

Upper Cretaceous deposits on the Northern side of the High Atlas Range of Marrakesh (Morocco): tectonics, sequence stratigraphy and paleogeographic evolution

Depósitos del Cretácico Superior en el flanco norte de la Cordillera del Alto Atlas de Marrakech (Marruecos): tectónica, estratigrafía secuencial y evolución paleogeográfica

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ABSTRACT

This paper presents a new interpretation of the paleogeographic evolution of the northern side of the High Atlas Range of Marrakesh (Morocco) based on a tectonic, lithological, sedimentological, and paleontological description of the three outcropping Upper Cretaceous Formations: The Anou-Nfeg Formation, the Ait Abbas Formation, and the Chichaoua Formation. In biostratigraphical terms, these formations areas signed to the Coniacian, Santonian, and Maastrichtian, respectively, and record three tectonic phases responsible for the geodynamic evolution of this part of the High Atlas Range. These phases are confirmed by the vertical elevation of the earth's surface and the formation of some small restricted basins. A sedimentary pause corresponding to the Campanian has been recorded. Based on these findings, we conclude that these Formations were deposited in a confined environment influenced by the episodic marine incursions under a hot and humid climate.

Keywords: Sequence stratigraphy, paleogeographic evolution, Upper Cretaceous, High Atlas of Marrakesh, Morocco.

RESUMEN

Este artículo presenta una nueva interpretación sobre la evolución de la estratigrafía secuencial y paleogeografía del flanco norte de la Cordillera del Alto Atlas de Marrakech (Marruecos), basada en una descripción tectónica, litológica, sedimentológica y paleontológica de las tres formaciones aflorantes del Cretácico Superior: la Formación Anou-Nfeg, la Formación Ait Abbas y la Formación Chichaoua. Bioestratigráficamente, estas formaciones se asignan respectivamente al Coniaciano, Santoniano y Maastrichtiano, y son el registro de tres fases tectónicas responsables de la evolución geodinámica de esta parte del Alto Atlas. Estas fases se confirman por un movimiento vertical ascendente de la superficie y la formación de pequeñas cuencas restringidas. La investigación de campo confirma una pausa sedimentaria durante el Campaniano. Sobre la base de estos hallazgos, llegamos a la conclusión de que estas formaciones se depositaron en un entorno confinado influenciado por incursiones marinas temporales en climas cálidos y húmedos.

Palabras clave: Estratigrafía secuencial, evolución paleogeográfica, Cretácico Superior, Alto Atlas de Marrakech, Marruecos.

1. Introduction

Three unequal extended gulfs were formed in Morocco during the Late Cretaceous (Senonian, according to Choubert and Salvan, 1950) as a result of sea-level fluctuations in the Atlantic Ocean (Figure 1): i) the Phosphate Plateau Gulf of the eastern Meseta or Inter-Atlasic Great Gulf, in the Khourigba-Boulemane-Tendrara area; ii) the Haouz Gulf, from Marrakesh to Essaouira, or “Sub-Atlasic Northern Gulf” which is separated from the Inter-Atlasic Great Gulf by the Jebilet Mass nearby Bengurir; and iii) the Souss-Ouarzazate Gulf or “Sub-Atlasic Southern Gulf”, which is separated from the Sub-Atlasic Northern Gulf by the rising High Atlas Range. This uplift of the High Atlas started during the Coniacian-Santonian (early Upper Cretaceous of Choubert and Faure-Muret (1962). Afterward, during the latest Cretaceous, the Atlantic-sea receded from a large part of the High Atlas Range (Choubert and Salvan, 1950; Choubert and Faure-Muret, 1962), and then a large transgression of the Atlantic-sea

during the Maastrichtian induced the formation of the Gulfs, like “fingers of glove”, following the topography of Jebilet, Rehamna and High Atlas areas. The focus of this article is on the Sub-Atlasic Northern Gulf, which is characterized by the progressive transition from marine, through lagoonal, to continental facies along a west to east transect (Algouti *et al.*, 2015). We propose an updated evolution of the stratigraphic and regional paleogeographic sequence of the northern side of the High Atlas Range of Marrakesh (Morocco) based on a re-assessment of the depositional age of the outcropping Upper Cretaceous (Senonian) formations.

2. Materials and Methods

Several field missions were conducted for the paleogeographic reconstruction of the northern side of the High Atlas Range of Marrakesh during the Late Cretaceous. A sedimentological facies

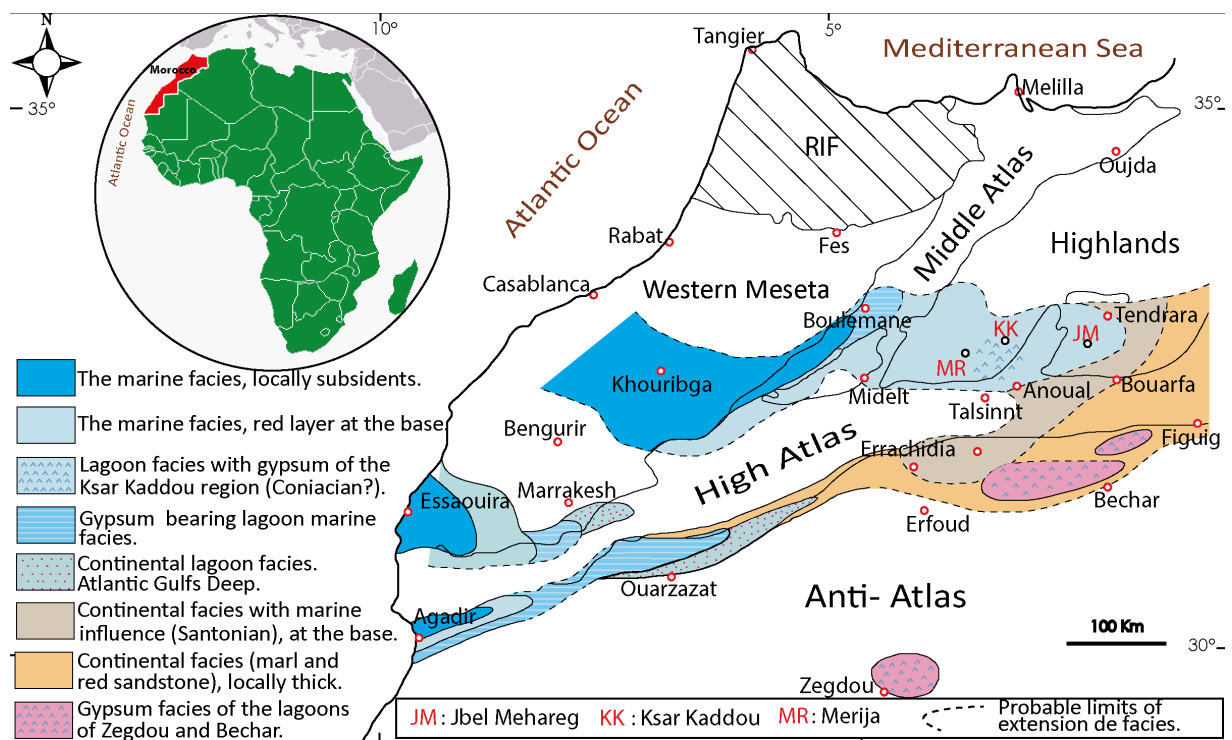


Figure 1 Facies map and schematic paleogeographic reconstruction of the Moroccan Atlas region during the Late Cretaceous (modified after Choubert and Faure-Muret, 1960-62).

analysis to determine the depositional environments was carried out in the field by recognizing sedimentary structures and textures. The lithological characteristics observed in ten selected areas (Figure 2) allowed a lithostratigraphic subdivision in three formations (the Anou-Nfeg Formation, the Aït Abbes Formation, and the Chichaoua Formation, from which synthetic columns are reproduced in Figures 3, 4, and 5, respectively), with a recognition of different types of facies. A correlation panel of the measured columns is shown in Figure 6.

For sampling of unconsolidated materials, the weathered horizon was removed up to about 30 cm deep. After sieving marl, silt, and sandstone samples on 315 µm, 400 µm, and 500 µm sized graded mesh, the residues were studied by scanning electron microscopy at the Cadi Ayyad University laboratory for exoscopic analysis. Thin sections of 250 consolidated rock samples were prepared at the Faculty of Sciences Semlalia of Marrakech

and studied under a petrographic microscope in the 2GRNT “Geoscience, Geotourism, Natural Hazards and Remote Sensing” laboratory. The ichnological analysis was limited to outcrop observations. The most marked trace fossils studied in the series (*Diplocraterion* and *Skolithos*) were recognized and recorded with photographs and their paleo-environmental significance was deduced from the observed context.

3. Results and interpretation

3.1 FORMATIONS AND DEPOSITIONAL SEQUENCES

Three Upper Cretaceous formations have been distinguished on the northern side of the High Atlas Range of Marrakesh, more precisely from Imin’Tanout village in the west to the “Cuvettes area” of Ait Ourir in the east (Figure 2): The Anou-Nfeg Formation, the Aït Abbes Formation, and the

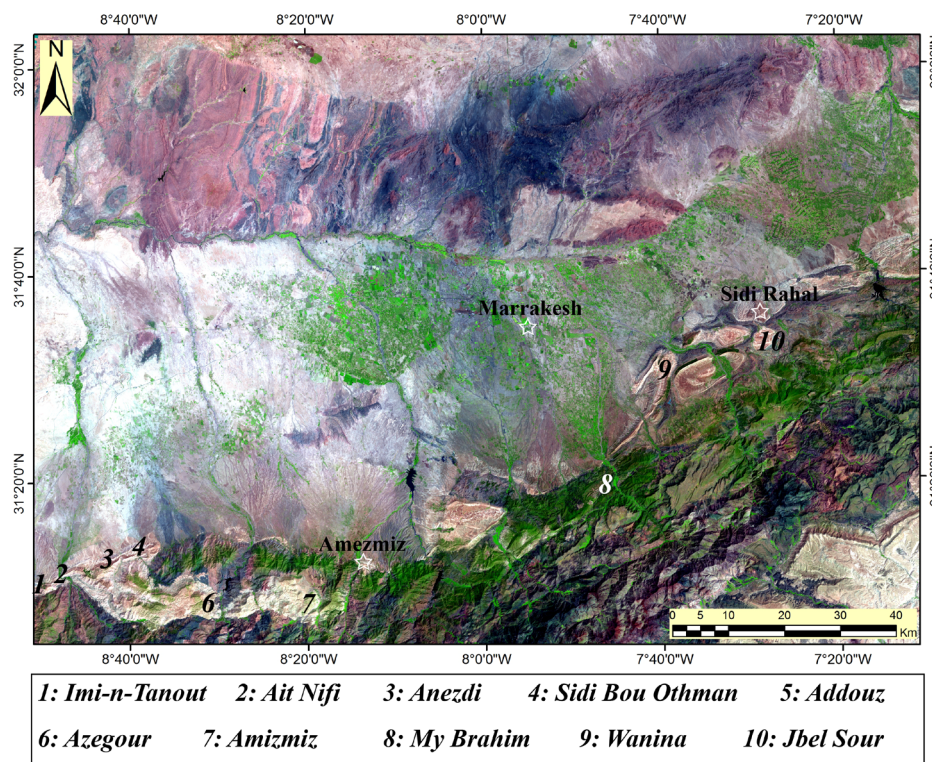


Figure 2 Location of the study area and measured sections.

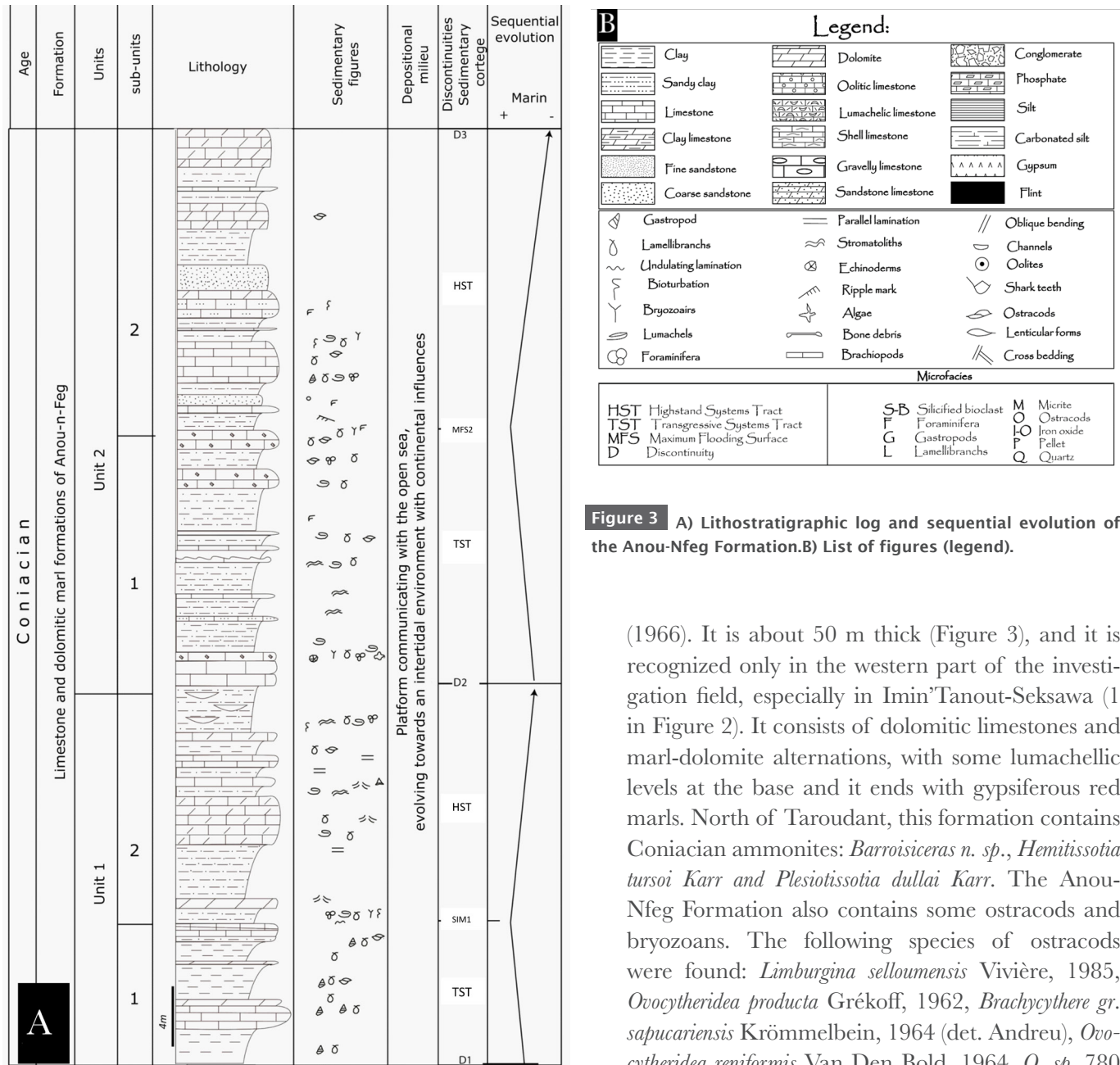


Figure 3 A) Lithostratigraphic log and sequential evolution of the Anou-Nfeg Formation. B) List of figures (legend).

(1966). It is about 50 m thick (Figure 3), and it is recognized only in the western part of the investigation field, especially in Imin'Tanout-Seksawa (1 in Figure 2). It consists of dolomitic limestones and marl-dolomite alternations, with some lumachellic levels at the base and it ends with gypsiferous red marls. North of Taroudant, this formation contains Coniacian ammonites: *Barrosiceras n. sp.*, *Hemitissotia tursoi* Karr and *Plesiotissotia dullai* Karr. The Anou-Nfeg Formation also contains some ostracods and bryozoans. The following species of ostracods were found: *Limburgina selloumensis* Vivière, 1985, *Ovocytheridea producta* Grékoff, 1962, *Brachycythere gr. sapucariensis* Krömmelbein, 1964 (det. Andreu), *Ovocytheridea reniformis* Van Den Bold, 1964, *O. sp.* 780 Donze, *O. brevis* Grékoff, 1962, *O. cf. reniformis*, *O. cf. brevis*, *Cytherella gr. ovata* Roemer, 1841, *Cythereis gr. algeriana* Bassoullet and Damotte, 1969, *Pterygocythere aff. allinensis* Grékoff and Deroo, 1956, and *Cythereis aff. morsottensis* Vivière, 1985 (det. Bismuth). The bryozoans found are *Biffustrai (Conopeum) sp.*, which also indicate a Coniacian age (Peron, 1893). Consequently, based on its faunal elements and on lithostratigraphic correlation with the Upper Cretaceous sediments of the southern side of the Western High Atlas (Algouti, 1999; Algouti *et al.*, 1998), the Anou-

Chichaoua Formation (Figures 3A and 3B). The Anou-Nfeg Formation covers the Cenomanian-Turonian Casbah Formation (Ettachfni, 1993). The Chichaoua Formation underlies (Algouti, 1999; Algouti *et al.*, 1998).

3.1.1. ANOU-NFEG FORMATION

This Formation was nominated by Duffaud *et al.*

Nfeg Formation was assigned to the Coniacian. The Anou-Nfeg Formation covers the Cenomanian-Turonian beds of the Casbah Formation of Agadir (Ettachfani, 1993) by a stratigraphic *discontinuity* surface, hereafter named *D1 discontinuity*, which is bioturbated, oxidized, and marked by flint nodules. This Formation includes two lithological units corresponding to the deposition of third-order sequences SI and SII (Units 1 and 2 in Figure 3) and which are bounded by another *discontinuity* surface between them, hereafter named *D2 discontinuity*.

THIRD-ORDER SEQUENCE SI

The sequence SI is about 30 m thick, is widely recognized in the Imin'Tanout area and is bounded at the base and the top by the *D1* and *D2* discontinuities, respectively (Figure 3).

The lower part of this sequence (sub-unit 1 in Figure 3) is characterized by a marl-limestone alternation and ends with a thin, oyster-rich condensed limestone bed (Figure 3). The upper part of this sequence (sub-unit 2 in Figure 3) is characterized by a carbonate-sandstone alternation (Figure 3). The carbonates are limestones with a mudstone texture and bearing ostracods and lamellibranchs at the base (Figure 7, Photo 1), which reveals a calm coastal depositional environment. However, at the top the sediments are barren and show tepee structures, stromatolite laminations, sheet cracks, mud cracks, and monogenic dissolution breccias, which indicate a mesolittoral depositional environment. The sandstones are dolomitic generally, coarsening-downward, lenticular, and having inclined laminations. At the top of this part, the sandstone bodies turn into azoic marls. Effectively, the morphoscopic analysis shows the abundance of rounded grains, which are mostly gleaming and rarely pecked.

THIRD-ORDER SEQUENCE SII

The sequence SII (30 m thick) is bounded by the *D2 discontinuity* at its base and by a new *discontinuity* (*D3*) at its top (Figure 3). The basal *discontinuity* (*D2*) corresponds to a noticeable facies change

(an abrupt shift from continental sandstones to marine carbonate deposits). The lower part of this sequence (sub-unit 1 of Unit 2 in Figure 3) is marked by the alternation of fossiliferous limestone layers, coquinas in places, generally associated with stromatolitic structures, and azoic sandy marls.

The upper part of this sequence (sub-unit 2 of Unit 2 in Figure 3) is characterized by azoic sand/silt deposits. The quartz grains are mostly rounded having a gleaming surface. The gleaming surface grains reveal an aeolian source with a significant sub-aquatic mixing. The vertical evolution of the sequence SII units records a transition from an intertidal to a supratidal zone where sand dune corridors were accumulated.

3.1.2 AÏT ABBES FORMATION

This Formation was nominated by Duffaud *et al.* (1966). It is formed by lumachellic limestones, often, sandstones at the base, then, green-yellow marly dolomitic limestone with some interspersed siliceous limestone beds. Brives (1905) found the ammonite *Texanites texanum* indicating lower Santonian. The Aït Abbes Formation is recognized over the whole study area. It includes two third-order sequences SIII and SIV bounded by the *D3* and *D8* discontinuities (Figure 4). Likewise, these sequences comprise several lithological units (Figure 4).

Due to its lithostratigraphic correlation with the sediments of the southern side of the Western High Atlas (Algouti *et al.*, 1999), and due to the detection of bryozoans, ostracod assemblages, echinoids, and ammonites within this formation, it was assigned to the Santonian. The bryozoans are represented by *Flustrina fcheuri* (det. P.D. Taylor), which characterizes the Santonian (Peron, 1893). This species has also been detected within the Santonian formations of Tunisia and Algeria (Abdallah, 1987; Matmati *et al.*, 1991).

The ostracod assemblages have been recognized within the Coniacian-Santonian levels of the High and Middle Atlas (Andreu, 1991). As

an example, we can mention: *Ovocytheridea producta* Grékoff, 1962, *Cythereis dupliciterornatus* Andreu, 1996, *Cytherella mediatlasica* Andreu, 1996, *Cytherella cf. sarakundaensis* Apostolescu, 1963, *Limburgina selloumensis* Vivière, 1985, *Cytheropteron piscatorius* Andreu, 1996 (det. Andreu), *Ovocytheridea sp.* B780 Donze, *O.aff. brevis* Bellion *et al.*, 1973, *Spinoleberis yotvataensis* Rosenfeld, 1974, *Cytherella aff. parallela* Reuss, 1846, *Protobuntonia aff. numidica* Grékoff, 1953, *Cythereis magnei* Donze and Saint Marc, 1981 (det. Bismuth).

Among the echinoids, *Clypeopygus pseudominimus* Peron and Gauthier (det. Rey) and *Petalobrissus species* indicate a Santonian age (Algouti, 1991). One of the found ammonites, unfortunately, is in a poor state of conservation but belongs to the *Tissotiidae* family (det. Kennedy) which characterizes the Coniacian-Santonian.

THIRD-ORDER SEQUENCE SIII

The sequence SIII includes two lithological units U3 and U4 bounded by the D3 and D5 discontinuities (Figure 4).

A) UNIT 3

At about 20 m thick, unit 3 extends between the D3 and D4 discontinuities (Figure 4). The D3 discontinuity corresponds to one noticeable facies change (an abrupt shift from terrigenous deposits of the upper part of the Anou-Nfeg Formation to subtidal carbonate deposits of the Aït Abbes Formation). The lower part of this unit (sub-unit 1), about 10 m thick, gradually decreases from west to east and vanishes at the Anezdi area (3 in Figure 2). It is generally characterized by the alternation of the limestone and marl layers, which are thinning-upwards and thickening-upwards, respectively. The faunal elements discovered in this sub-unit 1 are: miliolids, planktonic foraminifera, echinoderms, bryozoans, ostracods, gastropods, bivalves, and brachiopods associated with dasycladaceans algae (Figure 7, Photo 2). The upper part of unit 3 (sub-unit 2), is characterized by the repetition of limestone, gypsum and marl facies in the west. The carbonate beds (centimetric thick layers) are dolomitic and whitish, with (saccharoid texture), and contain some

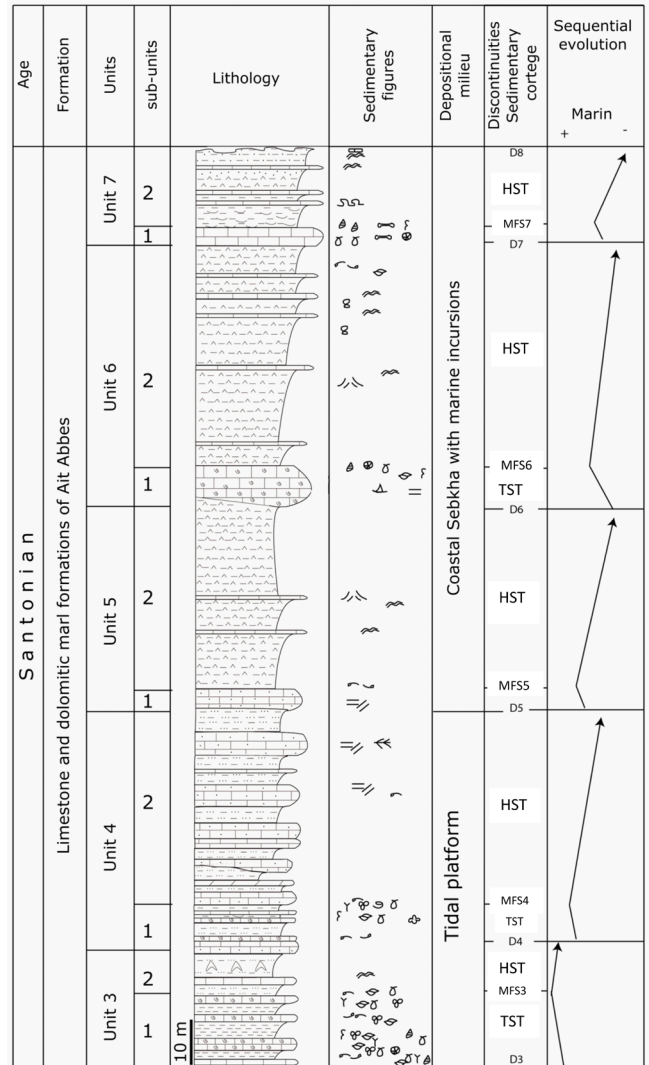


Figure 4 Lithostratigraphic log and sequential evolution of the Ait Abbes Formation.

gastropods and stromatolites, while the marls are azoic. To the east, silty facies and sandstone bed intercalations are more frequent, the carbonates become sandy and azoic, and include monogenic dissolution breccias and fenestrae (Figure 7, Photo 3). The overall lithostratigraphic evolution of this unit 3 reveals a change from infralittoral to intertidal and to supratidal environments.

B) UNIT 4

Unit 4 is recognized in most of the study area, but it is absent in Amizmiz, Douar Sour near My Brahim, and at the east of Wanina (Figure 2). Unit 4 is bounded by the D4 and D5 discontinuities

(Figures 3 and 5). The D4 *discontinuity* elsewhere corresponds to an erosive surface and more often to facies change from silty and evaporitic deposits to marine carbonate deposits. Generally, the lower part of this unit 4 (sub-unit 1 in Figure 4) is a metric dolomitic limestone layer including some planktonic foraminifera, bivalves, ostracods, echinoderms, bryozoans, and algae. Eastwards, this layer has a lenticular shape and brecciated appearance including stromatolites, evaporitic dissolution voids, and bioturbation traces. The surface of this layer is covered by a thin ferruginous crust in some places. From west to east, the lithostratigraphic profile of unit 4 reveals a change from a subtidal environment, with a temporary link to open-sea, to a more or less confined intertidal and supralittoral environment.

The upper part of this unit 4 (sub-unit 2 in Figure 4) is characterized by the alternation of azoic silts, channelized coarse sandstones (Figure 8, Photo 1), and predominating carbonate beds. The thickness of this sub-unit 2 is variable from one region to another (Figures 2 and 6); about 80 m in Imin'Tanout, 94 m in Sidi Bou Othman, and relatively reduced elsewhere (16 m). Westwards of Sidi Bou Othman, the metric carbonate layers are bioturbated and silicified with channelized aspects (Figure 8, Photo 2). They are gravelly and dolomitic with a wackestone texture, bivalve bioclasts, and dissolution vacuoles evidencing pre-existing evaporites. Furthermore, these carbonates display some horizontal laminations, oblique laminations, and herringbone structures suggesting that the sedimentation was dominated by tidal currents (Figure 8, Photo 3). Eastwards, these carbonate beds are whitish, thin- to very thin-bedded, azoic, dolomitic, and evaporitic, and show in some places large tepee structures (Figure 8, Photo 4) associated with the dissolution breccias, cavernous facies (cargneule) with local collapses, large desiccation cracks, and water-escape figures.

These carbonates were deposited in a tidal-flat environment ranging from intertidal to supratidal with brines, which are frequently emerged in the eastern area. From their lenticular aspect, the silts indicate marine sedimentation in shallow waters.

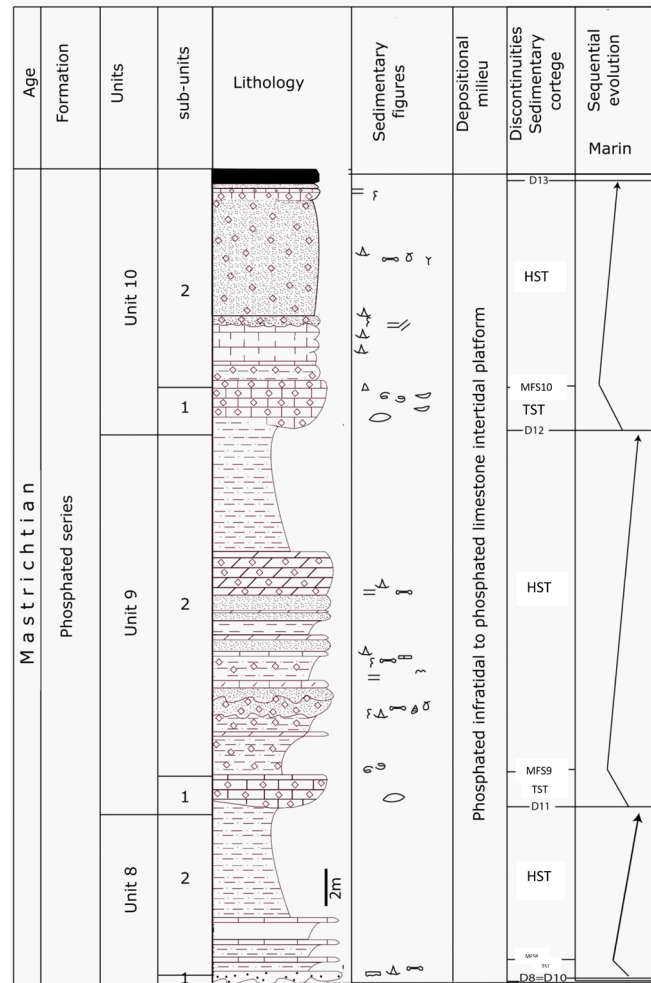


Figure 5 Lithostratigraphic log and sequential evolution of the Chichaoua Formation.

THIRD-ORDER SEQUENCE SIV

The sequence SIV is about 100 m thick and is recognized over the study area except for Douar Sour area (Figure 2). The sequence SIV consists of three lithological units: unit 5, bounded by the D5 and D6 discontinuities; unit 6, bounded by the D6 and D7 discontinuities; and unit 7, bounded by the D7 and D8 discontinuities. The D5 *discontinuity* is a great regional erosional surface with abrupt facies change from supratidal or continental gypso-detrital to subtidal carbonate deposits. The D6 and D7 discontinuities are associated with rapid facies changes from evaporitic to carbonate layers containing ostracods, gastropods, bivalves, echinoids, and fish teeth. Carbonates facies indicate

an increasing water level and agitation in shallow subtidal environments. In terms of lithology, units 5, 6, and 7 are relatively monotonous and made of a succession of carbonates, gypsum, marls, and silts.

The carbonates are centimetric platy (sandy or dolomitic) limestone layers with a mudstone texture. Sometimes they contain, some bivalves, stromatolites of LLH type (laterally linked hemispheroids: Logan *et al.*, 1974), fenestrae, sheet-cracks, tepees, vacuoles formed after dissolution of halite, radial calcined anhydrite, and silicification traces (quartzine, lutecite, chalcedony, mosaic megaquartz, microcrystalline quartz (Figure 7, Photo 4). These platy limestones characterize a shallow, intertidal to supratidal, restricted environment with a high salinity, affected by repeated emersions probably under hot and humid climates (Afenzar and Essamoud, 2020). Furthermore, according to Cussey (1979), the most sedimentary structures identified within platy limestones indicate carbonated sabkha-type environment. The gypsum layers are generally whitish, with saccharoid textures and laminated, nodular, and enterolithic structures (Figure 9, Photos 1-4). According to Kinsman (1969) and Shearman (1978), this type of facies indicates an evaporitic environment of sabkha-type. The marls and silts are often reddish to greenish, gypsiferous and azoic, locally showing siliceous nodules. This type of facies characterizes a supratidal restricted environment. Consequently, the sequence SIV documents a restricted environment of sabkha-type under a hot and humid climate (Afenzar and Essamoud, 2020). On the other hand, the sequence SIV is presented essentially by thick sandy-silty and conglomeratic detrital deposits in Ait Nifi, Anezdi, Amizmiz, and in the western part of Jebel Sour. These deposits indicate the existence of mountains as the sedimentary source. The exoscopic study of the quartz collected from Amizmiz area provides valuable insights into the environmental evolution. Indeed, the quartz grains collected from the base of the sequence show some uniform surfaces with shock traces (Figures 10A and 10B). Furthermore, the dissolution figures

(Figure 10C) around the edges and cavities, and the globular silica deposits within cavities (Figure 10D) indicate an intertidal environment (Le Ribault, 1975). However, the quartz grains collected from the top of this sequence show some violent shock traces and a high polishing, reflecting a fluvial heritage. Moreover, the presence of the flower-like silica with diatomaceous sequestration indicates subaerial exposure in a confined supratidal environment over a long period.

3.1.3 CHICHAOUA FORMATION

The Chichaoua Formation was named by Dufaud *et al.* (1966) and is also known as Phosphatic Series as it is characterized by phosphatogenesis (Slansky, 1980). It was traditionally reported to the Maastrichtian (Roch, 1930), which is confirmed by ammonites dating: *Baculites cf. boulei* Collignon, *Nostoceras sp.* and *Baculites sp. anceps*. Lemarck. This dating was confirmed by the occurrence of shark remnants *Ganntouria variabilis* Noubhani, 1993, *Ginglymostoma botmaense* Noubhani, 1993, *G. pectinatum* Noubhani, 1993, and *Plicatoscyllium yousoufaense* Noubhani, 1993, within the phosphated series of the Moroccan basins (Noubhani, 1993). The Chichaoua Formation is recognized over most parts of the study area except in the Amizmiz and Douar Sour areas. Three third-order sequences were distinguished within this formation: SV (Unit 8), SVI (Unit 9), and SVII (Unit 10). The sequence SV (about 10 m thick) is recognized in the Imin'Tanout and Azegour areas (Figure 2) and is bounded by the D8 *discontinuity* at the base and the D9 *discontinuity* at the top. Generally, the D8 *discontinuity* is an erosional surface in the Imin'Tanout area, where it is associated with rapid evaporitic to phosphatic facies changes, while it is represented by a karstified surface in Azegour area. The Sequence SVI (about 20 m thick) is observed in the Imin'Tanout, Azegour, and "Cuvettes area" of Ait Ourir (Figure 2). It is restricted by the D9 and D10 *discontinuities*, which are both represented by rapid facies changes accompanied by erosional surfaces. The sequence SVII (about 10 m thick) is recognized in

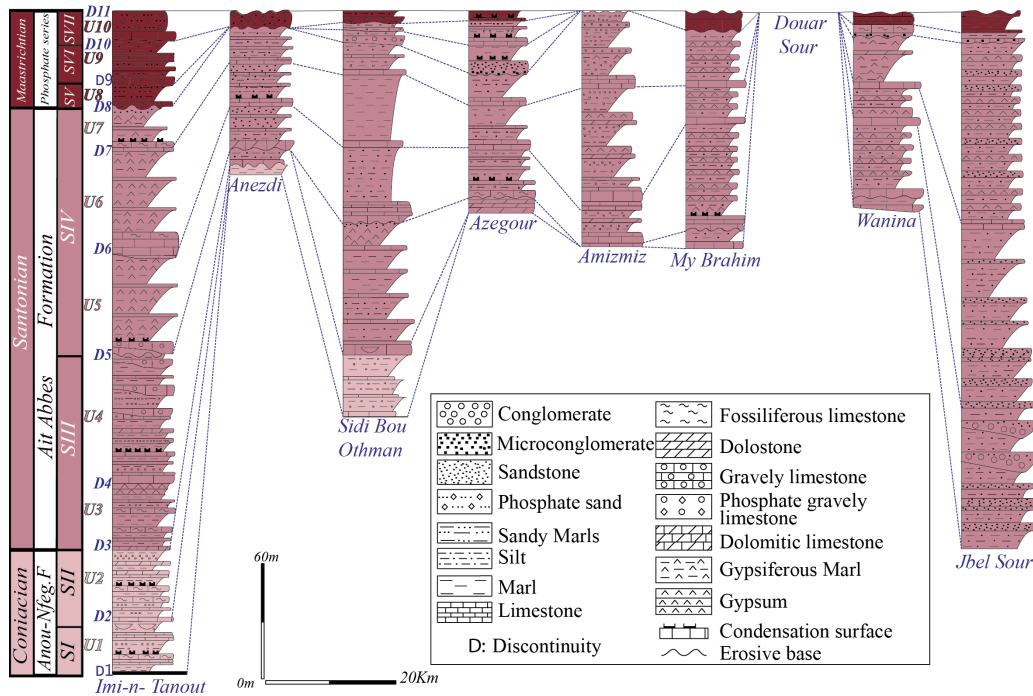


Figure 6 Lithostratigraphic correlations.

the whole study area except in the Amizmiz and Douar Sour areas and is bounded by the D10 and D11 discontinuities. The latter is mainly a bioturbated, oxidized, and karstified surface, in which the centimetric and metric irregular cavities are overfilled with some coarse sediments. D11 is a regionally omnipresent *discontinuity*, noticeably also recognized in Algeria (Belkodja *et al.*, 1994), Tunisia (Abdallah, 1987; Matmati *et al.*, 1991), and Greece (Pomoni-Papaioannou and Solakius 1991). Each sequence generally begins with a centimetric to metric fining-upwards deposit of its phosphatized and bioturbated microconglomerate that contains foraminifera, fish teeth, and other vertebrate bone debris, with an erosional basal surface and overlaid by an accumulation of oysters. In addition, each sequence ends by an alternation of channelized, fining-upwards microconglomerates, phosphatized and bioturbated sands (Figure 7, Photo 5), and carbonates. The sands show some oblique laminations, herringbone structures, and mega-ripples in the Ait Nifi-Anezdi area. The carbonates are represented by some phosphatized,

fossiliferous, and bioturbated (*skolithos*) calcarenites or by dolomitic, fossiliferous, and bioturbated centimetre-thick platy limestones.

In the eastern part, the carbonates are represented by dolomitic and more or less silty mudstones/wackestones containing some ostracods and dissolution voids (vacuoles), which indicate evaporitic depositional environments. The limestone plates display some horizontal and undulated laminae, stromatolites (Figure 7, Photo 6), brecciations, micro-channels, lenticular bedding, tepees, water-escape figures, silicified levels as centimetric nodules or laminae, and *Diplocraterion* burrows. According to Seilacher (1967), these sedimentary structures are typical of a coastal and infralittoral environment exposed to moderate or relatively high energy conditions.

In summary, the Chichaoua Formation is characterized by phosphatic sedimentation within a restricted and hypersaline environment, which was influenced by the temporary marine incursions under a hot and humid climate, suitable for marine vertebrate fauna. The depth of this

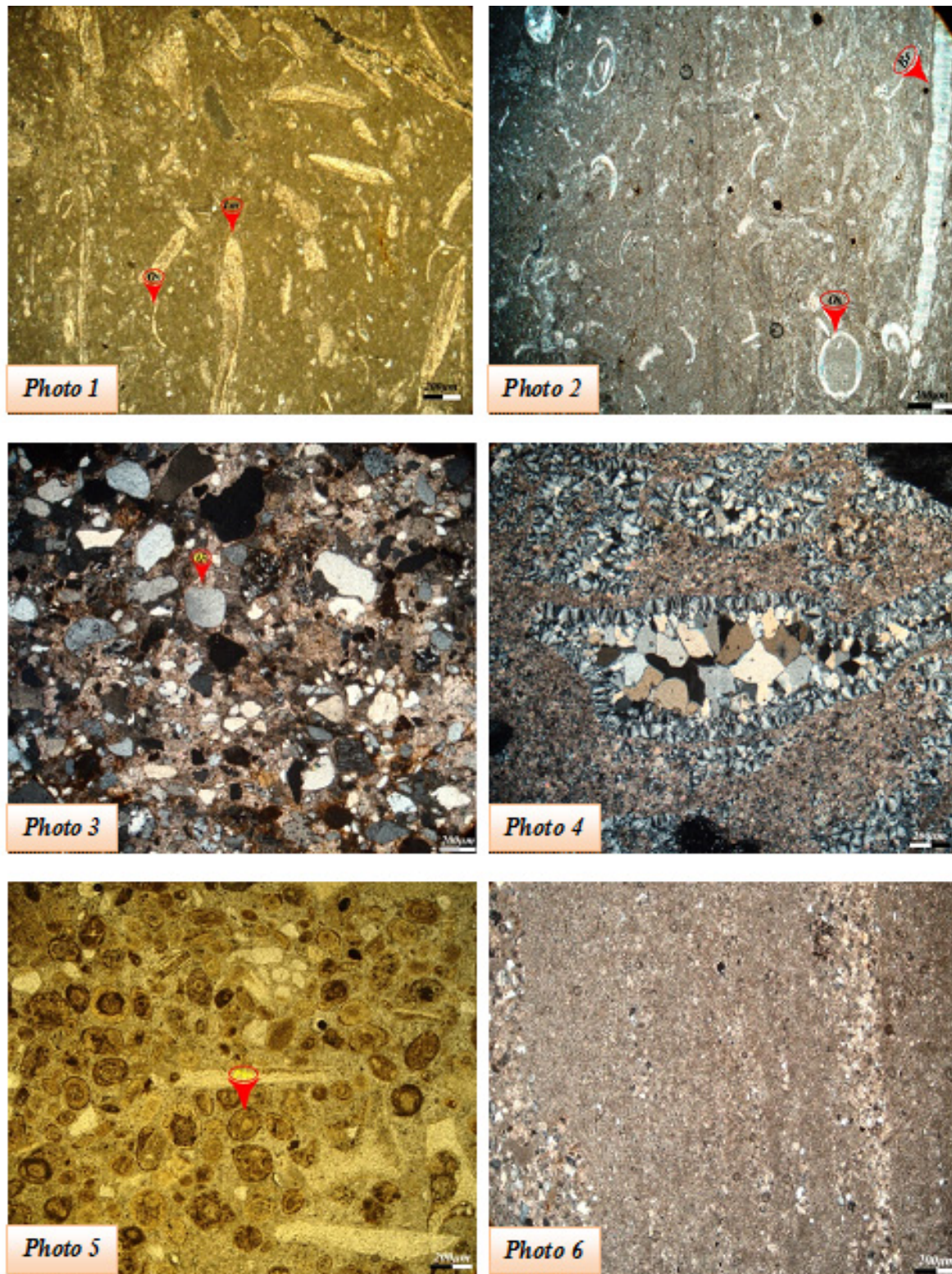


Figure 7 Carbonate microfacies. Photo 1: Biomicrorite with lamellibranch bioclasts (Lm) and ostracods (Os) of the Anou-Nfeg Formation (SI). Photo 2: Micrite with ostracods (Os) and bioclasts of brachiopods (Br) of the Aït Abbes Formation (unit 1 of SIII). Photo 3: Carbonated sandstone with poorly sorted, subrounded to angular quartz grains (Qz), Photo 4: Vacuoles filled by diagenetic silica, Photo 5: Phosphate grains (Phs) silicified with carbonate cement, Photo 6: Alternation of lighter detrital and darker micritic laminae.

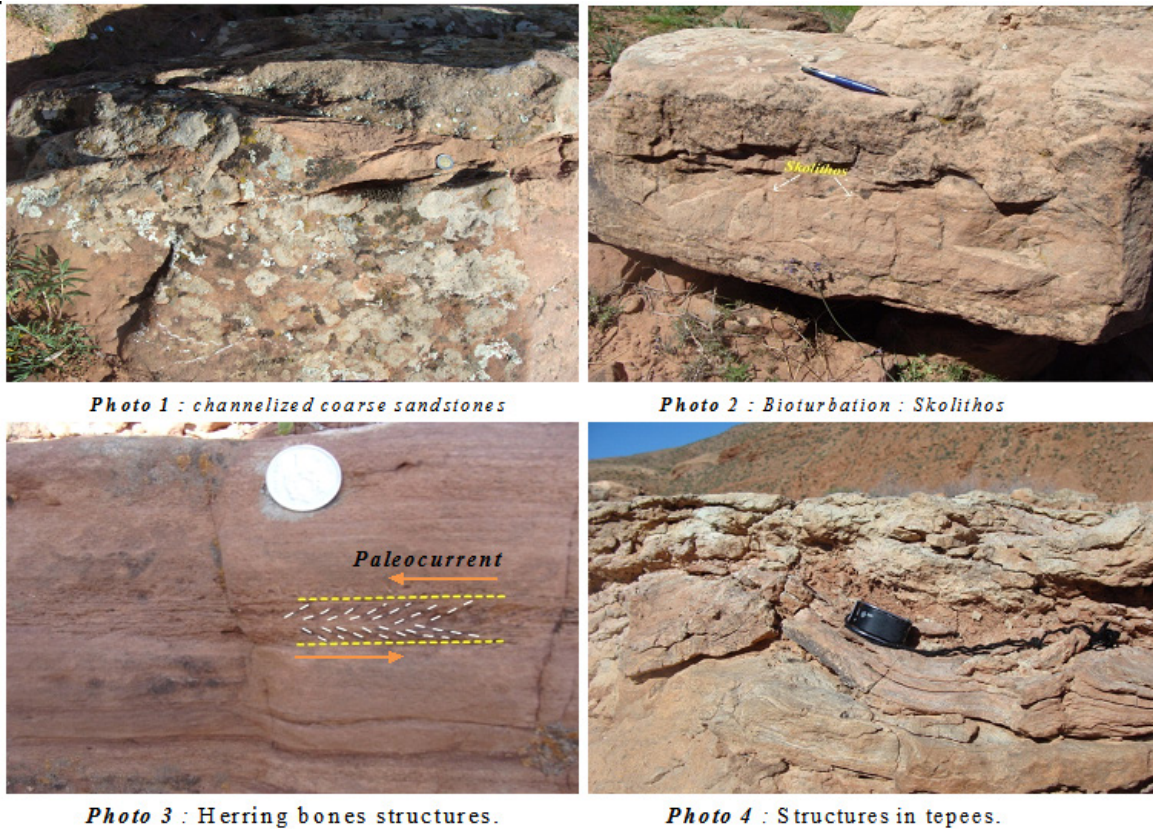


Figure 8 Sedimentary figures and structures found in the Ait Abbes Formation. Photo 1: Coarse-grained channeled sandstone; Photo 2: Skolithos type bioturbation in sandstone beds; Photo 3: Herring bone structures; Photo 4: Tepees structures in carbonate levels.

environment ranged from shallow to intertidal to deeper subtidal waters. The intertidal zone was influenced by hot periods promoting dolomitization and mixed sedimentation of carbonates and phosphates, while the subtidal zone was characterized by the sole sedimentation of phosphates.

3.2 PALEOGEOGRAPHIC AND GEODYNAMIC EVOLUTION

During the Coniacian (SI and SII), the eastern part of the study area from Ait Nifi to Jebel Sour (Figure 2) was emergent while the western part (precisely from Imin’Tanout to Seksawa) drowned to an intern infralittoral to supralittoral environment, episodically connected to the open-sea (Figure 12). This paleogeographic scheme indicates a major regression related to a pre-Coniacian tectonic phase that was responsible for the subaerial expo-

sure of wide parts of northern Africa. However, this tectonic phase is not recorded in the “Casbah of Agadir” and “Anou-Nfeg” Formations. At the beginning of the lower Santonian (SIII), the sea had transgressed progressively from west to east over the Imin’Tanout, Seksawa, and Sidi Bou Othman areas (Figure 12).

At the end of the lower Santonian (SIII), the transgression was more important and reached the eastern end of the study area, notably the “Cuvettes area” of Ait Ourir (Figure 12). This transgression was followed by a second phase of tectonic instability that structured the whole region into shoals (Ait-Nifi Anezdi), low emerged lands (Amizmiz, Douar Sour and Jebel Sour), and some small restricted shallow basins. Indeed, this transgression covered from west to east the “My Brahim” and “Wanina” shallow basins. The “My Brahim” basin is separated from Sidi Bou Oth-

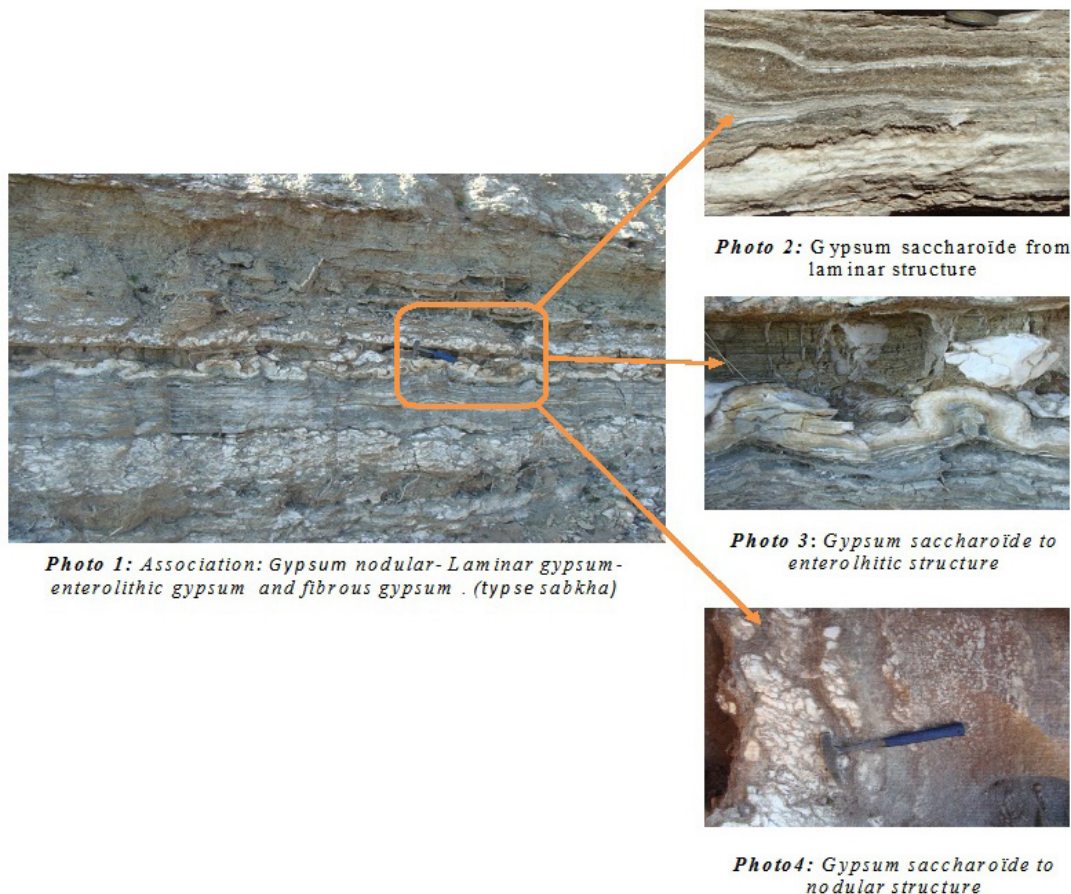


Figure 9 Gypsiferous structures found in the Ait Abbes Formation (eastern area) within the SIV.

man’s western shallow basin by the emergent land of Amizmiz. The Wanina basin is separated from My Brahim basin by the emergent land of Douar Sour (Hadach *et al.*, 2017 and Algouti *et al.*, 2017).

The second tectonic phase is recorded by an angular unconformity between the Upper Cretaceous deposits (SIV) and the rest of the Mesozoic cover of Jebel Sour and Sidi Bou Othman (Figure 11, Photos A-B; see also Algouti *et al.*, 2016, 2018), and by the presence of some microfaults, monogenic breccias, and paleolandslides. The upper Santonian deposition (SIV) is marked by an important peneplanation of the whole region (Figure 12), related to the decrease of the water level in a confined environment of sabkha-type due to the hot and humid climate (Hadach *et al.*, 2015, Afenzar and Essamoud, 2020). During this period, higher subsidence induced the deposition of a thick evaporitic series in the west (Imin’Ta-

nout area) and in the east (Jebel Sour area). During the early Maastrichtian, a third tectonic phase accentuated the pre-existing reliefs (high rises and emergent land), especially those of Sidi Bou Othman, Amizmiz, Douar Sour, and Jebel Sour. In the whole region, the Santonian sediments are directly overlain by the Maastrichtian sediments, evidencing a sedimentary gap during the Campanian. During the Maastrichtian (SV, SVI and SVII: Figure 12), the Atlantic eustatic transgression had covered the whole region (Roch, 1930; Algouti, 1999) and reached, at south-east and east, the Saharan Platform, southern Tunisia, and eastern Egypt.

The sediments are unconformable, lying over the former deposits especially in Chichaoua and Jbel Sour. The Maastrichtian subtidal and mesolittoral deposits were deposited, from west to east, into several aligned small confined basins, suitable

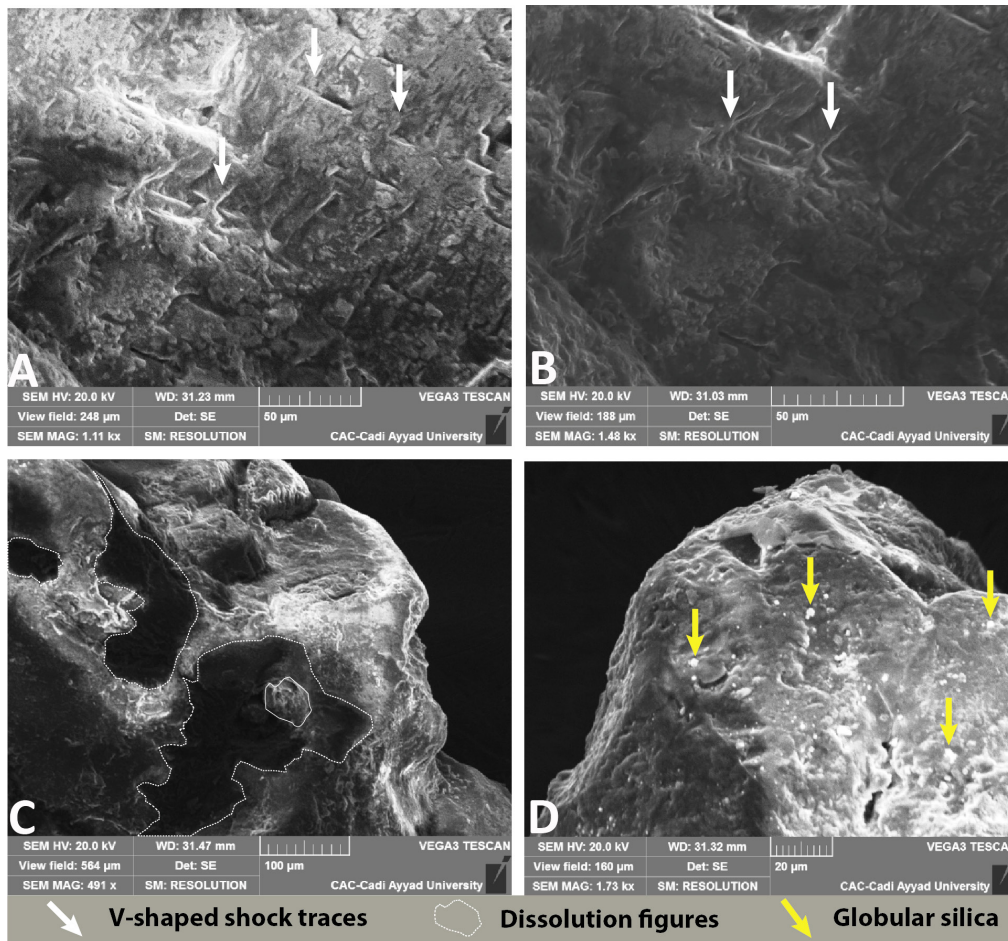


Figure 10 Exoscopy of quartz grain from sandstones of the SIV of the Ait Abbes Formation in the Amizmiz area SIV. (A and B) V-shaped shock traces, (C) Dissolution figures, (D) Globular silica.

for phosphate deposition (Sidi Bou Othman, My Brahim, Wanina and Jebel Sour).

4. Conclusions

The reassessment of the Senonian Formations of the High Atlas nearby Marrakesh led us to obtain some new sequence stratigraphic and paleogeographic data:

- 1) The Anou-Nfeg Formation, which includes two depositional sequences (SI and SII), was assigned to the Coniacian on the basis of ostracod assemblages.
- 2) The Ait Abbes Formation is also divided into two sequences (SIII and SIV) and, due to

its faunal composition of bryozoans, ostracods, echinoderms, and ammonites, was assigned to the Santonian.

3) The Chichaoua Formation was assigned to the Maastrichtian age due to the presence of selachian faunas and includes three depositional sequences (SV, SVI and SVII). The Campanian Oued Lahouar Formation was not detected in the area.

4) Even if the role of eustasy is beyond doubt, three tectonic phases strongly impacted the sedimentary record in the area.

5) The first phase (ante-Senonian), was responsible for an important regression in the eastern area and promoted subsidence in the western area during the Coniacian. According

to Floquet (1984), who made a correlation of the sedimentary discontinuities of the Upper Cretaceous Mesogean and Atlantic, the main cause for this Turonian-Coniacian sequence boundary is related specifically to the opening phase of the Atlantic.

6) The second tectonic phase structured the whole region into several high rises and low emergent lands. Several small confined basins were formed in the eastern area during the early Santonian. Effectively, several authors demonstrated the existence of halokinetic processes in the Essaouira basin, which resemble those observed in the eastern Atlantic margin (Jansa and Wiedman, 1982; Ruellan and Auzende, 1985). Moreover, due to the important pene-

planation accounted at that time, sebkha-type environment spread over the whole area, and some short marine incursions reached the eastern basins (Late Santonian).

7) The third important regional tectonic phase (ante-Maastrichtian) accentuated the pre-existing paleotopography. During this period, a slow convergence started between Africa and Europe, which was indeed evidenced in the western Mediterranean (Taponnier, 1977). This tectonic phase triggered an important tectonic compression activity in Morocco. This activity is well marked in the southern side of the Central High Atlas Range (Toundout aquifer) (Laville *et al.*, 1977). During the Campanian, the region recognized a sedimentary pause.

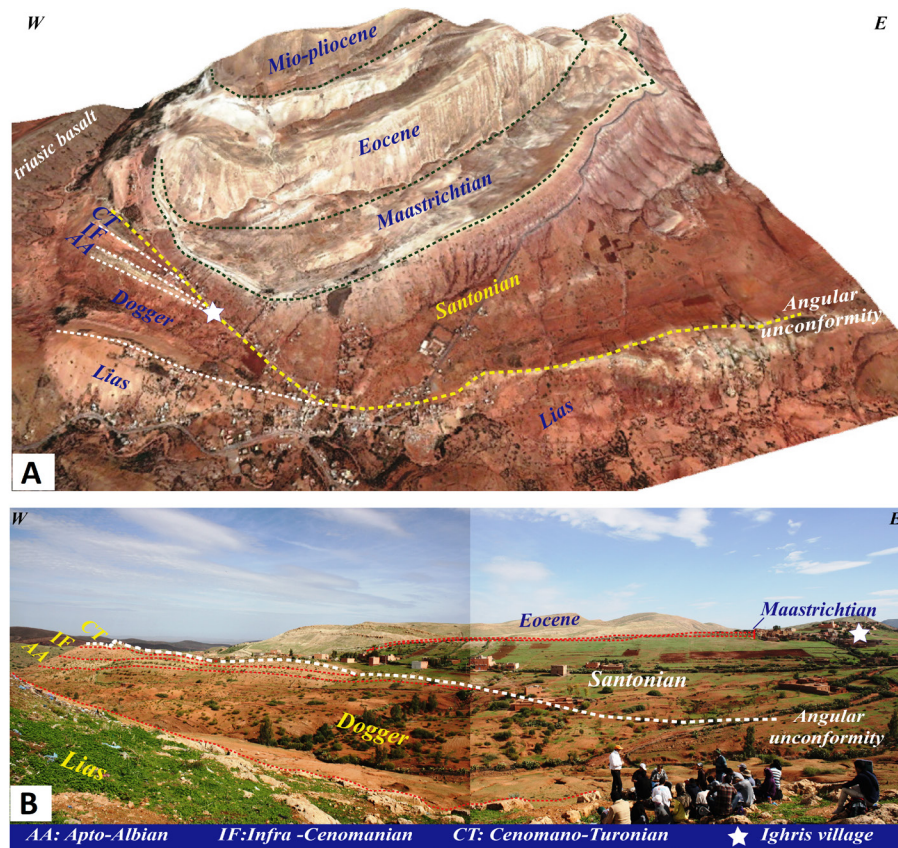


Figure 11 An angular unconformity encountered at the basin of Jbel Sour. (A) An image, through Google Earth, showing the Jbel Sour basin with a beveling to the east of almost all the Mesozoic series (Dogger, Apto-Albian, Infra-Cenomanian and Cenomano-Turonian), The Late Cretaceous (Senonian) is angularly unconformable with the rest of the cover. It shows a reduced thickness in the west, which becomes significant towards the east. (B) A panoramic view of the western part of the Jbel Sour basin showing the Late Cretaceous (Senonian) deposited in an angular unconformity on the rest of the Mesozoic cover.

8) Indeed, according to Rosenbaum *et al.* (2000) the convergence between Africa and Eurasia began by c.a. 84 Ma (Santonian) and according to (Guiraud and Bosworth, 1997; Garfunkel, 1998; Guiraud *et al.*, 2005, and Bosworth *et al.*, 2008) this convergence is recorded in northeast Africa by a set of discontinuous compressive events during the Santonian, the end of the Cretaceous and the middle-late Eocene. Moreover, following the Santonian tectonism, an extensional (rifting) phase occurred in Central and North Africa, spanning from Campanian to Maastrichtian or Paleocene times (Guiraud and Bosworth, 1997).

9) During the Maastrichtian, eustatic rise, a marine transgression from the Atlantic Ocean

flooded the area of the former (Late Santonian) small confined basins. During this period, essentially the phosphatized sands were deposited unconformably on the whole Cretaceous deposits.

This Maastrichtian transgression is related to the ante-Maastrichtian embryonic phase, and was accompanied by an erosional surface covered by coarse-grained sediments, generally (micro) conglomerates. In addition, the presence of the synsedimentary faults detected at the base of the Maastrichtian was certainly the result of tectonic events that, as well as a formation of angular unconformities, accounted between the Campanian and the deposition of the phosphate series (Chichaoua Formation).

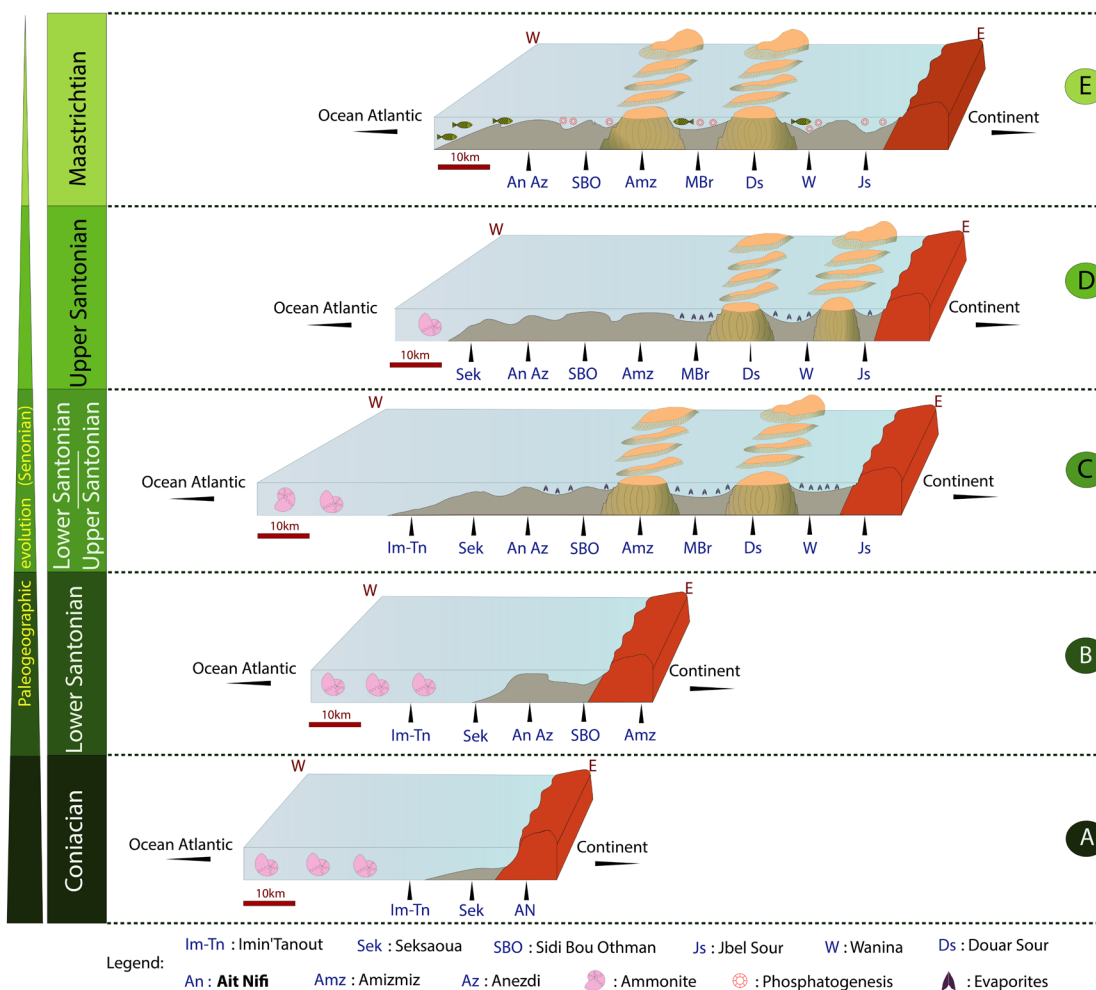


Figure 12 Paleogeographic evolution of the Late Cretaceous of the Northern side of the High Atlas Range of Marrakesh.

The latter is best recorded at:

- * Chichaoua where the Maastrichtian is directly laid on the Casbah formation of Agadir;
- * Timahdit, where the Danian lays unconformably on all of the Cretaceous and Jurassic terms until it reaches the Lower Jurassic;
- * And Meskala where an unconformity between the Campanian and the Maastrichtian was observed (Ambroggi, 1963).

10) In our study area, this tectonic phase is accompanied by a second halokinetic activity, which will accentuate the pre-existing Santonian reliefs. The study area behaves, then, in small sedimentary basins showing lagoon-brackish influences and functioning as morphological traps facilitating the precipitation of phosphate in a hot and arid climate, an environment that favored the development of vertebrates.

11) The end of the Maastrichtian is marked by a hardened, generally karstified surface, the result of the sea retreating during this period. It is a very extensive regional *discontinuity* that can even be encountered beyond Morocco, for example in Algeria (Belkoudja *et al.*, 1994), Tunisia (Matmati *et al.*, 1991), and Greece (Pomoni-Papaiouanou and Solakins, 1991).

Furthermore, the mass extinction of living beings, occurring on a global scale during this period, was probably due to the regression at the end of the Cretaceous (Ginsburg, 1984).

Contributions of authors

Ahmed Algouti and *Abdellah Algouti*: investigation, methodology, writing-original draft Validation, writing-review and editing, supervision. *Fatiha Hadach*: investigation, methodology, writing-original draft. *Farah Abdelouhed*: investigation, methodology, writing-original draft. *Ali Aydda*: investigation, methodology, writing-original draft. The authors read and approved the final manuscript.

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Conflicts of interest

The authors declare that they have no competing interests

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