomeratic limestone; **(c)** Oncoids in dolomitic matrix; **(d)** Grainstone with oncoids, lithoclasts, benthic foraminifera; **(e)** Conglomeratic limestone microfacies, with rhyolite clasts; the cement is dolomitized “microgranular dolomite”; **(f)** Packstone with sponge spicules-bearing lithoclast (Yellow dashed line) displays peloids and bipyramidal quartz; **(g)** Massive grayish to bluish micritic limestone, the upper part of the Bechtout Limestone, Bechtout regions; **(h)** Massive yellowish dolomite, Bou Rheddou section.

2. Frid Ammonitico Rosso Formation

The Frid Ammonitico Rosso Formation was defined by [Atrops & Benest \(1986-1994\)](#) in the Kef El Frid region, where it outcrops notably at Bou Rheddou, which constitutes its type locality. The thickness of this formation varies: 5m at Bechtout and 15m at Bou Rheddou. It consists of a succession of nodular red limestones ([Fig5.d](#)) characteristic of the Ammonitico Rosso facies. The nodules, measuring several centimeters in size, are spherical to sub-spherical, sometimes angular, and red to occasionally grayish in color. They may be contiguous or

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dispersed within a red micritic matrix, which is sometimes replaced by red clays (Fig5.b & e). In some cases, altered ammonites may themselves form nodules. The contact between the nodules is ensured by a red clay matrix.

This facies is particularly rich in ammonites, generally poorly preserved, associated with belemnite rostra and a few aptychi (Fig5.c). The formation begins above a stratigraphic discontinuity (D1), and the transition from Bechtout Limestone Formation is marked by a clear lithological change. Its upper limit is characterized by a gradual transition from a red ammonite-bearing limestone facies to a red marly facies, corresponding to a change in lithotype.

The Frid Ammonitico Rosso Formation corresponds to the lower part of the Ain El Hamra Nodular Limestone Formation defined by Tchoumatchenco *et al.*, (1992). Its age is primarily attributed to the middle Oxfordian, based on the ammonite fauna, with the identification of the *Plicatilis* and *Transversarium* zones. Atrops & Benest (1986, 1994) initially assigned this formation to the *Transversarium* zone, while Sadji *et al.*, 2021 confirmed the presence of the *Plicatilis* zone at Bechtout and Bou Rheddou by the presence of *Campylites* (*Neoprionoceras*) sp (Fig5.a Fig6.A). Our new collection includes the following ammonites *Subdissosphinctes* sp (Fig6.F), *Passendorferia* sp., and *Grygoreceras* sp (*Transversarium* zone) (Fig6.G&H), associated with abundant *Lythoceras* and *Phylloceras*.

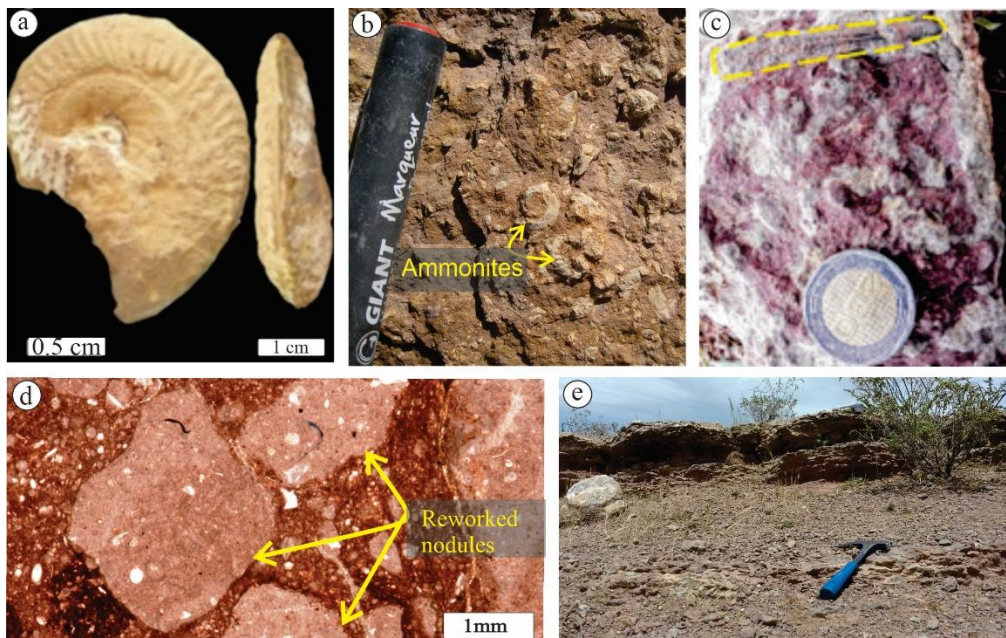


Fig.5: Middle Oxfordian (Frid Ammonitico Rosso Formation), (a) *Campylites* (*Neoprionoceras*) sp., *Plicatilis* zone; (b) The Red Ammonitico Rosso facies with ammonites; (c)

Ammonitico Rosso with belemnite; **(d)** Nodular fabric with probably reworked nodules floating in reddish micrite; **(e)** Calcareous Ammonitico Rosso facies.

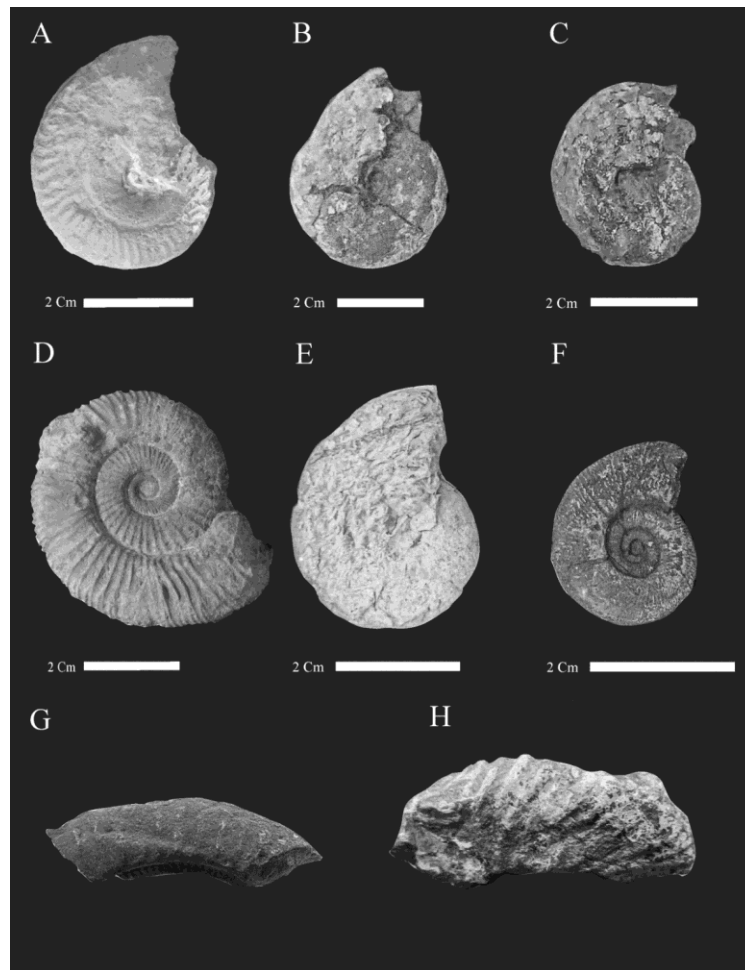


Fig.6: Middle Oxfordian ammonites of Frid Ammonitico Rosso Formation: **(A)** *Campilithes neoprotoceras* sp. Area in *Plicatilis* (Bechtout); **(B)** and **(C)** *Sowerbyceras Torisulcatum*, **(A, B and C)**: Sadjji's collection); **(D)** *Perisphinctes (dichotomeceras)* QUENSTEDT, Bou Rheddou (Atrops collection); **(E)** indeterminate ammonites; **(F)** *Subdiscosphinctes* sp; **(G)** fragment of *Passendorferia* sp, Bechtout; **(H)** Fragment of *Grygoreceras* sp, Bou Rheddou. After [Touaf, 2022](#)

3. Kheneg Red Clay Formation

The Kheneg Red Marl and Limestone Alternating Formation was initially defined by [Atrops & Benest \(1994\)](#) as The Kheneg Red Clay Formation. This unit was renamed by [Sadjji \(2021\)](#) to better reflect its dominant lithological nature. It consists of alternating red micritic limestone and red clay marl, indicating rhythmic marl-limestone sedimentation. Towards the top, The Kheneg Red Clay Formation is a wackestone/packstone with echinoid fragments

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associated with bioclasts and abundant grains of quartz (Fig 7.c), oncoids, ammonites, foraminifera, dasycladacean algae (*Clypeina jurassica*) (Fig 7. f).

This formation is separated from the underlying unit by a clear lithological discontinuity marking a gradual change towards the top. Locally, the marl-limestone alternation includes, detrital sandstone layers (Fig7.a & b), This alternation is highly bioturbated. Ichnofossils include *Ophiomorpha* (Fig.7 e), *Neonereites*, (Fig.7 d) *Zoophycos*, and *Thalassinoides*, interpreted as a medial member, reaching approximately 5 m in thickness at Bechtout and 15 m at Bou Rheddou.

The total thickness of the formation shows notable lateral variability, ranging from 59 m at Bechtout to 80 m at Bou Rheddou, reflecting differentiated depositional conditions within the basin. Stratigraphically, this unit represents the middle and upper part of the Ain El Hamra Limestone Formation defined by Tchoumatchenco *et al.*, (1992).

From a chronostratigraphic perspective, the Kheneg Red Marl and Limestone Alternation Formation is attributed to an interval ranging from the upper Oxfordian to the lower Kimmeridgian, characterized by the *Bifurcatus* zone in the upper Oxfordian, and the *Bimammatum* and *Planula* zones in the lower Kimmeridgian.



Fig.7: Kheneg Red Clay Formation, upper Oxfordian and early Kimmeridgian. (a & b) Bechtout and Bou Rheddou upper Oxfordian sandstone; (c) Wackestone with echinoid remains and aptychi with

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abundant quartz grains; (d) Sandstone with *Neonereites*; (e) Sandstone with *Ophiomorpha*; (f) *Clypeina jurassica* with quartz.

4. Bou Rheddou Limestone Formation (Fig8.c)

The Bou Rheddou Limestone Formation is defined on the right bank of Oued El Hallouf in Bou Rheddou region by [Atrops & Benest \(1994\)](#). It consists mainly of regular, medium to thick-bedded limestone (10-60cm) ([Fig8.b](#)), bleu to grey in color, locally cherty and micritic. The lower part of this formation includes thin marly intercalation. The transition from the underlying unit is marked by a pronounced discontinuity (D3), corresponding to a major lithological change from red marls of the "Marly Ammonitico Rosso" to bluish-grey micritic limestones ([Fig8.a](#)). The formation reaches approximately 55 m in thickness at Bou Rheddou and around 50 m at Bechtout.

Biostratigraphically, the basal part of the formation is dated as Kimmeridgian, characterized by ammonite assemblages of the *Platynota* and *Divisum* zones. The formation is particularly rich in *Saccocoma* remains including; *Saccocoma tenella*, *Saccocoma quenstedti*, and *Crassicoma* sp.

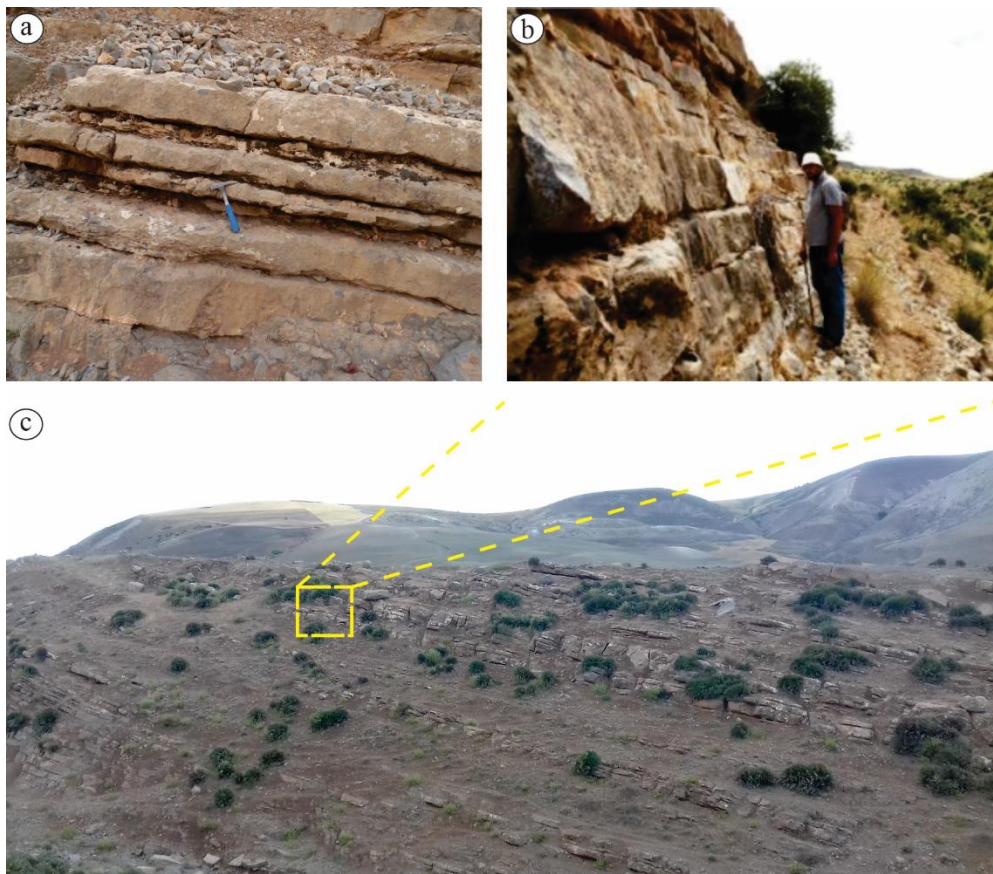


Fig.8: Bou Rheddou Limestone Formation (Kimmeridgian). **(a)** Bluish-grey micritic limestones; **(b)** Formation of the Bou Rheddou Limestone (Bou Rheddou, Oued Kheneg); **b** Zoom on **(c)** shows micritic limestone beds.

5. *Gratene Marl Formation*

The Gratene Marl Formation is predominantly marly and crops out exclusively in the Bou Rheddou (Fig9.d) region, where it was originally defined by Atrops & Benest (1994). It reaches a thickness of approximately 34 m and conformably overlies the micritic limestone of Kimmeridgian age. The lower boundary of the formation is marked by a sharp lithological change from micritic limestone to marl (D3), whereas the upper boundary corresponds to a return to limestone sedimentation.

The formation begins with yellowish marl of earliest Tithonian age, assigned to the *Hybonotum* zone. These basal marls contain ostracods associated with rare benthic foraminifera. Up section, the marls become grey and progressively alternate with thin limestone beds. This marly-limestone alternation is characterized by abundant pyritized cephalopods, vadose silt (Fig9.a) including belemnites, millimetric ammonites and aptychi, as well as common small brachiopods (Fig9.b & c). Although a diagnostic ammonite fauna of the *Hybonotum* zone is restricted to the lower part of the formation, the entire Gratene Marl Formation is assigned to the Tithonian.

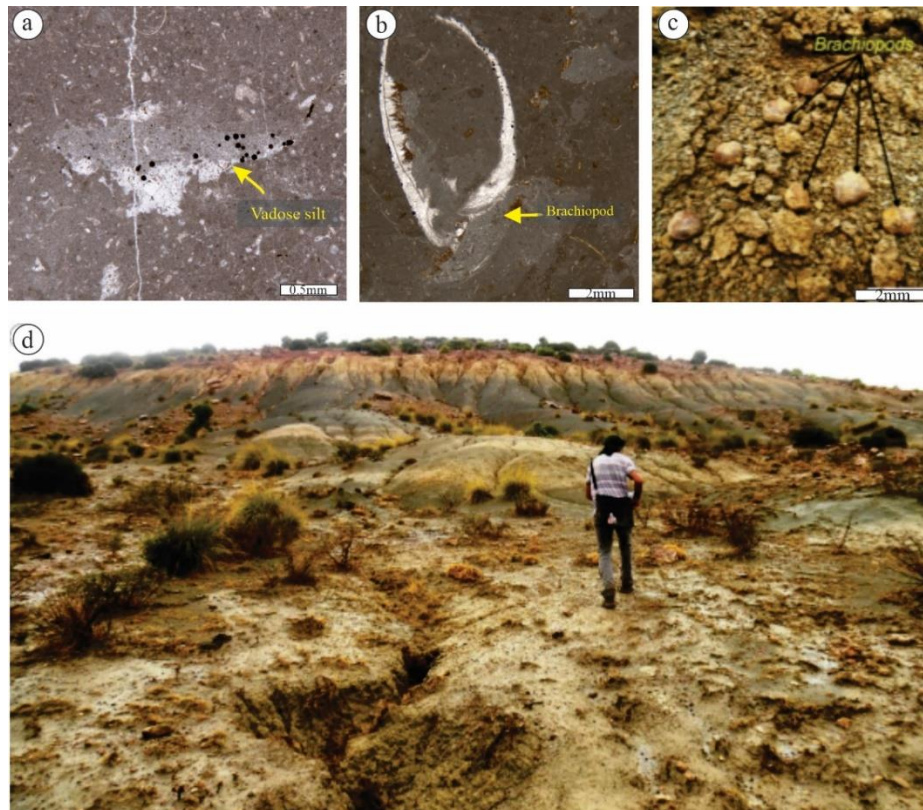


Fig.9: Gratene Marl Formation (lower Tithonian). **(a)** Wackestone with vadose silt; **(b)** Micritic limestone with brachiopods; **(c)** Marl bearing abundant small brachiopods; **(d)** Close-up view of the Gratene Marl Formation.

6. Guelt Halouf Limestone Formation

The Guelt Halouf Formation was defined by [Atrops & Benest \(1994\)](#) in the Bou Rheddou region, where it crops out on both sides of the upper course of Oued Guelt Halouf. The formation reaches a thickness of about 36 m and is composed of thick to very thick bedded limestone, locally slightly dolomitized, containing chert and characterized by abundant benthic microfauna and very intense bioturbation. The limestones display wackestone to grainstone microfacies. They are rich in peloids, micritic ooids (including ooids with pelagic nuclei, referred to as "pelagic ooids" by [Jenkyns 1972](#)), oncoids, lumps, echinoid fragments, microbial mats, assorted bioclasts ([Fig10.a &b](#)).

Ammonites are absent throughout the formation; consequently, its age is constrained by stratigraphic bracketing. It is therefore assigned to the lower Tithonian.

7. Bou Rharda Limestone-Marl Alternation Formation

This formation was defined by [Atrops & Benest \(1994\)](#) in Bou Rheddou region. It reaches total thickness of about 70 m, and its type section is located west of Oued Guelt Halouf, near the marabout of Sidi Abd El Kader (1033 m). The base of the formation is marked by the D4 discontinuity, which corresponds to a major lithological change.

The formation is subdivided into two members. The lower member, about 60 m thick, is dominated by marls, whereas the upper member, approximately 10 m thick, is limestone-dominated and includes levels of oolitic limestone ([Fig10.c & d](#)). Overall, the formation consists of alternating greenish to yellowish marl and bioturbated micritic limestone, yielding macrofossils such as crinoids, belemnites, brachiopods and rare ammonites. The uppermost part of the formation is entirely composed of massive, thick-bedded blue to grey limestones.

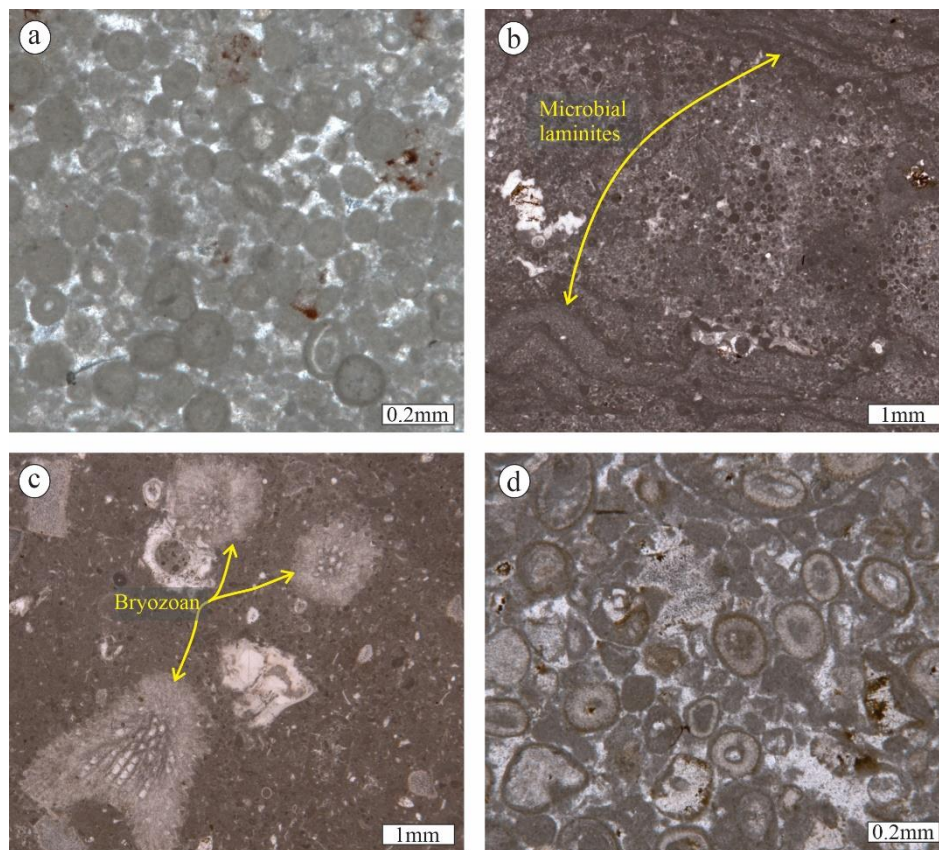


Fig.10: (a) Grainstone with micritic ooids and peloids; (b) Microbial laminites trapping peloids and some ooids (a and b from Guelt Halouf Limestone Formation, lower Tithonian); (c) Wackestone with bryozoan and lithoclast; (d) Packstone with peloids, radial-fibrous ooids with outer rims stained by hematite, with sparite cement; (c-d from Bou Rharda Limestone-Marl Alternation, upper Tithonian).

III. Lithostratigraphic synthesis

The lithostratigraphic study of the Upper Jurassic Formations in the Bechtout and Bou Rheddou regions, is characterized by significant carbonate sedimentation, notably including the well-known Ammonitico Rosso Facies.

The Callovian of the Bechtout region is characterized by an alternation of oncoid limestones and conglomerates, followed by dolomites overlain by ooid limestones and micritic limestones containing rare altered gastropods. The upper part of the formation consists of micritic limestones with sponge spicules, occasionally containing belemnite rostra. In the Bou Rheddou region, the succession is dominated by dolomites overlain by centimeter-thick micritic and oolitic limestone beds, with a sparse fauna represented mainly by belemnite rostra. This formation corresponds to the lower part of the Nador Formation [Tchoumatchenco, \(1992\)](#), dating from the Bathonian to the early Oxfordian. However, [Atrops & Benest, \(1994\)](#) propose an early to middle Callovian age.

The middle Oxfordian is marked by the establishment of the Frid Ammonitico Rosso Formation, composed of nodular red limestones with marly interbeds. This formation is characterized by an abundant ammonite fauna, allowing for the identification of *Transversarium* zones. It corresponds to condensed sedimentation.

The upper Oxfordian shows a transition to alternating marl and limestone, locally including levels attributed to *Bifurcatus*, *Bimammatum* and *Planula* zones. The upper Oxfordian is dominated by massive limestones with thick beds.

The Kimmeridgian formation is mainly composed of medium-bedded micritic limestones and more or less thick marly intercalations, yielding a rare ammonite fauna indicating the *Divisium* zones.

The overlying Tithonian at Bou Rheddou exhibits a clear lithological evolution. It begins with marls of earliest Tithonian age, bearing rare benthic foraminifera [Atrops & Benest, \(1984\)](#), alternating with thin limestone beds. The lowermost ammonite zone of the lower Tithonian is the *Hybonotum* Zone.

The lower Tithonian is composed of slightly dolomitized, well-stratified limestone of considerable thickness, locally containing chert. The upper Tithonian is characterized by an alternation of greenish to yellowish marls and bioturbated micritic limestones, and is finally capped by a thick, massive blue to gray limestone unit.

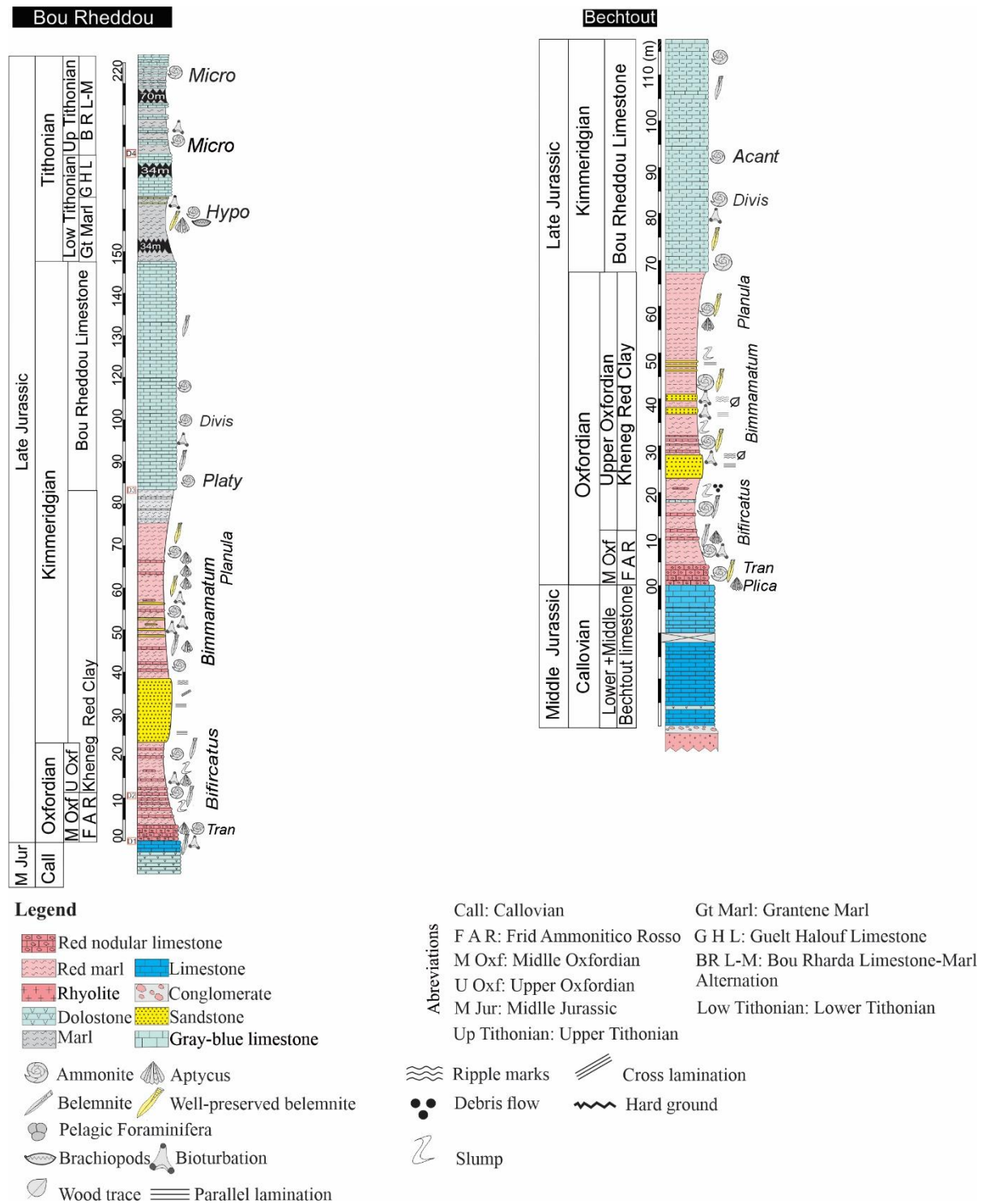


Fig.11: Lithological sections for the two studied outcrops of the Upper Jurassic (Ouarsenis Mountains, northwestern Algeria).



Third chapter

Sedimentology



I. Introduction

This chapter presents a detailed sedimentological (microfacies) study of the Middle- Late Jurassic carbonate succession in the Bechtout and Bou Rheddou regions. This study integrates macroscopic observations (sedimentary structures and fossil content), with petrographic analysis and the identification of several associated microfacies, with particular emphasis on the microscopic examination of coated grains.

II. Classification of carbonate rocks

Several classifications have been proposed for the microscopic (microfacies) study of carbonate rocks, most notably those of Folk (1959) and Dunham (1962), later supplemented by (Embry & Klovan, 1971). These classifications are based primarily on the abundance of allochelemes and the micrite/sparite ratio (orthochemes) to determine the texture type. For the purposes of this work, the Dunham classification (1962) was selected (Fig.11) as it is the most practical and widely adopted in academic and petroleum industry fields (Lokier and Junaibi, 2016). Dunham identified several textural features that are especially useful for classifying carbonate rocks: (1) presence or absence of carbonate mud (particles less than 20 microns), (2) abundance of carbonate grains (particles larger than 20 microns), (3) whether the grains are mud supported or grain supported, and (4) evidence of organic binding during deposition.

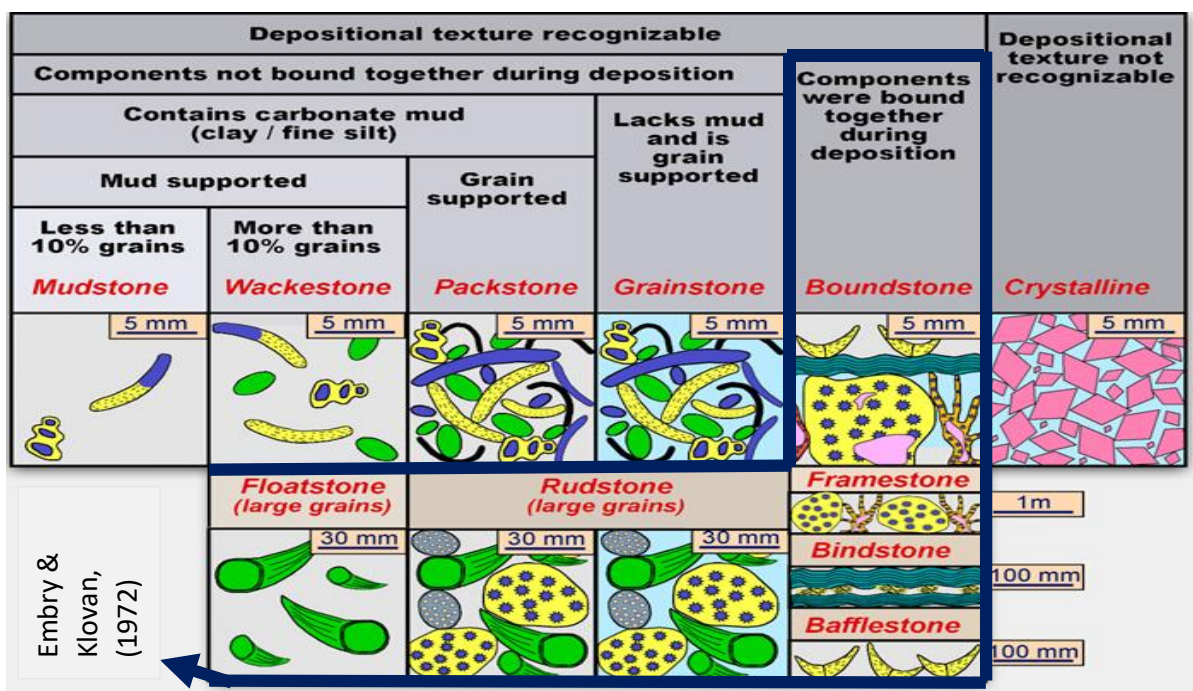


Fig.12: Dunham classification of carbonate rock texture (after Dunham 1962, Loucks and Kerans, 2003).

III. State of knowledge

- **Coated grains**

Coated grains comprise a more or less well-defined nucleus, surrounded by a coating of calcareous material, typically fine-grained, known as the cortex. In many coated grains the cortex is, at least in part, laminated. Numerous different names and definitions have been used for coated grains [Peryt, \(1983\)](#), based on criteria such as size, shape, regularity of concentric laminations, presence of obvious biogenic structures and, often, an interpretation of their origin. As is common elsewhere in carbonate sedimentology, a discrepancy exists between what is observed in recent environments and what is preserved in the geological record ([Adams & MacKenzie, 1998](#)) Carbonate coated grains include cortoids, ooids, oncoids and pisoids;

Cortoids, or micrite-coated grains, are carbonate grains ranging in size from less than 1 mm to several centimeters, most commonly between 500 μm and 1 mm. They consist primarily of bioclasts, although non-skeletal grains may also be present, surrounded by a thin (generally less than 100 μm), structureless, non-laminated micritic envelope. This micrite coating may be destructive (altering the original grain margin), constructive (forming through micrite precipitation), or a combination of both ([Flügel, 2004, 2010](#)).

Cortoids typically originate through micritization processes caused by endolithic micro-organisms, including cyanobacteria and endolithic or epilithic algae. These organisms bore into and modify carbonate grains while they remain temporarily exposed on the sea floor in shallow marine settings. Cortoids are characteristic of shallow platform-top environments, ranging from intertidal zones to subtidal lagoons and back-reef facies along platform margins, and they may occur under both low- and high-energy conditions. An increase in microboring intensity may reflect elevated nutrient levels in the depositional environment (*e.g.*, [Merino-Tomé *et al.*, 2012](#); [Della Porta *et al.*, 2013](#)).

Oncoids, range from millimeter to centimeter sized ([Flügel, 2010](#)), though they are commonly larger than 2 mm. They are characterized by a more or less distinguishable nucleus, often composed of fossil fragments, surrounded by a thick coating made up of irregular, non-

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concentric and partially overlapping laminae. These laminae result from the growth of one or more encrusting biogenic components, and unlike ooids, the sphericity of oncoids does not necessarily increase during growth. Oncoids originate through biogenic encrustation, typically involving algal, microbial, and cyanobacterial activity, and the laminae may embed various biogenic structures such as encrusting foraminifera, bryozoans. Several types of oncoids can be distinguished, including: 1) type C characterized by concentric layers, 2) type I includes biconvex lenses, featuring inverted hemispheres, have an irregular contour, 3) type L consists of an irregular and random growth, 4) type R is elongated in shape and composed of randomly arranged hemispheroids, and 5) micritic oncoids formed by the cyanobacterial calcification of microbial mats (Fig.13). Algal-microbial nodules, including cyanobacterial forms, are widespread in both non-marine and shallow-marine limestones. In shallow-marine deposits of the Phanerozoic, carbonate oncoids have been recorded in a wide range of environments, from intertidal, lagoon, shoal to open-marine settings, locally associated to reefal structures (e.g., Shi and Chen, 2006; Védrine *et al.*, 2007; Bádenas and Aurell, 2010; Reolid and Nieto, 2010; Sequero *et al.*, 2019).

Oncoids types	Microfabric of the cortex	Environment
Type C 	Characterized by concentrically stacked spheroid layers	Indicating relatively consistent, low to moderate energy, or frequent overturning in a specific orientation.
Type R 	Oncoids consisting of randomly arranged hemispheroidal layers	Indicating frequent, unpredictable, or overturning and movement.
Type I 	Biconvex lenticular oncoids exhibiting Inverted hemispheres describes a particular case characterized by the interruption of oncoid growth, partial destruction and renewed growth after reworking and transport	Suggesting specific, complex, or inverted positioning within the sediment or water column
Type L 	Irregular random growth also can produce lobate growth forms	Often found in low-energy or crowded, stable settings
Micritic 	Typically described as a "micritic mashwork" formed by the cyanobacterial calcification of microbial mats.	Low-to-moderate energy

Fig.13: Descriptive table of oncoid types and their environment. (Flügel, 2010)

Ooids, are small coated carbonate grains, most which are smaller than 2 mm in diameter; with many ranging between 0.5 and 1 mm in size (Flügel, 2010). They are spherical to sub-spherical or ovoid in shape and consist of one or several regular, concentric laminations developed around a nucleus, which may be a peloid, bioclast, quartz grain, or intraclast.

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Several types of ooids can be distinguished (Fig.14), including concentric ooids, pelagic ooids, radial fibrous ooids, compound ooids, and micritic ooids. Ooids typically form in agitated, shallow-water environments within carbonate sand bodies such as dunes and ripples, where grains are continuously reworked by waves, tidal currents, and storm activity.

Modern marine ooids may be aragonitic with tangentially arranged acicular crystals (approximately 2 μm long), aragonitic or calcitic with a radial microfabric, or micritic (as in Bahamian ooids) where the original lamination is partially obliterated by micritization. In saline lakes, ooids are commonly aragonitic with a radial microfabric. Their formation is generally attributed to abiotic carbonate precipitation around a nucleus under hydrodynamic agitation, although biogenic influences related to microbial activity and biofilms may also contribute to their development (*e.g.*, Adams & MacKenzie, 1998; Flügel, 2004).

Ooids types	Microfabric of the cortex	Environment
Concentric ooids (tangential) 	Concentric laminae consisting of tangentially arranged crystals whose long axes are aligned to the surface of the laminae	Very shallow, warm low-latitude seas; common in high-energy settings
Radial fibrous ooids 	Cortical laminations preserving the morphology of the nucleus	Marine oolites from sheltered environment
Pelagic ooids 	They frequently possess nuclei made up of planktonic Foraminifera or the remains of deep-sea organisms. They have a thin outer layer (cortex) composed of micrite	Found on isolated carbonate platforms or "seamounts" where currents are sufficient to keep the grains moving
Compound ooids 	Formed by the coalescence of two or more ooids enveloped by concentric layers	Formed in shallow, specific high-energy, episodic depositional environments
Micritic ooids 	Micritization of the cortex (by repeated perforation by algae or bacteria)	Common in shallow marine

Fig.14: Descriptive table of ooid types and their environment.

Pisoids, are coated carbonate grains that are structurally similar to ooids, but have a diameter larger than 2 mm (Flügel, 2010). They display a sub-spherical to irregular shape and commonly possess a non-biogenic nucleus surrounded by concentric laminae composed of dark micritic or hyaline carbonate (aragonite or calcite), showing either tangential or radial microfabric.

Their formation is commonly related to micritization processes driven by endolithic microorganisms, which produce both destructive and constructive micritic rims around grains. This activity typically occurs in shallow-water environments where carbonate grains remain temporarily exposed on the sea floor and are affected by photosynthetic and non-photosynthetic organisms (*i.e.*, cyanobacteria and endolithic or epilithic algae).

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Pisoids develop in a variety of depositional settings, including shallow marine carbonate platform tops from supratidal zones (often associated with tepee structures) to shallow subtidal ponds. They are also characteristic of hypersaline to freshwater environments. (*e.g.*, Adams & MacKenzie, 1998; Flügel, 2004, 2010).

IV. Paleoenvironment overview

1- Middle Jurassic “Callovian” (*Bechtout Limestone Formation*)

The succession begins with calcareous conglomerates resting unconformably on a Viséan rhyolitic basement, indicating an initial transgressive phase in a high-energy coastal environment. These deposits upward evolve into oncoidal limestones and dolomites (*Fig.15 b*), followed by micritic limestones dominated by coated grains, benthic fauna (foraminifera, gastropods, *Fig.15 a & c*). This vertical evolution reflects a transition from high-energy beach settings to shallow lagoonal environments with decreasing hydrodynamic energy (*e.g.*, Gammon *et al.*, 2000; Sadji *et al.*, 2025).

2- Late Jurassic

2.1 Middle Oxfordian (*Frid Ammonitico Rosso Formation*)

Characterized by nodular red limestones rich in ammonites, with common hiatuses and hardgrounds, indicating low sedimentation rates. Microfacies include abundant planktonic, associated with benthic foraminifera (*Fig.15 d*). According to Santantonio, (1993), these deposits correspond to condensed pelagic sedimentation on pelagic carbonate platforms (PCPs).

2.2 Upper Oxfordian (*Kheneg Red Clay Formation*):

Composed of alternating marls and limestones, strongly affected by slumps, faults, and gravity flows. Microfacies range from mudstone to packstone with ooids, oncoids, ostracods, benthic foraminifera and ammonites (*Fig.15 e & f*), and quartz. This unit reflects slope environments with resedimentation processes. blocks (Santantonio, 1993, 1994; Reolid *et al.*, 2015).

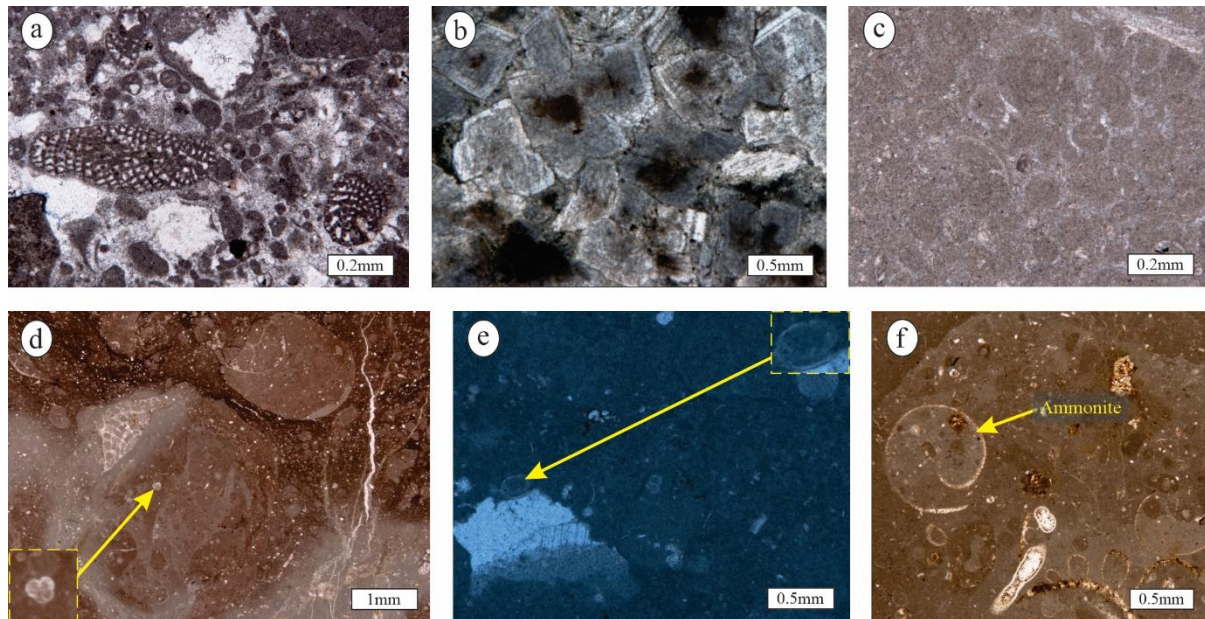


Fig.15: Callovian-upper Oxfordian microfacies of Bechtout and Bou Rheddou regions. **(a)** Packstone with peloids, cortoids and benthic foraminifera; **(b)** Dolomite crystals form a mosaic; **(c)** Packstone with ooid (**a-c** from Bechtout Limestone Formation); **(d)** Wackestone/packstone with oncoids, benthic and planktonic foraminifera (The yellow square, from Frid Ammonitico Rosso Formation); **(e)** Wackestone with vadose silt, planktonic foraminifera and ostracods (The yellow square); **(f)** Wackestone with planktonic foraminifera and ammonite. (**e-f** from Kheneg Red Clay Formation).

2.3 Kimmeridgian

Represented by the Bou Rheddou Limestone Formation, consisting of thick micritic limestones with mixed benthic and pelagic fauna (abundant *Saccocoma* remains) (Fig.16 b). Oncoids are abundant (two generations: allochthonous and autochthonous), (Fig.16 a). Microfacies indicates deposition within the photic zone (Riding, 1983; Reolid & Gaillard, 2007; Védrine *et al.*, 2007). The environment corresponds to an inner to mid carbonate ramp with low to moderate energy and open-marine influence.

2.4 Tithonian

This stage shows a complex evolution controlled by sea-level fluctuations and tectonics:

Lower Tithonian (Gratene Marl Formation)

Marls with interbedded limestones and abundant pelagic fauna (ammonites, *Saccocoma* remains) (Fig.16 c), indicating a deposition in an open marine environment with a rapid deepening (*e.g.*, Fauré *et al.*, 2015; Elmi *et al.*, 1982).

Chapter3 Sedimentology

Middle Tithonian (Guelt Halouf Formation)

Limestone–dolostone with chert, dominated by ooids and peloids (Fig.16 d), reflecting a return to shallow, high-energy shoal conditions due to uplift or sea-level fall.

Upper Tithonian (Bou Rharda Limestone-Marl Alternation Formation)

Alternation of marls and limestones evolving into massive grainstones rich in benthic fauna (Fig.16 e & f), indicating a regressive trend and development of a restricted shallow-marine shoal environment.

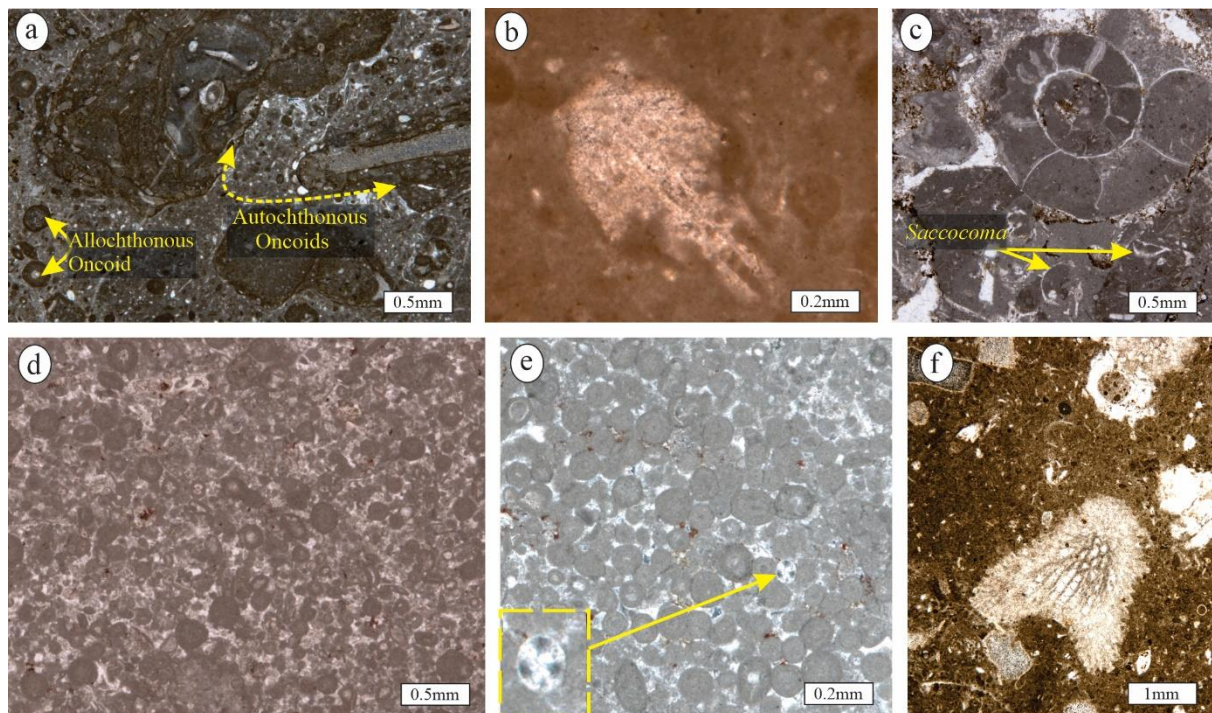


Fig.16: Kimmeridgian-upper Tithonian microfacies of Bechtout and Bou Rheddou regions. (a) Bioturbated micritic limestone containing 1) autochthonous oncoids (with several generations of growth; one oncoid exhibits *Troglotella incrustans*, dashed yellow arrows), and 2) allochthonous oncoids (rounded and smooth: yellow arrows), lumps, peloids, and filaments; (b) Wackestone with peloids and *Saccocoma* fragments, (a-e from Bou Rheddou Limestone Formation); (c) Packstone with pelagic fauna (ammonites and *Saccocoma* fragments) and lithoclast (from Gratene Marl Formation); (d) Grainstone with micritic ooids and peloids (from Guelt Halouf Formation) ; (e) Grainstone with micritic ooids, peloids and belemnite (The yellow square); (f) Wackestone with bryozoan and bioclasts (e-f from Bou Rharda Limestone-Marl Alternation).

V. Microfacies results

Coated grains of the Middle Late Jurassic of Bechtout and Bou Rheddou regions

1. Oncoids

The oncoids recorded in the Bechtout and the Bou Rheddou regions display a wide variability in size, shape and internal structure. They range from well-rounded to irregular shapes, and vary in diameter from a few millimeters to several millimeters. When present, they bear bioclastic and intraclastic nuclei, along with cortex of variable thickness, these oncoids are also associates with ooids, peloids, quartz fragments and certain organisms such as foraminifera. Based on the internal structure of the cortex, five types of oncoids can be distinguished: 1) micritic oncoids, 2) oncoid type C, 3) oncoid type R, 4) oncoid type I, and 5) oncoid type L. A detailed description of each type is provided below.

Micritic oncoids

Description: They are spherical to sub-spherical in shape, and reaching up to 0.4 mm in size. They occur in rudstone to packstone facies, containing a bioclastic nucleus and occasionally bearing *Saccocoma* remains (Fig.17 a & c). They are associated with sponge spicules, peloids and some ooids. Micritic oncoids are observed at different stratigraphic levels; they occur in the Callovian (Bechtout Limestone Formation), the middle Oxfordian (Frid Ammonitico Rosso Formation), the Kimmeridgian (Bou Rheddou Limestone formation) of Bechtout, and the Tithonian of Bou Rheddou (Gratene Marl Formation).

Interpretation: The micritic oncoids described above are interpreted as having formed in shallow, low-to-moderate energy settings. This interpretation is supported by the packstone texture and the presence of some planktonic organisms such as *Saccocoma* remains. Although the environment was generally calm, it was occasionally influenced by higher-energy events. Additional supporting evidence includes the spherical to subspherical shape and the small size of the oncoids, which suggest limited movements of oncoids on the sea floor under weak to moderate energy conditions, as well as moderate biological activity.

Typically, these oncoids formed within lagoon, inner to mid-ramp, and platform margin environments, always within the photic zone (e.g., Flügel, 2010; Sadji et al., 2025).

Type C oncoids

Description: They are spherical to irregular in shape with wavy contours, with diameters up to 5 mm. They are composed by alternating continuous and concentric micritic and organism-bearing laminae, quartz grains (Fig.17 d), and associated with peloids and some micritic oncoids, found in rudstone/ packstone and rarely wackestone texture. This type occurs exclusively in the Callovian of the Bechtout (Bechtout Limestone Formation).

Interpretation: The type C oncoids exhibit relatively higher energy leading to the spherical shape and the concentric laminae of the cortex. Further evidence in support is the greater size of this type of oncoid (up to 5 mm). They reflect shallow-water environment, based on the associated microfacies they indicate, most likely, lagoon environment (e.g., Flügel, 2010).

Type R oncoids

Description: They are elongated in shape and composed of randomly arranged hemispheroids, with diameters ranging from a few to several millimeters. They contain some bioclasts embedded in the cortex (Fig.17f), and are associated with micritic oncoids, type L oncoids, peloids, and ooids in packstone to rudstone texture. This type is common in the calcareous conglomerate facies; Callovian of Bechtout (Bechtout Limestone Formation).

Interpretation: The morphology of the type R oncoids indicates continuous overturning of the grains during deposition. The larger size and the presence of embedded bioclasts within the cortex suggest periods of relative stability (low energy) interrupted by high-energy events that triggered the overturning. The association with conglomeratic facies and the packstone to rudstone texture support deposition in a beach environment where intermittent turbulence affected the sea floor. The random arrangement of hemispheroids reflects continuous reworking and rotation of the oncoids under moderate to high-energy conditions, preventing the development of regular concentric lamination (e.g., Flügel, 2010).

Type I oncoids

Description: They are biconvex lenticular in shape, exhibiting inverted hemispheres with diameters around 1 mm, and present an irregular contour (Fig.17b). They occur in

wackestone to packstone texture, and accompanied with echinoids, peloids, micritic oncoids, type C oncoids, and some ooids. They occur in the Callovian (Bechtout Limestone Formation), and the Kimmeridgian (Bou Rheddou Limestone Formation) of Bechtout region, and Lower Tithonian of Bou Rheddou (Gratene Marl Formation).

Interpretation: Type I oncoids are characterized by a biconvex lenticular shape with inverted hemispheres, a configuration that suggests a predominantly stationary growth habit within the water column rather than continuous rolling along the sea floor. Their irregular contour and relatively small size (approximately 1 mm in diameter) suggest limited transport and intermittent episodes of burial or overturning. The occurrence of these oncoids in a wackestone to packstone texture, together with echinoids, peloids, and mixed oncoid types in points to a low-to moderate-energy subtidal environment. with episodic sedimentation events. The inverted hemispherical growth pattern reflects alternating phase of microbial mat development on the upward-facing surface, followed by intermittent overturning possibly triggered by storm-induced currents or sediment gravity flows-allowing microbial growth to resume on the opposite side. The interpretation aligns with the lenticular growth form described in the ([Logan et al., 1964](#)) classification, which is linked to intermittent agitation.

Their occurrence in the Callovian and Kimmeridgian of Bechtout supports an interpretation of deposition in distal inner ramp to proximal mid-ramp settings, possibly below fair-weather wave base but within the reach of storm waves, where periodic disturbance allowed for distinctive growth morphology (*e.g.*, [Sadji et al., 2025](#)).

Type L oncoids

Description: They exhibit irregular and random growth, and may also develop lobate growth forms. These oncoids occur within wackestone to packstone texture that includes some bioclasts, quartz grains ([Fig.17e](#)), peloids, type I oncoids, and micritic oncoids, with a diameter of up to 1 mm. This type of oncoid has been found only in the Kimmeridgian of Bechtout (Bou Rheddou Limestone Formation).

Interpretation: The Type L oncoids are characterized by irregular, random growth patterns and lobate morphologies. According to ([Flügel, 2010](#)) such growth forms typically indicate stationary or in-situ growth with little to no rolling or overturning. The absence of well-developed concentric laminae of lobate outlines suggests that these oncoids formed

under consistently low-energy conditions, where intermittent, weak currents were insufficient to induce regular rotation. The small size (up to 1 mm) and the wackestone to packstone texture suggest a setting with limited hydraulic reworking. The presence of quartz grains together with bioclasts and peloids reflects a mixed carbonate-siliciclastic depositional environment, likely located in a nearshore or shallow subtidal setting influenced by terrigenous input.

The irregular growth morphology reflects fluctuating environmental controls, possibly related to changes in; 1) sedimentation rates (intermittent burial of microbial coatings), 2) nutrient supply or light availability (affecting microbial mat development), or 3) water chemistry (influencing carbonate precipitation).

The lobate morphology suggests episodic microbial growth interrupted by sediment influx or slight changes in water chemistry. These oncoids are interpreted to have formed in shallow marine environments within the photic zone (Lagoon to inner ramp).

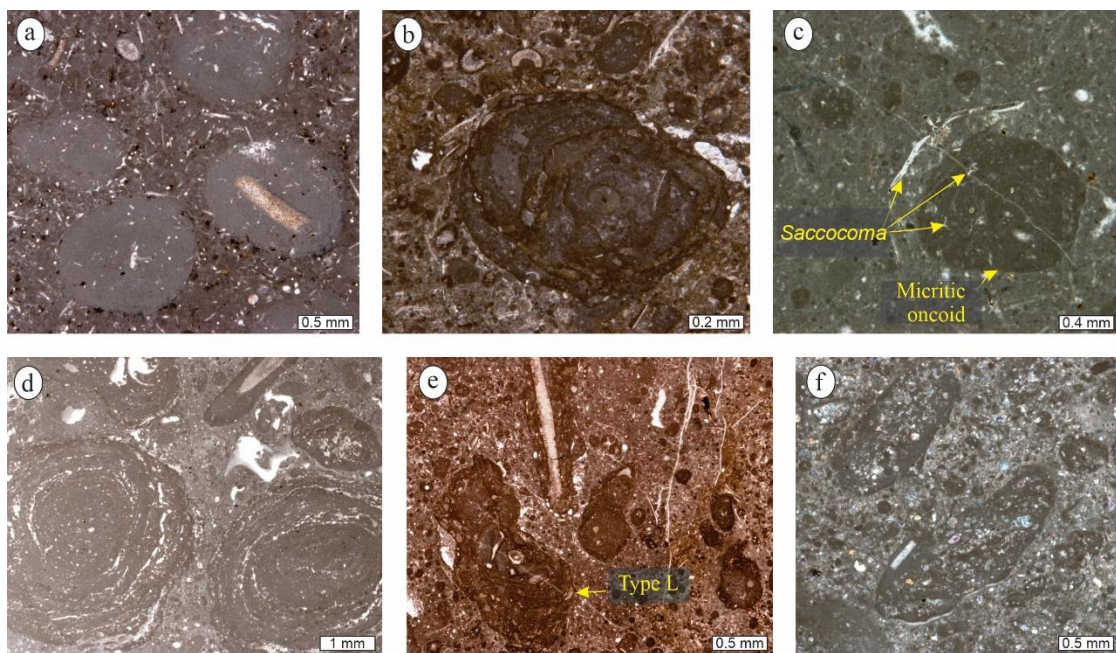


Fig.17: Oncoids types. **(a)** Micritic oncoids with bioclast as nuclei bearing spongy spicules (Bechtout Limestone Formation); **(b)** Oncoid type I bearing some bioclasts (Bechtout Limestone Formation); **(c)** Micritic oncoid bearing *Saccocoma* (Gratene Marl Formation); **(d)** Oncoids type C with concentric lamina (Bechtout Limestone Formation); **(e)** Oncoid type L, lump and bioclasts (Bou Rheddou Limestone Formation); **(f)** Oncoid type R with bioclasts, quartz fragments as nuclei (calcareous conglomerate facies).

2. Ooids

The ooids identified in the Bechtout and Bou Rheddou regions exhibit significant variability in size, morphology, and internal structure. Their shapes range from concentric to composite, with diameters of a few millimeters. When present, their nuclei are composed of bioclastic or intraclastic material, organisms, etc., and are surrounded by a cortex of varying thickness. Based on the internal organization of this cortex, five distinct types of ooids can be identified; 1) concentric ooids, 2) radial fibrous ooids, 3) pelagic ooids, 4) compound ooids, and 5) micritic ooids. A detailed description of each type is provided below.

Concentric ooids

Description: They composed of a nucleus (typically foraminifera, bioclasts, and quartz fragments) surrounded by a cortex composed of numerous, thin, concentrically arranged laminae. Their size ranges between 0.5 and 1 mm, and they occur in packstone to grainstone texture. They are common in the Callovian (Bechtout Limestone Formation), where they are associated with benthic foraminifera, sponge spicules ([Fig.18a](#)), micritic pelagic ooids, and oncoids, as well as in the upper Oxfordian (Kheneg Red Clay Formation). They are also present in the Kimmeridgian (Bou Rheddou Limestone Formation) of Bechtout, as well as the Tithonian of Bou Rheddou (Bou Rharda Limestone-Marl Alternation Formation).

Interpretation: The well-developed, thin, concentric laminations around varied nuclei, indicate continuous rolling in agitated shallow-marine environments. The regular concentric structure reflects sustained hydrodynamic energy sufficient to maintain the grains in suspension (motion), promoting uniform carbonate precipitation around the entire grain surface. The grainstone texture and association with high-energy indicators such as quartz and well-sorted bioclasts support deposition in very shallow-marine environments ([Flügel, 2010](#)), most likely within shoal complexes or platform-margin settings.

Radial Fibrous Ooids

Description: They consist of alternating layers of fibrous crystals. Their size varies from 0.1 mm (small nucleus with thick cortex) to 0.2 mm. They contain a nucleus composed of quartz grains. they occur in packstone to grainstone texture, associated with peloids, benthic and planktonic foraminifera, cortoids, compound ooids, and bioclasts ([Fig.18d](#)).

This type occurs only in the Tithonian of Bou Rheddou (Bou Rharda Limestone-Marl Alternation Formation).

Interpretation: The radial fibrous ooids are characterized by their distinctive fibrous crystal fabric, which suggests precipitation under physicochemical conditions different from those favoring concentric ooids. The fibrous radial structure indicates formation in waters with lower agitation or different carbonate saturation states (Flügel, 2010), where crystals grew radially inward rather than tangentially. The small size (0.1–0.2 mm) and the presence of quartz nuclei indicate availability of terrigenous material and moderate energy conditions. The association with both benthic and planktonic foraminifera, cortoids, and compound ooids in a mixed assemblage suggests a shallow marine environment with fluctuating energy levels.

Pelagic Ooids

Description: They consist of concentric laminations with micritic cortex. Their size ranges from 0.1 mm to 0.2 mm. They contain planktonic foraminifera as their nucleus (Fig.18c), occur in grainstone facies. They are common in the Callovian (Bechtout Limestone Formation) and upper Oxfordian (Kheneg Red Clay Formation) of Bechtout, and the upper Tithonian of Bou Rheddou (Bou Rharda Limestone-Marl Alternation Formation), where they are associated with micritic to concentric ooids, radial fibrous ooids, and peloids.

Interpretation: The pelagic ooids are distinguished by their planktonic foraminiferal nuclei and micritic cortex, indicating formation in open marine settings far from high-energy shoal environments. Their small size (0.1–0.2 mm) and the presence of planktonic organisms as nuclei suggest that these ooids formed in the water column or on the sea floor in relatively deep, low-energy environments. The micritic cortex indicates partial recrystallization or micritization of originally concentric laminae, possibly due to microbial activity or early diagenetic alteration. The association with other ooid types and peloids in mixed facies suggests redeposition of this ooids type from shallower areas or condensation processes. These ooids are interpreted to have formed on the top of drowned platforms or seamounts, where pelagic sedimentation prevailed and carbonate production was reduced (Jenkyns, 1972; Santantonio, 1993, 1994; Sadjji *et al.*, 2025).

Compound Ooids

Description: They consist of two or more micritic to concentric ooids enveloped by a common micritic layer. The compound ooids are less than 1 mm in size. They are common in the Kimmeridgian (Bou Rheddou Limestone Formation) and Tithonian (Bou Rharda Limestone-Marl Alternation Formation) of Bou Rheddou. They are associated with oncoids, peloids, cortoids, radial fibrous ooids, and some bioclasts in packstone to grainstone facies (Fig.18f).

Interpretation: Compound ooids consist of multiple ooids aggregated within a common micritic envelope, indicating episodes of reworking, aggregation, and subsequent micritization. The encasement of several individual ooids by a shared micritic layer suggests periods of reduced energy, during which ooids accumulated, were bound by microbial mats or early cement, and then experienced micritization. The small size (less than 1 mm) and the association with diverse coated grains and bioclasts in mixed packstone to grainstone textures indicate a shallow marine environment with fluctuating energy conditions.

Micritic Ooids

Description: These ooids are characterized by the near-complete obliteration of their original lamination by a micritic layer. The nuclei are often not visible, though sometimes contain bioclasts or *Saccocoma* remains as nuclei. Their diameters range from 0.1 mm to 0.2 mm.

These micritic ooids are associated with concentric pelagic ooids, quartz grains, and some bioclasts in grainstone texture (Fig.18b & e). They occur in the Callovian (Bechtout Limestone Formation), upper Oxfordian (Kheneg Red Clay Formation), and Kimmeridgian (Bou Rheddou Limestone Formation) of Bechtout, as well as in the Tithonian (Guelt Halouf Limestone Formation) of Bou Rheddou.

Interpretation: The micritic ooids exhibit extensive micritization that has obscured or destroyed original concentric or radial structures, indicating prolonged exposure to microbial boring and early diagenetic alteration. Their small size (0.1–0.2 mm) and the frequent absence of visible nuclei suggest advanced micritization and possible multiple episodes of reworking. The association with pelagic ooids, quartz grains, and bioclasts in variable textures indicates a range of depositional environments from shallow-marine water

to slightly deeper settings (Sadjj *et al.*, 2025; Flügel, 2010). The presence of *Saccocoma* remains as nuclei in some specimens confirms open marine conditions and potential condensation. These micritic ooids are interpreted as Bahamian-type ooids that formed in shallow marine environments where microbial micritization was intense, possibly in lagoonal or restricted platform settings with elevated nutrient levels.

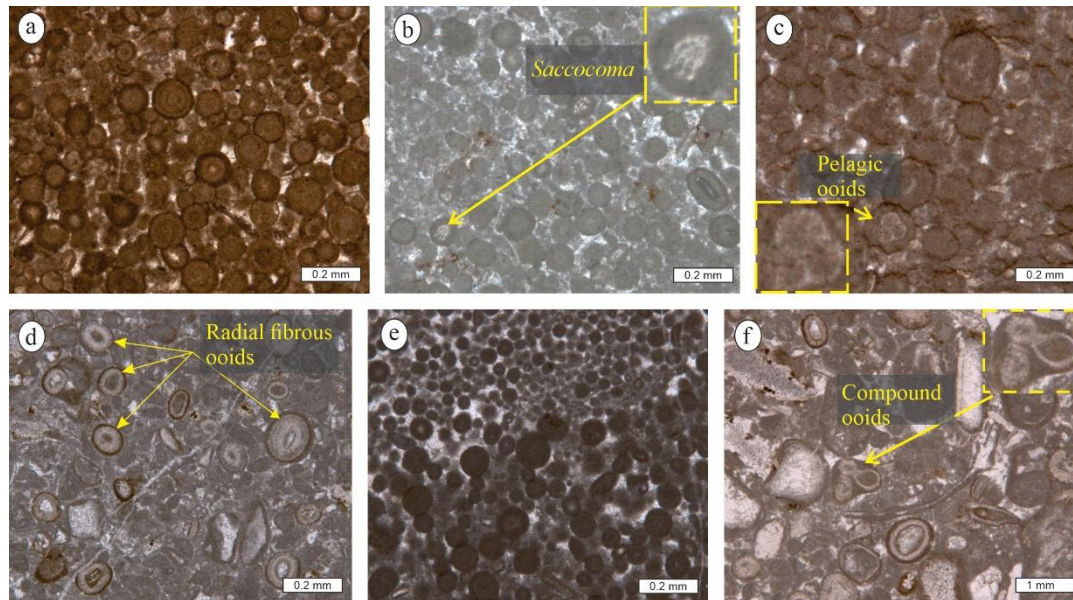


Fig.18: Ooids types. **(a)** Grainstone bearing concentric ooids associated with some micritic ooids (Bou Rharda Limestone-Marl Alternation Formation); **(b)** Grainstone with mixing between concentric ooids and slightly micritized ooids bearing *Saccocoma* as a nucleus, Radial ooids (Bou Rharda Limestone-Marl Alternation Formation); **(c)** Grainstone with pelagic ooid bearing planktonic foraminifera as a nucleus associated with micritic ooids (Bechtout Limestone Formation); **(d)** Packstone with radial fibrous ooids accompanied by cortoids (Bou Rharda Limestone-Marl Alternation Formation); **(e)** Grainstone bearing Bahamian ooids associated with some peloids (Bechtout Limestone Formation); **(f)** Packstone with compound ooids with some bioclasts, cortoids, radial fibrous ooids and oncoids (Bou Rharda Limestone-Marl Alternation Formation).

3. Cortoids

Description: The cortoids identified in the Bechtout and Bou Rheddou regions are interpreted as coated grains with a "destructive envelope" resulting from microbial boring processes that modify the original grain margins. These grains exhibit significant variability in size, shape, and internal structure. Their diameter ranges from a few millimeters to

several millimeters (2 mm), their shapes vary from rounded to elongated, and their nuclei, when preserved, are either bioclastic or intraclastic. some grains are surrounded by a thin micritic envelope. The cortoids are frequently associated with other carbonate components in wackestone to packstone texture, including ooids, peloids, oncoids ([Fig.19b](#)), quartz grains, and various bioclasts such as foraminifera ([Fig.19a](#)).

Stratigraphically, cortoids are particularly abundant in the Tithonian deposits of Bou Rheddou (Gratene Marl and Bou Rharda Limestone-Marl Alternation Formations) ([Fig.19d & e](#)) and the Callovian deposits of Bechtout (Bechtout Limestone Formation). They are less frequent in the Kimmeridgian (Kheneg Red Clay Formation) ([Fig.19c](#)) of Bechtout and the middle Oxfordian of Bou Rheddou (Frid Ammonitico Rosso Formation).

Interpretation: The cortoids display a thin, structureless, non-laminated micritic envelope that partially or completely surrounds varied nuclei, representing the product of intensive microbial micritization by endolithic cyanobacteria and algae ([Flügel, 2010](#)). The destructive nature of the micritic envelope, which alters and obscures original grain margins, indicates prolonged residence time on the sea floor in shallow marine settings where microbial boring was active. The variable sizes and shapes, from rounded to elongated, reflect the diverse nature of the original grains (bioclasts, intraclasts) that were subjected to micritization. The wackestone to packstone texture and association with other coated grains, peloids, and quartz fragments suggest deposition in low-energy environments with moderate biological activity and some terrigenous input. These cortoids are interpreted to have formed in shallow, low-energy lagoonal settings where water circulation was restricted, nutrient levels were elevated, and grains were exposed to intense endolithic microbial activity.

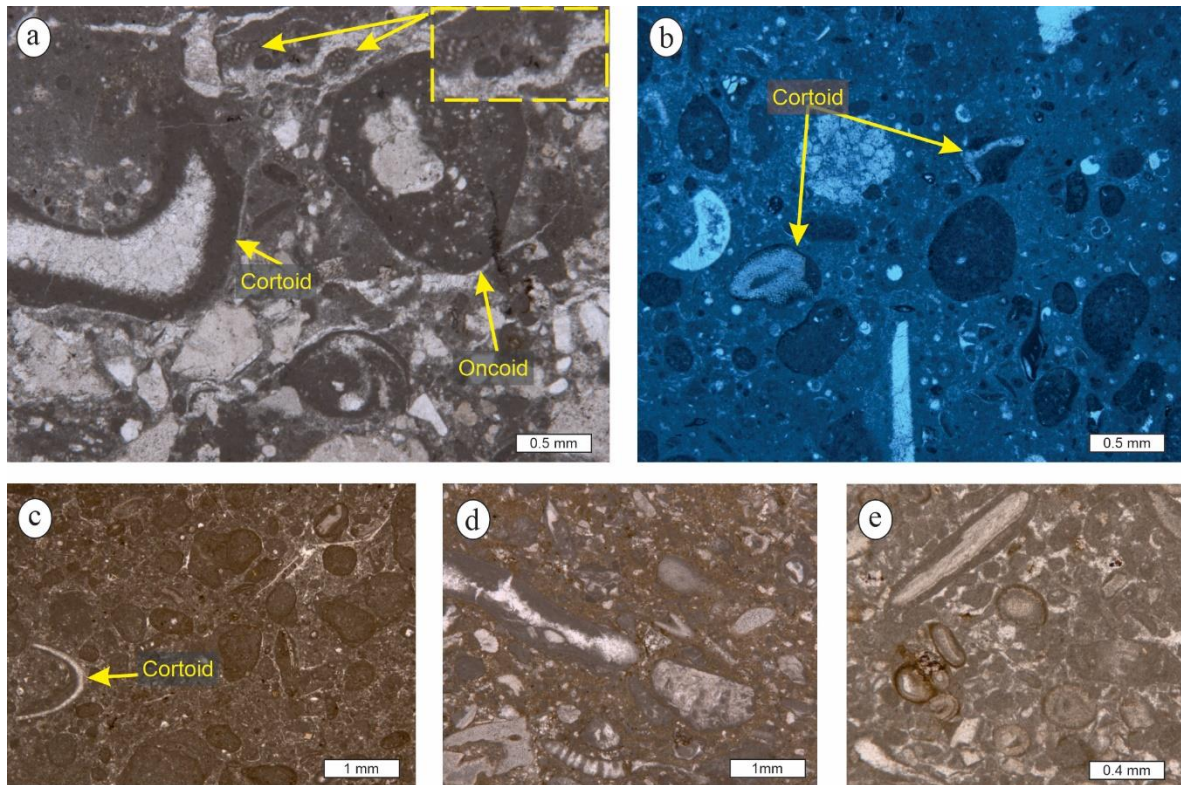


Fig.19: (a) Cortoid associated with bioclasts, oncoids, peloids and benthic foraminifera “The yellow square” (Bechtout Limestone Formation); (b) Cortoids bearing bioclasts, intraclasts, peloids and oncoids (Frid Ammonitico Rosso Formation; Bou Rheddou); (c) Elongated and rounded cortoids accompanied with bioclasts, peloids and oncoids (Kheneg Red Clay Formation; Bechtout); (d) & (e) Elongated cortoids with some oncoids, radial fibrous ooids, bioclasts and quartz (Gratene Marl and The Bou Rharda Limestone-Marl Alternation Formations).

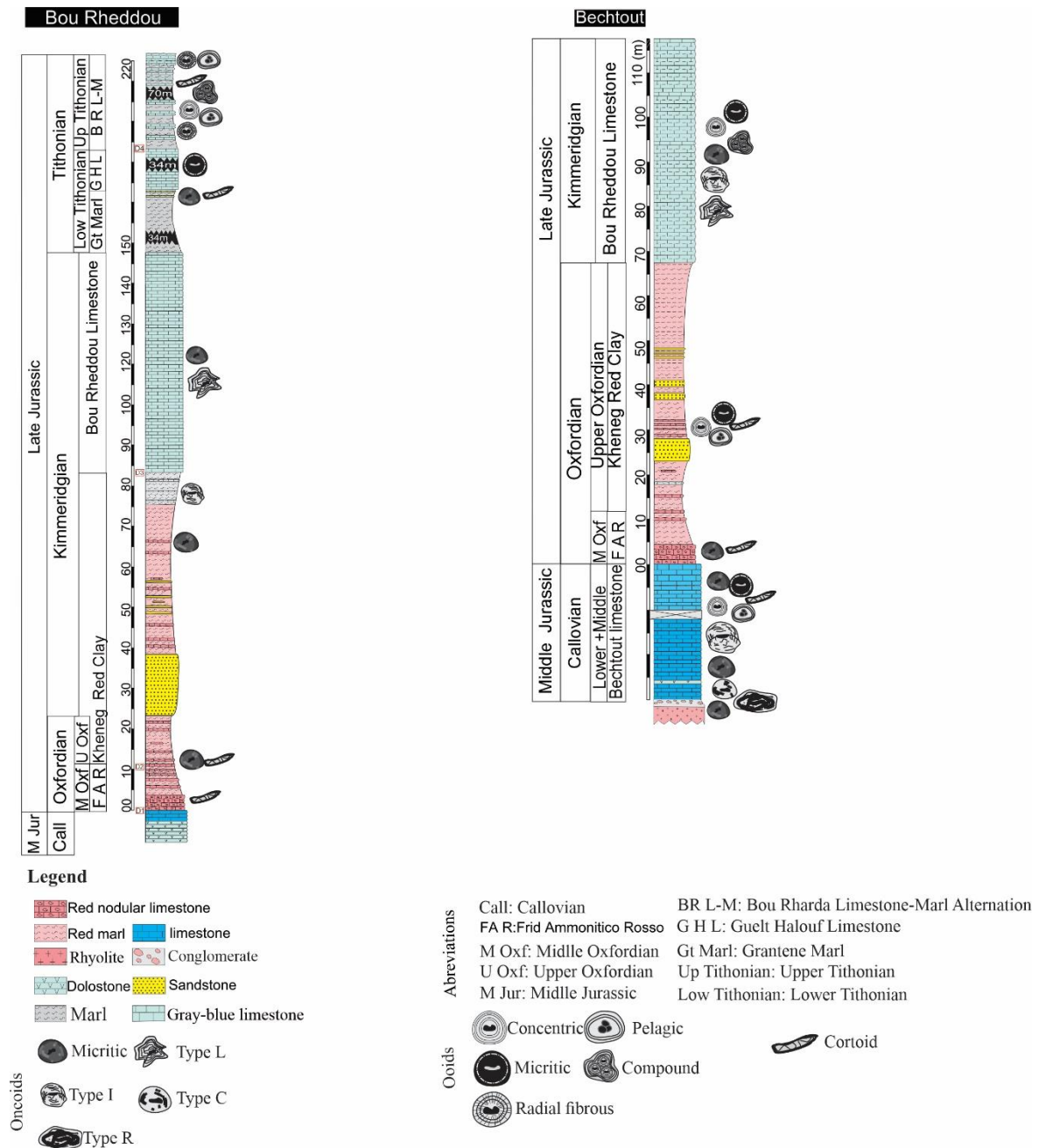


Fig.20: Distribution of coated grains on the lithological sections of the two studied outcrops of the Upper Jurassic (Ouarsenis Mountains, northwest Algeria).

VI. Discussion

The coated grains identified in the carbonate successions of the Bechtout and Bou Rheddou regions provide important evidence for understanding the evolution of the Middle-Late Jurassic carbonate platform of the Ouarsenis Mountains. The abundance, diversity, and stratigraphic distribution of ooids, oncoids, and cortoids reflect the interaction between biological

productivity, hydrodynamic conditions, terrigenous input, and relative sea-level fluctuations during the Callovian-Tithonian interval (Fig.20).

1. Oncoids as indicators of shallow, productive environments

The dominance of oncoids in several facies suggests the development of relatively shallow-marine environments located within the photic zone and characterized by active microbial growth. Five distinct oncoïd types (micritic, C, R, I, and L) were identified, each reflecting specific hydrodynamic and depositional conditions.

Micritic oncoids (spherical to subspherical, up to 0.2 mm) occur in packstone to rudstone facies from the Callovian to Tithonian. Their small size and shape indicate limited transport under weak to moderate energy conditions, typical of lagoonal to inner-ramp settings within the photic zone (Flügel, 2010; Sadjı *et al.*, 2025). Type C oncoids (spherical to irregular, up to 2 mm) with continuous concentric laminae occur exclusively in the Callovian of Bechtout (Bechtout Limestone Formation), reflecting higher-energy conditions that promoted regular rolling. Type R oncoids (elongated, randomly arranged hemispheroids) from the Callovian Calcareous Conglomerate facies indicate continuous overturning under moderate to high-energy conditions, with embedded bioclasts suggesting intermittent stability. Their association with conglomeratic facies supports deposition in beach environments. Type I oncoids (biconvex lenticular with inverted hemispheres, ~1 mm) from the Callovian and Kimmeridgian display irregular contours and occur in wackestone to packstone textures. Their growth morphology indicates predominantly stationary growth with intermittent overturning, likely below fair-weather wave base but within storm-wave reach in distal inner-ramp to proximal mid-ramp settings (Logan *et al.*, 1964; Sadjı *et al.*, 2025). Type L oncoids (irregular, lobate growth, up to 1 mm) from the Kimmeridgian of Bechtout (Bou Rheddou Limestone Formation) exhibit random growth patterns indicating stationary, in-situ growth under consistently low-energy conditions with limited hydraulic reworking, likely in lagoon to inner-ramp environments.

According to Sadjı *et al.* (2025), the Jurassic carbonate platform of the Ouarsenis Mountains evolved under favorable ecological conditions during the Callovian, allowing the establishment of productive carbonate systems (i.e., a healthy carbonate platform). Similar interpretations were proposed by Riding (1983), who demonstrated that oncoids are commonly associated with shallow marine settings influenced by microbial activity and moderate hydrodynamic energy. The occurrence of laminated microbial coatings in the studied thin sections therefore indicates

phases of a healthy carbonate platform, where carbonate productivity was high and environmental conditions remained relatively stable.

2. Ooids as indicators of hydrodynamic agitation and open-marine influence

The ooids identified in the studied regions exhibit five distinct types (concentric, radial fibrous, pelagic, compound, and micritic), each recording specific environmental conditions.

Concentric ooids (0.5-1 mm) occur in packstone to grainstone textures from the Callovian to Tithonian. Their well-developed, thin concentric laminations around varied nuclei (foraminifera, bioclasts, quartz) indicate continuous rolling and abrasion in agitated shallow-marine environments, typically within shoal complexes or platform-margin settings. Radial fibrous ooids (0.1-0.2 mm) occur only in the Tithonian of Bou Rheddou (Bou Rharda Limestone-Marl Alternation Formation). Their distinctive fibrous crystal fabric suggests precipitation under lower agitation or different carbonate saturation states, with radial crystal growth rather than tangential arrangement.

Pelagic ooids (0.1-0.2 mm) contain planktonic foraminiferal nuclei and a micritic cortex. They occur in the Callovian (Bechtout Limestone Formation), upper Oxfordian (Kheneg Red Clay Formation), and upper Tithonian (Bou Rharda Limestone–Marl Alternation Formation). Their association with open-marine settings far from high-energy shoals, combined with planktonic nuclei, suggests formation in the water column or on the seafloor in relatively deep, low-energy environments, possibly on drowned platforms or seamounts ([Jenkyns, 1972](#); [Santantonio, 1993, 1994](#); [Sadjı et al., 2025](#)).

Compound ooids (<1 mm), consisting of three micritic to concentric ooids enveloped by a common micritic layer, occur in the Kimmeridgian and Tithonian of Bou Rheddou. They indicate episodes of reworking, aggregation, and subsequent micritization, with shared micritic envelopes suggesting periods of reduced energy during which ooids accumulated and were bound by microbial mats or early cements. Micritic ooids (0.1-0.2 mm) exhibit near-complete obliteration of original lamination by micritization, indicating prolonged exposure to microbial boring and early diagenetic alteration. The presence of *Saccocoma* remains as nuclei confirms open-marine conditions and potential condensation.

The development of ooidal facies in the Bechtout and Bou Rheddou regions supports the interpretation of an active carbonate ramp system connected to the southern Tethyan margin. [Sadjı et al. \(2025\)](#) emphasized that these carbonate platforms experienced repeated

transgressive and regressive cycles, which controlled the distribution of high-energy carbonate shoals and shallow-water facies. Such grains generally form in warm, shallow, agitated marine waters characterized by active carbonate precipitation (*e.g.*, Flügel, 2010; Peryt, 1983).

3. Cortoids as indicators of microbial micritization in restricted settings

The cortoids identified in this study display a thin, structureless, non-laminated micritic envelope that partially or completely surrounds varied nuclei (bioclastic or intraclastic), representing the product of intensive microbial micritization by endolithic cyanobacteria and algae (Flügel, 2010). Their diameters range from a few millimeters to several millimeters, with shapes varying from rounded to elongated. The destructive nature of the micritic envelope, which alters and obscures original grain margins, indicates prolonged residence time on the seafloor in shallow marine settings where microbial boring was active.

Stratigraphically, cortoids are particularly abundant in the Tithonian deposits of Bou Rheddou (Gratene Marl and Bou Rharda Limestone-Marl Alternation Formations) and the Callovian deposits of Bechtout (Bechtout Limestone Formation). They are less frequent in the Kimmeridgian (Kheneg Red Clay Formation) of Bechtout and the middle Oxfordian of Bou Rheddou (Frid Ammonitico Rosso Formation). The wackestone to packstone texture and association with other coated grains, peloids, and quartz fragments suggest deposition in low-energy environments with moderate biological activity and some terrigenous input. These cortoids are interpreted to have formed in shallow, low-energy lagoonal settings where water circulation was restricted, nutrient levels were elevated, and grains were exposed to intense endolithic microbial activity (Reolid & Nieto, 2010).

4. Stratigraphic evolution: platform growth and demise

The stratigraphic evolution of coated grains records intervals of both vigorous carbonate production and significant reduction or interruption. The appearance of marly intercalations, condensed facies, and Ammonitico Rosso deposits suggests that carbonate production was hampered by detrital input and environmental instability. According to Sadjji et al. (2025), increased terrigenous influx during the upper Oxfordian-lower Kimmeridgian interval likely reduced water transparency and limited carbonate productivity within the Ouarsenis platform system. Similar conclusions were proposed by Santantonio (1993, 1994), who linked condensed pelagic carbonate facies in the Tethyan realm to phases of reduced platform growth, drowning processes, and relative sea-level rise.

The coated grains therefore record the complete cycle of carbonate platform growth and demise:

Callovian: Carbonate production was intense and platform development remained stable, reflecting optimal ecological and hydrodynamic conditions. Oncoid types C, R, and I are abundant, along with concentric and pelagic ooids, indicating a healthy carbonate platform with both high-energy shoals and protected lagoonal areas.

Oxfordian–Kimmeridgian: Tectonic activity, relative sea-level rise, and detrital influx contributed to the reduction of carbonate productivity and to the establishment of condensed pelagic sedimentation. The Ammonitico Rosso facies (middle Oxfordian) and slope deposits with gravity flows (upper Oxfordian) record this interval of platform stress. cortoids become less frequent, and pelagic ooids appear.

Tithonian: Renewed shallow-water conditions favored the re-establishment of ooidal shoals and the partial recovery of carbonate production. Radial fibrous ooids, compound ooids, and abundant cortoids characterize this interval, with the Guelt Halouf Limestone Formation recording a return to high-energy shoal conditions and the Bou Rharda Limestone–Marl Alternation Formation reflecting a regressive trend with restricted shallow-marine shoal environments.

5. Regional and global context

Comparable coated-grain studies have been conducted in several carbonate platform systems worldwide. In the Zagros Basin and Persian Gulf, coated grains were linked to sea-level fluctuations and variations in carbonate productivity within shallow marine carbonate ramps ([Naderi-Khujin & Tavakoli, 2022](#)).

Similar paleoenvironmental interpretations were also proposed for the North China Platform, where ooids were used as indicators of depositional conditions and environmental evolution in carbonate settings ([Hao *et al.*, 2022](#)). These examples demonstrate that the Jurassic carbonate platforms of the Ouarsenis Mountains evolved under sedimentological and paleoenvironmental conditions comparable to those of other Tethyan and epicontinental carbonate systems worldwide.

6. Conclusion

Overall, microfacies analysis confirms that coated grains are reliable paleoenvironmental indicators and valuable tools for reconstructing Jurassic carbonate platform evolution in the Ouarsenis Mountains. The five oncoid types, five ooid types, and cortoids documented in this study provide a high-resolution record of changing hydrodynamic energy, water depth, terrigenous input, and microbial activity. Their distribution reflects the combined influence of biological activity, hydrodynamic conditions, detrital supply, tectonic instability, and sea-level fluctuations along the southern Tethyan margin.



General Conclusion



General conclusion

This study highlights the importance of coated grains as key indicators for reconstructing the depositional environments of the Middle–Late Jurassic carbonate successions in the Bechtout and Bou Rheddou regions of the Ouarsenis Mountains. Through detailed microfacies analysis, it has been possible to identify a wide diversity of ooids, oncoids, and cortoids, each reflecting specific environmental conditions and sedimentary processes. The results demonstrate that oncoids dominate the studied successions and indicate shallow marine environments within the photic zone, controlled by microbial activity and moderate hydrodynamic conditions. Ooids, with their varied types, reflect fluctuations in energy levels, from high-energy shoal environments to quieter settings influenced by micritization and diagenetic processes. Cortoids, on the other hand, provide evidence of early diagenesis and microbial alteration in low-energy lagoonal environments.

The stratigraphic distribution of these coated grains reveals a clear paleoenvironmental evolution. The Callovian is characterized by shallow, transgressive carbonate deposition, followed by more complex and locally deeper conditions during the Oxfordian–Kimmeridgian interval, marked by condensed sedimentation and slope processes. The Tithonian records a return to shallow, high-energy conditions associated with regressive phases and the re-establishment of carbonate platform systems.

Overall, the study confirms that the evolution of the Jurassic carbonate platform in the Ouarsenis Mountains was controlled by the combined influence of tectonic activity, relative sea-level variations, biological processes, and diagenetic alteration. Diagenesis, particularly early micritization and microbial alteration, played an important role in modifying the original textures and fabrics of carbonate sediments and coated grains, thereby influencing their preservation and the resulting microfacies characteristics. The integration of microfacies data with regional stratigraphy provides a coherent model of carbonate ramp evolution along the southern Tethyan margin. This work not only refines the paleoenvironmental interpretation of the studied area but also contributes to a broader understanding of Jurassic carbonate systems in North Africa.



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