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Sedimentary Environment and Fluvial Trace Fossils of the Middle Jurassic in the Ait Ourir Basins, Western High Atlas, Morocco

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Abstract

The Middle Jurassic continental deposits in the Ait Ourir basins belong to the western High Atlas region of Morocco. More precisely, it is a part of the Northern Sub-Atlasic zone of the Marrakech High Atlas. These deposits, also known as "Couches Rouges," overlie the last marine deposits. In this paper, we present an analysis of the sedimentological and ichnological analysis of the study area. A detailed description of the ichnofacies, facies, and recognition of architectural elements characteristic of the deposition environment reveals the evolution of a paleoenvironment, transitioning from an alluvial fan environment to a braided river system that becomes meandering. In the end, the system moved to a marginal-littoral environment characterized by fine to coarse deposits. The ichnological study aims to recognize the following Ichnogenera: *Taenidium*, *Palaeophycus*, *Planolites* and *Arenicolites*. These ichnogenera can be grouped into the continental *Skolithos* ichnofacies, *Mermia* and *Scoyenia* ichnofacies, typical of fluvial channel and Lake Margin deposits in semi-arid to arid regions.

Keywords: Debris flow Red Beds; Continental ichnofacies; Lithofacies; Floodplain; High Atlas

1. Introduction

This paper presents a sedimentological and ichnological study of the Middle Jurassic detrital series in the Ait Ourir region (Western High Atlas (WHA), Morocco). The WHA remained the site of Atlantic intertidal zone sedimentation over most of the Atlas domain during the Middle Jurassic. Continental red beds extended significantly throughout the Atlas domain and were deposited after the closure of sea grooves (Du Dresnay, 1979).

The study area is located within the Jbel Sour Basin, situated to the southeast of Marrakech. In this region, the Middle Jurassic red beds are intercalated between the silt-carbonate evaporite deposits of the Zaouiat Ahansal Group (Liassic in age) and the dolomitic limestones of the Tadhart Formation (Upper Aptian in age) (Hadach et al., 2015; Hadach et al., 2020). The Middle Jurassic period represents a filling Megasequence consisting of continental red detrital deposits, indicating a transition from a floodplain environment dominated by conglomeratic, sandstone, and clay to a margin littoral plain that was submerged and predominantly received finer detrital material (Bah, 1993).

The description, classification, and interpretation of the fluvial deposits are based on several criteria, such as lithofacies, architectural analysis, facies geometries (Miall, 1978; 1985; 2006), and ichnofacies analysis. These characteristics allow for the reconstruction of the paleoenvironment in the Ait Ourir basins. This study aims to provide new insights into the depositional history and paleoenvironmental conditions of the Ait Ourir basins by analyzing these deposits for the first time through a combination of sedimentological and ichnological approaches.

2. Geographical and Geological Setting

The Ait Ourir region belongs to the Western High Atlas region of Morocco, more precisely, the northern Sub-Atlasic zone of the High Atlas of Marrakech (Moret, 1931). It is bounded to the north by the Haouz plain and to the east by the Oued R'dat (Fig. 1).

The Ait Ourir basins have a Mesozoic cover that was folded into broad, flat-bottomed, and subhorizontal synclines, separated by ejected and sharp anticlines during the Atlasic orogeny (Ferrandini and Le Marrec, 1982; Algouti, 1999; Hadach, 2020). During the Jurassic, the sedimentary tectonics of the Western High Atlas underwent two distinct phases: an embryonic phase in the Lower Jurassic (Bajocian-Bathonian) (Michard, 1976) and a paroxysmal phase in the Middle Jurassic (Jenny et al., 1981; Monbaron, 1982). These two stages are characterized by extensional tectonics. In the Lower Jurassic, a rise in sea level marked by the development of coral reefs occurred, subsequent to a new Atlantic transgression in the Late Tithonian, characterized by Calpionnelles limestones (Taj-Eddine et al., 1985). The Middle Jurassic detrital sedimentation is interpreted as a consequence of the uplift of the High Atlas at the end of the Liassic period, resulting in the filling of the Atlassian lagoon-marine gulf.

This region is primarily structured by a network of faults oriented N-S and NNE-SSW, which represent the main orientations of the High Atlas fault system (NE-SW) (Nidsaid et al., 2022).

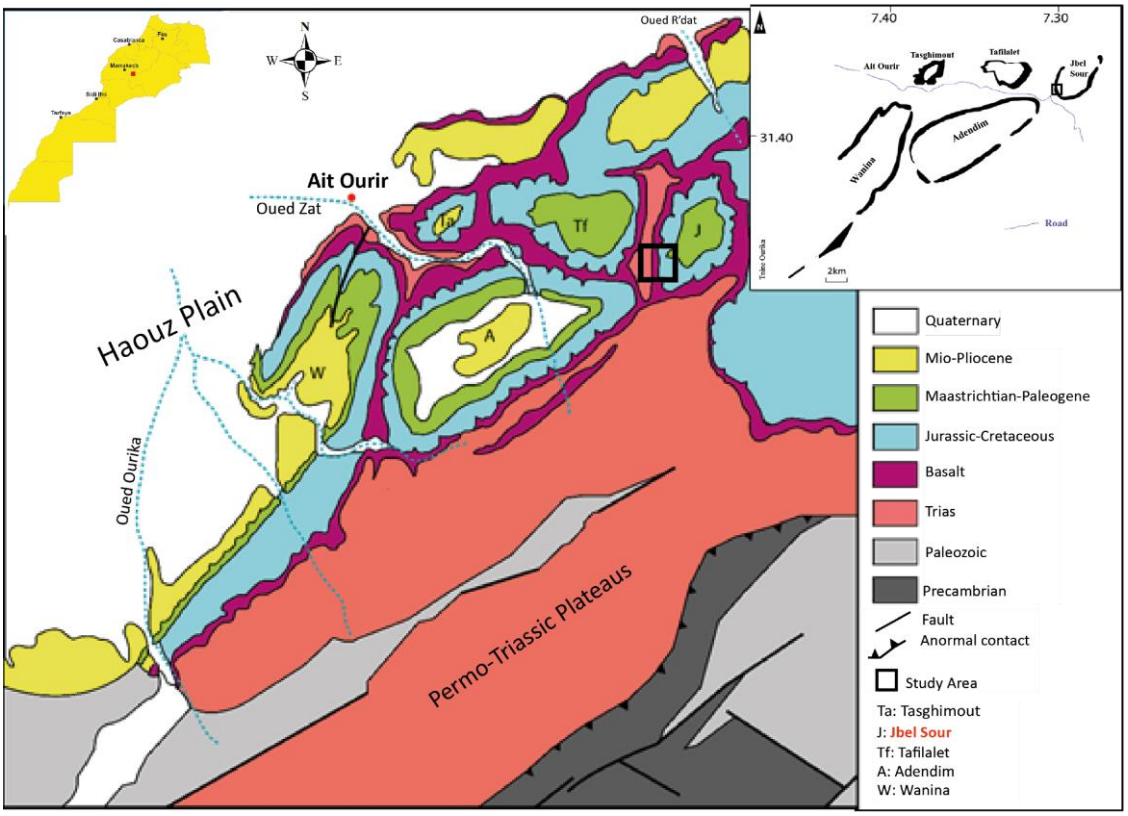


Fig.1. Geological map of the Ait Ourir basin showing the location of the section studied (modified after Hadach et al., 2020; Nidsaid et al., 2022; Aboulfaraj et al., 2024)

3. Materials and Methods

The main objective of this two-step study is, firstly, several field missions were conducted to perform a detailed analysis of field sections, including lithofacies, sedimentary structures, and textures recorded during the missions. This analysis aims to provide a comprehensive view of sedimentary bodies and their special arrangements in order to characterize the various facies, their associations, and architectural elements (Miall, 1985; 2006).

This approach facilitates the reconstruction of the evolution of depositional environments. The codes of different lithofacies studied were developed following the facies code by Miall (1977; 1978; 2006). Secondly, an ichnological study was carried out, and traces of fossils were collected through photography (often imperfect) to identify and reconstruct the paleoenvironment.

4. Results

The section studied in the Ait Ourir basins (Figs. 2 and 3) is intercalated between two marine formations: the Liassic carbonates (Hadach, 2015) and the upper Aptian Tadhart Formation (Hadach, 2020). This section is subdivided into three formations: the Guettioua Formation (U1), the Iouariden Formation (U2), and the Jbel Sidal Formation (U3). In this study, the section was taken from the Jbel Sour Basin.

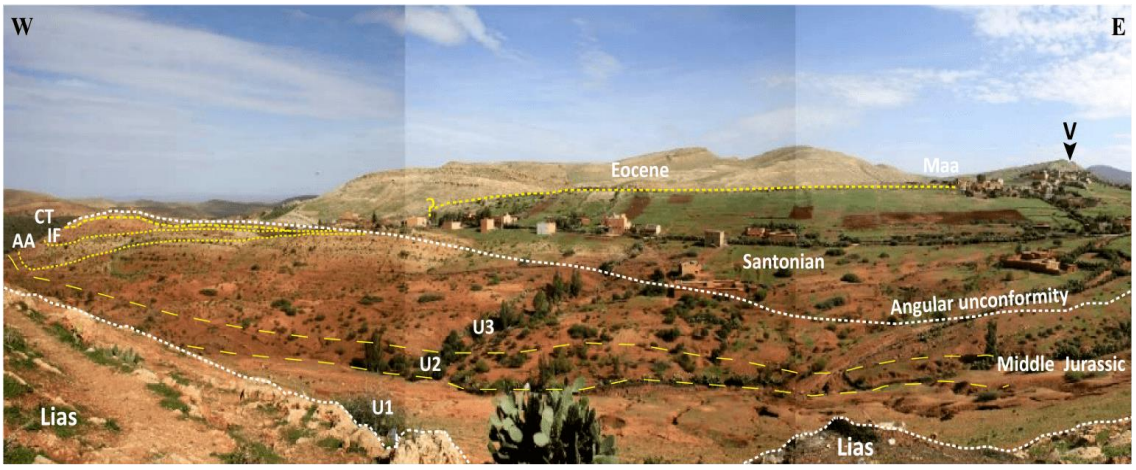


Fig. 2. Panoramic view of Jbel Sour basin showing the Middle Jurassic red beds succession (U: unit, V: Village, IF: Infracenomanian, CT: Cenomano-Turonian, AA: Apto-Albian and Maa: Maastrichtian)

4.1. Sedimentary Facies Analysis

4.1.1. Conglomerate facies (F1)

This facies is identified in the red beds at the base of the Guettioua Formation (Fig. 4A) up to 30 m thick; it is differentiable from underlying pale red units by its very dark brown color. Massive conglomerates dominate it, and the fraction is characterized by clast compositions, including calcareous and siliceous pebbles and cobbles derived from Precambrian-Paleozoic and Jurassic reworked rocks forming the shoulders of synclines. Table 1 summarizes different types of facies and sub-facies, and their depositional environment.

- F1a: These disorganized conglomerates are angular and polygenetic. They are poorly sorted and poorly imbricated (Fig. 4B-E). The cement in this conglomerate is sandstone-carbonate or, more frequently, sandstone with clay and iron oxide. This facies corresponds to facies Gms of Miall (1978; 1985; 2006). According to Miall (1977; 1978; 2006), it can be deposited by debris flow in alluvial

fans. The lack of trace fossils can be attributed to high hydrodynamic energy and corresponding high sedimentation rates.

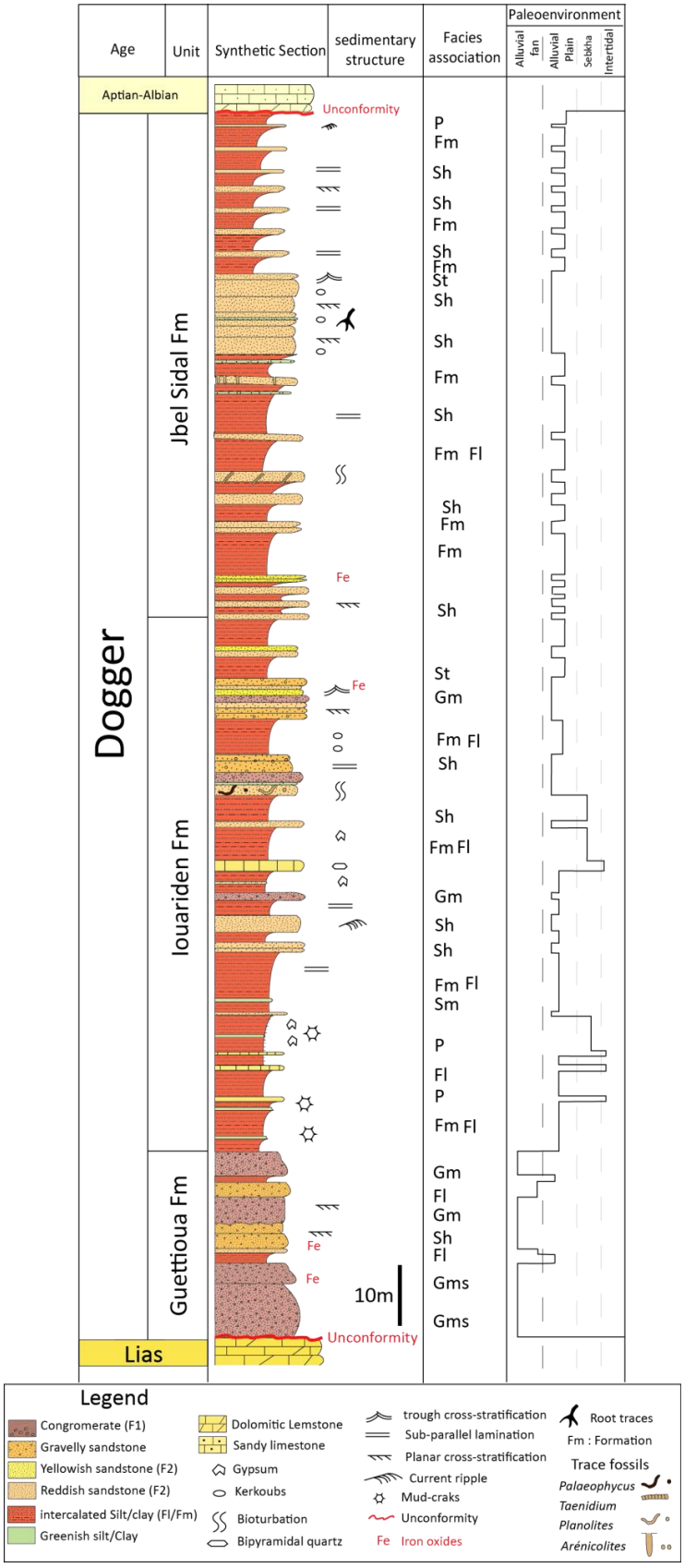


Fig. 3. Lithostratigraphic column of the basin area of Ait Ourir (Jbel Sour Basin)

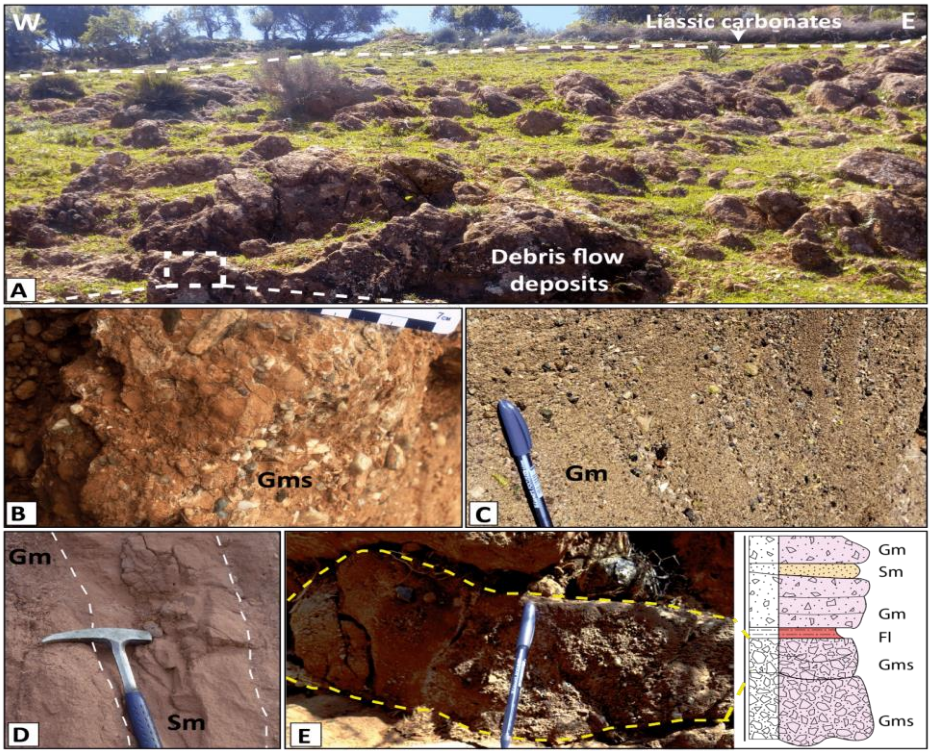


Fig. 4. (A) Field panorama showing the sedimentary structures found in the Guettioua Formation of the red beds in the Jbel Sour Basin; (B) Massive conglomerate with angular to subangular pebbles and cobbles (sub-facies F1a); (C) Crudely bedded gravel and massif sandstone (sub-facies F1b); (D) Gravelly sandstone (sub-facies F1c); (E) Massive conglomerate (sub-facies F1a)

- F1b: These conglomeratic facies are characterized by subangular centimeter-sized pebbles and gravels, which are stratified and sometimes imbricated in a sparse matrix (Fig. 4C). This facies corresponds to Gm facies of Miall (1978; 1985; 2006), deposited on longitudinal bars in a braided fluvial channel (Miall, 1977; 1978; 2006).
- F1c: Cross-stratified gravelly sandstone, Gm facies, is characterized by poorly sorted, medium to coarse-grained sandstone (Fig. 4D) and reflects a channel deposits environment (Miall, 1996).

4.1.2. Sandstone (F2)

- F2a: These facies are the most abundant in the Middle Jurassic formations, alternating with red silt-clay (Fm and Fl), and consisting of massive coarse sandstone 1.5 to 3 m thick (Fig. 4D). An apparent absence of any form of sedimentary structure is found in this facies. It sometimes contains millimetric to centimetric fragments at the base, which tends towards a microconglomerate. This facies corresponds to the massive sandstone (Sm) of Miall (1978, 1985, and 2006). According to Miall (2006) and Menkem (2013), this facies indicates rapid deposit during flooding or gravity flows (Table 1).
- F2b: It is a massive to coarse grained sandstone with a lenticular geometry and an erosive base, always intercalated within clay-silty layers. These lenticular sandstones are generally massive but may locally be oblique and through cross-bedding (Figs. 5F and 6E). This facies corresponds to Miall's (1996) lithofacies St, which is interpreted as the filling of minor channels (Miall, 2006).
- F2c: This lithofacies represents a medium to fine grained sandstone (Fig. 5B) commonly interbedded with clay and silt facies. It has a medium thickness and horizontal planar bedding with parting lineation. This facies is similar to the Sh facies described by Miall (1977; 1978; 2006). The

horizontally stratified sandstone may originally have been deposited in the upper flow regime by traction currents (Miall 1978; 1996).

- F3: It is a pink to light gray color siltstone in the form of lenses, with a thickness ranging from 0.2m to 2m, and several meters in length (Fig. 5E). These lenses represent two primary internal structural characteristics: a massive structure or with lightly inclined bedding. This facies is marked by desiccation cracks (Fig. 5A) and trace fossils, and greenish to greyish interlayers can be observed in the facies, indicating the transformation of iron in the sediment (Fig. 5D). The characteristics of these facies resemble the Fl facies determined by Miall (1978; 2006), deposited by vertical accretion (laminar flow of very low energy). This facies may have formed as an arid alluvial plain deposit or abandoned channel (Miall, 1978; 1996; 2006).
- F4: This lithofacies consist of red claystone (Fig. 5C-E) interbedded with centimetric to metric sandstone beds, small dolomite limestone beds, and greenish gray siltstone "reduction spots" that may have developed due to the reduction of iron or manganese. These facies is regionally extensive across the study area and weakly bedded. Desiccation cracks and trace fossils mark the top. These facies are similar to the facies Fm defined by Miall (1978; 2006). The fine-grained well-sorted sediments suggest that this facies resulted from suspension deposition, probably in an overbank setting, as described by Miall (1978; 2006). The overbank deposits correspond to vertical accretion during low flows (Miall, 1977; 1978; 2006), while the presence of desiccation cracks indicates longer term drying out of the floodplain.

4.1.3. Paleosol facies (Pf)

The paleosol facies F5 (Figs. 5A and 6F-G) represents 10% of the total succession of the red beds, which have a variable color ranging from dark brown to rusty reddish and purplish. The thickness of this facies is not uniform and varies across different areas. It is composed of fine-grained sediments, including clays and silt. The sedimentary characters of these facies are nodular and contain traces of rootlets.

Table 1. Description and interpretation of various facies and sub-facies, and their depositional environments, corresponding with those of Miall (1985; 2006)

Facies and sub-facies type		**Description**	**Interpretation**
F1 F1a	Gms	Massive conglomerate, poorly graded	Debris flow deposit
F1b	Gm	Crudely bedded gravel, imbrication	Longitudinal bars,
F1c	Gm	Channelized cross-stratified gravelly sandstone poorly sorted medium coarse-grained	Channel deposits. Channel deposits.
F2 F2a	Sm	Massive sandstone, fine to coarse	Sediment gravity flow deposit
F2b	St	Trough cross-bedded sandstone	Fluvial channel, 3-D ripples and dunes.
F2c	Sh	Sand, fine to coarse-grained, planar or sub planar lamination	Fluvial channel/ transverse bar/2d megaride.
F3	Fl	Silty, fine lamination, small ripple	Overbank, abandoned channel
F4	Fm	clay with siltite intercalations, desiccation cracks	Floodplain
F5	P	Nodular dolomite, pedogenitic features	paleosol

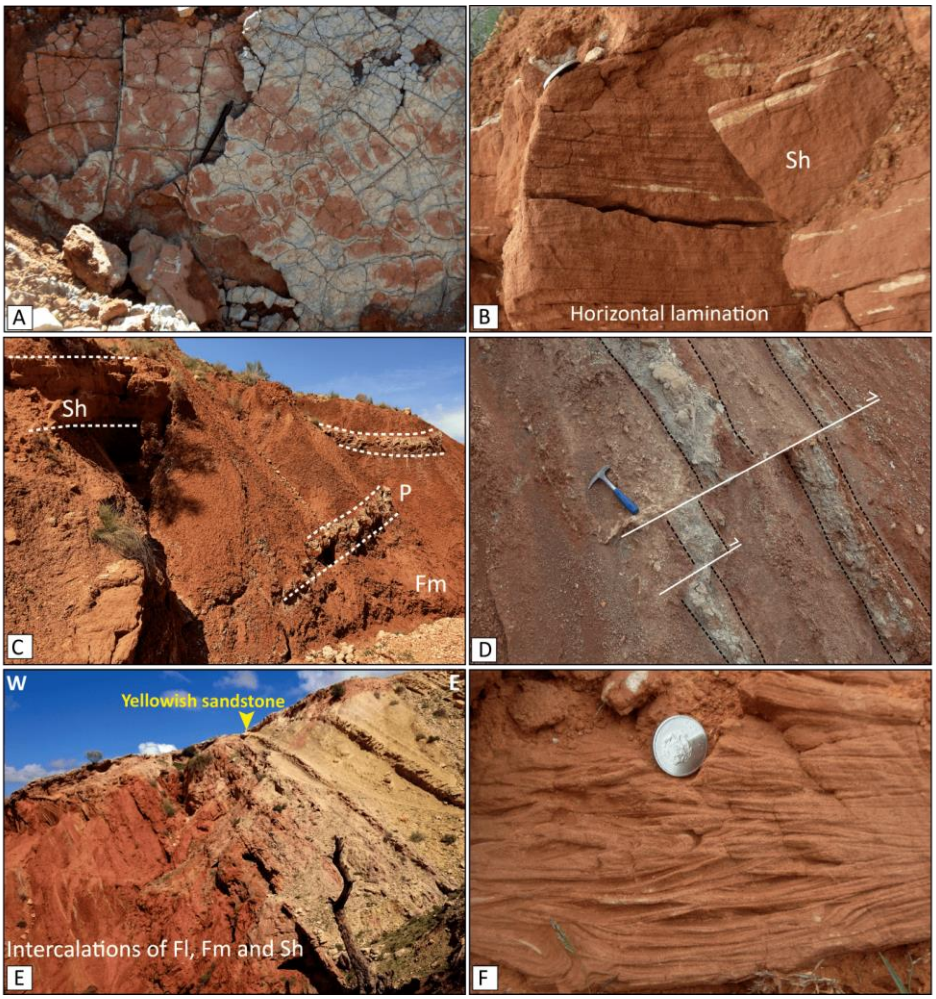


Fig.5. Outcrop of the Iouaridene Formation: (A) Paleosol in an outcrop of shallow lake deposit in the red beds, exhibiting filling mud cracks (Facies F5); (B) Horizontally laminated sandstone (sub-facies F2c); (C) Centimetric limestone-sandstone bed interspersed with silty-clay (Facies F4) in the highest part of the Iouaridene Formation; (D) Syn-sedimentary normal faults oriented N-S; (E) Interbedded silty-clay and laminated sandstone (sub-facies F2c, F3 and F4 Facies); (F) Trough cross-bedded sandstone (sub-facies F2b)

4.2. Analysis of the Sedimentary Architectural Elements

Four architectural elements were recognized: sediment gravity flow deposits (SG), gravel bars and bedforms (GB), overbank fines (OF) and playa lake and sabkha facies association (AFPS). Not all of these features were observed at each outcrop. These elements, defined by their lithofacies, geometries and bounding surfaces (Miall, 1996), form the basis for interpreting depositional environments.

- Sediment gravity flow Facies Association (SG): This element outcrops above the Liassic dolomitic limestone of the Jbel Sour basin and includes facies associations F1a and F1b, which correspond to facies Gms and Gm of Miall (2006). These deposits consist of poorly sorted pebbles and gravels usually supported by a heterogeneous matrix of sandstone and carbonates deposited in a proximal alluvial fan environment.
- Gravel Bars and Bedforms Facies Association (GB): It is formed by an assemblage of course lithofacies containing stratified and imbricated pebbles and gravels (Gm), frequently intercalated with Sm and Sh lithofacies. These are deposited on gravel bars and intercalated with thin bedded sandstone deposited during low-flows (Massari, 1983; Miall, 1985; 2006).

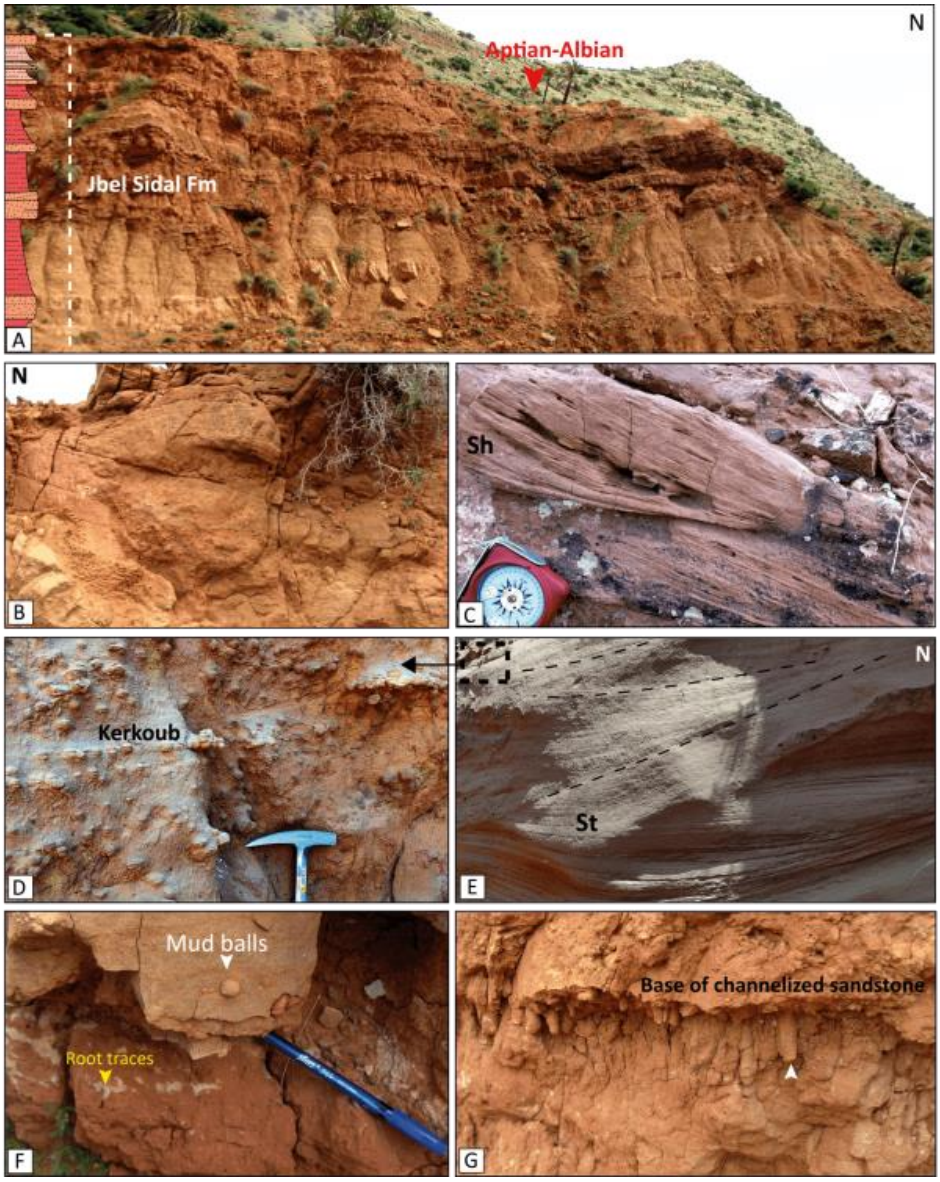


Fig. 6. (A) Panoramic view of the Jbel Sidal Formation showing: (B) and (C) planar cross bedded sandstone, lenticular form (sub-facies F2c); (D) Spherical concretions (Kerkoub) in a sandstone bed with cross stratification; (E) Trough cross-stratified sandstone (sub-facies F2b); (F) Root traces in brown mudstone interbedded with channelized sandstone showing Mud balls (Facies F5); (G) Plant remains in fine-grained sandstone bed (Facies F5)

- Overbank fines Facies Association (OF): This association represents fine lithofacies, including floodplain deposits Fl, Fm, and Sh. It is the most abundant element in the region, with thicknesses exceeding 60 m. It is composed of thick-bedded red claystone and siltstone, often showing marmorisation. These deposits are occasionally massive, with frustrated laminations attributed to the calmer hydrodynamic condition (Allen, 1985; Blatt et al., 1980). Additionally, this facies is also represent horizontal lamination and intercalations of thin sandstone. According to Miall (1978; 2006), this element represents overbank or abandoned channel deposits.
- Playa Lake and Sabkha Facies Association (AFPS): This facies association, not described by Miall is composed and characterized by cyclic deposition of fine-grained siltstone and mudstone (Fl, and Fm) with horizontal lamination. Other structures seen in this association are mud cracks, which are

present in mudstone to fine-grained sandstone. These deposits are indicative of playa lake and sabkha environments (El Arabi, 1988; Liu and Wang, 2001; Afenzar and Essamoud, 2020).

4.3. Paleoenvironmental Reconstructions

Associations of different facies and sub-facies (Table 1), along with depositional models (Fig. 9) have been developed to provide different depositional paleoenvironments of the study area. These paleoenvironments vary from alluvial fan and alluvial plain to the margino-littoral zones.

- Alluvial Fan (E1): This environmental association includes the facies F1a (conglomerates), sub-facies F1b (Crudely bedded gravel) (Fig. 4C-D), F1c (gravelly sandstone) and possibly F2 (Massive sandstone) (Fig. 4C), forming two main architectural elements SG and GB. The massive (Gms) (Fig. 4B) or stratified conglomerates (Gm) reflect a proximal-median alluvial fan environment (Miall, 1985; 2006), transitioning to a distal for F1c (channelized gravelly sandstones). This association is observed in the lower part of the Guettioua Formation, where conglomerate beds are coarse and very frequent.
- Alluvial Plain (E2): This environment, which includes F1c (cross-bedded sandstones), F2 (horizontal bedded sandstones), F3 (siltstones), and F4 (mudstones), is considered one of the most prominent in our study area (Fig. 5). It includes the architectural element OF (overbank fines) and AFPS Facies Association. The cross-bedded sandstones (St) represent fluvial channel infillings, while the horizontal bedded sandstones (Sh), siltstones (Fl), and mudstones (Fm) reflect floodplain and crevasse-splay deposits. Mud cracks (Fig. 5A) indicate surface exposure during non-flood periods, suggesting the temporary emergence of the floodplain. The dominance of channel-filling sandstone facies suggests an important major fluvial system characterized by bedload channels (Galloway and Hobday, 1983).
- Sabkha (E3): This environment includes claystone and siltstone facies (Fl and Fm) interbedded with thin fine-grained sandstone (Sh), reflecting a sabkha environment.

4.4. Ichnology

In the western High Atlas, the red bed formations are characterized by an absence of body fossils, which makes a fine chronostratigraphic calibration of this succession difficult. However, some ichnofossils were observed in very fine-grained sandstones and silt-clay deposits of the floodplain, which can assist in reconstructing the paleoenvironment. The following ichnogenera characterize the trace assemblage.

4.4.1. Ichnogenus Taenidium (Heer, 1877)

- Description: These trace fossils (Fig. 7A) are cylindrical, horizontal or inclined, unlined or very thinly lined, and unbranched. In our study area, Taenidium occurs in very fine-grained sandstones and is red to brown, generally ranging in width from 8 mm to 2 cm. The trace fossils contain a segmented fill articulated by meniscus-shaped parting (D'Alessandro and Bromley, 1987).
- Interpretation: The meniscate burrows observed in the red beds are attributed to the continental trace fossils of the Scoyenia ichnofacies (Buatois and Mángano, 2004; 2011; Rodríguez-Tovar et al., 2016) (Fig. 8). These burrows are produced by deposit feeders (arthropods, hemipterans and earthworms). The presence of these trace fossils suggests transitional zones between terrestrial and shallow water or temporarily submerged environments. These environments are characterized by non-marine, low energy conditions that are periodically exposed) (Table 2), specifically within fluvial floodplains and lake shore zones (Savrda et al., 2000; Hembree and Hasiotis, 2008; Knaust, 2015; Rodríguez-Tovar et al., 2016; Mineiro et al., 2017).

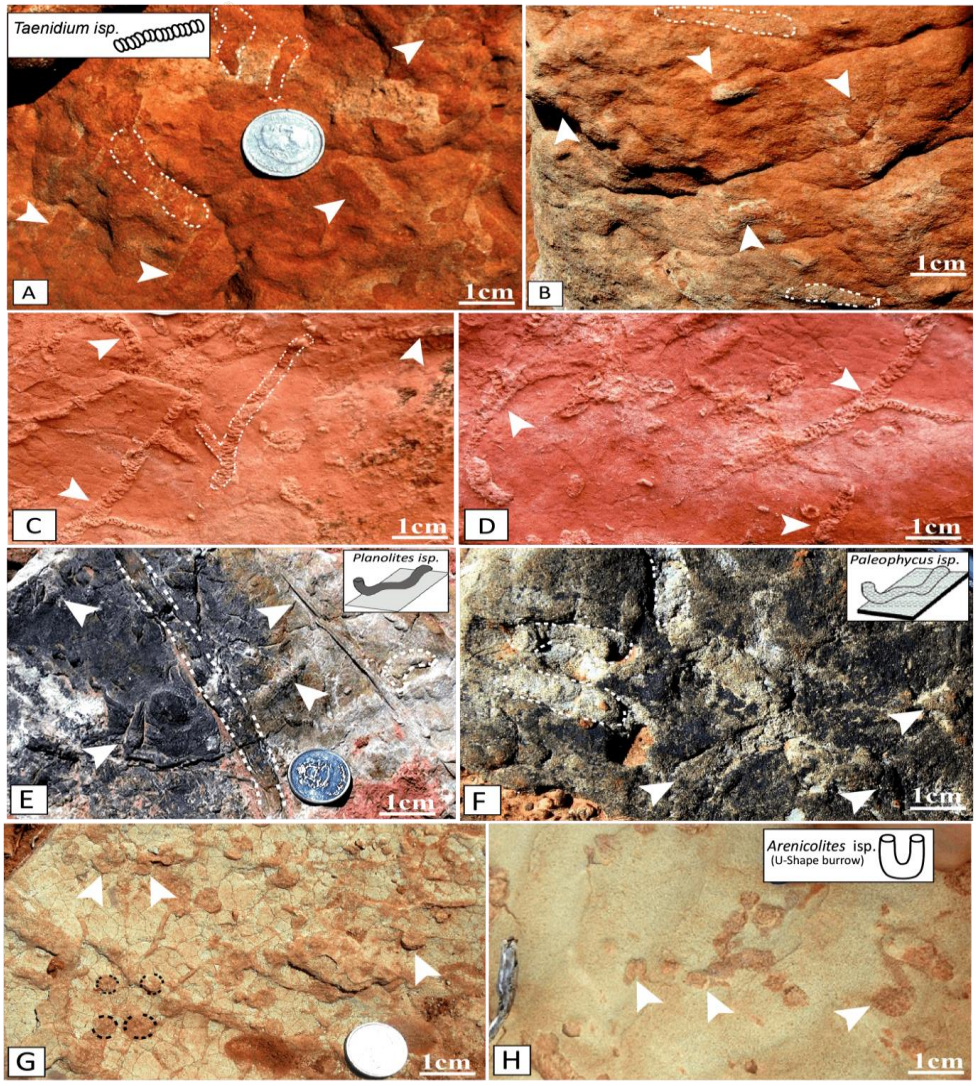


Fig. 7. Invertebrate trace fossils from the Middle Jurassic of Jbel Sour basin. (A) and (B) Fine grained sandstone showing general aspects of *Taenidium isp.;* (C) and (D) Detail of *Taenidium isp.*; (E) Simple horizontal burrows *Planolites isp.*; (F) *Palaeophycus isp.*; (G) and (H) Plan view of *Arenicolites isp*

4.4.2. Ichnogenus Palaeophycus (Hall, 1847)

- Description: This ichnotaxon is represented by horizontal, straight to curved, or cylindrical burrows preserved in full relief on the top of layers. The burrows fill is massive and identical to the host sediment (Pemberton and Frey, 1982); they have a diameter of 1cm and a length of up to 5cm. These trace fossils are mainly found in thin bedded siltstones and greenish silty mudstone (Fig. 7D), which locally contain desiccation cracks.
- Interpretation: Palaeophycus is generally considered a domichnial trace fossil, interpreted as the dwelling of predatory crustaceans and other arthropods (Häntzschel, 1975; Gouramis et al., 2003), suspension-feeding (Pemberton and Frey, 1982; Mángano et al., 2005), or annelids (Keighley and Pickerill, 1997). This trace fossil is mainly found in thin-bedded green siltstone or silty mudstonethe trace fossils contain a segmented fill articulated by meniscus-shaped, and it is commonly thought to appear in the periodically exposed overbank lake (extremely shallow lacustrine) sedimentary environment (Fig. 8). Additionally, this trace fossil is recorded from the Precambrian through the Pleistocene (Knaust, 2017).

Table 2. Expression of ichnofacies found in fluvial deposits

Ichnofacies	Description	Included ichnogenera	Implications
Scoyenia	Simple meniscate Burrow	*Taenidium*	Sandy to argillaceous sediments deposited in low-energy subaqueous areas that periodically emerged
Mermia	Horizontal, simple, straight to curved burrow	*Planolites* *Palaeophycus*	Low energy permanent subaqueous condition of flood basin ponds.
Skolithos	U-shaped burrow	*Arenicolites*	Moderate to high energy shoreline and delta environments

4.4.3. Ichnogenus Planolites (Nicholson, 1873)

- Description: *Planolites* (Fig. 7C) is a feeding burrow (Fodinichnion) of deposit feeders, produced by vagile endobenthic organisms such as polychaetes (Alpert, 1975; Pemberton and Frey, 1982). It is a simple, horizontal, oblique burrow, unlined to thinly lined, unbranched, cylindrical or subcylindrical tunnels, straight or slightly curved, ranging from 4 to 7 mm in diameter, with a massive filling different from that of the host rock (Pemberton and Frey, 1982).
- Interpretation: This trace fossil is found in association with *Palaeophycus* burrows (Fig. 7C-D) and it is reported from various environments throughout the Phanerozoic. *Planolites* and *Palaeophycus* may be confused due to their similar characteristics: both are simple, horizontal to inclined, cylindrical burrows with complete relief preservation. However, *Palaeophycus* is distinguished by its lined walls and a passive fill that commonly matches the host rock (Pemberton and Frey, 1982).

4.4.4. Ichnogenus Arenicolites (Salter, 1857)

- Description: This ichnotaxon is characterized by a rounded structure (Fig. 7B) with vertical "U"-shaped burrows without any connection between the limbs (Salter, 1857). The diameter of the burrow tube is approximately 3 mm, with a width between the two limb tubes ranging from 1 to 2cm. The burrows are preserved in full relief and the infill is identical to the host rock.
- Interpretation: *Arenicolites* are interpreted as dwelling and feeding burrows of suspension-feeding annelids (Hakes, 1976) or small crustaceans (Goldring, 1962). These trace fossils occur in various environments but are typical of shallow marine settings with moderate to high hydrodynamic energy (Pemberton and Wightman, 1992; Gingras et al., 1999; Mángano and Buatois, 2004) (Table 2).

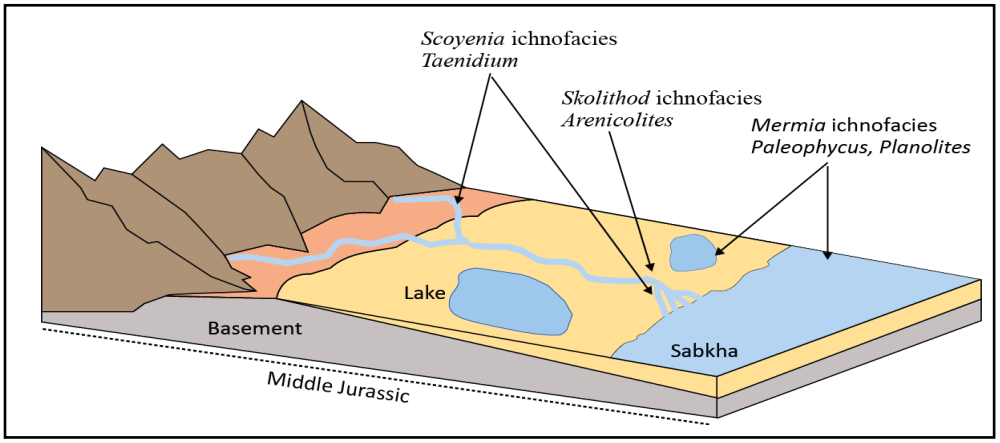


Fig. 8. Schematic model for the distribution of continental ichnofacies in the Middle Jurassic red beds of the Jbel Sour section

5. Discussion

In most of the Moroccan Atlas domain, the continental "Red Beds" precede the Late Cretaceous transgression (Choubert and Faure-Muret, 1960- 1962) and succeed the basin fill of the Tethyan Jurassic troughs (Du Dresnay, 1979). In the western High Atlas, Middle Jurassic “red beds” outcrops in various syncline basins bounded by Lower Jurassic formations, referred to as a supra-tidal to intertidal coastal environment (Ferrandini et al., 1982; Hadach et al., 2015) and are overlain by Aptian-Albian marine formations (Hadach et al.,2020). The “red beds” are organized into three characteristic formations: the coarse-grained fluvial Guettioua and Jbel Sidal formations separated by the Iouaridene Formation (Jenny et al., 1981). This section has not been studied in detail before, indeed, the results obtained are correlated with previous research on the “red beds” in the Moroccan High Atlas (Charrière and Haddoumi, 2016; Cavallina, 2019; Adardor, 2021; El Ouali, 2021).

The alluvial unit (Guettioua Fm) is located in the lower part of the red beds. This formation consists of massive or channelized conglomerates, cross-stratified sandstones, and gravelly sandstones. This facies association (conglomerates and gravelly sandstones) suggests an alluvial fan environment (E1). This depositional setting is comparable to model 1 described by Miall (1996; 2016). The presence of massive, disorganized, and angular to sub-angular conglomerate indicates deposition by debris flow, which are associated with relatively rapid sedimentation and high energy flow conditions (Nemec and Steel, 1984; Postma, 1984).

In the Ait Attab and Ouaouizaght synclines, the top of this formation is marked by basaltic lava flows (B1) (Haddoumi et al., 2002; 2010).

The Iouariden Formation is composed of massive mudstone-siltstone and fine-grained laminated sandstone containing ripple marks, mud cracks, and burrows. These characteristics indicate an ephemeral, playa-lake and lacustrine environment, distinguished by high periods of desiccation. The succession studied reaches a maximum thickness of up to 50 m, although, in the western sector of the Beni Mellal High Atlas, its thickness increases to several hundred meters (charrière and Haddoumi, 2016). In contrast, in the southern front of the Central High Atlas, this formation is absent or represented by lithologically different equivalents, such as in the Dades River valley (Benvenuti et al., 2017). In the Ait Attab and Ouaouizaght synclines, the base of this formation is marked by the presence of B2 basalts (Haddoumi et al., 2002; 2010; Bensalah et al., 2013).

The Jbel Sidal Formation represents the second fluvial unit of the Middle Jurassic “red beds” in the High Atlas of Marrakech. It is composed of silty clays interbedded with sandstone and microconglomerate beds, corresponding to a floodplain environment transitioning into a marginal-littoral plain environment. So, the stratigraphic section starts with deposits from a proximal to median alluvial fan environment, represented by the Guettioua Formation. This is followed by the Iouariden Formation, characterized by floodplain deposits. The upper of the section transitions into a marginal-littoral environment (Jbel Sidal Formation). Two models are proposed to explain the depositional environments of these tree studied formations (Fig. 9).

Upon completing this sedimentological and ichnological study of the red beds in the Ait Ourir region (western end of the Atlas Gulf), the results were compared with previous studies of the red beds in the Central High Atlas. Based on the paleoenvironmental data available from both regions, the Middle Jurassic red beds are more appropriately compared with those on the southern side of the Marrakech High Atlas. However, the three lithostratigraphic units identified at the NW part of the Central High Atlas (Beni-Mellal region) are also present in our study area.

Significant variation in lithology and formation thickness has been observed, ranging from 300 to 600 meters in the various basins of the Demnat region to only a few tens of meters in the Ait Ourir region. These lithological and thickness variations within the formations can be attributed to the potential uplift in the High Atlas (Baudon et al., 2009).

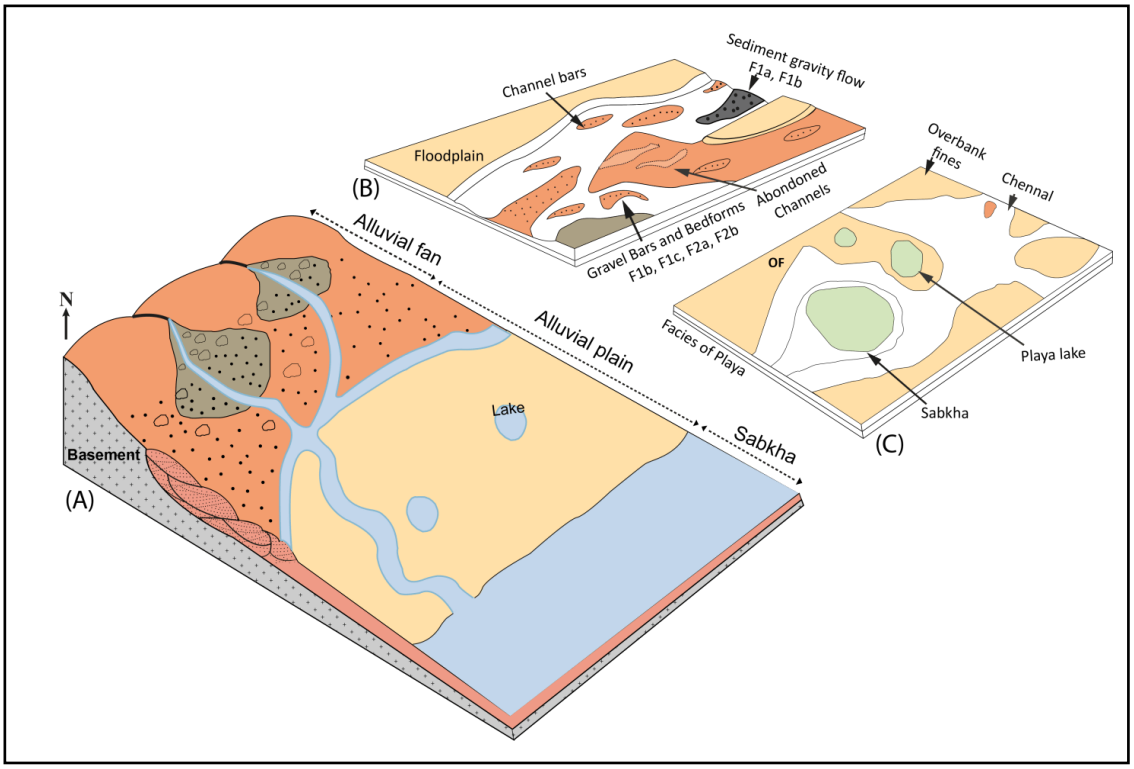


Fig. 9. (A) Depositional model of the study area illustrating different environments; (B) Depositional model corresponding to an alluvial cone system with gravity flow; (C) alluvial plain associated with playa lakes and sabkha

The absence of evaporites (except for a few traces of gypsum) is also observed in the Marrakech High Atlas. This can be attributed to more limited tectonic subsidence in this region, resulting in a thinner sedimentary accumulation. However, the basaltic flows B1 and B2 found in the Beni-Mellal region (the NW side of the Central High Atlas) are absent in our studied area. This can be attributed to the fact that uplift was identified under an anorogenic context notable in the NW and western Central High Atlas, where the continental separation was quite significant.

The trace fossils within the red bed formations are characterized by low ichnodiversity, represented by a combination of the Scoyenia ichnofacies (e.g., *Taenidium* isp.) and the Mermia ichnofacies (e.g., *Palaeophycus* isp. and *Planolites* isp.) within the Iouariden Formation, as well as the Skolithos ichnofacies (e.g., *Arenicolites* isp.) within the lower part of Jbel Sidal Formation. These ichnofacies suggest the presence of frequent incursions by shallow, short-lived lacustrine or wetland environments onto an extensive alluvial plain (Fig. 7).

The *Mermia* ichnofacies is indicative of low-energy, permanently subaqueous conditions, typically associated with periodically exposed overbank lakes (extremely shallow lacustrine) environments. The *Scoyenia* ichnofacies reflects low to moderate energy conditions at fluvial-lacustrine transitions (Savrda et al., 2000; Hembree and Hasiotis, 2008; Knaust, 2015; Rodríguez-Tovar et al., 2016; Mineiro et al., 2017), and the *Skolithos* ichnofacies is characteristic of moderate to high energy environments, such as shorelines and deltas (Buatois and Mángano, 2007).

6. Conclusions

Sedimentological and ichnological analysis of the continental red beds has provided insights into the sedimentary record and paleoenvironmental evolution of the Middle Jurassic. The sedimentological analysis allowed for the identification of five facies types, reflecting different depositional environments ranging from continental to marginal-littoral domains.

The results indicate that the sediments were deposited in a proximal system characterized by alluvial fan (debris flows) generated by high-energy hydrodynamic flows, transitioning to a braided fluvial environment, then to a distal fluvial environment typically associated with alluvial plains and playa lakes, and ultimately leading to a marginal-littoral plain environment.

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