Morphological Typology and Petrography of Plio-Quaternary Continental Carbonates of Aït Chaib, Skoura Basin, Middle Atlas, Morocco

Mohamed Salah¹*, Hicham El Asmi¹ and Lahcen Gourari¹

¹ Department of Geology, Faculty of Sciences Dhar El Mehraz, University Sidi Mohammed Ben Abdellah, Fez, Morocco
* Correspondence: mohamed.salah2@usmba.ac.ma

Abstract
The Plio-Quaternary Ait Chaib basin occupies the northwestern part of the Skoura Syncline, which is part of the northern Middle Atlas Folded Zone. This intracontinental basin was formed probably in the Pliocene after the Tortono-Messinian regression sea. The Plio-Quaternary deposits are bound by fluvial conglomerates and continental carbonates. They consist of barrage travertines; travertine limestones and oncholitic travertine silts and sands of the upstream and downstream deposits. These travertines laterally pass to lacustrine limestones at the bottom of the basin. The genesis of these continental carbonates, correlative to phases of karstification, has affected the Meso-Cenozoic carbonate deposits of the folded Middle Atlas, and is linked to favorable paleo-environmental conditions of geological, geomorphological, hydrogeological, hydrological and bioclimatic order. The petrographic study of these lacustrine limestones shows laminar structure allowing to assimilate into continental stromatolites. They were formed by cyanobacterial mats in a shallow lacustrine environment in which water were non-turbid and supersaturated in limestone solution, coming from karstic springs staking out the Middle Atlasic North Accident. The important diagenesis evolution is linked to the surface water table contain, which has as a floor gypsiferous lagoonal marl of the Upper Miocene age.

Keywords: Folded Middle Atlas; Skoura syncline; Travertines; Lacustrine limestones; Plio-Quaternary; Stromatolites

1. Introduction
Plio-Quaternary continental carbonate deposits are observed in many parts of the world. These deposits are of external origin and produced by the precipitation of calcium carbonates in springs, streams, and lakes in karstic areas (Arenas et al., 2014; Fouke et al., 2000; Henchiri, 2014). They are remarkable features in many Mediterranean and other semi-arid regions (Arenas-Abad et al., 2010; Ford and Pedley, 1996; Pedley, 2009; Pentecost, 1995; Viles and Goudie, 1990; Viles and Pentecost, 2007). The Plio-Quaternary carbonate deposits of Aït Chaib (Morocco) are developed from fluvial systems fed by aquifers retained in karstified Mesozoic carbonate formations of the Middle Atlas. These fluvial systems fit the barrage-cascade model of Pedley (1990, 2009) or the stepped fluvial system of Arenas-Abad et al. (2010).

The continental carbonate deposits are used in paleoclimatic reconstructions. Variable terminologies have been used to describe carbonate facies and depositional systems in many previous
studies (Henchiri, 2014; Pedley, 1990). Fouke et al. (2000) and Pentecost (2005) recommended that the term travertine to be adopted for all non-marine carbonate deposits precipitated in or near springs, rivers, and lakes. This work focuses on the Plio-Quaternary continental carbonates of the Aït Chaïb Basin, located in the Tazouta region, which is part of the Folded Middle Atlas. In this mountainous and karstic region, continental carbonates are omnipresent and are composed mainly of travertines and lacustrine limestones. The study of these carbonate formations will focus on their stratigraphic and geometrical relationship with the substratum formations, morphological organization, lithostratigraphy, sedimentology, and petrography. In the petrographic part, morphological classification of the edifices and the travertine encrustations is established, followed by macroscopic and microscopic descriptive analyses of the various morphotypes of the encrustations in order to identify their constituents and their microstructures. The results obtained from this multidisciplinary study are interpreted in order to specify, firstly, the genetic processes of these deposits, and, secondly, the paleoenvironmental conditions of their formation.

2. Geographic Location and Geological and Geomorphological Context

The basin of Aït Chaïb belongs to the central Middle Atlas and is located east of the rural commune of Tazouta, which is administratively part of the province of Sefrou that belongs to the region of Fez-Meknes. This basin, known by its marble quarries (travertine limestones and travertines), is located 55 km southeast of the Fez city and 29 km southeast of Sefrou. From the geological point of view, this region and its adjacent areas are formed by terrains of various natures and ages ranging from Paleozoic and Quaternary successions (Fig. 1).

The Paleozoic terrains are exposed in the northwest of the North Middle Atlasic Accident (NMAA) in the inlier of Bsabis. They are mainly constituted by Ordovician Schists (Charrière, 1990; Martin, 1981).

The Mesozoic terrains, which lie in major angular discordance on the Paleozoic basement, are formed by red clays (with gypsum and halite) with intercalation of altered doleritic basalts of Triassic age that are surmounted by a thick series of Jurassic dolomites, limestones, marlstones and silico-clastic detritus (Charrière, 1990).

The Cenozoic and Quaternary terrains begin with Miocene age formations that are surmounted by Plio-Quaternary age formations.

The Miocene formations lie in angular discordance on the Jurassic terrains and are constituted at the base by orange-red silt with volcano-sedimentary intercalation. Towards the top, these terrains change to bariolate marls containing thin intercalations of white limestone banks that constitute the Oued Zraa formation dated to the Vallésian (Charrière, 1990). Salmon-pink gypsum marls were deposited on top of yellowish, bioclastic sandstones that may locally become micro-conglomeratic. These sandstones, beginning at the base by conglomerates of fluvio-deltaic type, are locally very rich in Ostreacrassissima bivalves.

The Plio-Quaternary formations rest in angular discordance on the Upper Miocene formations. They include conglomerates, continental carbonates, avalanches and fluvial deposits arranged in terraces along the valley of Oued Mdez, which remarkably follows the axis of the syncline of Skoura, which is oriented SW-NE.
Fig.1. (a) General geologic map of northern Morocco; (b) Geological map of Skoura syncline (Martin, 1981): (1 and 2) Middle and recent Quaternary; (3) Carbonate encrustations and travertines of Middle Quaternary age; (4) travertines of Pliocene age; (5) "Poudingues de Skoura"; (6) Sandstone and conglomerate channelized, fluviodeltaic facies (Upper Miocene); (7) Clays and marls (formation of Ouad Zraa); (8) Reef limestones of the Upper Miocene; (9) Marls with silt-sandstone intercalations; (10) Marly Limestone interspersed with oolitic bars of Lower Bathonian-Upper Bajocian; (11) Boulemane marls formation of Middle Bajocian; (12) Amane Ilila limestone formation of Middle Toarcian to Lower Bajocian; (13) Bechine marl formation with pyritic Ammonite of Lower Bajocian-Toarcian age; (14) Massive Liassic dolomite; (15) Triassic clays

The study area presents a rather complex geological structure that includes an angular discordance of Mesozoic terrains on a very tectonized Paleozoic basement. The cover deposits are affected by a Jurassic folding that is materialized by a succession of narrow anticlines and very wide and very large synclines. The bottoms of the synclines of Bathonian core are covered in angular discordance by the Miocene and Plio-Quaternary deposits (Charrière et al., 1994).

The fault network is divided into three important systems: the first system is in the NW-SE direction, the second in the NE-SW direction and the third in the E-W direction. Geomorphologically, this basin occupies the northwestern part of the Skoura syncline depression.

3. Bioclimate and Hydrology

The climate of the region of Ait Chaib is of cold semi-arid type (Labhar, 1998), with an average annual rainfall of 426 mm (Martin, 1981). The vegetation is represented by dense Phoenician junipers...
on fairly high altitudes and scattered on low altitudes represented by matorrals with thuya, dense matorrals with lentisque (Pictacialentiscus), oak groves and rosemary.

From a hydrological point of view, this basin is part of the Sebou hydrographic basin. It is crossed by the Oued Mdez that flows along the axis of the Skoura syncline (SW-NE), since the confluence of the two main branches that meet in the basin of Skoura: the Oued Serrhino-Massère and the Oued Guigou. The flows vary from one season to another in which the maximum is in March (40 m$^3$/s) and the decrease of the spring flows is slower than their increase in winter. During the summer season, the river maintains an average base flow of about 6-7 m$^3$/s (Martin, 1981).

4. Materials and Methods

The realization of this study was based on geological prospect in the basin of Aït Chaïb. This prospecting allowed us to identify the best sections where the structural, lithostratigraphic and sedimentological characters of the deposits, especially Plio-Quaternary and their relations with the grounds of the substrate are well illustrated. These sections were surveyed, described, analyzed and interpreted using descriptive and analytical data from the field and clarified by photographs. The description and analyses were carried out on the polished sections (descriptive and analytical macroscopic petrography) and on the thin sections (descriptive and analytical microscopic petrography), supported by microphotographs and interpreted according to the bibliographic data. Geomorphological and geological field insights (stratigraphy, structural and sedimentological) together with petrographic analysis are used to reconstruction of the sedimentary processes that governed the formation of carbonates of the Aït Chaïb Basin and other detrital facies, relative to the paleoenvironmental conditions.

5. Results

5.1. Description of the Section of Aït Chaïb

This section has been carried out across the “travertine table” to the west of the Aït Chaïb basin. It is formed by two formations: formation of substrate and superficial formation.

5.1.1. The substrate of the carbonate formations

The substratum of carbonate formations corresponds to marine deposits of the Upper Miocene, formed of marl with sandstone-siltstone intercalations (Charrière, 1990).

5.1.2. Superficial formations

The Superficial formations show angular discordance with marine formations of the Upper Miocene. They are composed of conglomerates gradually passing towards the top to continental carbonates(travertine and lacustrine limestone); of fluvio-lacustrine type and become alluvial fans and fluvial terraces, strath to fill terraces in the Oued Mdez valley.

The conglomerates rest on the marl with sandstone intercalation of the Upper Miocene through a well-recognized ravinement surface and have a maximum thickness of about 1.70 m (Fig. 2b). These fluvial conglomerates generally show a fining-upward, the clasts are generally heterometric, polygenic with subangular to subrounded shapes, and supported with argillaceous and carbonate cement.

The carbonate edifices are formed by diverse travertine encrustation types of different morphologies, which named travertine s.l and lacustrine limestone deposits.
5.2. Morphological Typology of the Travertine and Travertine Encrustation of Aït Chaïb

5.2.1. Morphological typology of the travertine of Aït Chaïb

Field observations have shown that the continental carbonates are constituted of travertine s.l and lacustrine limestones. The travertines occupy the western edge of the basin and are morphologically presented in the form of “stepped tables” from west to east. They are constituted by barrage travertine, the most important of which fossilize the slopes generated by normal faults of SW-NE direction and facing the SE back- and fore-barrage tuffaceous limestones and oncholithic sandy and silty travertine. These travertine transitions; at the bottom of the basin to lacustrine limestones that constitute their lateral facies passage (Fig. 2a).

**Fig. 2.** (a) Geological section grouping the typologies of the Plio-Quaternary carbonates of the Douar of Aït Chaïb: (1) silty clays of Quaternary age; (2) lacustrine limestones of Plio-Quaternary age; (3) chenalized conglomerates; (4) downstream barrage tufa; (5) Upper Miocene sandstones; (6) Upper Miocene marls; (b) Conglomerates gradually passing towards the top to limestone

- The travertine of the cascade barrage

This type is located at the level of the Douar d'Aït Chaïb and at the top of the Gara of Tazouta (Figs. 3a, and 3b), which are formed by a sub-vertical and prograding beds toward the center of the basin (Fig. 3c), over a length of about 100 m. They are formed by hard rocks, karstified, brownish to grayish color and rich in calcified plant prints, represented mainly by cylindrical crust buildups on stems and branches
of trees (Fig. 3d). The travertine of Douar shows fewer fractures than those of Tazota, which comprises two different origin. The travertine of the upstream barrage.

These deposits are located behind the barrage-cascade buildup, which are massive, white, laminated, and vacuolated, 2 to 3 m thick, and they rest as angular discordance on the Upper Miocene sandstones and by the intermediary of conglomerates whose base is not exposed. They are covered by clays and silts, with pebbles and scattered gravels corresponding to colluviums.

- The travertine of downstream barrage

These deposits are located at the bottom of the barrage in cascades. They comprised of stratified beds and arranged into lenticular layers, channelized and inclined towards the center of the basin. These detrital deposits are white color, formed of oncholithic travertine sands and silts with intercalations of edifices and encrustations of varied morphology, that are surmounted by a slab of hard calcrete, of variable thickness from 10 to 20 cm. The calcrete becomes thicker towards the East to become 1 m thick at the bottom of the basin where the topographic conditions were much more favorable to its formation.

![Fig. 3.](image)

Fig. 3. (a) General view of travertine table at the south of the Aït Chaib; (b) Looking north of the Tazouta Travertine Gara; (c) Progradation in karstified travertines at the level of a plio-quaternary palaeo-cascade; (d) Vegetable prints

- The Lacustrine Limestones

These are white color (Fig. 4a) and composed of an alternation of clear and dark laminae, which can be regular or irregular and continuous or discontinuous (Fig. 4b). The clear laminae have a thickness that varies from 0.2 to 8 cm, whereas the dark laminae have a thickness oscillating between 0.2 and 5 cm.
These limestones of the laminar structure are vacuolated (Fig. 4c). The vacuoles are elongated, lenticular to sub-spherical in shape and millimeter to centimeter in size. They are more or less enlarged by dissolution and can reach decimetric dimensions. These vacuoles are partially filled by secondary diagenetic calcite. Two forms of calcite were identified, the first is stalactite and stalagmite and the second is whitish wall belonging to a cylindrical conduit (Fig. 4d).

![Fig. 4](image-url)

**Fig. 4.** (a) Operating career; (b) dark and clear laminae in lacustrine limestones; (c) vacuolar appearance of lacustrine limestones; (d) palisade calcite; (e) clay detritic fraction; (f) coarse sand palaeo-channels and clays; (g) intraformal breach with limestone cement; (h) traces of plants

Calcite is sometimes associated with reddish or green clayey sediments (Fig. 4e). The lacustrine limestones occur in three stratigraphic units (Fig. 5).
Fig. 5. Stratigraphic log of the Douar d’Aït Chaïb quarry

The lower unit is composed of conglomerate overlying lacustrine limestone (gradual passage). These are resting upon upper Miocene marls with ravinement surface and attains 1m thick. The limestone is laminated, white colored and has a thickness of 10 m. The vacuoles are less frequent at the base or totally folded by the calcite.

The middle unit is composed of conglomerate with coarse sand supports with carbonate cement and attaining lenticular channelized shape. The channel is 10 m long and 1 m thick. The upper unit comprised highly porous brownish limestone attaining 7 m thick. The limestone is interbedded with marl, conglomerate, and coarse pebbly sandstone intercalation (Figs. 4f, and 4g). It shows plant prints (Fig. 4h). Intraformational breccia was identified in the western edge of this limestone succession. The breccia fragments are elongated of 2 to 20 cm in diameter and supported with sandy carbonate cement (Fig. 4g).

5.2.2. Morphological typology of travertine encrustation

Four morphological types of travertine encrustation were identified. These are: oncolith encrustation, cylindrical encrustation, planar encrustation and undulated encrustation.
• Oncoliths encrustations

The oncolith is composed of a nucleus coated by cotex of concentric laminae having a spherical, subspherical, oval, or elongated shape (Figs. 6a, and 6b). In the latter case, the oncoliths often have oval or elongated shapes depending on the length of the fragment of the cylindrical encrustation, which may be small or large (Figs. 6c, and 6d). The formation of several generations of laminae is manifested by interruption phases typically marked by ravinement surfaces of the oncolith shape towards the spherical form. In cross section view, oncoliths can be symmetrical or asymmetrical. In the symmetrical type the cortex presents the same thickness all around the nucleus and the asymmetric is the opposite case. The nucleus can be formed by a gastropod shell (Fig. 6e). These shells are identifiable when the cortex or the thickness of the encrustation does not exceed a few millimeters.

• Cylindrical encrustations

It is of cylinder shape encrusted around plant fragments as an isolated or groups of autochthonous or allochthonous clumps of steams, stemlets, roots, or brunch fragments (Fig. 6d). Like oncolith, these encrustations can be symmetrical or asymmetrical. This structure results from concentric, continuous, or discontinuous superposition of laminae of millimetric thickness of different colors and structures. The clear laminate is whitish, beige, or light brown, while the dark laminae is dark brown to black. On the other hand, the structure of these laminae is compact, vacuolar, or fibrous. Compact laminae are typically harder than vacuolar and fibrous laminae.

![Fig. 6. Oncolithic encrustation; (a) Asymmetrical oncholite; (b) Symmetrical Oncholith; (c) Oncoliths of subspherical to oval form; (d) Oncoliths of elongated, low-cortex form developed on nucleus formed by cylindrical crust fragments; (e) shells of encrusted gastropods (four shells on the right) and encrusting (last shell on the left)](image)

• Planar to undulated encrustations

These have typically been observed within the upstream barrage tufa deposits. They are formed by a superposition of planar to undulated alternating laminae of light and dark colors and of different structures. The dark laminae are brown, while the light laminae are whitish in color. The structures are vacuolar, compact but rarely fibrous. Vacuolar structure, involving the presence of vacuoles with various forms, they can be lenticular, spheric, subspheric or oval shape. These vacuoles are variously oriented except for the lenticular, which are generally arranged parallel to the lamination. These vacuoles, which
are generally millimetric in size, can take on a larger dimension, of centimetric order, deriving from the fusion of small vacuoles by dissolution. These vacuoles can be empty or filled by pinkish to reddish-brown clayey sediments.

5.3. Petrography of the travertines

5.3.1. The travertine of the cascade barrage

- Analysis of the polished sections

  The polished section shows a brown color and a high porosity, which is related to the presence of abundant vacuoles corresponding to vegetal traces. The latter shows various sections: transversal, longitudinal, and tangentially linked to their various dispositions in the rock, which corresponds to travertine with plants. The variation of the vacuoles diameter is related to the dimensions of the initial plants, i.e., stems and leaves. The sections of the calcified stems have oval (tangential sections), circular (transverse sections) and elongated (longitudinal sections) forms. The sections of the leaf traces are oval. The vacuoles, are usually empty, or partially filled by secondary, whitish calcite (Fig. 7A).

- Petrographic analysis of thin section

  It showed a calcified plant formed by an association of stems and leaves. The calcified plant imprints show sometimes cells with both plasma membranes (inner and outer) calcified by dark micritic calcite. The intermembrane space is cytoplasmic and can be empty or partially filled or totally by secondary calcite. This calcite presents in two morphological types (Fig. 7i): a palisadic calcite with continuous fringe of 0.25 mm thick that passes towards the center to an equigranular mosaic calcite associated with calcite in dog’s teeth pattern (Fig. 7h).

![Fig. 7.](image-url)

Fig. 7. (A) Polished section of travertine barrage with plants and microscopic views:

(a) vegetal traces in circular, ovoid and tangential sections, empty or partially filled with sparitic calcite and showing concentric micro-zonation (LPA); (b) ostracode valves (LPNA); (c) tangential sections of calcitized stems, fragmented by desiccation (LPA); (d and e) cortical cells filled with clear sparitic calcite of diagenetic origin, indicative of charophyte stems (LPNA and LPA); (f) traces of stems encrusted and cemented by a calcite (in dog teeth) sparitic of diagenetic origin (LPNA), Tc: Thalle of encrusted Cyanophyceées of hemispherical form and with concentric micro-zonation

The encrustation shows a concentric micro-zonation that is expressed by a regular alternation of dark micritic and clear sparitic micro-laminae (Fig. 7a). Some of these sections showed traces of cortical cells, evidencing the presence of charophytes, and filled by a limpid sparitic calcite of diagenetic origin.
The tangential sections are branched and calcitized by a sparite or a mixture of micro-sparite and micrite. The latter filled the stems and sometimes showed dissipated fragmentation (Fig. 7c). A few ostracod valves (Fig. 7b) were identified with traces of calcified roots and a few rare silty quartz detrital grains, as well as lenticular traces of concave shape and are partially filled by secondary sparry calcite. These traces correspond to gypsum crystals.

5.3.2. The lacustrine limestone

- Analysis of polished sections

The polished section of lacustrine limestone reveals a laminar structure (Fig. 8A) of millimetric size of varying thicknesses ranging from 1 to 10 mm, with an average of about 3 to 4 mm. The laminae are of frequently whitish to beige, or less commonly brownish. The structure is vacuolar or compact. The lamination is mostly planar or more or less undulated. Simple or composite formed by a superposition of alternating light and dark colors. The light laminae are whitish or beige, while the dark laminae are brownish. The vacuolar laminae contain vacuoles of various sizes and forms. The density of the vacuoles is also variable. That may be, more commonly, elongated parallel to the lamination, or randomly distributed with regular or irregular shapes. Regularly shaped vacuoles may be subspherical to spherical or lenticular and wavy, concave or convex. Their size varies from millimeter to 10 mm. The large vacuoles are filled with detrital sediments or chemicals (calcite), or both together. Some laminae showed angular unconformity. The laminations are related to aligned and juxtaposed vacuoles molded by the overlying laminae and show an undulated appearance.

- Microscopic analysis of thin sections

A regulated superposition of alternative vacuoles and more or less compact laminae were identified in thin section slides. The compact laminae showed a fibrous structure, arranged almost perpendicular to the lamination plane. The vacuolar laminae are formed by vacuoles that are often elongated and with irregular or sawtooth limits. They are often enlarged by dissolution and can be empty or filled by a limpid sparitic calcite. Some vacuolar laminae are lined in the upper part by a dark micritic micro-laminate having a thickness of 25 μm. This undulated micro-laminate is affected desiccation and by dissolution (Figs. 8a and 8h).

The filamentous laminae are divided into two types: dense filamentous laminae and loose filamentous laminae. The dense filamentous laminae are formed by individuals arranged in a fan shape (Fig. 8g). Each fan is formed by concentric zonation columns (Fig. 8b). This zonation is linked to a rhythmic superposition of light and dark laminae (Figs. 8d and 8e): the dark laminae are micritic while the light laminae are micro-sparitic. These laminae are linked by filaments grouped in a bouquet. The contact zones of these laminae are filled by a micro-sparitic to sparry calcite (Fig. 8c). Laminae can contain a few silt size quartz grains (Fig. 8f). These grains, having been trapped in the algal carpet in the process of encrustation, can be either of eolian or aquatic origin.

5.3.3. Cylindrical encrustation

- Analysis of polished sections

The polished sections showed that this encrustation is developed on two lots of plant supports that are subcircular in shape in cross section view. The encrustation has a concentric laminar structure with two distinct parts: an irregular inner part with a multi-lobed shape where the laminae are undulated, and an outer part where the undulations of the laminae tend to diminish progressively with the crust towards the outside. The amplitude of laminae undulations becomes less pronounced outward (Fig. 9A).

The laminae structure is due to a superposition of continuous to discontinuous laminae of millimeter strength, alternately light and dark in color, and of different structures. The dark laminae are
brown, dark brown, or black in color, while the light laminae are beige to white. The structure of the laminae can be vacuolar, fibrous, or compact. However, this structure was observed to be mixed in some areas with compact and fibrous laminae. Therefore, both compact and slightly vacuolar laminae and fibrous and slightly vacuolar laminae are present.

The vacuolar structure results from the presence of millimetric vacuoles of lenticular or sub-spherical shape that can be empty or partially filled by whitish to pinkish sediment. The density of these vacuoles is variable; some are dense and others are loose. These vacuoles can fuse and give larger vacuoles. Some laminae may show micro-lamination related to alternating light and dark color.

**Fig. 8.** (A) polished section of lacustrine limestone and microscopic views: (a) dense algal filament laminations and loose filament laminations affected by gas desiccation or exhaust (LPNA) patterns; (b) hemispherical micro-dome morphology of a calcified algae micro-edifice with concentric microzonation of Rivularia Haematite (Cyanophyceae of the family Rivulariaceae) (LPNA); (c) columnar morphology at the base and arborescent at the apex of calcified algae thalli (LPNA); (d) organization of cycle calcified algal carpets (LPNA and LPA); (e) fan morphology of calcified algal thallus (LPAN); (f) trapped detrital quartz grain (LPA); (g) desiccation figures of algal carpets (LPNA); (h) microcollapses (LPNA)

- **Microscopic analysis of thin sections**

  Microscopic observation showed that the lenticular vacuolar laminae have a hemispherical to semi-oval shape and are convected downward (Fig. 9a). The top of these vacuoles is lined by a dark, micritic micro-lamina, about 0.1 mm thick and probably of bacterial origin. Its base presents a denticulated shape. These vacuoles are empty and dispersed in a sparitic calcite, which encloses dark and entangled algal filaments.
The dark brown laminae are very rich in algal filaments, which are oriented in two different ways: they are either drawn up vertically or obliquely in the form of fans compared to the lamination (Figs. 9d and 9e) or laid down parallel to the lamination. These filaments are enclosed in a limpid sparitic calcite arranged in gerbs (Figs. 9b and 9c).

The light brown laminae are formed by a well-developed sparitic calcite with a gerb texture. This calcifies algal filaments arranged in juxtaposed and overlapping micro-bunches. These are locally separated by elongated vesicles, more or less sinuous, and partially filled by a secondary sparitic calcite of diagenetic origin.

![Image](image_url)

Fig. 9. (A) polished section of a cylindrical encrustation and the microscopic views: hemispherical to hemi-oval vacuoles; V: void corresponding to insect larval (Chironomid) habitats (LPNA); (b) and (c) vertically and obliquely erect calcified algal filaments (LPNA and LPA); (d) and (e) sparitic lamina of algal origin interspersed with finely micro-laminated micritic lamina of algo-bacterial origin (LPNA and LPA)

6. Discussion

The surficial formations consist of terrigenous detrital and biochemical carbonate deposits. The continental carbonates are constituted by travertines and lacustrine limestones. The travertines are formed by barrage travertines (Hammer et al., 2007) back-barrage travertine and springs that developed on slope breaks that correspond to fault slopes, and pass laterally to lacustrine limestones.

The transition from conglomeratic detrital to biochemical carbonate deposits denotes an important climatic change during the Plio-Quaternary in Northwest Africa. This change was expressed by a shift from an arid, warm climate to a humid, warm climate (Nutz et al., 2019). The formation of the continental carbonates, formed by travertines and lacustrine limestones, is linked to very favorable paleo-environmental conditions of paleo-climatic, geological, hydrogeological, hydrological, geomorphological, and topographical nature (Arenas-abd et al., 2010; Henchiri, 2014; Pedley, 1990).

Paleo-climatic conditions: The travertine shows an important porosity (Idan et al., 2020; Mahdi et al., 2022) and reaches the maximum deposition during warm and humid periods (Andrews et al., 1997; Chafetz et al., 1991; Pedley, 2009; Pentecost, 1995). Enhanced humidity would have allowed an important development of a forest cover that would have protected the reliefs against mechanical
erosion and favored the chemical dissolution of substrate geological formations. These bioclimatic conditions would favor soil development and increase their organic matter content, whereas the biochemical degradation thereof is an important source of CO₂. As a result, while it percolates into the soil, water becomes more enriched in carbon dioxide. On the other hand, farther downstream, degassing or evaporation processes are common, thereby triggering loss of CO₂ and, eventually, calcite precipitation (i.e., travertine development) (Arenas-Abad et al., 2010; Pentecost, 2005; Chafeet et al., 1991).

Geological conditions: the geological substratum is formed mainly by carbonates and is sensitive to chemical dissolution or karstification because of its textural characteristics and tectonic crushing, thus leading to the supersaturation of water with regard to calcium carbonate (Arenas et al., 2014; Pedly, 2009).

Hydrogeological and hydrological conditions: permeable carbonate soils resting on impermeable terrains (clays and marls) allow the formation of profound and superficial aquifers that exchange their waters through faults, thus resurgent waters in the form of karstic sources (Arenas et al., 2014; Pedly, 2009). Geomorphological and topographical conditions: the existence of narrow and profound valleys, dug by vertical incisions in the elevated zones, allows turbulent flows to lead to their supersaturation in limestone solution by loss of CO₂. This loss increases further at waterfalls that develop at slope ruptures that often correspond to fault talus (Gourari, 2001).

The petrographic analysis showed that all the laminae are formed by more or less dense and calcified algal filaments and attain fine micro-lamination, which results in an often rhythmic superposition of clear sparitic and dark micritic micro-laminae, of bacterial origin (Boggs, 2009; Chafeet et al., 2020). This evidences the stromatolitic nature of these continental carbonates of Aït Chaïb. The vacuolar structure, of the travertine laminae and lacustrine limestones, is related to the presence of insect larval habitats corresponding to Diptera or Chironomids with aquatic larval stage. The laminae are organized in cycles of annual rhythmicity. The most complete cycles are formed from the base to the top by a superposition of three laminae: the vacuolar lamina, the compact lamina and the fibrous lamina. In the vacuolar laminae, the algal mat is rudimentary because it is consumed by the larvae. In the compact laminae, the algal filaments are dense, and their calcification is formed by spary calcite, while in the dark fibrous laminae. The algal filaments are loose and calcified by dark micrite.

The filamentous laminae with loose filaments are formed by very spaced algal individuals affected by erosion phenomena. The fragments, resulting from this erosion of chemical-dendritic origin, are presented in angular to subrounded grains and of silty to sandy dimension. The voids between the algal filaments are filled by sparitic calcite, which also ensures the cementation of the eroded algal debris that forms internal sediment.

The two filamentous laminae, namely the dense filamentous lamina and the loose filamentous lamina, reflect ecological conditions that are favorable and unfavorable to the development of the algal mat. These conditions would be related to a seasonal climatic variation during the year. The dense-filament lamina develops during the dry, warm season that encompasses late spring-summer-early fall, whereas the loose-filament lamina forms during the rest of the year, which is the period that spans late fall-winter-early spring. The vacuoles composing the vacuolar laminae are often enlarged by dissolution (Chafeet et al., 2020), especially in the lake facies exploited in marbrerie which leads to their fusion and increase in size. These vacuoles are often filled partially or totally by Silty sediments and/or a limpid calcitic cement (Chafeet et al., 2020; Flugel, 2010), vadose to phreatic diagenetic origin, the most frequent case in the lacustrine limestone.

The breccia corresponds to a desiccation breccia resulting from the erosion of laminated limestones of algal origin, formed under a low water table and having undergone desiccation after emersion. The fragments were mobilized over a short distance by water flows and then deposited on the bottom of a more or less calm water body.
The symmetrical oncholiths characterize fluvial environments with turbulent flows, allowing their continuous rolling and reworking, whereas the asymmetrical oncholiths are formed in calm fluvial or lacustrine margin environments. The continuous immobility of the nucleus, in these calm continental subaqueous environments results in the formation of a hemispherical type of encrustation, which develops only on the upper half of the nucleus that is in contact with water.

The colonnettes are separated by more or less sinuous conduits and partially filled by secondary sparly calcite (Török, 2004). They correspond of gas and water vapor escape structures (Fig. 8a). These conduits or pores formed by evaporation during periods of emersion, thus of climatic origin, are used for the infiltration of rainfall and/or snowmelt and also for the rise of phreatic water by capillary action. These waters entrainment diagenetic phenomena that are expressed in the rock by phenomena of dissolution and cementation (Chafeet et al., 2020) according to their degree of saturation in calcium carbonate solution. The aforementioned vesicles would correspond to gas escape structures or desiccation cracks. They are affected by dissolution phenomena and can be filled by internal sediment derived from erosion and micro-collapse of the algal-calcitic mat.

7. Conclusions

The continental carbonates of the Aït Chaib intracontinental basin are deposited in an angular unconformity on the Upper Miocene laguno-marine deposits, composed of marl with silty and sandstone intercalations that are topped by conglomerates.

They begin with fluvial conglomerates with argilaceous cement, followed by continental biochemical carbonates, composed of travertines on the border of the basin and lacustrine limestone in the center, and end with fluvial sedimentation, essentially detrital and biochemical, deposited by the Oued Mdez and arranged in fluvial terraces.

The evolution of the sedimentary environments developed from i) alluvial fans, ii) fluvio-lacustrine, and iii) fluvial, expresses the passage from a closed continental or endoreic environment to an exoreic environment. The geological period of this passage from endoreism to exoreism is synchronous with the passage from fluvio-lacustrine sedimentation of the second episode to fluvial sedimentation of the third sedimentary episode.

Lacustrine carbonates are of cyanobacterial origin, and they can be considered stromatolites. Their formation is linked to favorable geo-environmental and bioclimatic conditions characterized by a humid and warm climate and a well-developed forest cover.

The good petrographic quality of the lacustrine limestones, currently exploited at the bottom of the cuvette, is related to their sedimentary and diagenetic evolution. Their sediment genesis was carried out by biochemical to biological way in a lacustrine environment of low profound. This environment, where turbidity was almost nil, because of the important development of the forest cover, had a strong power of carbonate development, linked to the supersaturation of water in calcium carbonate solution and to the important development of the cyanobacterial carpet.

Their advanced diagenesis, responsible for strong induration by recrystallization and cementation of the voids, is linked to the presence of an important superficial water table in the underlying conglomerates, which currently outcrop at the bottom of the most profound quarries.

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