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RESEARCH PAPER

Contribution to the Sedimentological, paleo environmental and paleogeographical study of Infra-Cenomanian sediments from the South Slope of the Central High Atlas (Morocco)

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Abstract

The sedimentological analysis of the lower Cretaceous red deposits in the Boumalne Dades region (Central High Atlas) presented in this article is based on field observations associated with sedimentological methods (morphoscopy, exoscopy, and mineralogy determination of clays) conducted to investigate the paleo-environment of this study area. The analysis of the surface of the quartz grains with a binocular magnifier and scanning electron microscopy (SEM), allowed us to reconstruct their formation environment. Exoscopic analysis allowed the characterization of a mixture of quartz morphotypes. The results obtained reveal numerous indications of short- and long-distance transport, which reflect different environments (continental to marine environment). The paleoenvironments of the units revealed by sedimentology are essentially continental with marine influences. Specifically, an alluvial fan is recorded at the base of the Ifezouane Formation at unit 1 and a fluvial meandering medium (unit 2) at the top of the same formation; the deposits of the Aoufous Formation correspond to a floodplain at the base (unit 3) and a playa at the top (unit 4).

Keywords: Infra-Cenomanian, Sedimentology, Stratigraphic, Ifezouane, Aoufous, exoscopy, Morphoscopy, Mineralogy, Ait Ibrirene, Central High Atlas.

Introduction

The Atlas Mountains of Morocco have a complex sedimentary tectonic history, from formation of basins during the Mesozoic with filling by carbonates and sediments (Laville et al., 1992), and followed by a Cenozoic structural inversion (Mattauer et al., 1977; Dominique Frizon de Lamotte et al., 2009). The Jurassic and Cretaceous, mostly continental and generally azoic series (red beds), are located in the High Atlas range (Fig. 1).

This study concentrates on the Infra-Cenomanian series deposited in the Moroccan Central High Atlas basin, between Boumalne Dades and M'Semrir. The studied series is poorly dated, but Upper Cenomanian or Lower Turonian ages have been inferred based on paleontological and sequence stratigraphic considerations (Martill., 2011). The Cretaceous marine transgression proceeds through successive steps from the Albian to the Turonian (Abioui et al., 2019). Stratigraphic, sedimentologic, petrographic, and structural studies of the Upper Mesozoic have recently been carried out in the Dades Valley and Jbel Istifane (Benvenuti et al., 2017a; Moratti et al., 2018). We have here carried out a sedimentological study (through field missions, morphoscopy, exoscopy, and mineralogical determinations of clays) of the Ait

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Ibrirene series, to contribute to the understanding of the geological and paleoenvironmental history of the Moroccan Lower Cretaceous (Infra-Cenomanian series). In the study area, the section was studied from the base to the top of the sedimentary series. Several samples with details allowed us to identify the facies and sedimentary figures, and to highlight different discontinuities, to track the evolution over time and space of the Infra-Cenomanian series of the Ait Ibrirene (Central High Atlas).

Location and Geological setting

Geographically, the Ait Ibrirene region is located in the southeast of Morocco at the southern foot of the Central High Atlas (Fig. 1). The region is situated in the province of Tinghir on the south side of the Central Atlas Mountains (Fig. 1), between approximately N31°35' and N30°0' and W6°30' and W05°95'. Ait Ibrirene is located about 150 km ENE of the city of Ouarzazate, following the national road N10 towards the city of Boumalne.

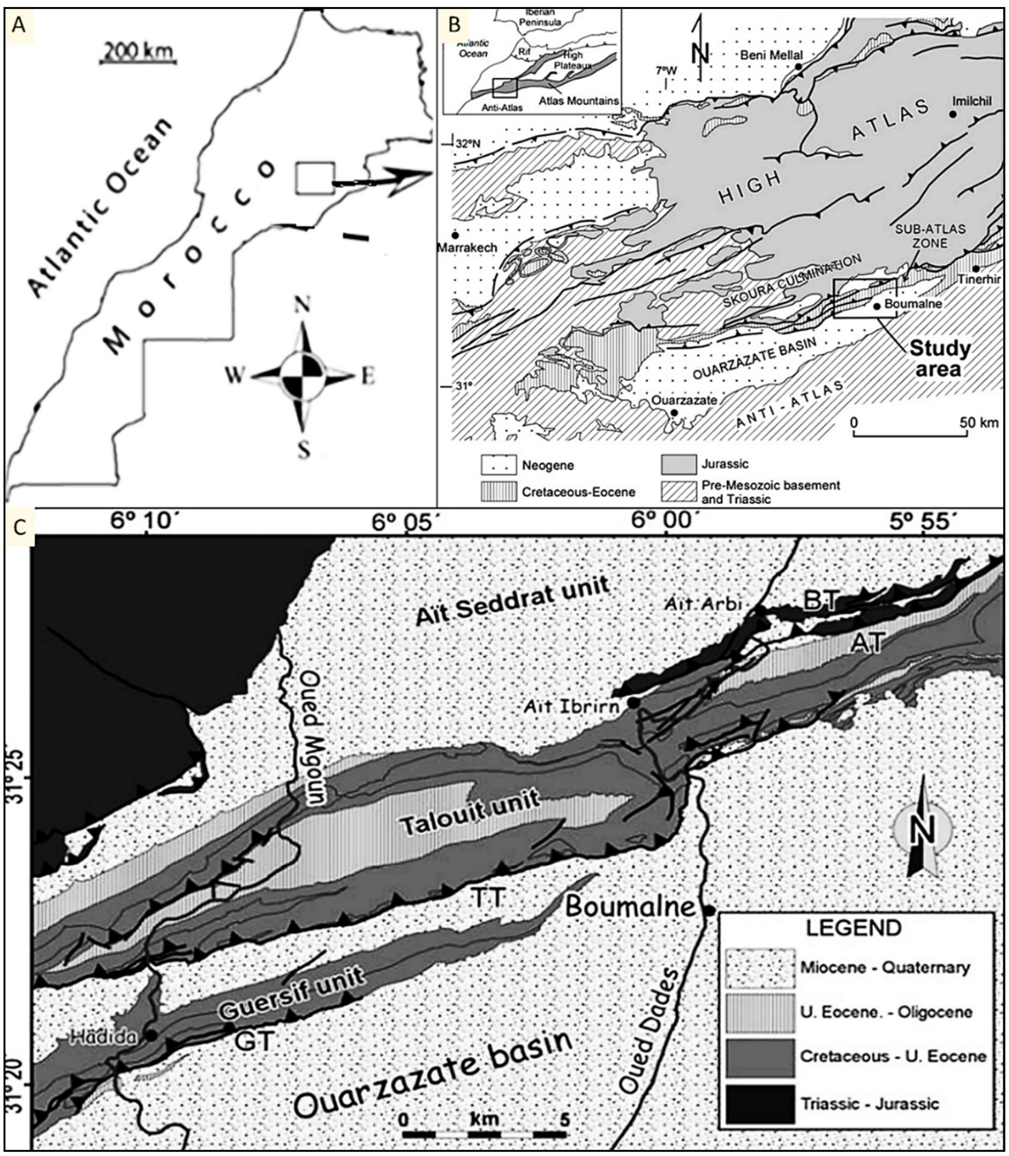


Figure 1. A) Morocco map, B) Structural sketch map of the study area (Teson, 2006). C) Location of the study area in Southern Morocco and schematic geological map (Teson, 2006)

The Moroccan High Atlas corresponds to a structural domain consisting of an intracontinental range (Gauthier, 1952; Mattauer et al., 1977) and the narrowest mountain in the world which extends in a WSW and ENE direction from Agadir to Tunisia over a distance of 2000 km and a width that varies from 60 to 80 km (Studer, 1980). It is the centerpiece of the Atlasic domain (Michard, 1976) which has the following structural units: 1) the Eastern High Atlas to the east of the Tamlelt massif, 2) the Western High Atlas to the west of the ancient massif of the Marrakech High Atlas, and 3) the Central High Atlas that extends between the first two (Choubert et al., 1956; Michard, 1976). The Central High Atlas is the highest mountain belt in Morocco and constitutes a barrier that separates the Saharan domain in the south from the Rifain and Mesetian domains in the north. Structurally, this domain consists of plateaus reaching 2500 m on average with peaks reaching more than 4000 m. The study area is part of the southern edge of the High Central Atlas. The region is characterized by a Hercynian basement and partially covered by Mesozoic to Cenozoic terrains (Benvenuti et al., 2017a; Hindermeyer et al., 1977; Massironi et al., 2007). To the north, the Ouarzazate basin is flanked by the marginal thrust belt of the sub-Atlas zone, with outcrops dominated by rocks of late Cretaceous to Neogene age (Gauthier, 1957) (Fig. 2). This range of the central High Atlas comprises Paleozoic-age bedrock covered by a Meso-Cenozoic-age cover. In the Boumalne Dades region, this cover is formed by marine and continental sediments that represent well-defined paleo geographic and structural domains. They are characterized by two parts: the lower part consisting of Meso-Cenozoic formations represents the filling of basins developed during the rifting phase of the Atlas (Mattauer, et al., 1977; Laville, et al., 1991); the upper part of the Meso-Cenozoic terrain represents either the cover of the High Atlas or the filling of the Ouarzazate basin.

The regional geology of Dades consists of three units mainly from north to south: The High Atlas, the Ouarzazate basin and the Anti Atlas (Fig. 2). Many authors (e.g., Ferrandini et al., 1985; Ettachfini and Andreu, 2004; Lézin et al., 2012; Andreu et al., 2013; Essafraoui et al., 2015; Lebedel et al., 2015) showed a deepening of a part of the High Atlas to the northeast, during the Cenomanian-Late Turonian period. The stratigraphic indications of the Infra-cenomanian are rare. A single fossil record of Cenomanian lamellibranchs was cited by Gauthier, 1960 near Tinghir. Vertebrate assemblages of Cretaceous units (Ifezouane, Aoufous, formations), in order to be consist, we are based in some investigation and comparison, that allowed by (Cavin et al 2010), about the age of the red beds, in the High Atlas Mountains of Morocco.

Material and Methods

The database used in this study includes geological and sedimentological data (field mission collection and laboratory sample processing). Over twenty samples were taken from the studied sections of the Infra-Cenomanian series. The sample sediments were sieved using a 50 µm mesh sieve after washing, to remove organic matter that could mask to the grain surface. The sample was then attacked with 10% hydrochloric acid (HCl) to destroy the carbonates, then rinsed with distilled water and placed in the oven at 110 °C for drying (Krinesley et al., 1968). The raw sample was washed with distilled water and dried following treatment with HCl. The granulometric fraction between 300 and 500 µm was selected. Then, the images acquired by scanning electron microscopy (SEM) were analyzed at magnifications typically between ×500 and ×400. The section studied in the Ait Ibrirene region displayed facies of the Infra-Cenomanian series (heterogeneous deposits comprising conglomerates, sandstone, silt, clays, etc.) which is characterized by several indices of a continental and playa environment. The nomenclature of facies in this study is comparable to that established by (Miall 1977; 1978; 1985; 2006).

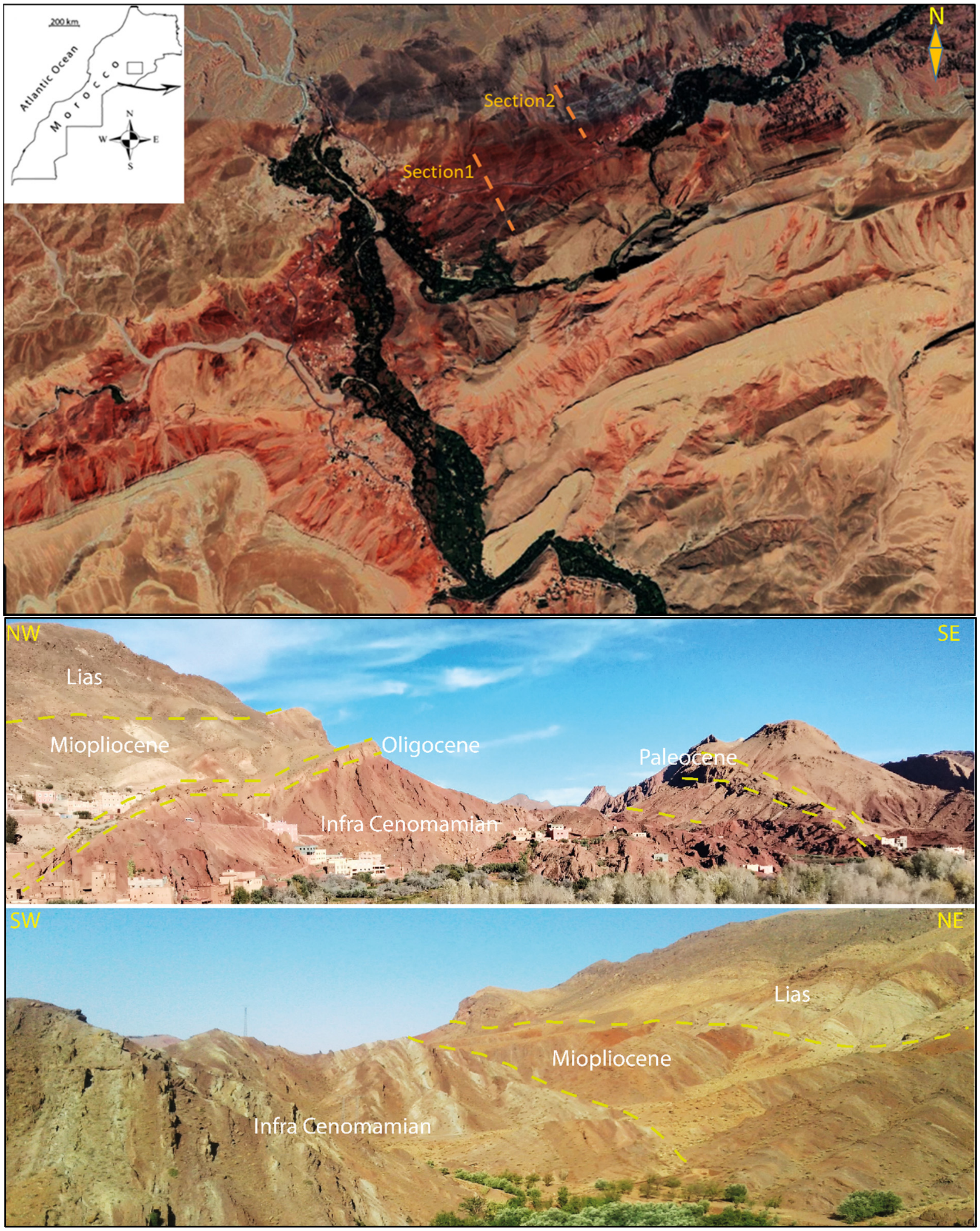


Figure 2. A) Map of the Infra-Cenomanian series. B) section1 of Ifezouane formation, C) section2 of Aoufous formation

Field descriptions of lithofacies, including particles size, color, composition, and tracking of sequential stratigraphic key surfaces were also conducted. The final product of this last step underwent: 1) The field work aims to determine the deposition patterns by carrying out research and the identification of lithology and sedimentary structures. 2) morphoscopic analyses of quartz grains using a binocular magnifier; observations were made on a small but representative number of samples, with 30 to 40 grains studied per sample (Le Ribault, 1974; 1975; Péttijohn, 1949; Cailleux 1947; Legigan, 2002), 3) exoscopy analyses of quartz grains; the exoscopy of quartz consists in studying their superficial aspects with a scanning electron microscope (Vega3 Tiscan), 4) The clays were studied mainly by X-ray diffraction. First, all samples were dried at 40°C for 48 h. Then, 15-30 g of crushed sample were taken, and distilled water was poured into a 1000-2000 cc polyurethane beaker and placed on a magnetic stirrer (Fig. 3). Hydrochloric acid (10%) was added by jet and the solution stirred so that the local concentration was not too high. After centrifuging the <2 µm particles, the clay paste of the centrifuging base was spread on a grooved glass slide. The clay paste must be well homogenized before removing it from the base because the particles are separated (by size and density) during centrifugation. This segregation may correspond to mineralogical segregation, which may distort the proportions of the different minerals in the sample (Stoll et al., 1964; Pomerol and Odin, 1974; Reynolds, 1985; Wilson, M.J., 1987; Drits et Plançon, 1994; Bouchet et al., 2000; Plançon et Drits, 2000; Hubert et al; 2009). The procedure for processing clay involves: 1) crushing the sample, 2) performing a HCl test, 3) non-carbonate/carbonate separation, 4) mixing in H2O/HCl in an agitator, 5) washing with H2O until maintained in suspension, 6) pipetting the 2 µm fraction, 7) centrifugation, and 8) spreading/orienting the 2 µm paste.

Results

The series studied within the Ait Ibrirene area (Fig. 3) consists of alternating detritus beds (conglomerates, sandstone, clay, and silt), passing to small limestone banks, greenish clays, and organic matter in the upper part, and follows the last marine Apto-Albian series.

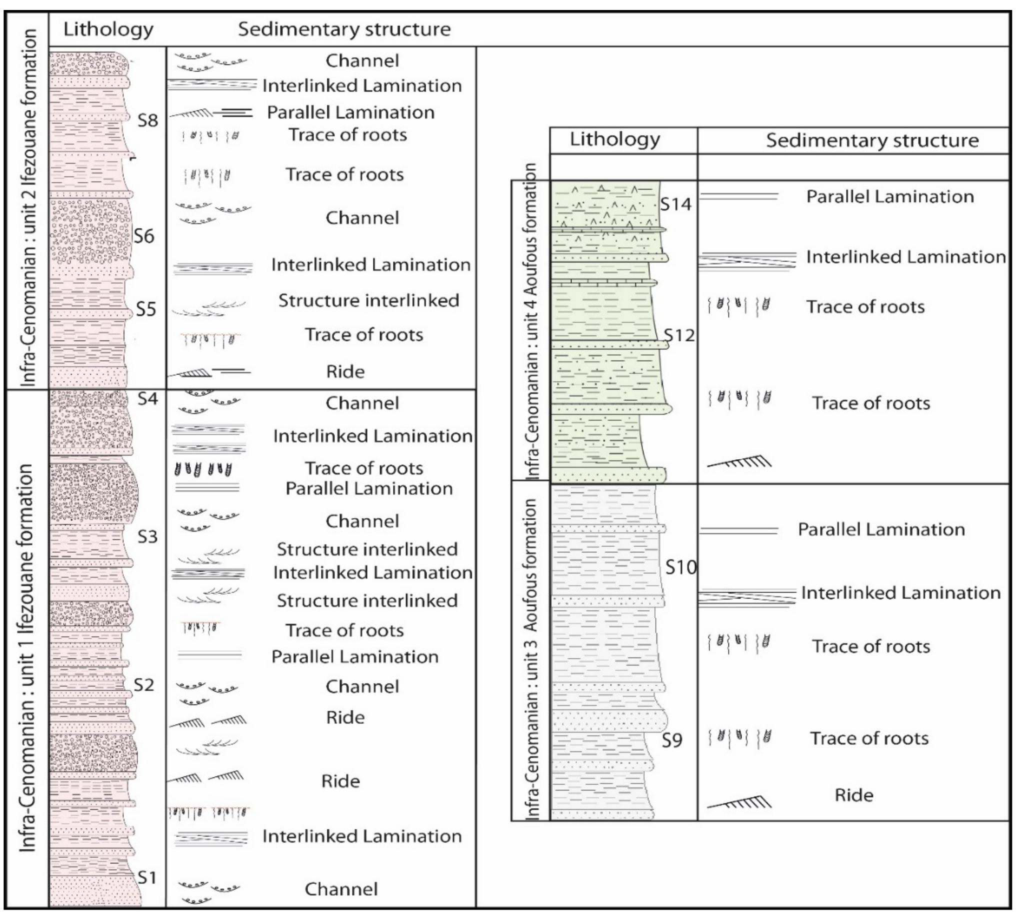


Figure 3. Stratigraphic log of the series studied with deferential units and sample locations

Table 1. Description and interpretation of the sedimentary facies identified in the basin and their correspondence with those of (Miall, 1985; 2006)

Facies	characteristics	interpretation
Conglomerates		
F1 : Gms	Heterogeneous conglomerate without granoclass	Debris flows, gravity flow deposits
F2a : Gm	Uncoated conglomerate, no cobble nesting.	Fluvial deposits
F2b : Gm	Low-matrix conglomerates with pebbles of different origins	Channel bottom deposits
Sandstones		
F3 : Sm	Solid sandstone, fine with parallel bedding	Gravity Flow Deposits
F4 : Sh	Sandstone with very fine to medium parallel plan	Horizontal beds, rides, dolomitisation and silicification are interpreted as before.
F5 :Gm	Solid sandstone, coarse with interlaced lamination.	Characteristics of braid flows
Silto-clay		
F6 : Fs	Laminated to solid siltstone	Over bank deposit
F7 : Fm	Massive or rolled argillites	Over Bank Deposit or Abandoned Channels
F8 : Fa	Greenish clay with soft and fragile black organic matter	Greenish massive argilities showing spots.
F9 : M	Azo Greenish Marl	Supratidal medium

The series is subdivided into two formations: The Ifezouane Formation (units 1 and 2), and Aoufous Formation (units 3 and 4).

The Ifezouane Formation: is formed by two units, the first unit (unit 1) is characterized by the superposition of detrital beds arranged by increasing grain size and increasing bed thickness. The second unit (unit 2) belongs to the top of this formation, and is characterized by a clayey dominance with emersion figures (desiccation cracks, roots traces, crusting, etc.) intersected by conglomerate channels of increasing granulometriy.

The Aoufous Formation is formed by two units: unit 3 is characterized by small sandstone banks and an abundance of clay and silt. Unit 4 is characterized by evaporate clays with minor gypsum, organic matter, and limestone.

The first unit (unit 1) at the base of the series is characterized by a detrital formation, continental, formed by alternating conglomerates (f1: GMS) (Miall, 2006), clays (f6: fs), and sandstones (f3: SM) (Miall, 1985, 2006) (Figs. 4, 5, 6). A conglomerate facies with pebbles of different sizes with different origins, and poorly sorted, and disorganized deposits were found at the top of unit 1 (Fig. 5A). Alluvial fans are characterized by a bed thickness unit coarsening upward sizes as defined by Marchi et al., 2000, Davoudi et al., 2019. Unit 1 is also characterized by thicker conglomerate beds at the base, alternating with thinner clay and sandstone beds. These deposits are dominated by river flow units (Fig. 4f) showing channelized conglomerates and sandy channels with cross-stratification (Fig. 4B), and strong amalgamation in the proximal zone. Moreover, the vertical evolution of facies demonstrated a sequence with coarsening s
Based on some studies (Marchi et al., 2000, Davoudi et al., 2019), this unit 1 corresponds to an alluvial fan (Fig. 5) that is also well characterized by a high-energy environment attested by the presence of different sandbanks with interleaved stratification, asymmetric current ripple marks, and fluvial conglomerates (improperly classified as debris flows). From this interpretation, we can conclude that this unit attributable to an alluvial fan (Figs. 4, 5). Indeed, the sedimentary structures (Figs. 4, 5) recorded in the facies show that they were exposed to gravity flows within an alluvial fan. These results found are compared to that of Miall, 2006. The red sandstone facies reappears as an oblique-bedded bar and terminates at a level of the river channels and overflow lobes. This level probably corresponds to the peak of the Ifezouane Formation, as previously revealed in the work of Dubar 1948. By these architectural facies characteristics, we can deduce that this depositional environment is comparable to model 1 of Miall 1996, 2016.

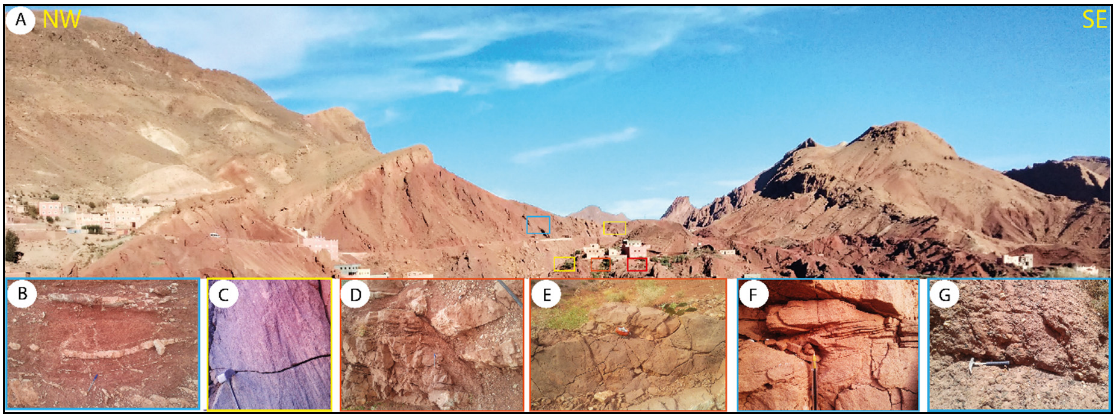


Figure 4. A) Panoramic view of the Ait Ibrirene Section. B, C) Sandstone facies with sedimentary structures. D) Alternating sandstones and clays. E) Sandblasted with rides. F) Sandblasted with interleaved laminations. G) Conglomerate

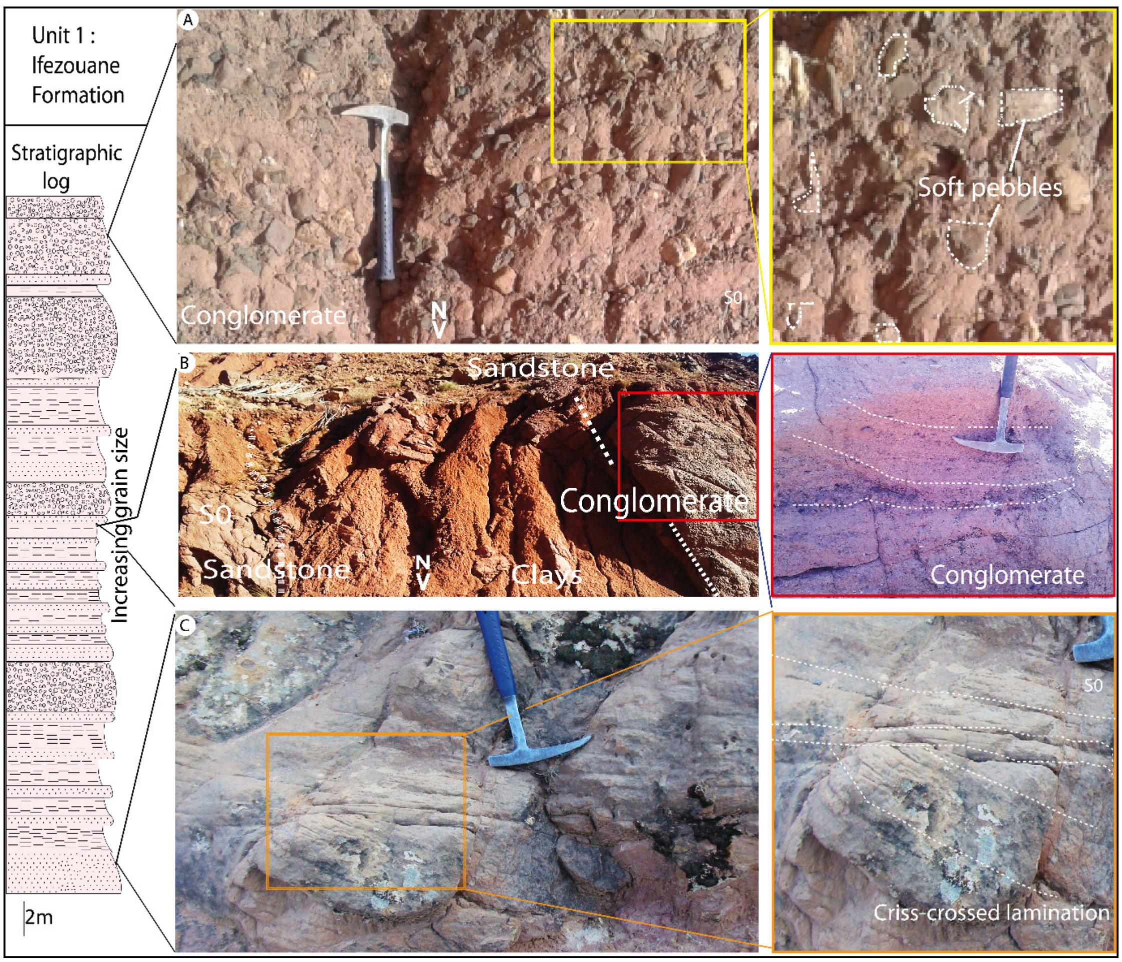


Figure 5. Facies and sedimentary structures found in unit 1. A) Conglomerates with angular pebbles, badly sorted and of different origins, B) Polygenic conglomerate with cross-stratifications, lenticular form, C) Sandstone beds with Interlinked lamination and Parallel lamination

The second unit (unit 2) is characterized by an alternation of conglomerates (F2: Gm), clays (F7: Fm), and sandstone facies (F4: Sh) (Miall, 2006) that are organized in meter- to centimeter-thick beds. The macroscopic analysis of these beds shows the increase in granulometry and the size of the sequence (Fig. 6), from the base to the top of this unit. Among the sedimentary structures (Lenticular structure, interlinked lamination, and parallel (Miall 1985 and 2006), herringbone cross-bedding) (Figs. 6A, 6B), linguoid ripples occur at the bottom of the channel, coarse sediment deposits reflect the migration and aggravation of the meander, and the strata were deposited in oblique beds during channel migration (Fig. 6). Traces of bioturbation (burrows) are observed in fine deposits (Fig. 6c). The top of this sequence consists of fine clay-silt facies, with traces of roots and fissures of desiccation. From this interpretation, and description and based on some studies (Delfaud, 1984), we can conclude that unit 2 records a meandering-type fluvial system. This tatter is similar to those of model 2 of Miall, 1996, 2016. Unit 3 is part of the Aoufous Formation in the studied series (Infra-Cenomanian) (Figs. 7) with a thickness of about 31 m of detritus facies consisting mainly of sandstones, clays, and silts. These facies are organized in a positive sequence, with fining upward beds sizes and characterized by sedimentary successions with oblique and horizontal lamination, alternating sandstones (F5: Gm), and clays (F7: Fm). Fine terrigenous facies are abundant within the unit and the footprint of pedogenesis is relatively strong with an intense presence of traces of roots (Purser, 1980). The thickness of the beds increases with decreasing particle sizes, and this set begins with clay facies and sandstone beds (Fig. 7). From this description, we can conclude that this unit is characterized by overbank deposits that formed in a flood plain (Fig. 7). In order to be consist, we are based in some investigation and comparison, that allowed by (Farrell, 1987, Miall, 2016).

Unit 4 of the Aoufous Formation is composed of clays (yellowish, red, and discolored) (Fig. 8B), marl, and gypsum (Fig. 8A) with thin beds interspersed with fine sandstone. The whole unit is surmounted by evaporated marls with a whitish color (F9:M), and organic matter is consolidated in the sandstone beds (F8: Fa) (Figs. 8C and D) and iron oxides (Fig. 8c).

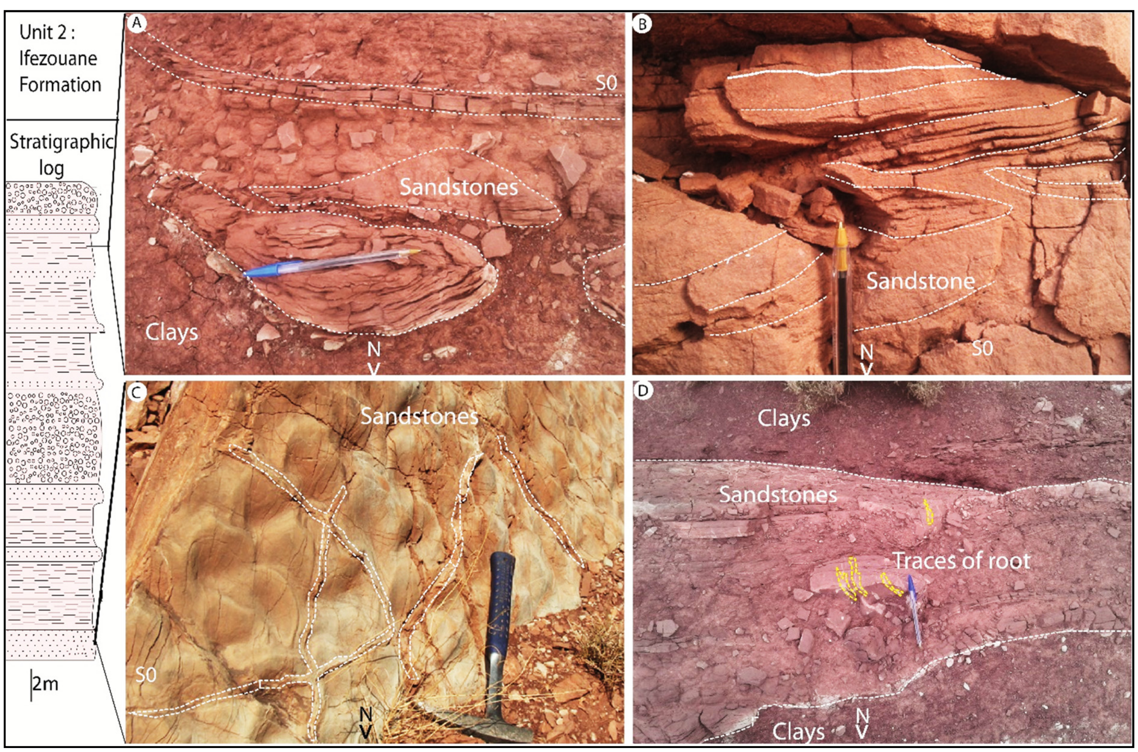


Figure 6. Meandering river sequence encountered in Unit 2. A) Lenticular structure in the sandstone beds. B) Interlinked lamination and Parallel lamination in the sandstone beds. C) Ride of courant and Bioturbation structure in the sandstone bank, D) Channel structure in the sandstone beds

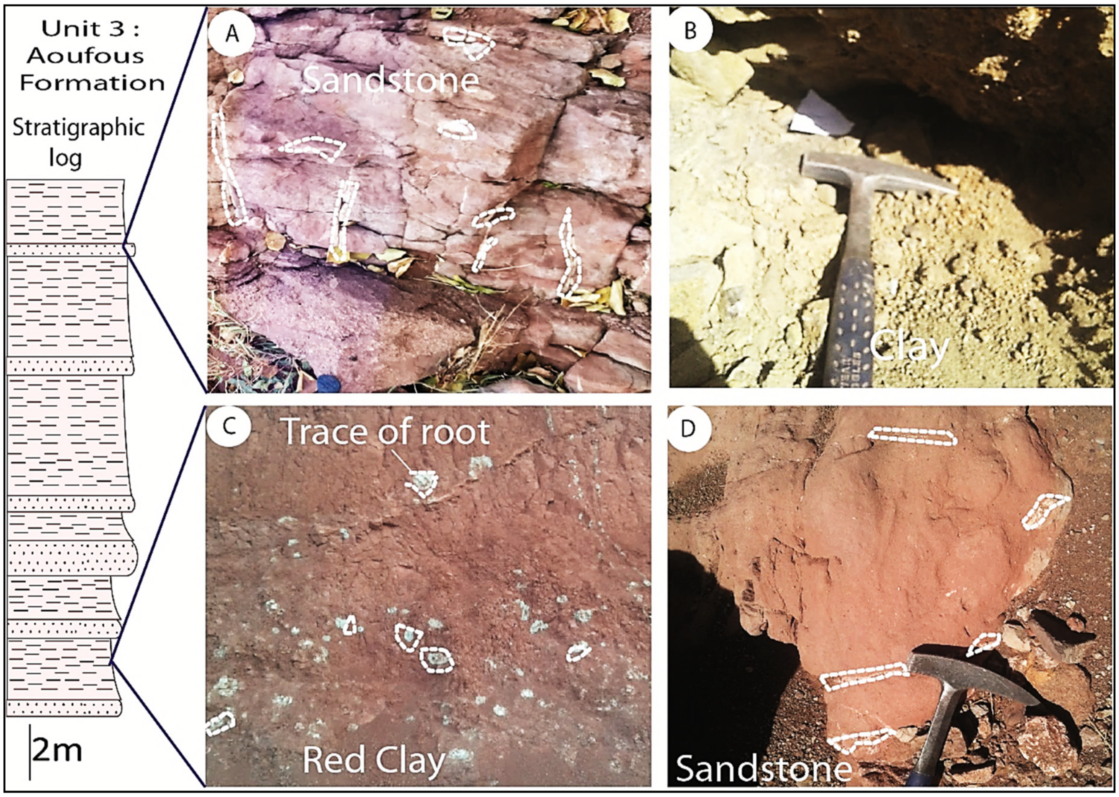


Figure 7. A) discontinuity, B) Alternating clay, marl, sandstone, C) marl, D) Marl and gypsum

This unit rests on thick clay beds with fine facies, followed by another deposit of clay and silt interspersed with fine sandstone benches (Figs. 8). The presence of the sandstone deposits also shows that the latter were shallow (Liu and Wang, 2001). From this interpretation and description, we can conclude that this unit is characterized by playa deposits (Figs. 8).

The vertical succession of lithofacies makes it possible to distinguish two formations. The first Ifezouane formation indicates an evolution beginning with the recurrence of the terrigenous sediments of an alluvial plain. The second Aoufous formation was followed by the varicolored gypsiferous marls of a playa. The lower units of the Dades Valley Ait Ibrirene region are capped in basalts placed recently dated to the Middle Aptian by Moratti et al., 2018. In this region, these basalts are stratigraphically located under the Ifezouane Formation. Therefore, the first Cretaceous transgression appears younger on the southern edge of the central High Atlas.

Morphoscopic

Using the analysis morphoscopy proposed by (Cailleux 1943), it allows us to calculate the relative percentages of the different types of grains of quartz in these four units' study in the Infra-cenomanian series. Three categories of grain were recognized: not worn, dull blunt and round matt (Table. 2 and Figs. 3, 9).

Table 2. Table percentage of morphoscopy results

Characters	S1	S2	S3	S4	S5	S6	S8	S9	S10	S11	S12	S13	S14
Not worn	36	56	56	60	38	48	50	34	28	24	14	08	03
Dull blunt	64	36	34	34	50	36	28	46	42	58	64	66	69
Round matt	0	8	10	6	12	16	22	20	20	18	22	26	28
Rock unit		U1				U2			U3			U4	

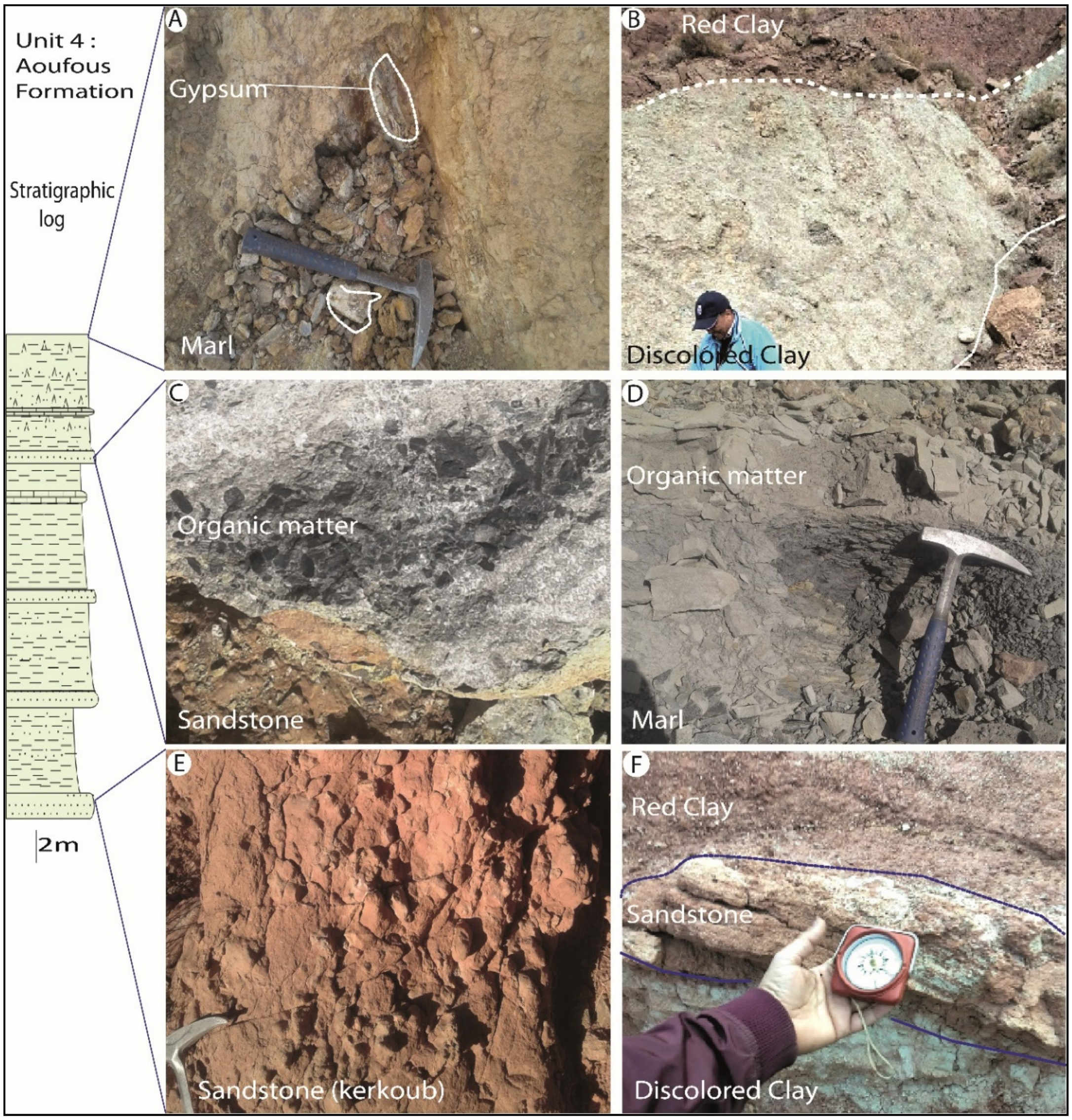


Figure 8. Lithology of Unit 4 of the Ait Ibrirene series (formation Aoufous). A) Marl and gypsum, B) clay red and clay discolored, C, D) Consolidated organic matter, E) Kerkoub, F) Progradation of the sediments

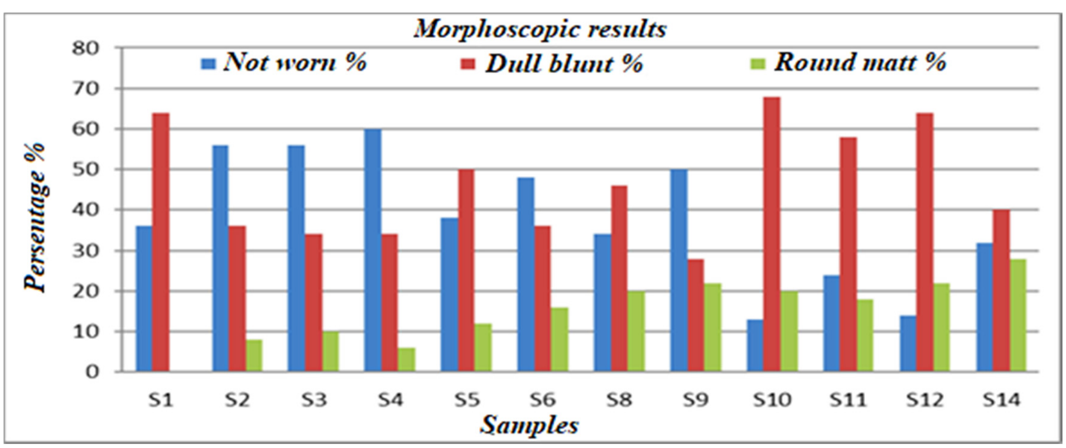


Figure 9. Histograms showing the percentages of different forms of quartz grains in the samples from Infra-Cenomanian series

The morphoscopic study from the base to the top of unit 1 (Fig. 9 and Table 2, samples S1, S2, S3, S4) revealed a significant percentage 64% of dull blunt grains, with not-worn grains comprising 36% of the assemblage and a very low percentage of rounds matt. The two types of quartz grains show two origins identified from a nearby source, and also indicate river transport and a high-energy environment. A vertical evolution is remarkable from the base to the top since the grains have an abundance of not worn grains; the latter are characterized by an angular shape and generally have a proximal origin, as previously stated by Fournier et al., 2012 in their study. These characteristics reflect deposition in an alluvial fan. Sample 8, on the other hand, collected at the summit level of the Ifezouane Formation (unit 2), shows a decrease in the percentages of not worn grains (50%), and an increase in the proportions of dull blunt grains (36%). The dominance of dull blunt grains indicates a medium transport in a fluvial environment, as defined by Legigan, 2002 in their study. This highlights the influence of short-distance aquatic transport and corresponding fluvial dynamics.

The proportion of dull blunt grains is very high (S1), with a very low percentage of the other elements (round matt and dull blunt grains). The morphoscopic analysis of quartz grains from the samples in this unit shows a decrease in the percentage of dull blunt grains. The proportion of unworn grains decreases from the base to the top of unit 2 (Fig. 3). Their percentages indicate that those grains have undergone short-range transport in a fluvial environment, as shown by (Krinesley et al., 1968) in their study.

The morphoscopic study of quartz grains in units 3 and 4 from the base to the top of the stratigraphic log of the Aoufous Formation (Fig. 9 and Table 2) shows dominance of round matt grains (S10, S11, S12, S14). The proportion of the round matts is high relative to the base of the studied series (Fig. 13, Table 2) with minor associations of dull blunt and not worn grains. This large percentage of round matt grains compared to the other units indicates a low energy environment as previously determined by Legigan, 2002 and Le Ribault, 1974. The analysis of the results obtained shows that grain transport occurred over a very long distance in an aquatic environment (EL konty et al., 2021). These characteristics indicate a calm and marine environment, corresponding to a flood plain and playa environment, as previously stated by Krinsley and Donahue, 1968 in their study. The variations of the grains indicate a change in sediment transport conditions between the base and the top of the studied formations.

Exoscopy

The exoscopic analyses consisted of studying the quartz grains with an SEM to determine their sedimentary histories and identify the micro-characteristics of variable origins (alteration, continental or aquatic transport, chemical, mechanic, biological) which progressively modified their surface (Le Ribault, 1977, Legigan, 2002). The tests carried on the surfaces of these grains have made it possible to identify various figures that can be related either to the primary crystal lattice of the quartz, or to the virulent actions associated with the weathering environment. Quartz grains underwent a complex evolution before their period of immobilization. Other grains have the shock (V) which attests to a fluvial mobilization.

The results obtained by exoscopy at the base of the Ifezouane Formation, in unit 1 (Fig. 10) show that the first generation of conchoidal breaks was affected by mechanical wear which produced fractures. These grains underwent strong stirring during transport, which gave the grains an angular form, and many increasing traces of shocks v. These characteristics indicate a high-energy fluvial environment (Flageollet, 1981, Liu et al., 2001).

A strong polishing of the edges of the breaks and strong desquamation with the release of scales, of which a very small number remains trapped in the depressions, can be observed in the upper part of unit 2 (Fig, 15). Micro-fractures and large conchoidal breaks with pronounced concavity on the surface of the quartz grains evolving in a fluvial medium also indicate a high a medium energy environment (Fig. 11), as defined by (Le Ribault, 1975; Liu et al., 2001) in their study.

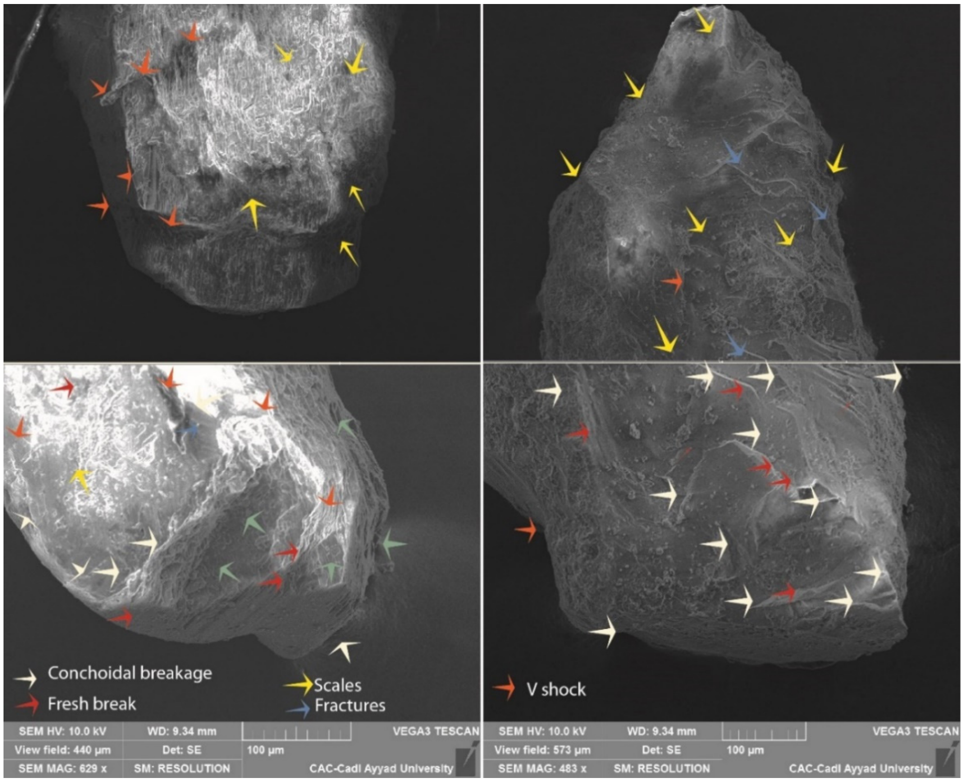


Figure 10. Exoscopy of the samples taken at the base of unit 1 Ifezouane formation

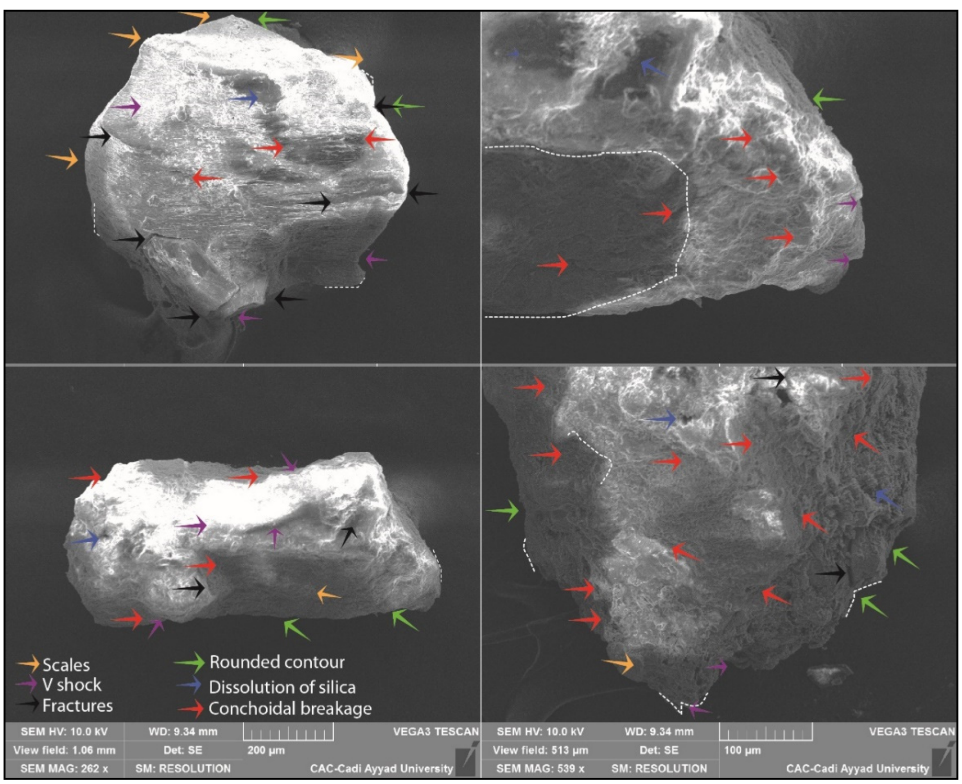


Figure 11. Exoscopy of the samples taken of the unit 2 Ifezouane formation

Remains of a stack of amorphous silica films covering the surface of the grains can be seen in unit 3 (Fig. 12), except at the level of the zones of contact with the other grains. Additionally, the medium of evolution corresponds to a chemical alteration within the host rock, with the formation of soil in places (Fig. 12), based on the study of Le Ribault, 1975; Liu et al., 2001. The interpretation of the results obtained by the exoscopic analysis of unit 4 (Fig. 13) is marked by the presence of dissolution at the level of the traces of shocks, peeling off the edges, and depressions. The grains affected by high wear have developed rounded contours (medium to lower energy) and underwent the dissolution of a large part of the silica film at the level of marine water circulation, and the distributed scales on the grain surface indicate the immobilization and small mechanical impact marks, indicating low energy transport) (Fig 13). Based on the study by Liu et al., 2001, the presence of sandstone deposits also shows that it is a shallow playa-type environment, based on the study of (Liu and Wang, 2001).

According to these exoscopic studies, the chronological evolution of grain environments in this area was determined by the treatment of the quartz grain. The grains of the section at the base of the studied series indicate a fluvial environment. The grains at the top of the series often point to a confined silica-saturated environment specified by intercalations of phases of immobilization, traces of dissolution and strong polishing, and some traces of the remainder of films evidencing a playa environment.

Clay Mineralogy

To establish the paleo-environment of the Ait Ibrirene Infra-Cenomanian series, the inherited and contemporary influences of the repository must be distinguished. For this, the mineralogy of the study area on the south side of the Central High Atlas was determined alongside investigating the vertical evolution of clay mineralogy processions of this study area.

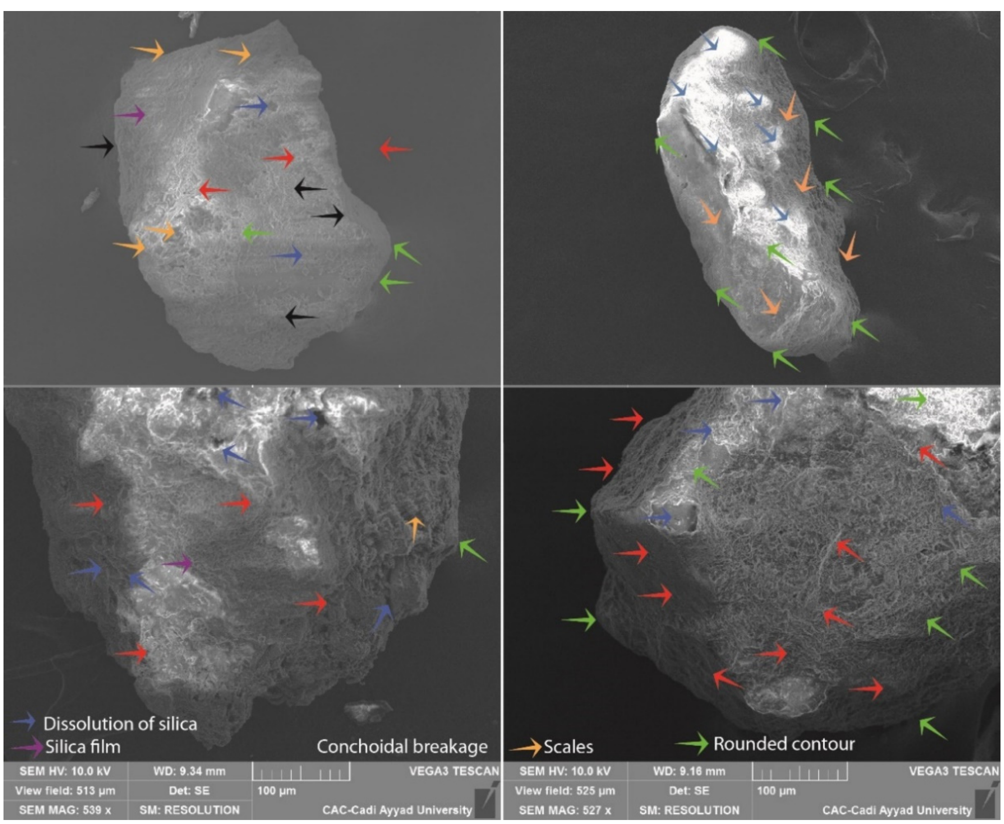


Figure 12. Exoscopy of the samples taken of the unit 3 Aoufous formation

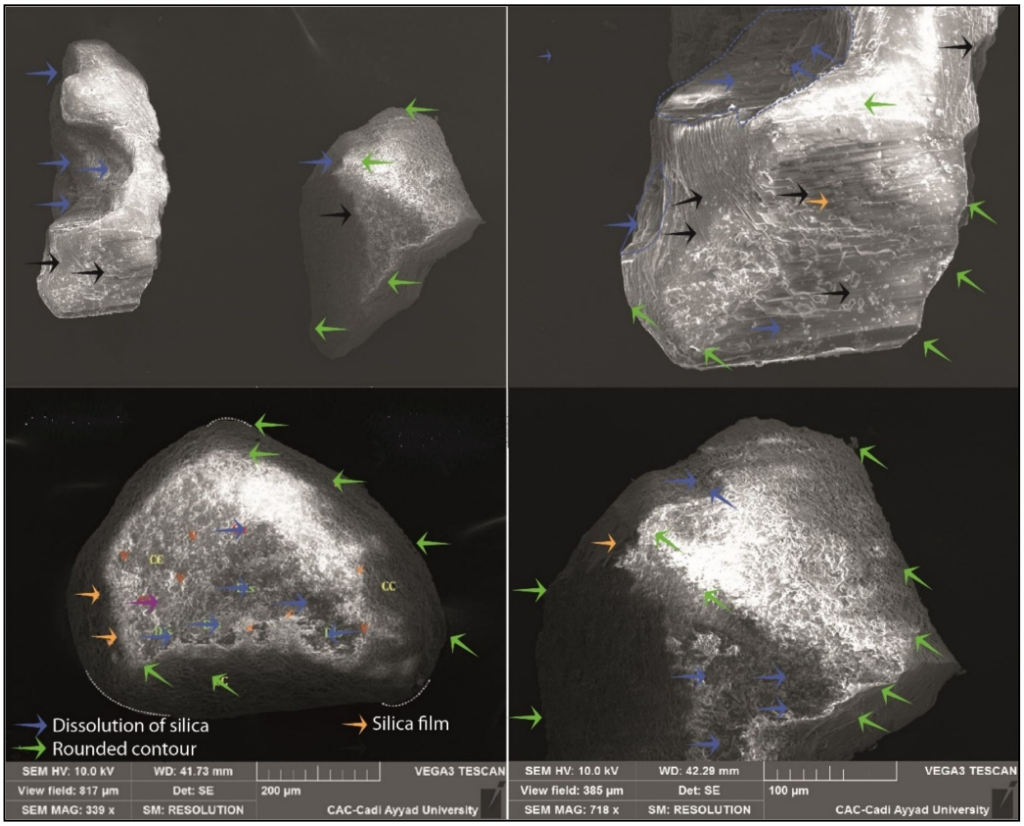


Figure 13. Exoscopy of the samples taken of the unit 4 Aoufous formation

The identified clays consist of seven species, five of which are simple (chlorite, illite, smectite, kaolinite, and vermiculite (Hubert et al., 2009). Among the minerals associated with clays, quartz, and oxides appear at certain levels. Variations in the relative proportions of these minerals allowed the identification of several distinct mineralogical zones from the bottom to the top of the studied series (Fig. 14).

From the base to the top of the Ifezouane Formation (units 1 and 2), the clays are represented by illite (38 - 50%) and smectite (45 - 22%). Illite remains the dominant clay mineral. Smectite and kaolinite show significant variations. Chlorite and irregular interstratified minerals are poorly represented. Kaolinite is the most abundant in a hot and humid climate (Dunoyer de Segonzac, 1969), as runoff or drainage ensures the mobilization of ions.

From a mineralogical point of view, unit 3 is characterized by the development of smectite (88%), which develops at the expense of illite (90%), kaolinite (60%), and chlorite (20%) (Fig. 14). The clay fraction in unit 4 is characterized by the simultaneous disappearance of illite, and by the development of smectite at the base of the Infra-Cenomanian series, in favor of kaolinite and illite; this reflects the establishment of a sedimentary model in a restricted range, testifying to the isolation of the medium, and favoring the confinement of water in a hot and arid climate (Hubert, 2008) (Fig. 14).

The smectites represent around 22% of the clay assemblages at the bottom of the Infra-Cenomanian series and reach 60% at the top of this series. On the other hand, at the top of this series, illite and kaolinite represent 5% and 10% of the clay fraction, respectively. The important illite inputs at the base of unit 1 are suggestive of active erosion resulting from the instability of the reliefs in the basin. However, the decrease in the proportions of illite towards the top of the studied series (unit 4) (Fig. 15) indicates the start of the stabilization of the reliefs. The important proportion of illite in this unit would therefore largely result from mechanical erosion from the adjacent domain (Anti Atlas) (Wurster and Stets, 1982).

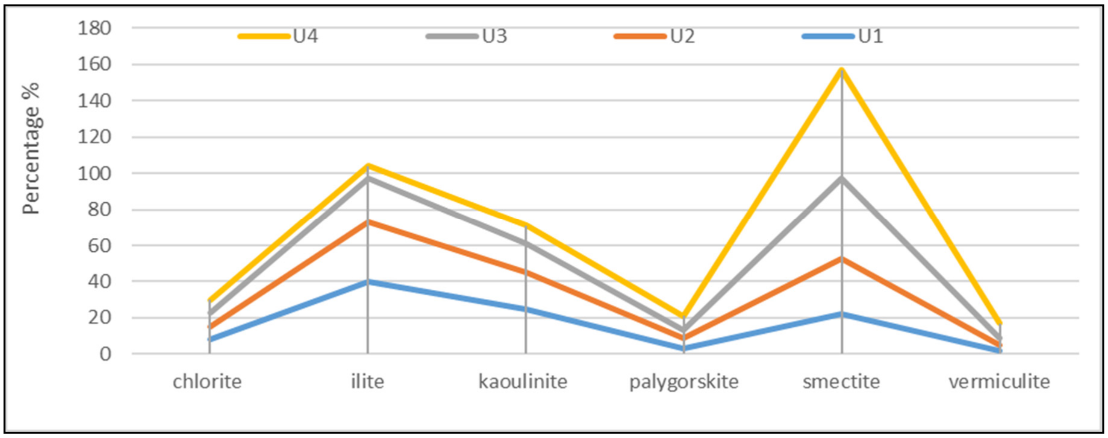
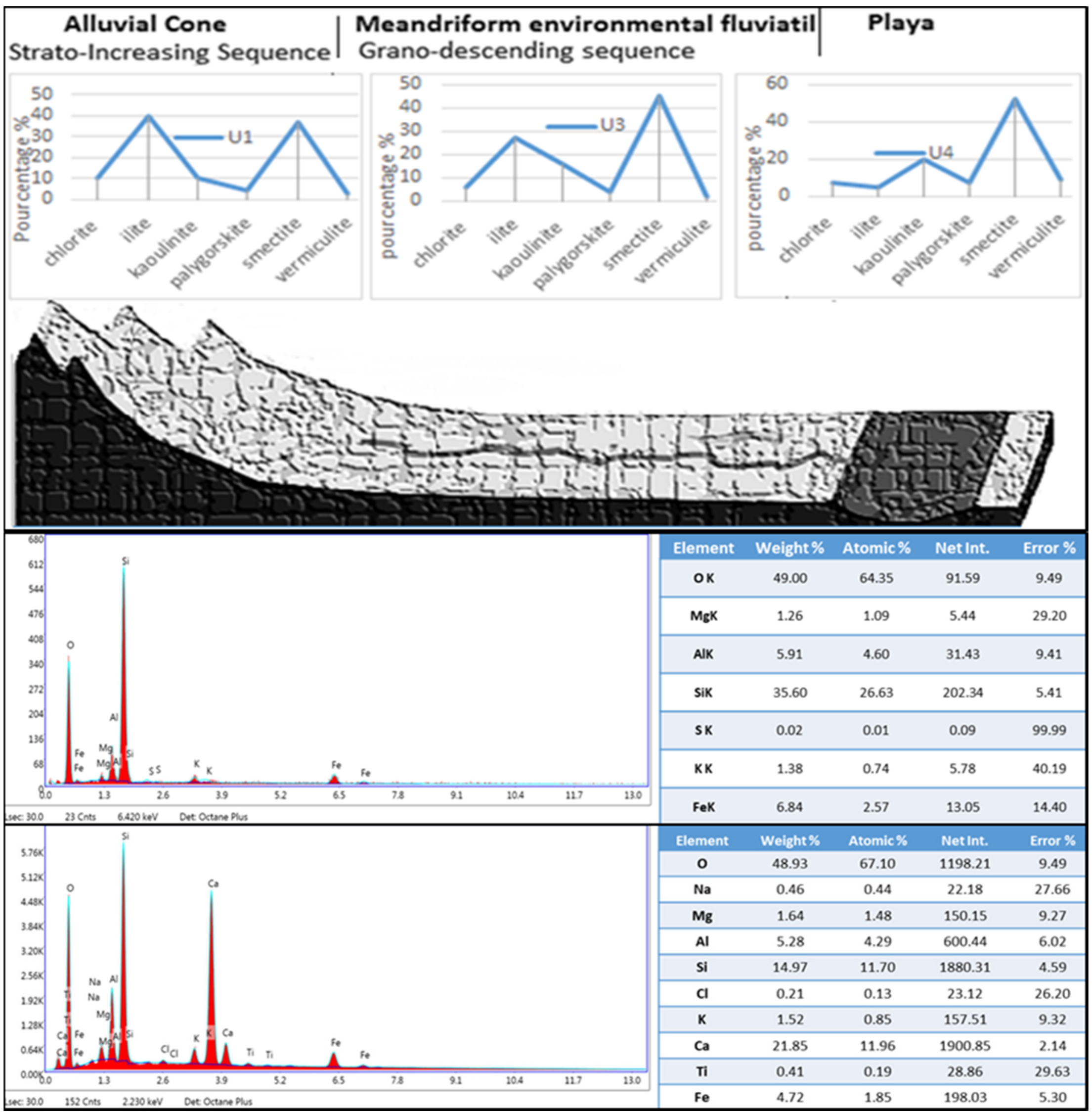


Figure 14. Results of the X-ray diffraction analysis by means of oriented thumb blades at the base of units 1, 2, 3, and 4



Element	Weight %	Atomic %	Net Int.	Error %
O K	49.00	64.35	91.59	9.49
MgK	1.26	1.09	5.44	29.20
AlK	5.91	4.60	31.43	9.41
SiK	35.60	26.63	202.34	5.41
S K	0.02	0.01	0.09	99.99
K K	1.38	0.74	5.78	40.19
FeK	6.84	2.57	13.05	14.40

Element	Weight %	Atomic %	Net Int.	Error %
O	48.93	67.10	1198.21	9.49
Na	0.46	0.44	22.18	27.66
Mg	1.64	1.48	150.15	9.27
Al	5.28	4.29	600.44	6.02
Si	14.97	11.70	1880.31	4.59
Cl	0.21	0.13	23.12	26.20
K	1.52	0.85	157.51	9.32
Ca	21.85	11.96	1900.85	2.14
Ti	0.41	0.19	28.86	29.63
Fe	4.72	1.85	198.03	5.30

Figure 15. The results of analysis by diffraction of the X-rays of the oriented argilo blades and element chemical of clay

Discussion

In summary, we have characterized our depositional environments based on field data (sedimentological, stratigraphic, and lithostratigraphic studies). A detailed analysis of some sedimentary figures and structures characteristic of the Infra-Cenomanian Formation, supported by analyses carried out in the laboratory, sufficiently correlated with the field data; the results on the depositional environment of the Infra-Cenomanian Formation (alluvial fan, floodplain, major bed environments) correlate with previous research on the same series studied in the Moroccan High Atlas (Essafraoui, 2015; Benvenuti et al., 2017; Charriere and Haddoumi, 2016). Although a comparison of the Infra-Cenomanian has been made between the two regions – the Central High Atlas and Western High Atlas – a similar series can also be found farther eastward in Algeria, in the Bechar region (Benyoucef et al., 2012; 2014).

Our study shows that the Infra-Cenomanian Formation consists of two detrital formations: The Ifezouane Formation, comprising clays, sandstone, and conglomerate beds, and the Aoufous Formation, mostly composed of sandstone, silt, clays, marl, and some gypsum interlayers. This series has not been studied in detail before, although our results are correlated by previous studies of red beds in the Central and Eastern High Atlas (Ferrandini et al., 1985; Rhalmi, 2000; Ettachfini and Andreu, 2004; Lezin et al., 2012; Andreu et al., 2013; Essafraoui et al., 2015; Lebedel et al., 2015). Finally, the depositional facies show that there is a succession of stages from the base to the top of the studied section. From the base upward, there is a progressive evolution of a proximal fluvial environment (Ifezouane Formation); the top of the section is characterized by an entirely plain and playa depositional environment (Aoufous Formation). This series consists of a large detrital group (Ifezouane Formation), covered by another more or less marine group (Aoufous Formation). This Infra-Cenomanian series ends with carbonate beds. The clay and conglomerate beds are limited by several meters-thick sandstone beds. The results of the sedimentological, morphoscopic, exoscopic, and mineralogical clay analyses of the continental deposits from the Infra-Cenomanian in the Ait Ibrirene region indicate that the medium of deposit has clearly changed over time. In the present study, two models (Figs. 16 and 17) are proposed to account for the depositional environments of the different units studied. The deposition environments changed from a proximal alluvial fan system to a braided river one, and then to a meandering system. These environments eventually evolved to an alluvial plain associated with a coastal plain with playa lakes.

The section begins with coarse-grained fluvial deposits, these continental deposits then become finer-grained to the top (mostly red claystone hosting marine green marlstone beds). In the figure of correlations (Fig. 18), the Ifezouane and Aoufous Formations, forming the Ait Ibrirene section (in the Central High Atlas) laterally correspond to the Tinghir and Tadighoste section in the others studied (El Ouali et al., 2021).

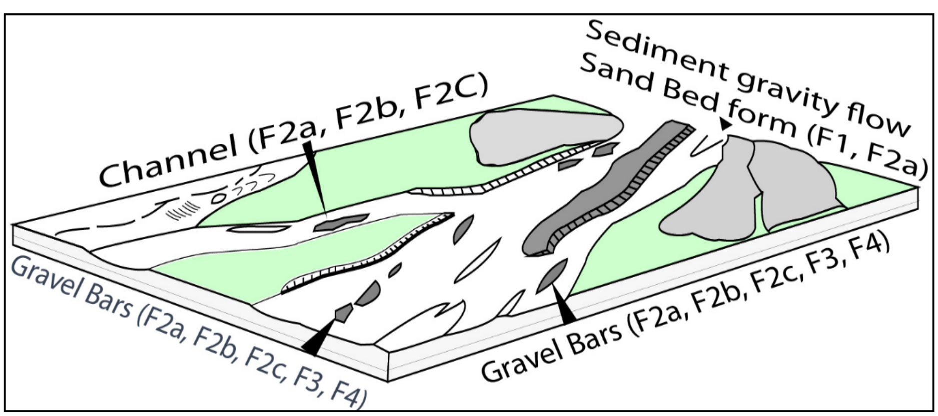


Figure 16. Depositionl model corresponding to an alluvial cone system with Gravity Flow

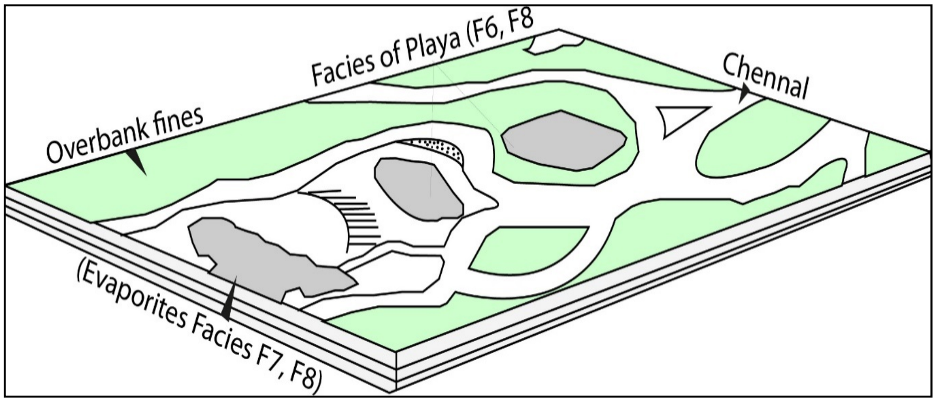


Figure 17. Deposition model corresponding to the coastal plains associated with playas

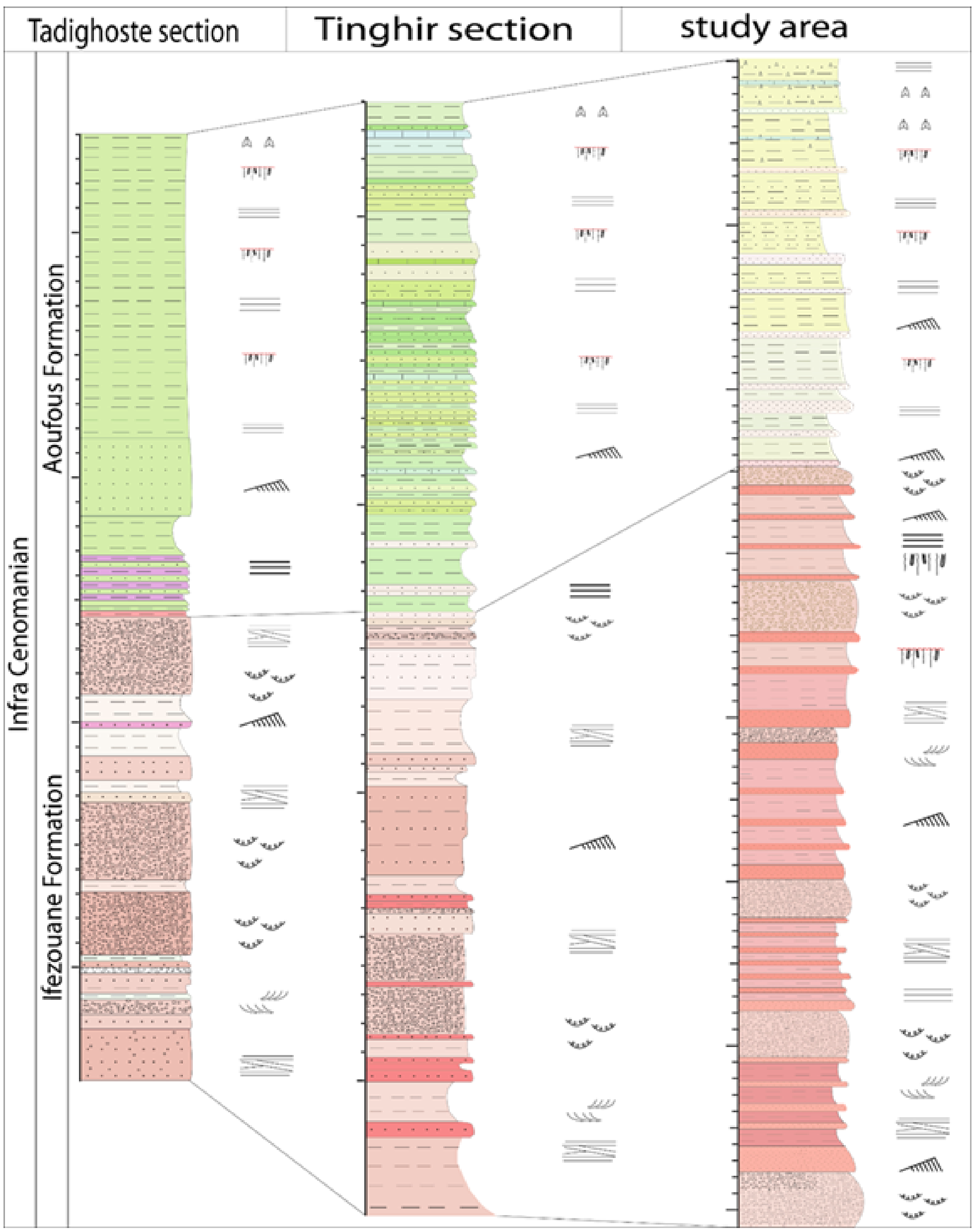


Figure 18. Lithostratigraphic correlations of the ‘‘Red beds’’ in the central High Atlas

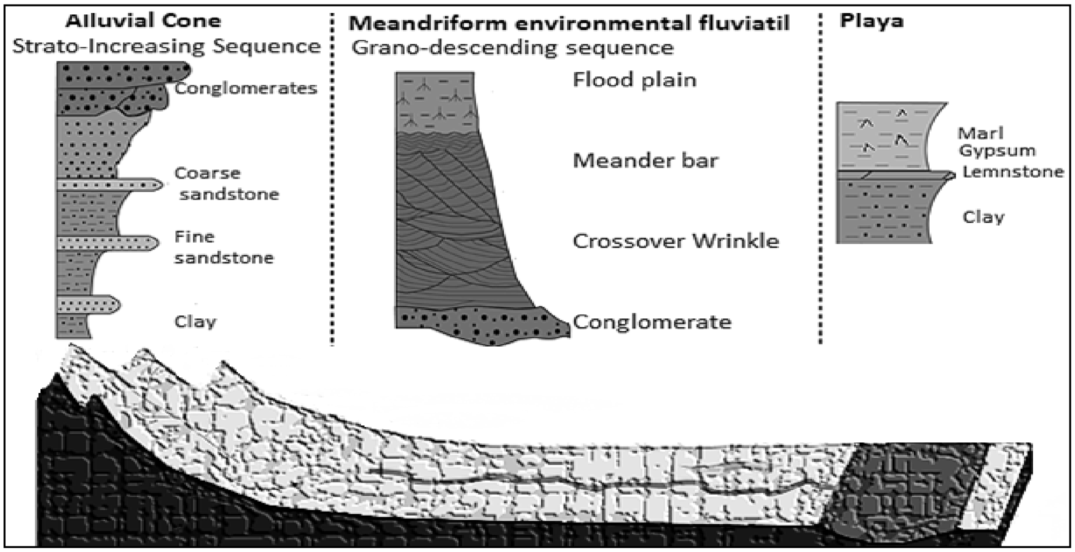


Figure 19. schematic representation of the paleogeographical environments of the Infra-Cenomanian in the Ait Ibrirene region

These formations are formed by a sandstone ensemble (Ifezouane Formation), covered by an alternation of red clays, green marls and gypsum (Aoufous Formation).

Conclusion

In this manuscript, sedimentological and lithostratigraphic analyses were combined with macroscopic, morphoscopic, and exoscopic analyses of clays and quartz grains to track the paleoenvironmental evolution of the sedimentary formations of the Ait Ibrirene region. These formations are overlain by the so-called Infra-Cenomanian' series. The latter consist of a basal big sandstone set (Ifezouane Formation), overlain by versicolor alternations (Aoufous Formation). The results show that the sediments were deposited in a continental environment, more precisely in a river system which changed over time. First, the sediments were raised in a proximal system (alluvial fan), then moved to a meandering river system which subsequently developed into a flood plain, and finally converted into a playa environment (Fig. 19).

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Competing interests The authors declare that they have no competing interests.

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