



Facies sedimentology, high-resolution sequence stratigraphy, and depositional environment in the Imini Triassic basin (southern High Atlas of Marrakech, Morocco)

Soukaina Obad¹ · Rachid Essamoud¹ · Abdelkrim Afenzar²

Received: 25 May 2022 / Accepted: 18 August 2022 / Published online: 2 September 2022
© Saudi Society for Geosciences 2022

Abstract

In this work, we present a detailed sedimentological study of the detrital and evaporitic deposits encountered in outcrop in the Triassic (Middle Triassic to Upper Triassic) Imini basin of the High Atlas of Marrakech, overlain by Upper Triassic-Lower Liassic basaltic flows. It rests in angular unconformity on the Cambro-Ordovician basement. It may be grouped in four formations: Timalizene formation (Anisian), Clayey Sandstone formation (Anisian), Ighil formation (Carnian), and Upper clayey Siltstones formation (Norien-Rhetian). A detailed facies analysis of several sections in the basin allowed the characterization of thirteen facies types, as well as their associations in six architectural elements, typical of channel bars, overbank deposits, floodplain... It allows to establish three depositional environment models: (1) a proximal alluvial fan system, (2) a braided system, (3) an alluvial plain associated with playas lakes and sebkhas. The interpretation of this series in terms of genetic stratigraphy has allowed the recognition of twenty-six genetic units (UG1.....UG26) characterizing continental environments. These genetic units are grouped in three minor cycles (C1, C2, C3) of progradation-retrogradation (stacking of genetic units), themselves grouped in a major cycle (C'1). This study allows to clearly show that these progradations-retrogradations are linked to the variation of the base level in the basin. The succession of proximal alluvial fans would thus mark a period of base level fall. The transition to low-energy conditions and a low-gradient system (floodplain) would then correspond to a phase of base level rise. This variation is of tectonic and/or climatic (alloycyclic) origin and is linked to the Atlasic rifting.

Keywords Triassic · Sedimentology · Facies · Depositional environment · Architectural elements · Genetic stratigraphy

Introduction

At the beginning of the Mesozoic, the northwestern part of the African continent was affected by a first fracturing associated with the first stages of the opening of the central Atlantic. At the east of this Atlantic rift, an Atlas rift

was developed at the location of the central (El Arabi 2007; Frizon de Lamotte et al. 2008) and eastern Moroccan Atlas system during the Triassic and Early Jurassic (Ouarhache et al. 2012). The first generation of continental and detrital syn-rift basins associated with evaporitic deposits appeared in the Late Triassic (Bertrand 1991; Medina 1995; Hminna et al. 2013) and is linked to (Hminna et al. 2013) a significant replay of some Hercynian sutures (Ouarhache et al. 2012).

In Morocco, the Triassic basins of the High Atlas, oriented ENE-WSW to E-W (Fig. 1), are oblique by 40° to the Atlantic Rift (oriented NNE-SSW) against which they terminate to the west in the Essaouira-Agadir region (Quarbous et al. 2003). These Moroccan basins can be grouped into two categories, according to their sedimentary filling (Fig. 1):

Basins containing a high thickness of detrital facies with some evaporites, they are mainly located in the High Atlas and Middle Atlas (Oujidi and Et-Touhami

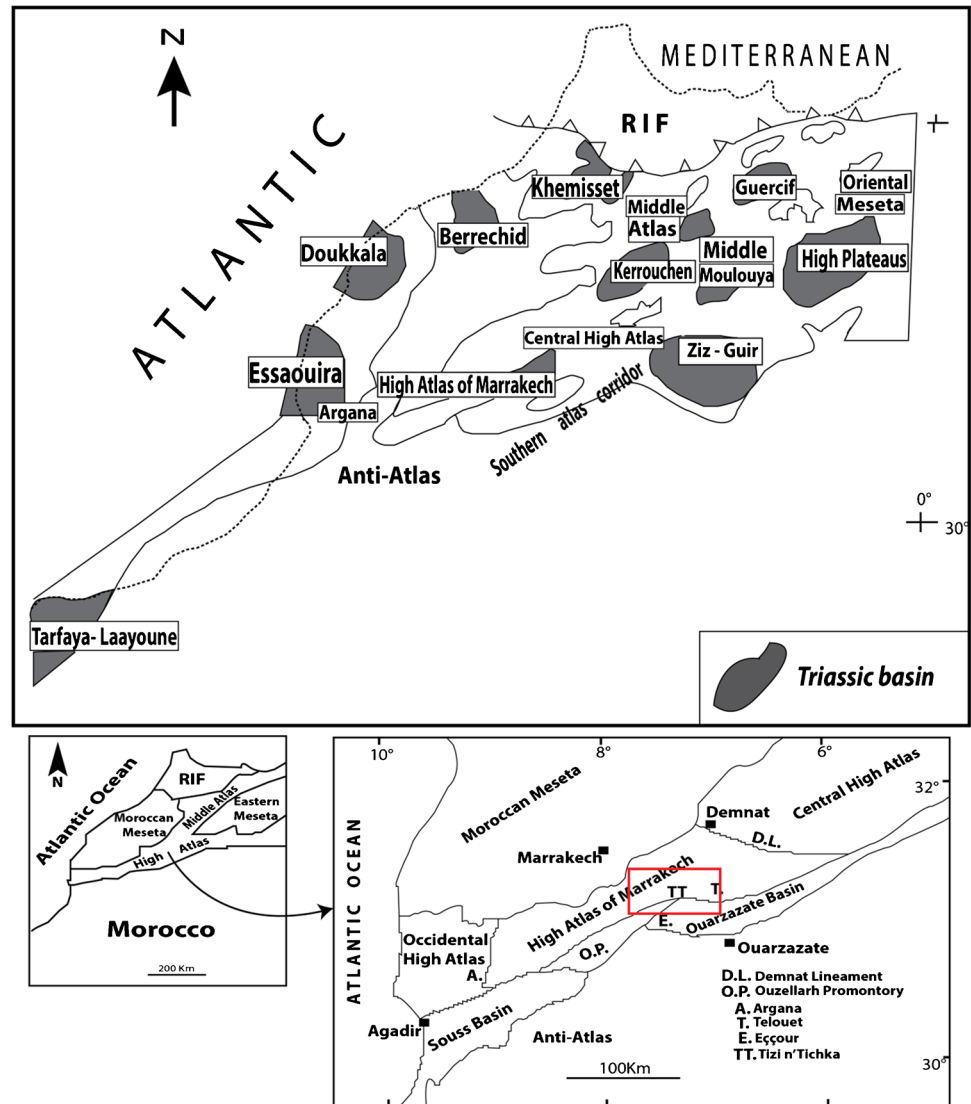
Responsible Editor: Attila Ciner

✉ Soukaina Obad
Soukaina.obad@gmail.com

¹ Geology Department, Laboratory of Geosciences and Applications, Faculty of Sciences Ben M'Sick, Hassan II University of Casablanca, AvDriss El Harti, B.P 7955 Sidi Othmane, Casablanca, Morocco

² Geology Department, Laboratory of Geosciences, Environment and Associated Resources, Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

Fig. 1 Map of the Triassic basins of Morocco (Van Houten, 1977)



2000): Argana Valley (> 2500); High Atlas of Marrakech (1500 m); Central High Atlas (1000 m); and Kerrouchene basin (600 m). The deposition of these detrital facies started in the Early Triassic, for example in the Argana Valley (Hofmann et al. 2000; Tourani et al. 2010; Klein et al. 2010); in the Middle Triassic in the Central High Atlas (El Arabi et al. 2006) and in the Oujda Mountains (Oujidi and Elmi 2000; Courel et al. 2003); and in the Upper Triassic in the Middle Atlas basins (Baudelot et al. 1990; Lachkar et al. 2000). In the Atlasian domain, the saliferous series is smaller and is represented in outcrop by gypsum levels (e.g., in the central High Atlas, (Courel et al. 2003; El Arabi 2007; Baudon et al. 2012; Vergès et al. 2017).

Basins with thick deposits of salt and mudstone generally overlying thin deposits of conglomerate and sandstone at the base. They are mainly developed on the Meseta and on the Moroccan Atlantic margin (Oujidi and Et-Touhami

2000) late Triassic: Middle Moulouya (Tamdaft, 950 m); Boufekrane (900 m); Mohammedia-Benslimane-ElGara-Berrechid (1500 m) (Afenzar 2018), Khemisset (1000 m) (Taugourdeau-Lanz 1978; Et-Touhami 1994); Essaouira (2300 m) (Slimane and Mostaine 1997; Hafid 2000), and the Doukkala Basin (1400 m) (Hminna et al. 2013).

The Imini basin which is our study area belongs to the Atlas rift basins and is located in the High Atlas of Marrakech. The Triassic outcrops show sedimentological, lithostratigraphic, and structural variations that give interesting information on the spatiotemporal evolution of the deposits recorded in this period of atlasic rifting.

The aim of this study is, from a detailed sedimentological analysis (1), to reconstruct the paleoenvironments, and their evolution during the Middle and Upper Triassic and (2) for the first time, to realize high-resolution sequence stratigraphic regional correlations within continental strata and their link with base level variations.

Geographic and geological situation

The present study concerns the Imini basin which is located about 80 km north of the city of Ouarzazate (road N9 Marrakech-Ouarzazate) (Fig. 2). It belongs to the southern sub-atlasic zone of the High Atlas of Marrakech, limited to the north by the region of Tizi n'Tichka, to the east by the uplands of Khela, to the south by the first landforms of Siroua and to the west by the ancient massif.

It is a rift-type basin whose opening was initiated by the reactivation of pre-existing structures in the basement. This basin is filled with red deposits of Triassic age (El Arabi 1988) that lie unconformably on the Ouarzazate Neoproterozoic Group (Fig. 3).

Methodology

The study of the basin is based on a detailed sedimentological analysis of the sections executed in different regions of the basin, which allows to identify the great variety of sedimentary facies and to characterize their associations as well as the architectural elements (Miall 1985, 2006).

In this phase, we based our methodology on the lithological, grain sizes, textural and sedimentary structures observed in outcrop; the nomenclature of facies is compared with that of Miall (1977, 1985 and 2006).

The vertical and horizontal arrangement of these facies gives rise to architectural elements. These are characterized according to several criteria determined by Allen (1983) and

Miall (1985, 2006) which are the nature of the lower and upper boundary surfaces, the external geometry, the scale, and finally the internal structures.

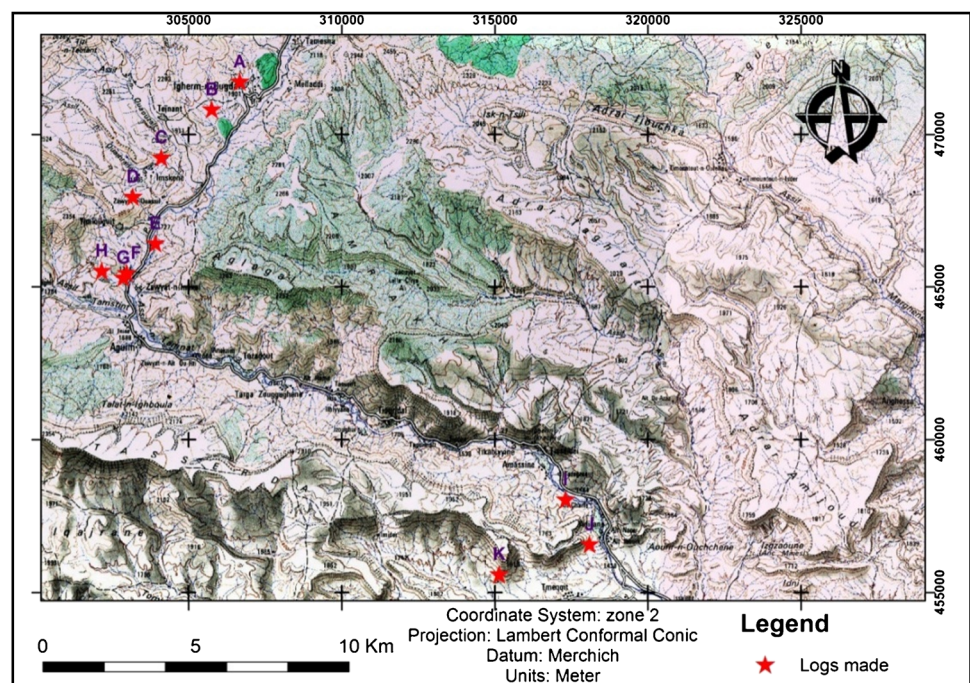
The determination of the paleo-environments is the ultimate phase based on the nature and types of lithofacies as well as the types of architectural elements.

The genetic stratigraphy applied in this study consists of a high-resolution correlation of field sections of the studied basin, which allows individualizing isochronous markers separated by a few tens or hundreds of thousands of years (Bourquin and Guillocheau 1993, 1996).

After characterizing the sedimentary facies, identifying the association of facies, interpreting the depositional environments, and setting up a sedimentological model, we characterized the genetic unit and then established a stacking diagram showing the evolution in time of the depositional environment.

The second step is to correlate the genetic sequences along two transects and according to reference levels that can serve as isochronous markers. For this purpose, four levels were identified: (1) the unconformity between the Hercynian basement and the first facies deposited in the basin; (2) the contact between the detrital facies and the first bioturbated facies; (3) the contact between the detrital facies and the first evaporitic (gypsum) facies deposited in the basin; (4) the lower part of the basaltic formation considered to be the boundary between the Upper Triassic and the Lower Liassic (Peretsman 1985). Genetic sequence mapping was performed below to obtain 2D and 3D geometries for better interpretation of the evolution of these genetic units as well as lateral facies crossings.

Fig. 2 Geographical position of the study area with the different sections studied at the basin level



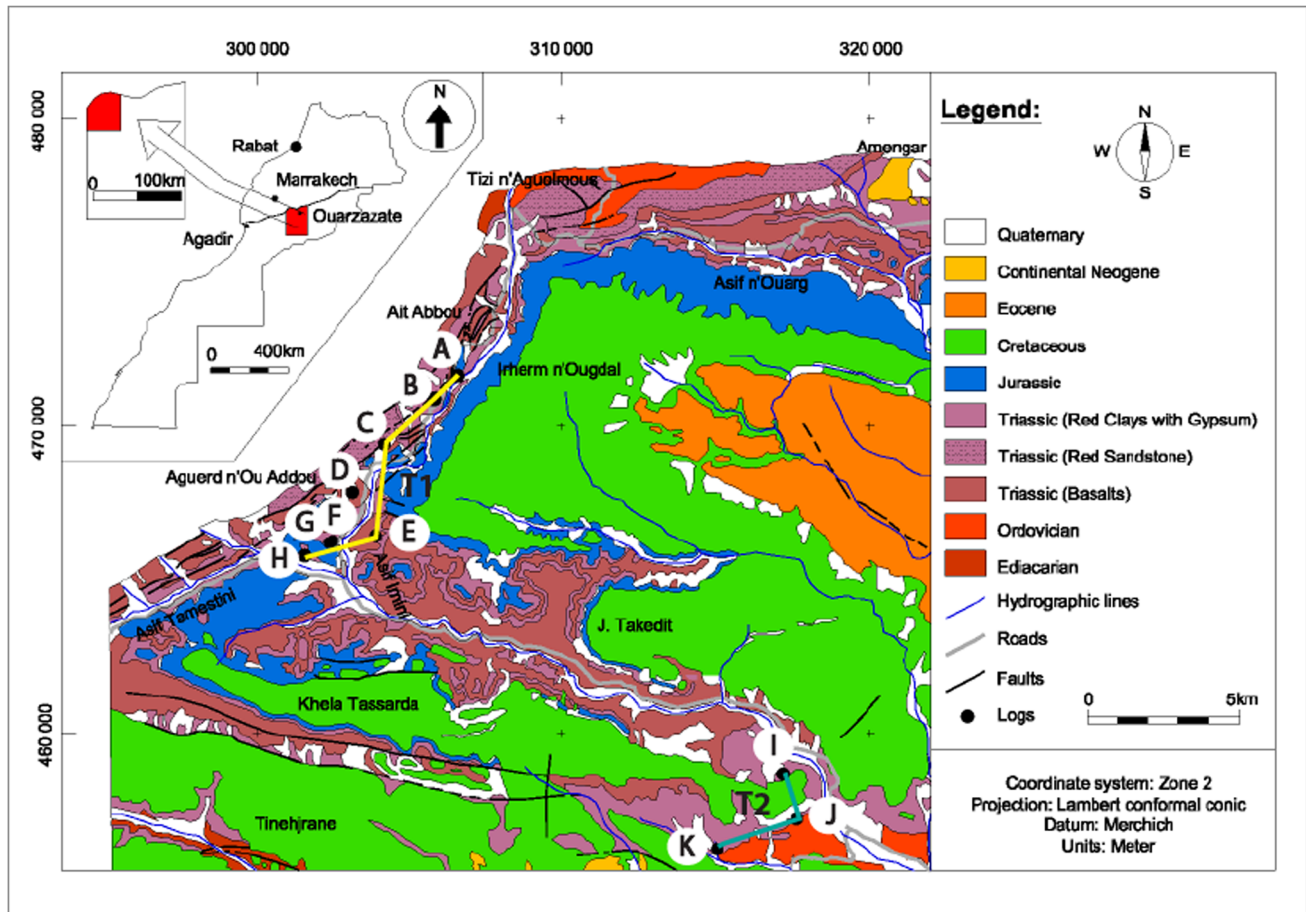


Fig. 3 Geological map of the Imini basin with the analyzed sections and the correlation transects in genetic stratigraphy (A Ighrem, B Dai Ighrem, C Inskerne, D Agrd Noudoz, E Inkel', F Inkel'', G: Inkel''',

H Timellouguit, I between Ait Ibourek and Tazegzaoute, J Adighane, K Imezgane, T1, T2: correlation transects)

Results of the facies analysis

Thirteen lithofacies (Table 1) were recognized in the studied outcrops of the Imini basin, which are dominated by conglomeratic facies (Gf1: Gmm; Gf2: Gcm; Gf3: Gh; Gf4: Gt; Gf5: Gp), sandstone facies (Sf1: Sm; Sf2: St; Sf3: Sp; Sf4: Sr; Sf5: Sh), and silt-clay facies (Ff1: Fl; Ff2: Fm). The evaporitic facies are less thick in the study basin as in most of the atlasic basins (Telouet, Asni, Ait Ourir) (Peretsman and Holser 1988).

Lithofacies

Coarse facies (conglomerates)

Facies Gf1

Description: This facies is identified at the base of the sedimentary series in the Imini area (Imezgane, Fig. 4) and

at the top of the Douar d'Inkel section. It is a purplish conglomerate, sometimes reddish massive, with subangular to angular elements, unorganized and poorly sorted size between 2 and 30 cm. The whole floats in a matrix of fine to very fine sandstone. In the Imezgane section, this facies reaches its maximum thickness in the basin (5 to 8 m); in the Douar d'Inkel, it becomes less thick (0.5 m). It is characterized sometimes by erosive surfaces, without sedimentary structures. These conglomerates are characterized by a carbonate calcitic epigenia, and these epigenia of pedological origin are related to the water tables that characterize the edge of the basin (slope nappes) (El Arabi 1988, 2007).

The basic conglomerates of the Imini basin series are formed by continental deposits of alluvial fans in the marginal basin. It includes all the formations discordant on the underlying Paleozoic (Fig. 5), before the "Ighil Sandstone." Its lower limit is an unconformity observed in many areas, it is also over 30° (El Arabi 2007).

Interpretation: This facies is probably related to a high viscosity that inhibits turbulence and because of a relatively

Table 1 Description and interpretation of sedimentary facies of the Imini Triassic series and correspondence with those of (Miall 2006; Fambrini et al. 2017; Shettima et al. 2018) for detrital facies

Lithofacies	Characteristics	Interpretation
Conglomerate facies		
Gf1: Gmm	Massive, poorly sorted, poorly organized conglomerate with abundant matrix	Plastic debris flows (high strength, viscous)
Gf2: Gcm	Poorly sorted, poorly organized conglomerate with little matrix	Pseudoplastic debris flows (low strength)
Gf3: Gh	Stratified conglomerate, imbrication of the pebbles	Longitudinal bar deposits
Gf4: Gt	Conglomerate with trough cross beds	Deposited by traction by a unidirectional current. Gt facies indicate minor channel deposition by digging and filling
Gf5: Gp	Conglomerate with planar cross-bedding	Planar cross-bedding also indicates lower flow regime conditions. Besides, it indicates straight crested bedforms (2D dunes and bars)
Sandstone facies		
Sf1: Sm	Massive sandstone, fine to coarse	Rapid deposition, gravity flow of sediments
Sf2: St	Sandstones with trough cross-stratifications	Linguoid bars
Sf3: Sp	Sandstone with plane cross beds	Planar-cross stratification is related to 2D subaqueous sand dunes along transverse bars under lower flow regime conditions
Sf4: Sr	Very fine to very coarse sandstone	Ripples of the low current regime
Sf5: Sh	Sandstones with horizontal stratification	Upper flow regime
Clayey-silt facies		
Ff1: Fl	Laminated to massive siltstone	Overbank deposits
Ff2: Fm	Massive or laminated mudstones	Abandoned overbank or channel deposits
Evaporite facies		
FF3: Ef	Fibrous gypsum	Lagoon or playa lake deposits

short transport mechanism (Miall 2006). The absence of sedimentary structures and the existence of a mixture of fine and coarse materials suggest that this conglomerate is deposited by gravity flows, debris flows (Miall 1977, 1978; Poli 1997; Opluštil et al. 2005; Malaza et al. 2013). According to (Miall 2006), these debris flows are interpreted following the visco-plastic flow model. These characteristics reveal a resemblance between this facies *Gf1* and the facies *Gmm* of Miall (2006). Its debris flow deposited at the more proximal part of an alluvial fan (Fig. 6a).

Facies Gf2

Description: This facies was observed at the base of the series (in the Agouim and Imini areas, Fig. 6b). It is characterized by the presence of a brownish to reddish conglomerate with subangular to angular elements of size between 1 and 15 cm, unorganized and poorly sorted. Its thickness reaches up to 5 m in the Imezgane and Imeskrane field sections. The matrix is not very abundant with a total absence of sedimentary structures.

Interpretation: According to Miall (2006), the presence of subangular to angular, poorly organized and poorly sorted elements is related to interactions between grains and a rather short transport mechanism. The absence of

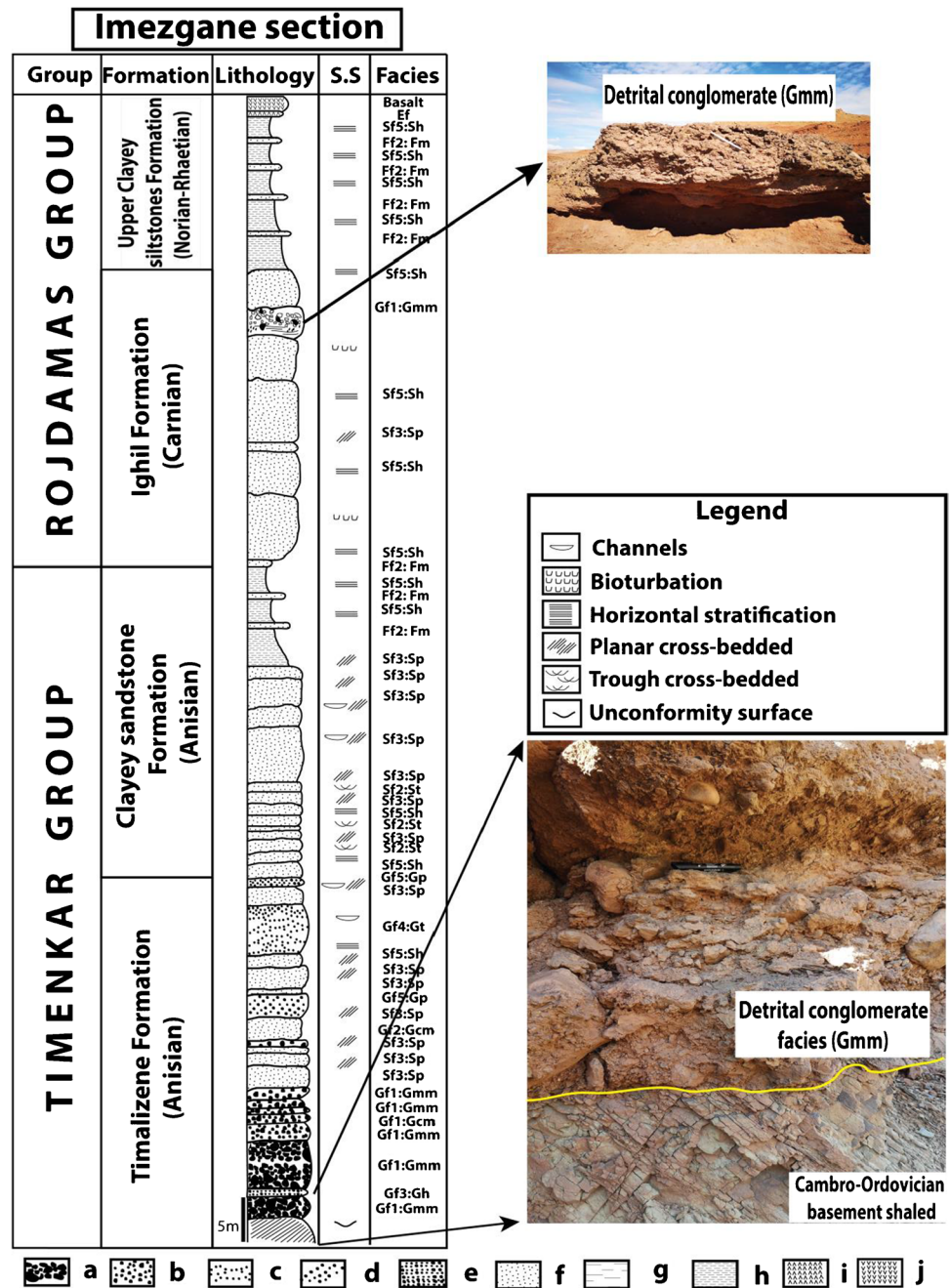
sedimentary structures and the existence of a mixture of fine and coarse materials suggest that this conglomerate is deposited by gravity flows, debris flows (Opluštil et al. 2005; Miall 2006; Malaza et al. 2013). They are low-strength pseudoplastic debris flows deposited by viscous, laminar, or turbulent flows (Miall 2006). They are interpreted according to the grain interstitial flow model (Miall 2006; Malaza et al. 2013). These features indicate a similarity between this *Gf2* facies and the *Gcm* facies of Miall (2006). Its debris flow deposited at an alluvial fan.

Facies Gf3

Description: The facies *Gf3* is identified in the Imini area (Imezgane section) with a variable thickness from 3 to 8 m. It is a reddish conglomeratic lithofacies; the elements are subrounded to rounded with a maximum size of 10 cm and are generally small to medium pebbles and gravels. These conglomerates are stratified (Fig. 6c), with pebbles sometimes imbricated. The sandstone matrix is occasionally abundant.

Interpretation: The presence of stratification and imbricated structure suggests that it has been deposited at longitudinal bars; the latter are characteristic of braided channels and usually form in the upstream part of a fluvial system

Fig. 4 Position of the Gmm conglomeratic facies on the Imezgane section. **a, b, c, d,** and **e** conglomerate; **f** sandstone; **g** siltstone; **h** mudstone; **i** gyp-sum; **j** basalt



(Walker 1975a, b a, b; Collinson 1978; Rust 1979). Based on all these characteristics, facies Gf3 corresponds to facies Gh (Miall 2006).

Facies Gf4

Description: This facies is a purplish conglomerate with sub-angular to sub-rounded elements of maximum size of about 4 cm and a matrix of fine sandstone. It presents through cross-bedding and is characterized by an erosive

base. This facies is 3 m thick in the Imini area and 6 m thick in the Imeskrane section (Fig. 6d).

Interpretation: The trough cross-bedding structures observed are the result of scour and fill fluvial origin (Miall 1977, 1978); a current, if locally strong enough, can erode the bottom of the bed over which it flows and create small depressions then filled with both coarse and fine material (Vaskou 1981).

According to these features, facies Gf4 is comparable to facies Gt (Miall 1978, 2006). It is a minor channel deposit.

Fig. 5 Panoramic view showing a lower boundary separating the Middle Triassic series from the shaly Cambro-Ordovician basement

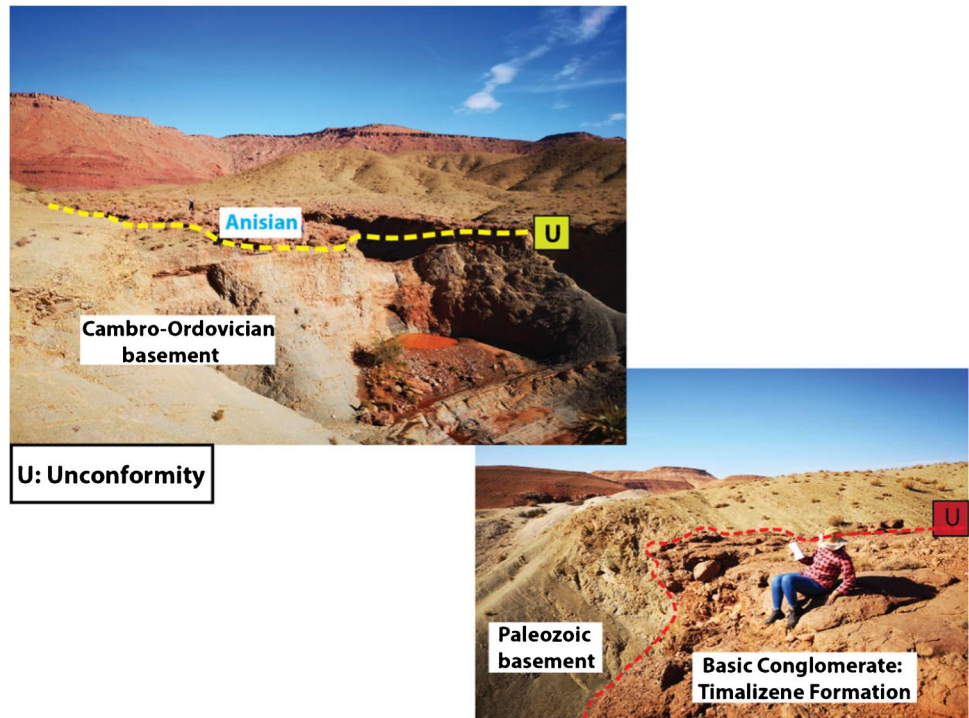
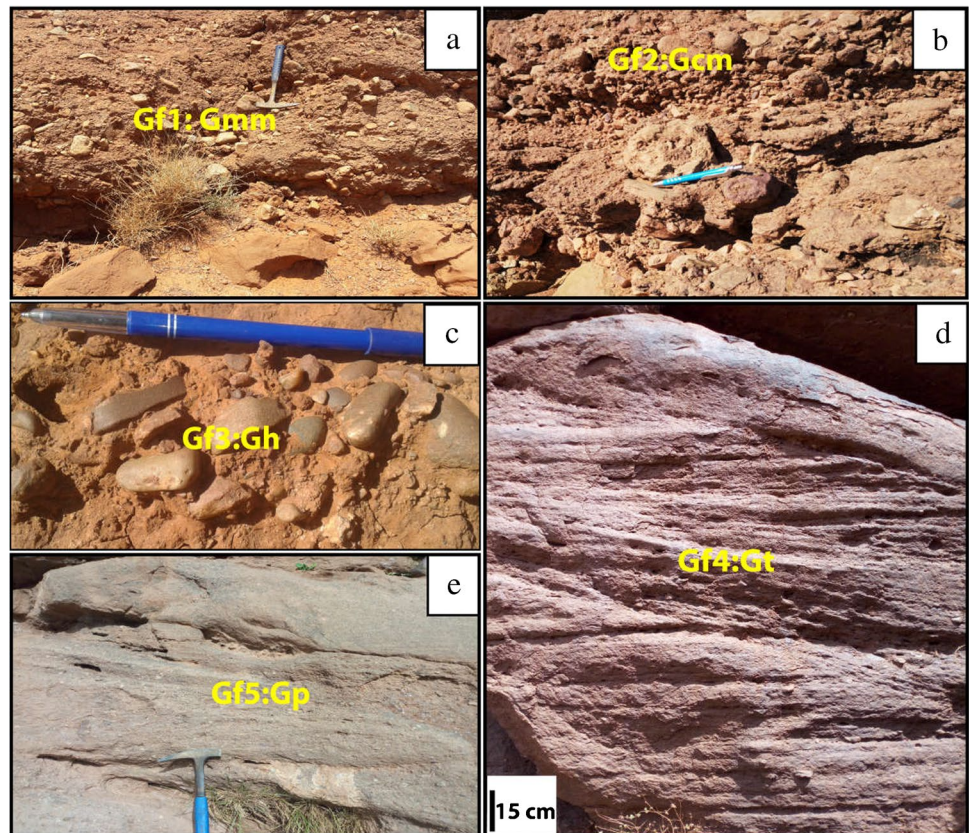


Fig. 6 Conglomerate facies identified in the basin studied. **a** and **b** Poorly sorted, poorly organized conglomerate (*Gf1: Gmm* and *Gf2: Gcm*). **c** Stratified conglomerate (*Gf3: Gh*). **d** Trough cross-bedded conglomerate (*Gf4: Gt*). **e** Planar cross-bedded conglomerate (*Gf5: Gp*) (Hammer and pen show the scale)



Facies Gf5

Description: This is a purplish conglomerate with sub-angular to sub-rounded centimetric elements, (2 to 10 cm) (Fig. 6e). The pebbles are planarly cross-stratified. The matrix is formed mainly by fine sandstone. In the basin, this facies was identified at many sections (Timellouguit, Agrd Noudoz, Dai Ighrem, Imezgane, and Imeskrane); it is 5 m thick.

Interpretation: The characteristics of the Gf5 facies conglomerates show that they were deposited by traction by a unidirectional current (Fambrini et al. 2017). The planar cross bedding also indicates a lower flow rate and straight crested bedforms (2D dunes and bars) (Boggs 2006). Facies Gf5 then corresponds to the Gp facies of Miall (1978, 2006). According to this author and also EjiUba et al. (2005), this facies was deposited as a transverse and linguoid bar in a shallow channel braided fluvial system.

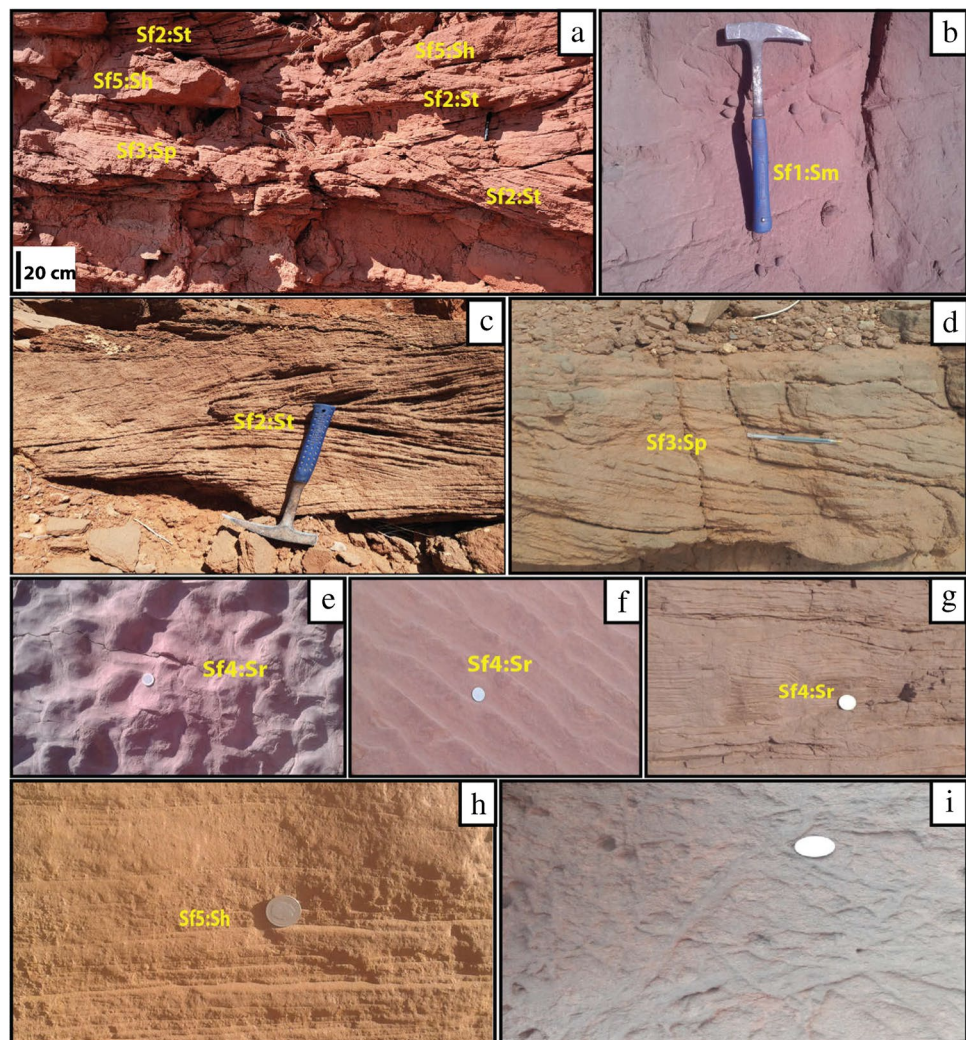
Medium facies (sandstone facies)

Facies Sf1

Description: Facies Sf1 was observed in the Imini area (Adighane section). It is a massive coarse sandstone, mar-morized, without sedimentary structures (Fig. 7b) and 2 to 7 m thick.

Interpretation: The massive aspect and the absence of any sedimentary structure show that facies Sf1 resembles to the Sm facies of Miall (1978, 2006). The presence of fragments of different sizes as well as the isolation of some from others is probably related to their fall along the slope (Sohn et al. 1997) associated with the depositional mechanism itself or movement in a high-load flow (Postma and Cruickshank 1988). According to (Miall 1985, 1996; Einsele 2000; EjiUba et al. 2005) and Afenzar and Essamoud (2020), this facies corresponds to deposition by gravity flows.

Fig. 7 Sandstone facies Identified in the studied basin. **a** Different sedimentary structures characterizing the sandstone facies. **b** Massive sandstone Sf1: Sm. **c** Cross-bedded sandstone Sf2: St. **d** Sandstone with planar cross bedding Sf3: Sp. **e, f, and g** Sandstone with ripples (climbing, asymmetric, and crescent) Sf4: Sr. **h** Sandstone with horizontal planar bedding Sf5: Sh. **i** Bioturbated sandstone surfaces (Hammer and coin show the scale)



Facies Sf2

Description: This facies was observed in six sections studied (Ighrem, Agrd Noudoz, Dai Ighrem, Imsekrane, Timelouguit, and Imezgane) with a variable thickness from 2 to 8 m. It is a medium to coarse sandstone, reddish color with trough cross-bedding and erosive basal limits (Fig. 7c).

Interpretation: This facies Sf2 is interpreted as the product of three-dimensional sinuous ridge bedforms (3D dunes and bars) migrating in channels under the conditions of the upper part of the lower flow regime (Miall 1977, 1981, 1996; Hjellbakk 1997). It may correspond to the St facies of Miall (1978, 2006) and often forms in linguoid bars.

Facies Sf3

Description: Facies Sf3 is a medium to coarse sandstone; it is stratified and presents planar cross-beds (Fig. 7d). It has been identified in almost all sections of the basin with a thickness varying from 1 to 8 m. Except in the sections of the Inkel area where it is absent.

Interpretation: This facies reflects the migration of small ripples on the surface of longitudinal bars as current competence decreases (Miall 1984; Cula and Courel 1987); it is formed in transverse and linguoid bars (lower flow regime) (Miall 1977, 1978, 2006; Bridge 2003; EjiUba et al. 2005; Boggs 2006; Malaza et al. 2013). Facies Sf3 corresponds to the Sp facies of Miall (1978, 2006).

Facies Sf4

Description: Facies Sf4 is composed of a medium to coarse sandstone with patches of marmorization, and its thickness varies between 0.5 and 1 m. It was observed in four sections (Douar d'Inkel, Imezgane, Agrd Noudoz, and Dai Ighrem) where it contains different well visible types of ripples (climbing, asymmetrical, and crescent) on the surface of the banks (Fig. 7e).

Interpretation: The variety of forms of these ripples is related to the current velocity because the gradual transition from one form to another occurs from increasing current speed (Collinson et al. 2006). This facies is formed by migration of current ripples with both traction and suspension deposition in the lower flow regime (low current regime ripples) (Gary 2009), thus facies Sf4 corresponds to facies Sr according to (Miall 1977, 1978, 2006).

Facies Sf5

Description: This facies Sf5 has been identified in all of the outcrops of the basin except between the village of Ait Ibourek and Tazegzaoute (which is formed essentially by argillites). It is a medium to very fine sandstone

characterized by horizontal laminations and parting lineations. Its thickness can reach 15 m (Fig. 7h).

Interpretation: Parting lineations result from the abutment of beds and fascicles of plane and horizontal sandy laminae (Mckee and Weir 1953) and are generated by small longitudinal eddies at the base of the internal turbulent layer and provide an excellent indicator of paleocurrent (Miall 2006). This type of deposit is interpreted as developed under conditions of high velocity currents (Reineck and Singh 1973; Harms et al. 1975) and more precisely under an upper flow regime (Tucker 2003; Miall 1978, 2006). So, Sf5 facies resembles to the Sh facies of Miall (1977, 1978, 2006).

The surface of this facies in the Imezgane section has bioturbations that are either vertical or inclined, meaning that this bioturbations indicates quiet periods allowing for the development of burrowing organisms (Soualhine et al. 2003) after high energy deposition (Fig. 7i).

Fine facies

Facies Ff1

Description: This facies is represented by siltstones, silty, and stones with horizontal laminations and massive clayey siltstones, with a variable thickness between 1 and 8 m (Fig. 8a). It reaches its maximum thickness at the level of the Adighane section and sometimes alternates with centimetric levels of gypsum. It has reddish to brownish aspect with greenish to grayish marmorization levels due to the transformation by leaching of iron oxides, which are the origin of the red color of the sediments.

Interpretation: According to Miall (1977, 1978, 2006), this facies corresponds to a vertical accretion deposit characteristic of a laminar flow of very low energy. This facies, which resembles the Fl facies of Miall (1977, 1978, 2006), can therefore be interpreted as a deposit on an alluvial plain.

Facies Ff2

Description: It has been identified in all the outcrops studied in the basin with a change in thickness from one area to another. On the Adighane section, the facies reaches its maximum thickness (40 m). Its minimum thickness is about 20 cm (Fig. 8b). Facies Ff2 corresponds to massive reddish and grayish clays showing levels of marmorisation without stratification and lamination. These argillites in the Imini and Ighrem Nougdal regions (section between Ait Ibourek and Tazegzaoute, Imsekrane and Ighremsections) contain evaporite fillings which are present in the form of fibrous veins (fibrous gypsum) (Fig. 8b and c).

Interpretation: This facies corresponds to very fine sediments deposited in calm, shallow, and later desiccated subaqueous environments, broadly defined. These are the most

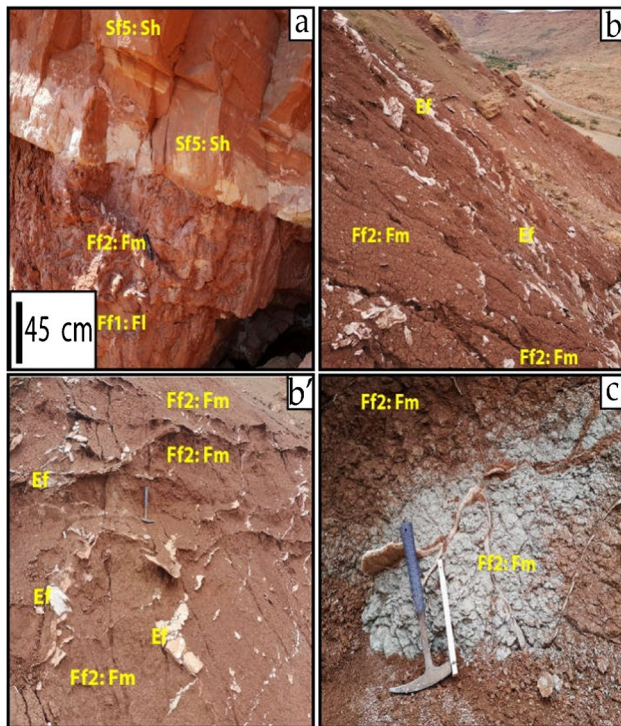


Fig. 8 Sandstone and fine facies observed in the study area. **a** Alternation of sandstones with horizontal plane bedding (*Sf5: Sh*), mudstones (*Ff2: Fm*), and siltites (*Ff1: Fl*). **b** and **b'** Alternation of clayey facies (*Ff2: Fm*) and evaporitic facies (*Ef*). **c** Grayish and reddish clayey facies (*Ff2: Fm*). (Hammer shows the scale)

distal deposits of a floodplain in a decanting fluvial zone (Fambrini et al. 2017). Settling of fine-grained particles in depressions between bedforms occurred, after flooding of the alluvial plains (Fambrini et al. 2017). This facies corresponds to Miall's (1977, 1987, 2006) facies *Fm* interpreted as an abandoned channel deposit (Miall 1985; Einsele 2000; EjiUba et al. 2005).

The (*Fl, Fm*) are sometimes associated with thin to thick, laminated (*St, Sp*), and rippled (*Sr*) sandstone beds and often alternate with horizontally bedded sandstone (*Sh*). The set of features noted suggests flood deposits. It is a floodplain deposit (Bourges 1987; Miall 1985, 2006).

Facies FF3 (Ef)

Description: The evaporitic facies *Ef* is a whitish to translucent gypsum, and it is represented in the form of horizontal and subvertical to inclined fibrous veins, filling pre-existing fractures in massive argillites. The thickness of these veins does not exceed tens of centimeters (Fig. 8).

Interpretation: According to Gustavson et al. (1994) and Afenzar and Essamoud (2020), this type of gypsum is the product of several concurrent processes that are duplicated

in most halite and anhydrite-bearing basins. The formation of fibrous gypsum veins requires the conjunction of several phenomena: (1) the creation of extensional fractures resulting from subsidence over halite dissolution zones, (2) hydration of anhydrite to gypsum by circulation of groundwater, and (3) transport of excess calcium sulfate and precipitation of gypsum in fractures.

Architectural elements and facies associations

The architectural elements and facies associations characterized in the studied basin are detailed below, six architectural elements were recognized: SG, sediment gravity; CH, channels; GB, gravel bars and bedforms; SB, sandy bed forms, flows; LS, laminated sand sheet; FF, overbank fines.

Architectural element SG "Sediment gravity flows" (AE1)

This architectural element characterized at the base of the series studied (Imezgane section) is formed by an association of facies *Gf1* and *Gf2* corresponding to facies *Gmm* and *Gcm* (Fig. 9) of Miall (2006). These facies are erosive-based, with elongated and sometimes narrow lobes of geometry (Miall 2006). The thickness of these facies can be up to 5 m and the widths vary between 2 and 4 m. The basal contact of the architectural element (*SG*) is discordant with the Cambro-Ordovician basement.

Interpretation: According to Miall (1985, 2006), the *SG* (sediment gravity flow) element is formed by gravity flow deposits, primarily poorly sorted pebbles and gravels, formed in the proximal regions of alluvial fans.

Architectural element CH "Channels" (AE2)

This architectural element has been characterized also at the base of the Imezgane section. It is formed by the association of sandy lithofacies *St, Sp, and Sh* and characterized by erosive bases concaved upwards. The beds are deposited as lenses and sheets comprising a multiple channel fill (Fig. 10A). The thickness of this element is variable from 0.7 to 2.5 m with a width that reaches 2 m.

Interpretation: The *CH* element has fourth and higher order (5th, 6th) basal boundary surfaces. These boundaries are sometimes slightly planar erosive and in other cases erosive and concaved upwards. Within the element, and between the lithofacies, small boundaries can be identified. According to Miall (1985), the determination of the *CH* element differs with the size and type of channel. Thus, in our case, this element was deposited in multiple channels that

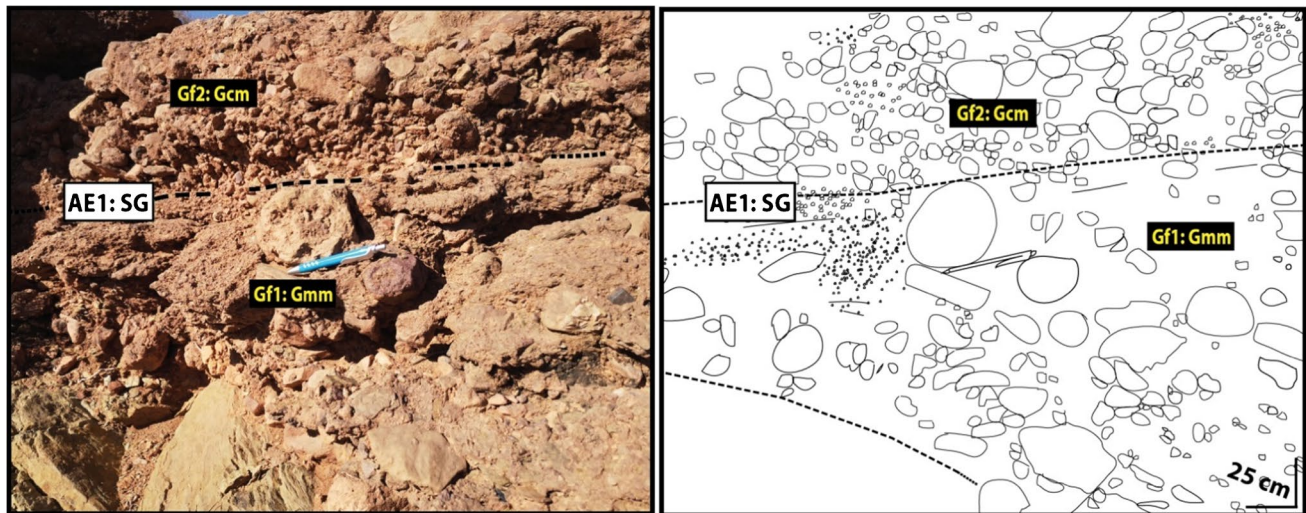


Fig. 9 Architectural element SG (sediment gravity flows) characterized in the basal “Timalizene” formation of the studied Triassic basin (*pen shows the scale*)

are highly mobile in space and time (Deleplancque 2016) and are characterized by a process of filling by migration.

Architectural element GB “Gravel bars and bedforms” (AE3)

The *GB* architectural element was identified at the base and top of the studied series, and it is formed mainly by the assembly of coarse imbricated and stratified lithofacies with planar cross bedding: *Gf3* and *Gf5* correspond respectively to the *Gh* and *Gp* facies of Miall (1977, 1978, and 2006). The majority of the lithofacies of this element are organized in tabular bodies 5 to 6 m thick; minor lithofacies have been identified between these major lithofacies as in the case where they present themselves in the form of sandy dunes *Sf5* (*Sh*) with a height that is between 0.5 and 0.9 m and a width of 1.5 m.

Interpretation: The preceding characteristics and the interpretations of Miall (1985, 2006) indicate that the *GB* (gravel bars and bedforms) architectural element (Fig. 10B) generally corresponds to coarse deposits deposited at the level of gravel bars. These coarse deposits are sometimes intercalated with sandstone that are deposited during low velocity flows (Massari 1983).

Architectural element SB “Sandy bedforms” (AE4)

The *SB* architectural element was determined at the Imezgane section (Imini region) and the Dai Ighrem section (Ighrem Nougdal region). It is formed by an assembly of medium to fine lithofacies which are *Sf2*, *Sf3*, and *Sf5* corresponding respectively to the *St*, *Sp*, and *Sh* facies of Miall (1978, 2006). The thickness of the facies of this element

is variable between 1 and 5 m. The beds have basal erosional contacts (Fig. 11) and are deposited as lenses and sheets including channel fill. This element is characterized by first-, second-, and third-order internal boundaries and fourth-order external boundaries (Miall 2006).

Interpretation: According to these characteristics, we note that the architectural element *SB* (sand bedforms) of Miall (1985, 2006) characterizes several depositional environments. The *SB* element in our case is dominated by the lithofacies *Sf3* (*Sp*) which is characterized by planar cross bedding and is interpreted as a crevasse fill facies. This element therefore corresponds to the crevasse channels and/or crevasse-splays deposits.

Architectural element LS “Laminated sand sheet” (AE5)

This element was identified at the base and top of the series studied on the three formations: Timalizene, sandstone-clay, and Ighil, where it intercalates with very thin laminated facies of siltstone in some sections studied, but on the section of Imezgane (Imini area), and it intercalates with red mudstone: facies *Ff1* (*Fl*) and *Ff2* (*Fm*), resulting in an assemblage of sandy lithofacies and fine to very fine lithofacies.

Interpretation: The *LS* element occurs as horizontal planar-bedded sandstone sheets, with thicknesses varying from area to area (ranging from 60 cm to 10 m) (Fig. 12). The stratified sand sheets have been interpreted as the product of flash floods (Miall 1977, 1984; Rust 1978; Sneh 1983) in Miall (1985). The sand (sandstone) sheets are deposited on flat to slightly eroded surfaces. The bedding of this element likely represents the margins of individual flood sheets (Miall 1985; 2006).

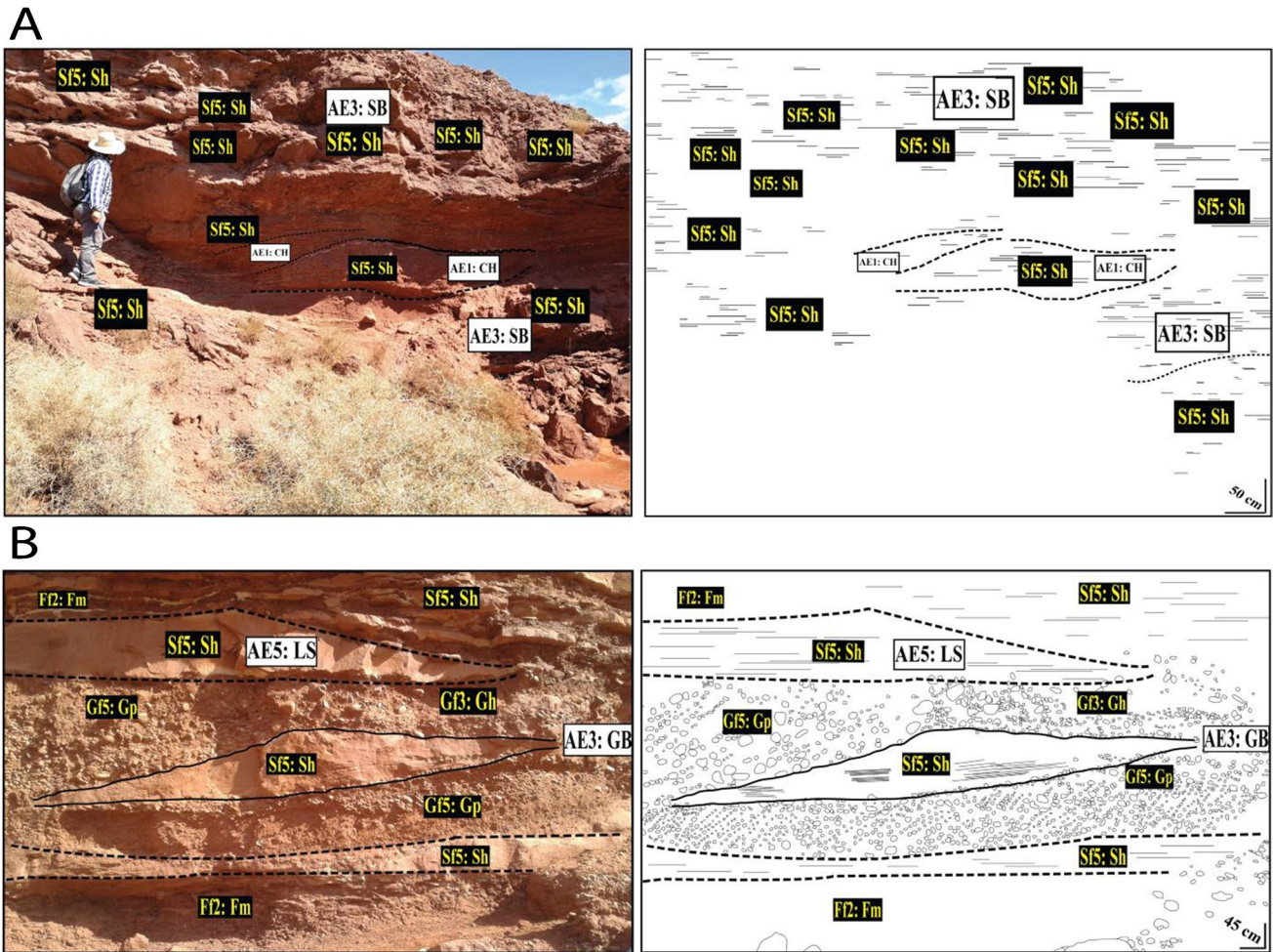


Fig. 10 Architectural elements CH (channels) (A) and GB (B) (gravel bars and bedforms) characterized in the sandstone-clay formation of the studied Triassic series

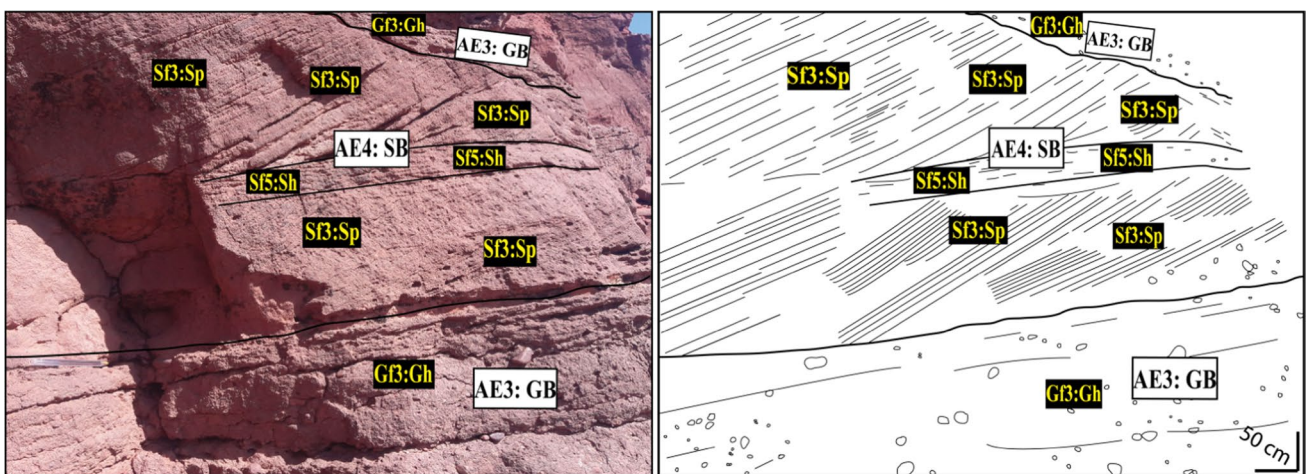
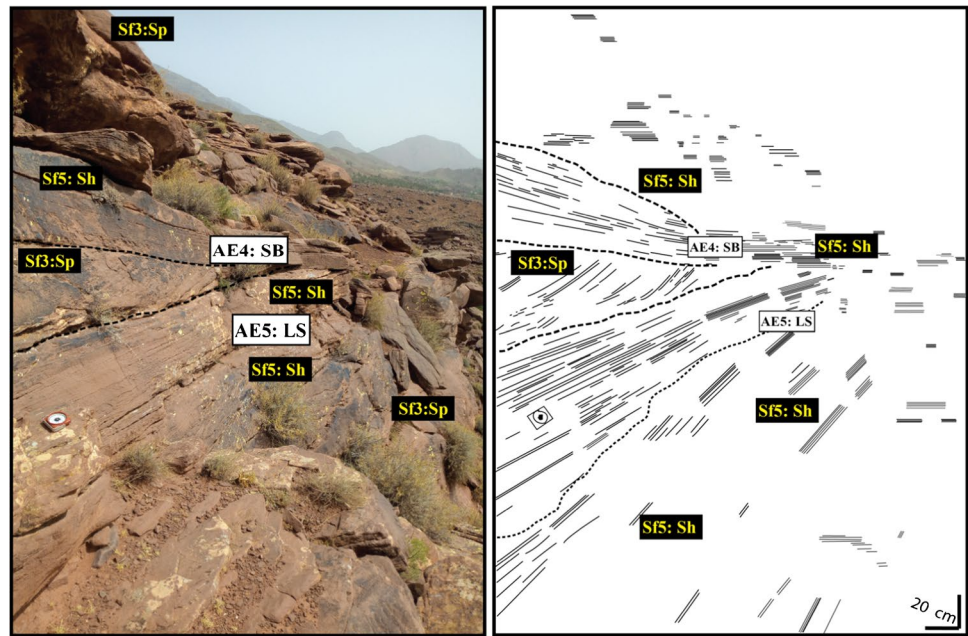


Fig. 11 Architectural element SB (sandy bedforms) identified in the Ighil formation of the studied basin

Fig. 12 Architectural element *LS* (laminated sand sheet) characterized at the top of the Ighil formation of the studied Triassic series (compass shows the scale)



Architectural element FF “Overbank fines” (AE6)

The *FF* element is the major element in the basin studied, as it dominates almost all outcrops, with great variation in thickness from one area to another. Its thickness can reach 40 m (in the outcrops of Adighane), while its minimum thickness is about 20 cm (in the outcrops of Inkel). It is an association of fine to very fine facies. The constituent facies of this element are *Ff1* (*Ff*), *Ff2* (*Fm*), and *Sf5* (*Sh*) (Fig. 13). These reddish facies sometimes show a massive aspect with crude laminations indicating a quiet depositional environment. In other cases, they show horizontal laminations with

very thin sandstone intercalations (8 to 20 cm) and show marmorization.

Interpretation: In most cases, the *FF* feature has a sheet-like geometry, reflecting its origin by vertical aggradation, and is characterized by fine facies that are overbank deposits (overbank facies) representing floodplain deposits, with temporary lakes and wetlands, probably under wetter climatic conditions (Miall 2006; Fambrini et al. 2017).

In addition to these six architectural elements of Miall (1985, 1996, 2006) recognized in our basin, two other facies associations not described by Miall have been characterized:

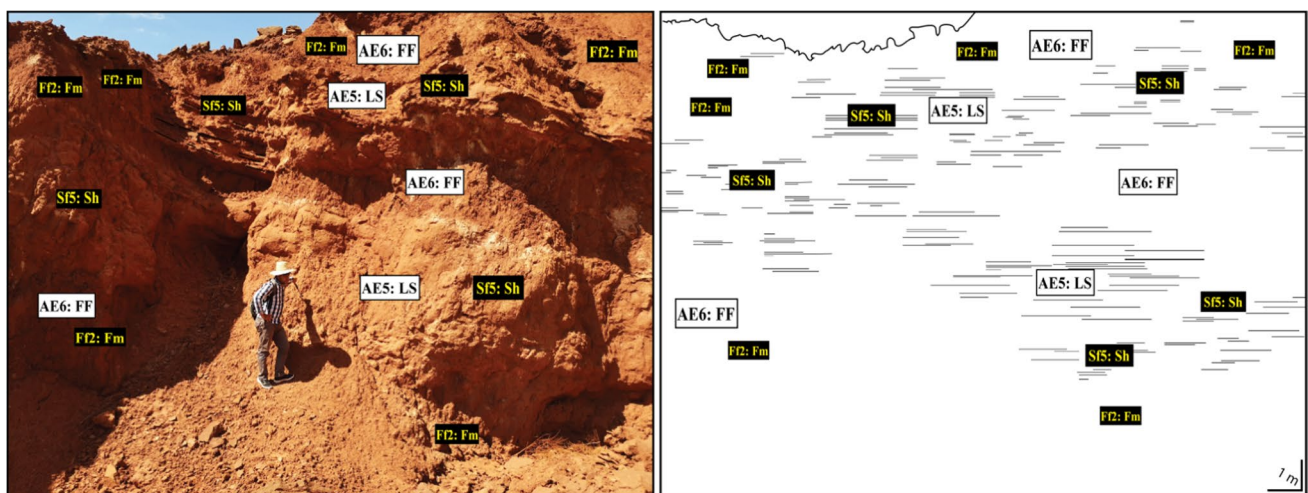


Fig. 13 Architectural element *FF* (overbank fines) observed at the level of the “upper clayey siltstone” top formation of the studied Triassic basin

Association of facies of playa and sebkhas (AFPS)

This facies association (AFPS) was identified in six sections studied: (Ighrem section, Agrd Noudoz section, Timelloguit, Imezgane, and Adighane section). Its assembly is 10 to 40 m thick. It is formed by alternations of fine red siltstones and mudstones (lithofacies *Ff1: Fl* and *Ff2: Fm*) and medium to fine sandstones sometimes showing horizontal planar bedding (lithofacies *Sf5: Sh*). The facies association (AFPS) shows a cyclicity of sandstone and silt–clay facies, which shows that their deposition occurred at playa lake and sebkhas (El Arabi 1988; Liu and Wang 2001; Afenzar and Essamoud 2020).

Studies of trace elements B, Ga, and Li on different sections of the southern flank of the High Atlas of Marrakech revealed a confined character of sebkhas on the whole southern flank (El Arabi 1988).

These confined sebkhas deposits continue with the rest of the upper clayey siltstone formation of the studied basin and up to the base of the Liassic as shown by the works devoted to the whole evaporitic series of the lower Mesozoic of Morocco, associated with the basaltic flows (El Arabi 1988).

Evaporite facies association (AFE)

It is an association of clayey facies (*Ff2: Fm*), silty facies (*Ff1: Fl*), and evaporitic facies (*Ef: gypsum*) from 1 to 40 m thick. This evaporitic facies has often a primary origin and in other cases, it is diagenetic. The presence of gypsum testifies a hot and humid climate, with however periodic contributions of fine detrital material (Afenzar and Essamoud 2020).

Geochemical studies have been carried out on the Upper Triassic–Lower Liassic Atlas evaporites and have shown that these evaporites are characterized by the following: a small extent and thickness of the deposit, a generally monomineral composition containing gypsum/anhydrite or halite, and highly variable sulfur and strontium isotope ratios (Holser et al. 1988; Beauchamp et al. 1995).

Depositional environments

Sedimentological analysis of Triassic deposits in the Imini basin indicates that fluvial conditions have changed markedly over time. In the present study, conceptual models were constructed to provide insight into the depositional environments. Internal sedimentary structures, lithofacies boundary surfaces, and their vertical associations (architectural elements) were used to interpret these depositional environments (Fig. 14).

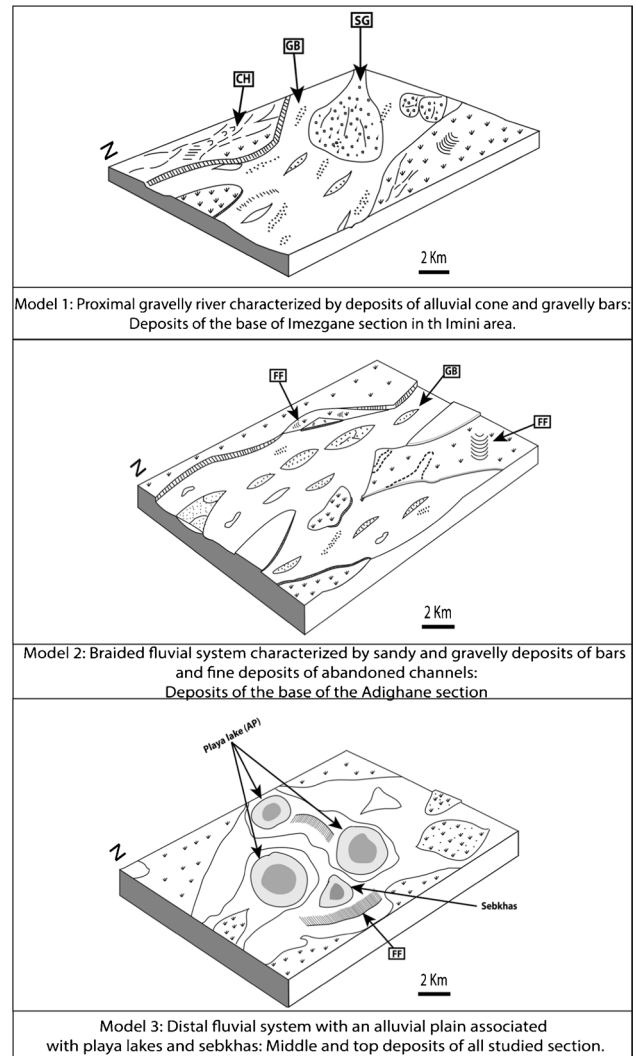


Fig. 14 Different depositional environments reconstructed in the study area

Proximal braided system with alluvial fans

In the Imini area (mainly in Imezgane section), the outcrops are dominated mainly by coarse and medium facies at the base and in the middle: facies *Gf1: Gmm*, *Gf2: Gcm*, *Gf3: Gh*, *Gf4: Gt*, *Gf5: Gp*, *Sf2: St*, *Sf3: Sp*, and *Sf5: Sh*. Three main architectural elements were formed by these facies: (*SG*), (*GB*), and (*CH*). The top of this section is marked by the finest facies; these are generally *Ff1: Fl* siltstones and *Ff2: Fm* mudstones more or less stratified and forming the architectural element *OF*. Thus, the coarse basal deposits were deposited in alluvial fans and gravity flowing gravelly rivers (model no. 1 of Miall 1985, 2006). The presence of silty and clayey facies of the *OF* element at the top is probably due to the migration of fine particles and their deposition at the abandoned channels.

Braided system with shallow channels and gravelly bars

In Adighane section which it is well represented, the coarse deposits at the base (stratified conglomerate with subangular and locally imbricated elements showing longitudinal bar deposition) are overcome by facies *Ff3: Sp*. This assemblage formed the *GB* architectural element. It was deposited in a braided fluvial system characterized by gravelly bars (model no. 2 of Miall 1985, 2006).

Distal fluvial system: alluvial plains associated with playas lakes and sebkhas

It is well presented in the Imeskrane section by fine to very fine deposits with very significant thicknesses (ten to a hundred meters). These facies are generally *Sf5: Sh, Ff1: Fl*, and *Ff2: Fm*. The *APS* facies association (playa and sebkhas association) is well identified. It is formed in this section by alternations of fine siltstone, claystone, and very fine sandstone showing an aspect of playa and sebkhas deposits. The assemblage gives rise to architectural element *OF*.

These medium and fine deposits that characterize the median and summit part of the studied series were deposited in a flood plain with playas lakes and sebkhas where evaporitic facies (gypsum) are formed by the evaporation of supersaturated water under a hot and humid climate.

Genetic stratigraphy and correlation

Identification of genetic units

High-resolution sequence stratigraphy in continental environments where interpretations are more complex is based on the analysis of high-frequency fluctuations of the base level defined from sedimentological studies (Bourquin et al. 1998).

A genetic unit is generally represented by a period of erosion and transit linked to the base level fall (progradation) and a period of base level rise (aggradation). Periods of erosion and transit correspond to low preservation of facies while the aggradation period corresponds to high preservation (Merzeraud 1992; Bourquin and Guillocheau 1996; Afenzar and Essamoud 2020).

Genetic units UG1 and UG2

These are the genetic units in which an alluvial fan system transit to a proximal braided system with an alluvial plain. The period of base level fall (progradational part)

is characterized by the deposition of massive facies without sedimentary structure with coarse, angular, poorly sorted elements bounded by erosional surfaces. These facies are deposited with angular unconformity on the Cambro-Ordovician basement and are organized into *AE4* architectural elements. The period of base level rise (retrogradational part) is characterized by the development of conglomeratic facies showing horizontal stratification with imbricated and well-sorted pebbles and sandstones showing planar cross bedding that are formed in bars in a braided fluvial system with an alluvial plain (Fig. 15).

Genetic unit UG3

At this genetic unit UG3, the period of base level fall (prograding part) is characterized by the deposition of massive conglomeratic facies without sedimentary structures. The rising base level phase (retrogradational part) is marked by well-organized facies with horizontal planar stratification and other facies showing planar cross bedding formed in channels and bars in a braided fluvial system (architectural elements *AE1* and *AE2*).

Genetic units UG4 and UG5

These genetic units show only a retrogradation phase (the rise of the base level). They are characterized by the development of distal fine facies deposited on the floodplain. The association of facies characteristic of these units is related to a large floodplain marked by the presence of an *FF* architectural element.

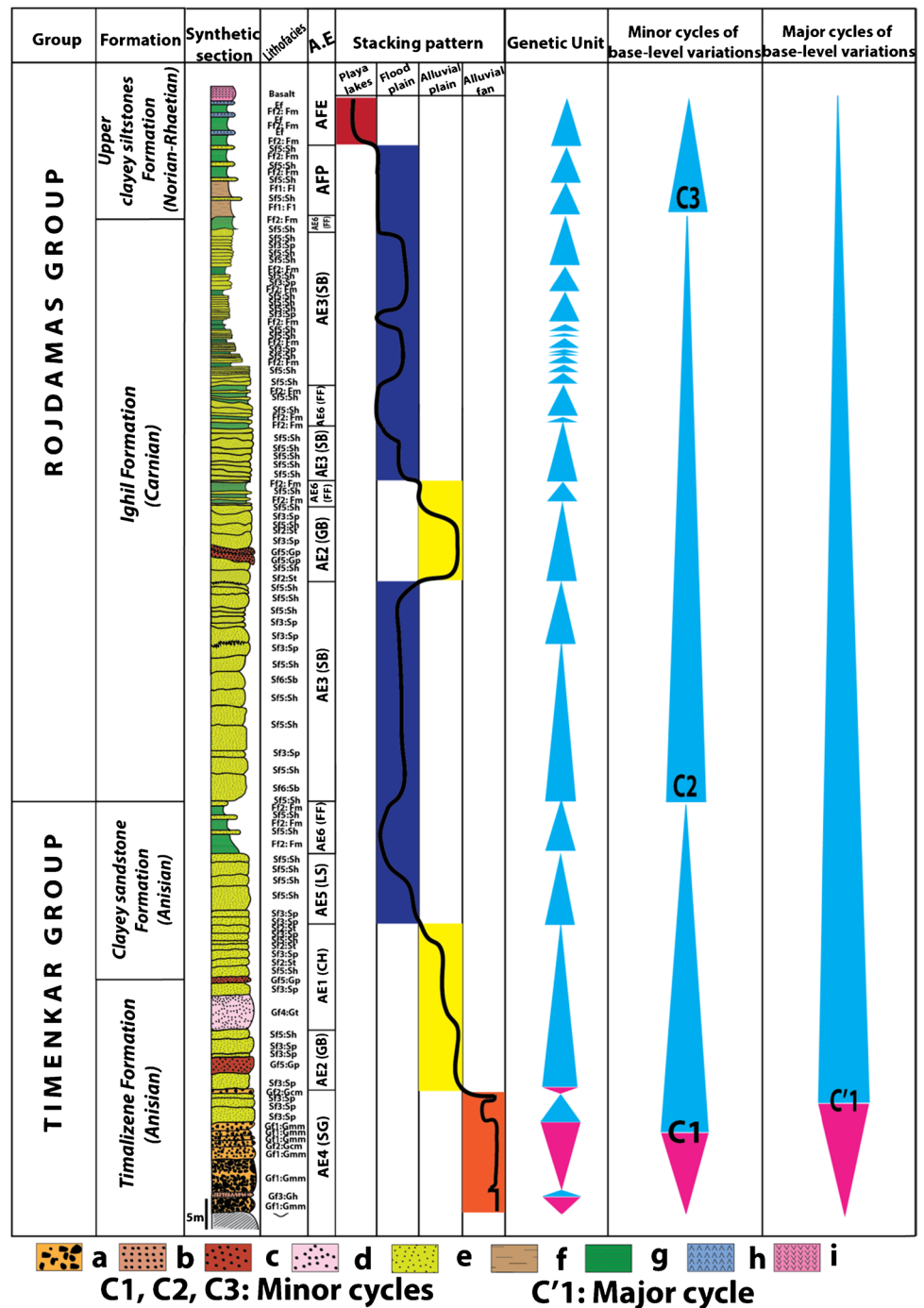
Genetic units UG6, UG7, and UG8.....UG12.....UG24

These genetic units show also only a period of base level rise (retrogradation). It is characterized by the abundance of sandstone facies showing horizontal beddings with significant bioturbation interpreted as subaqueous flood deposits (Bourquin et al. 1998). The basal boundary of these units is sometimes marked by the transition from coarse facies formed at bars in a braided system to fine floodplain facies (Fig. 15).

Genetic units UG25 and UG26

Genetic units UG25 and UG26 are characterized by alternating sandstone, silty, clayey, and evaporitic facies (organized into architectural elements *AE6*, *AFPS*, and *AFE*) formed in floodplains associated with playa lakes. The maximum flooding surfaces of these units are between the mudstone and evaporitic facies.

Fig. 15 Synthetic sedimentary log of the basin with minor and major cycles of base level variations. **a, b, c, and d** conglomerate; **e** sandstone; **f** siltstone; **g** mudstone; **h** gypsum; **i** basalt



Genetic units correlations

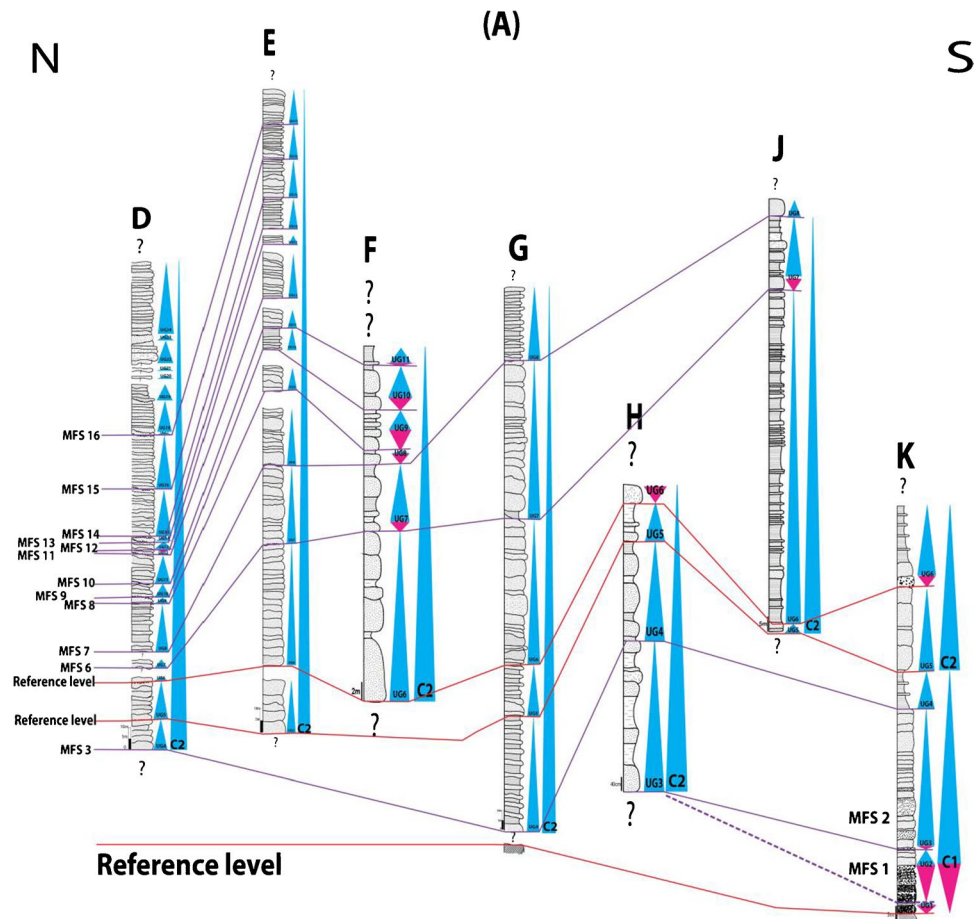
Figure 16A and B show the lateral relationships between sedimentary environments by correlating genetic units from one section to another. This correlation is based on the determination of reference levels. Three levels are recognized in our study:

1. The basal contact: unconformity between the Hercynian basement and the first Triassic facies formed in the basin;

2. The contact between the detrital facies and the first evaporite facies (gypsum);
3. The beginning of the basalt formation considered the Upper Triassic-Lower Liassic boundary (Peretsman 1985).

The first retrogradational/aggradational cycle (C1) is characterized by conglomeratic and sandstone deposited unconformably on the Hercynian basement. The maximum flooding surface (MFS1) is marked by the transition from

Fig. 16 Correlation of genetic units based on the study of the northern and southern sections of the basin (transect: N-S)



coarse, massive, poorly organized conglomeratic facies deposited in proximal alluvial fans (weak preservation) to conglomeratic and sandstone facies formed in a braided fluvial system (UG1, UG2, and UG3).

The second cycle (C2) shows a continuous increase in base level. It is characterized by a vertical aggradation of sandstone, siltstone, and mudstone facies formed in an alluvial plain of a braided system.

The third cycle (C3) was identified on four sections studied (Ighrem, Imskerne, Inkel, and the section between Ait Ibourek and Tazegzaoute). This retrogradation continues and is characterized by the appearance of the first evaporitic facies. Its base is represented by:

1. Gypsiferous red mudstones;
2. Intercalations of gypsum and red to gray mudstones formed in playas.

The set is capped by Upper Triassic-Lower Liassic basalt.

Cartography of genetic units at the scale of the basin

The objective is to obtain a stratigraphic correlation between all the sections throughout the basin in order to study the

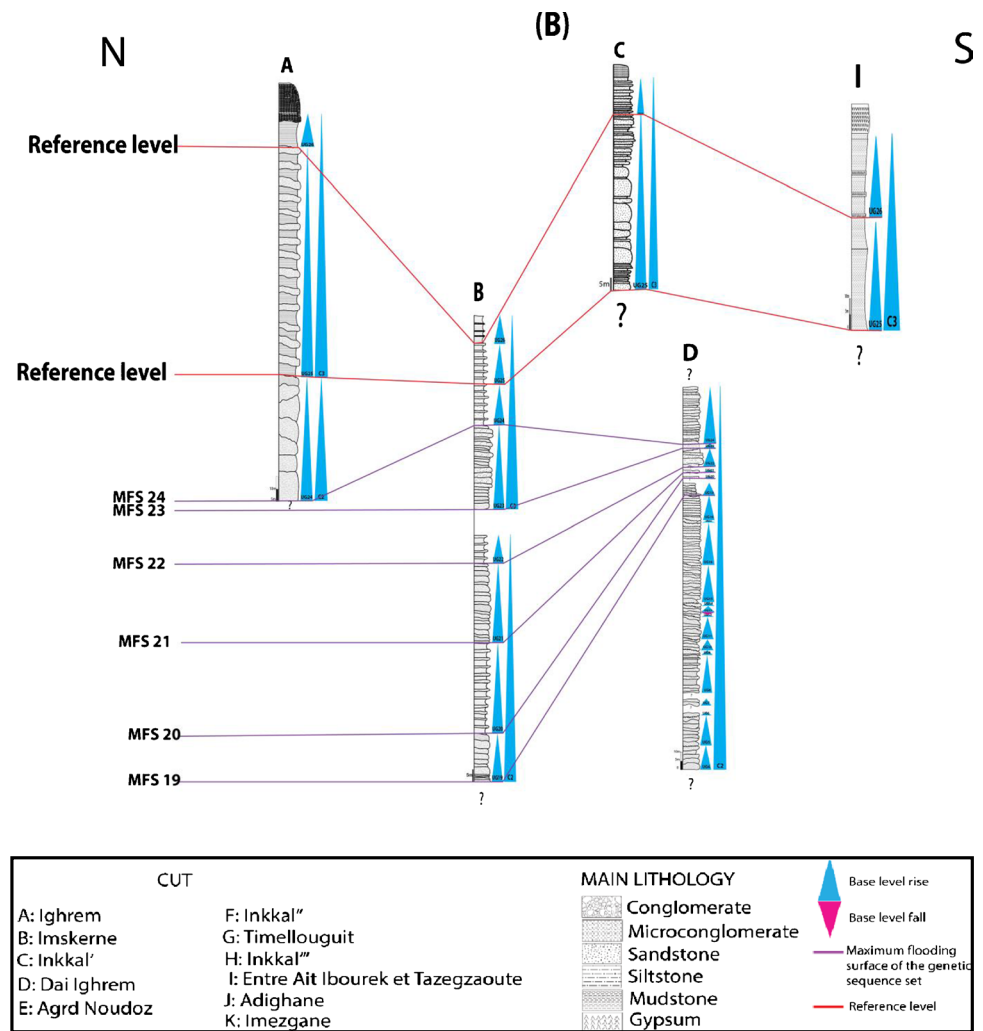
distribution of facies in space and their evolution over time. In particular, the genetic relationships between siliciclastic and evaporitic sediments are studied. The result is a paleogeographic reconstruction for each genetic unit (Figs. 17 and 18).

At the base of MFS1, significant conglomerate levels develop towards the south pole of the first transect (T1) (Fig. 17), and these conglomerates correspond to the Timalizene formation (basal conglomerate formation) and laterally evolves to sandstone facies towards the north pole.

Between MFS1 and MFS2 (center of transect T1), some of the conglomeratic facies of the retrograde part of the UG2 genetic unit become thinner and evolve laterally to sandstone facies. For transect (T2), these conglomerates are less abundant and locally absent. The genetic units (UG1) (UG2) of cycle (C1) represent proximal depositional environments: alluvial fans, proximal braided system.

Between MFS2-MFS3, conglomeratic facies positioned on the south pole of the first transect (T1) of the genetic unit (UG3) have significant thicknesses and transition laterally to sandstone facies toward the north pole. This genetic unit (UG3) of cycle (C1) represents a proximal depositional environment: proximal braided system.

Fig. 16 (continued)



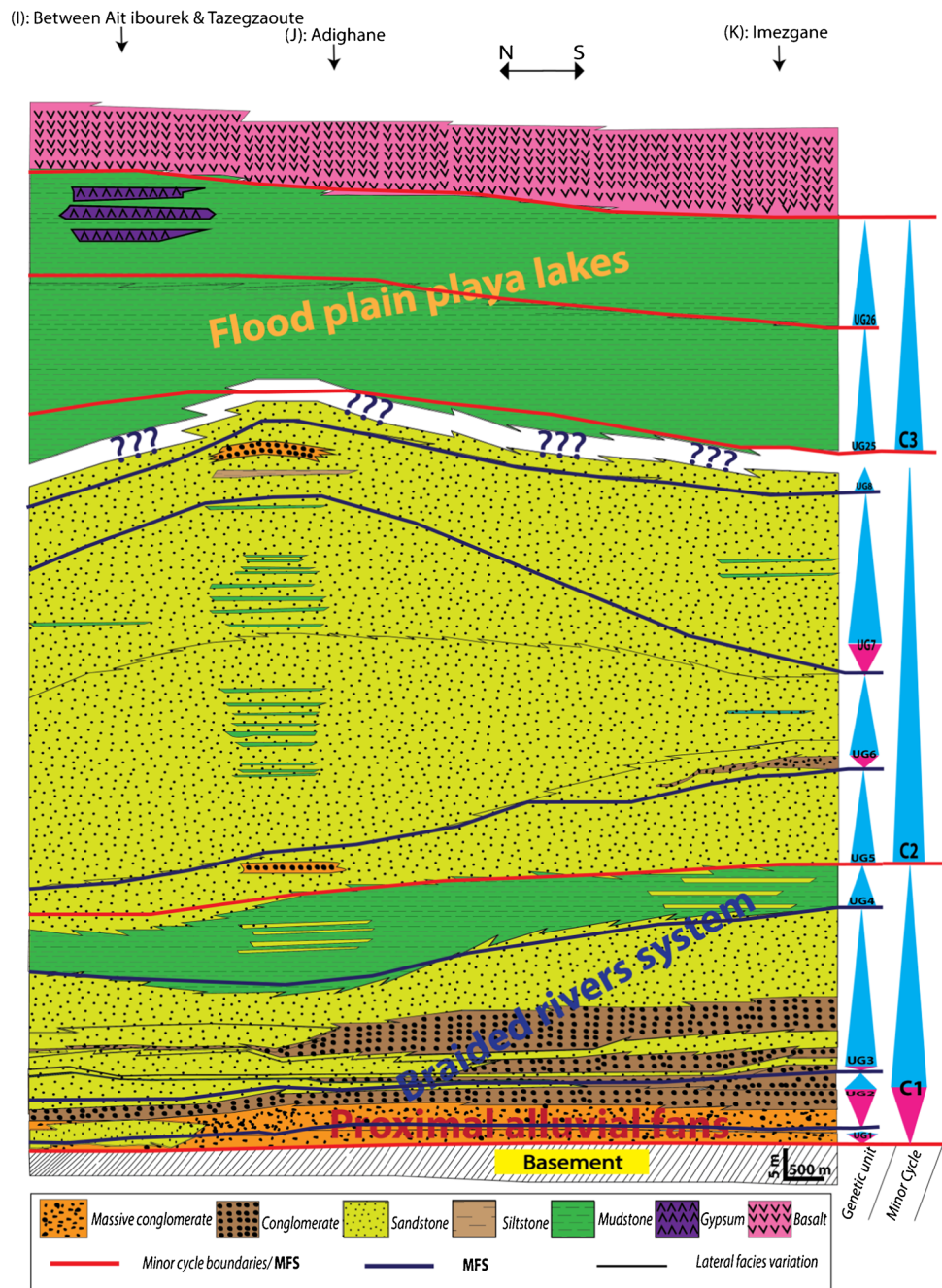
Between *MFS2* and *MFS8*, a rise of the base level leads to a change in the depositional environment towards an alluvial plain characterized by very thick deposits of sandstone and mudstone as well as siltstone deposits. This rise of base level is the origin of the appearance of better sorted facies (Gf3: Gh; Gf4: Gt; and Gf5: Gp) with: (1) a disappearance of angular elements; (2) an important presence of bioturbation which also characterizes an episode of maximum flooding (*MFS5*) of the UG6 genetic sequence, and this bioturbation indicates subaqueous flood deposits (Bourquin et al. 1998); (3) better preservation of the floodplain facies; (4) the transition from facies without free sedimentary features (Gf: Gmm; Gf2: Gcm) to facies with trough cross bedding (Sf2: St), planar cross bedding (Sf2: Sp), or with small ripples (facies Sf4: Sr) and then to horizontal planar bedding alternating with mudstone (facies Ff2: Fm) (Poli 1997; Afenzar and Essamoud 2020). The lateral transition is observed in the south of transect (T1) (Fig. 17) and throughout transect (T2) (Fig. 18).

Between *MFS9* and *MFS10*, we observed the appearance of evaporitic facies that are concentrated at the north

pole of the first transect (T1) (Fig. 17) and change laterally to clayey facies at the same genetic unit. For transect (T2) (Fig. 18), the appearance of evaporitic facies is marked on the interval (*MFS12*-*MFS13*) which are concentrated at the north pole and in the middle of this transect (T2). These evaporitic facies were overlain by basaltic flows in the late Triassic-early Jurassic and transit laterally to clayey facies at the same genetic unit. This transition from evaporitic to clayey facies is likely due to either migration of the depositional environment during the same time interval or dissolution and erosion of these exposed facies at outcrop (Afenzar and Essamoud 2020).

These genetic units and progradation-retrogradation cycles show an evolution of proximal environments (alluvial fans moving laterally to a braided system) at the base of the transect (T1) (Fig. 17, orange and dark brown color), an evolution of alluvial plain environments (proximal braided system becoming more distal) at the base of transect (T2) (Fig. 18, yellow and green color), to distal environments (floodplains associated with playa lakes and

Fig. 17 First transect (T1) N-S correlation and mapping of genetic units and minorcycles of base-level variation



sebkhas) at the top of both transects T1 and T2 (Figs. 17 and 18, green and purple color).

Discussion

Paleoenvironment

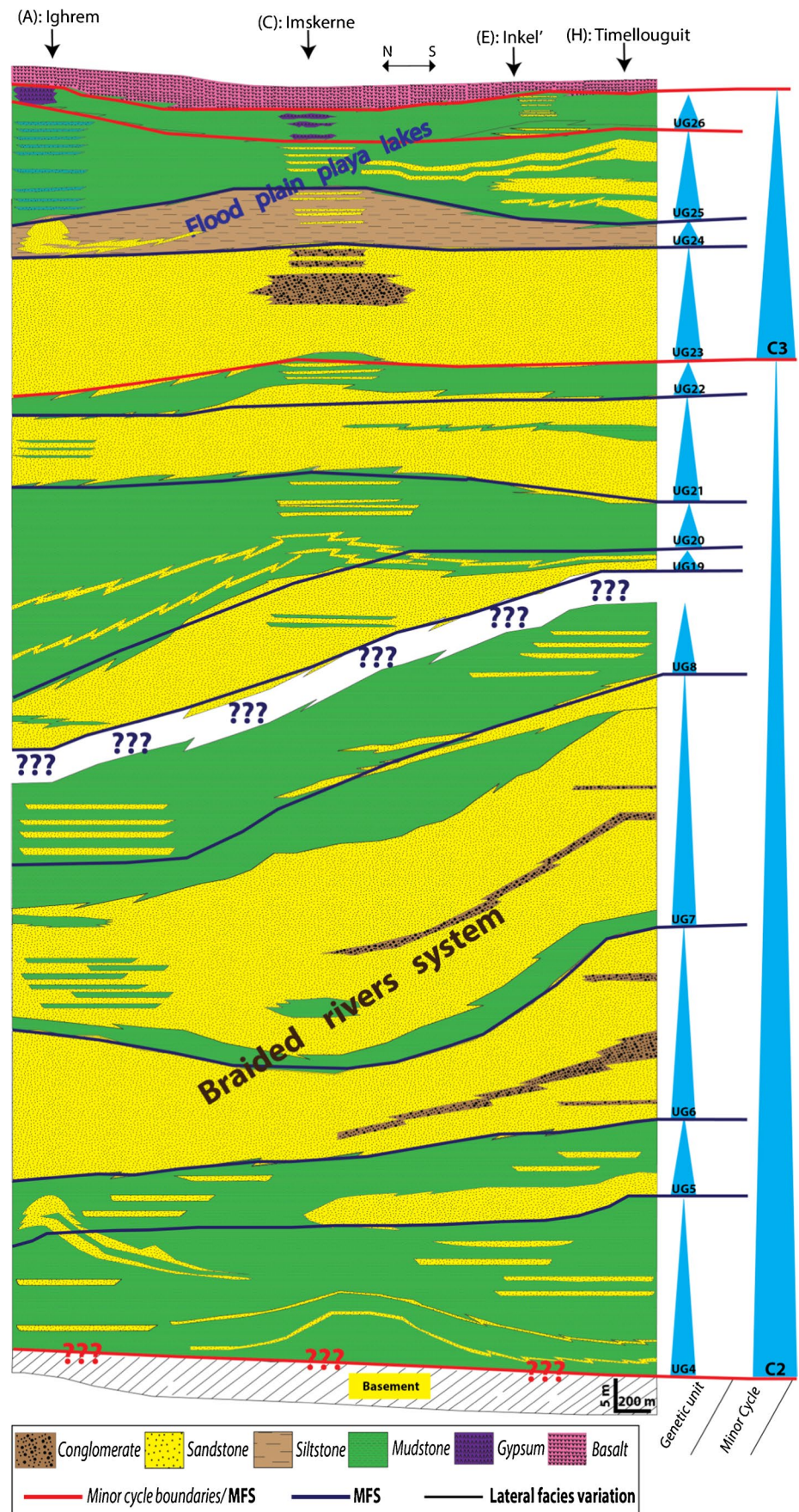
According to the sedimentological analysis, the Imini basin is characterized by detrital silico-clastic sedimentation at the beginning and then evaporate at the end of the syn-rift

sedimentary filling (Fig. 16). The sediments from the first depositional cycle are eroded from a mountainous source area and deposited at the edge of the basin in alluvial fans or transported to an alluvial plain (Miall 2006).

Based on identified facies, characterized architectural elements, and fluvial styles, the depositional environments evolve over time from:

1. A proximal system of alluvial fans characterized by the accumulation of sediments flowing by gravity to a proximal braided system characterized by conglomeratic and sandstone bars.

Fig. 18 Second transect (T2) N-S correlation and mapping of genetic units and minor cycles of baseline variation



2. Subsequently, the depositional environment evolved into a well-developed braided system characterized by coarse gravel facies, medium and small-scale transverse stratifications formed by dunes with ripples, strata formed by dune migration and channel filling, etc.... The major facies identified in this system have been reported in a number of other studies of ancient and modern sandy braided rivers of different scales and braiding intensities (Smith et al. 2005).

3. At the end, these environments evolve towards an alluvial plain where lakes of playas and sebkhas are developed. In this phase, the syn-rift sedimentary series was influenced by continental groundwater (Kendall. 1978) in the Late Triassic with gypsiferous sedimentation. This is deduced from the presence of a thinner gypsiferous series with little lateral extension, whose isotopic ratios of sulfur and bromine contents indicate their continental origins (Holser et al. 1988; Beauchamp et al. 1995). These evaporites appear stratified in the Imini area within the “upper siltstone” at a location where coarse deposits are more dominated (El Arabi 2007) such as the American basins belonging to the southern and central segment (example basins of Newark, Deep-river, Culpeper, Fundy, Franklin....) Withjack and Callaway (2000), Tanner and Brown (2003), Syamsir et al. (2010), Withjack et al. (2012), and Leleu et al. (2016)) and are not developed with the same strength as those in the Atlantic syn-rift series where evaporites are extremely well developed (e.g., the Essaouira Basin) (Hafid 1999).

Paleoenvironmental evolution was also controlled by paleoslope evolution. Leleu and Hartley (2010) suggest that in most continental basins, the paleoenvironmental transition is diachronic, so that it cannot be related to global or megaregional climatic controls and that the pattern can be explained by a decrease in source area relief through erosion in a hydrologically closed basin.

Evaporite origin

Many evaporites that are formed in continental environments were derived in part from marine input; it is difficult to identify the relative importance of continental and marine influences (Kendall 1978).

Several studies have shown that the transgression of the Tethys is announced as early as the Upper Ladinian with the first marine deposits in the NE of Morocco (Oujda region). It then extends during the Carnian to reach the other basins through the central High Atlas (Oujidi et al. 1997, 2000), which explain that there is a marine incursion during the Upper Triassic where the evaporites can be formed.

Van Houten (1977) showed that the marine incursion into the Moroccan Atlas belt did not occur until the Late Liassic,

extending southwest from the Tethys to the Marrakech, where it was stopped by the block of uplifted basement of the ancient massif.

More of these last studies, several geochemical analyses which were carried out on the evaporites of the Moroccan atlas, indicated and confirmed that these evaporites are of continental origin (Krueger and Reesman 1983; Holser et al. 1988; Beauchamp et al. 1995) as in our case of study.

Comparable evaporitic sequences of mostly Late Triassic age have also been identified in North Africa, more to the northeast and east, in the eastern High Atlas, the Tunisian Atlas, and even the Algerian Tell (Kamoun et al. 2001; Frizon de Lamotte et al. 2011; Raulin et al. 2011), the Outer Betic of southern Spain (Arche et al. 2002; Suarez 2007), the Iberian chain (Arche et al. 2004; Ortí 2004; Virgili et al. 2006; Diez et al. 2007; Vargas et al. 2009; Bourquin et al. 2011; López-Gómez et al. 2012, and Escudero-Mozo et al. 2015).

Tectonic factor

The detrital deposits of the Imini basin generally appear as a subsidence zone with hemi-graben structuring controlled by remobilization of Hercynian and late-Hercynian faults ENE-WSW or E-W in a quasi-uniform NW–SE distensive regime. The prevalence of this syn-sedimentary tectonics has a very important role in the elaboration of the studied basin as well as in the distribution of the facies of the different formations (Medina 1988; El Arabi 1988; Amghar 1995). According to El Arabi (2007), a synsedimentary tectonics in the form of striated normal faults active during the deposition of upper mudstones in the basin are responsible for the distribution and concentration of evaporites.

The Imini basin is therefore a purely continental area, which has favored the recording of alluvial fans, high energy fluvial systems and then gradually filling in, we passed to lakes, sebkhas, and evaporites. The importance of this typical succession lies in the relationship between basin capacity and sediment and water supply (Schlische and Olsen 1990). This capacity is created by tectonics, which leads to the conclusion that this succession is associated with a rift-type geodynamic context. The sediments are predominantly red. This reflects the oxidizing conditions under which sedimentation occurred (Biron 1982; Van Houten 1973; Afenzar and Essamoud 2020).

Climatic factor

In addition to the tectonic control demonstrated on the architectural style of the Late Triassic sediments, climatic variations also have an important role.

During the Upper Triassic and the early Liassic, the southern and central part of the Imini basin were characterized by

playa lakes and sabkhas deposits as well as the appearance of evaporitic facies resulting from local climatic conditions, as we have shown previously.

The existence of a hot and humid climate (Afenzar and Essamoud 2020) in the late Triassic probably contributed to the precipitation of the evaporitic sequence, as in our study area where the evaporites of the upper mudstone siltstone formation are controlled by local climatic conditions (El Arabi 1988).

Relationship with the atlas rifting

Several authors consider that the opening of several Moroccan Triassic sedimentary basins was initiated during Triassic rifting. This opening was controlled by the reactivation of pre-existing zones of weakness in the Paleozoic basement inherited from the Hercynian orogeny (Le Roy and Piqué, 2001; Hafid 2000; Courel et al. 2003; Laville et al. 2004; Saber et al. 2007; Leleu et al. 2016).

The Imini basin is part of the eastern High Atlas province of Marrakech (Morocco) where the Triassic deposits are considered syn-rift.

Conclusion

The results of this study show a syn-rift Triassic series with two sedimentary episodes. During the first episode, the sedimentation is silico-clastic in nature and forms under purely continental conditions. The detrital material was derived from the erosion of nearby Paleozoic landforms. During the second episode, the deposits consist of evaporites formed in a hot and humid climate and controlled by a set of tectonic structures that led to the opening of the basin.

The depositional environment evolved over time during these episodes. This evolution was controlled by climate, tectonics, paleoslope, and base level variations. The depositional environments evolved from a proximal alluvial fan to a braided river system. These environments evolved gradually into an alluvial plain where playa lakes and sabkhas are developed. These vertical variations in the nature and size of the sediments are due to the variation of the base level and the supply of sediments during sedimentation in the basin. This variation is of tectonic and/or climatic (allo-cyclic) origin.

During early sedimentation, the base level decreased and led to the formation of poorly organized conglomeratic facies in a proximal fluvial zone. Then it began to rise, leading to the formation of a fluvial-type sedimentary series followed by evaporitic facies before magmatic activity at the Triassic-Jurassic boundary.

Correlation and mapping of genetic sequences and progradation/retrogradation cycles provided 2D/3D geometries

of the basin along the two correlation transects. This indicates a growth in the thickness of these sequences vertically and laterally. These correlations also show lateral changes from mudstone facies (SW-NE boundary) to evaporitic facies (N boundary and central basin).

Declarations

Conflict of interest The authors declare that they have no competing interests.

Signed by all authors Soukaina Obad, Rachid Essamoud, Abdelkrim Afenzar.

References

- Afenzar A (2018) Sédimentologie de faciès, paléoenvironnements et interprétation en termes de stratigraphie séquentielle haute résolution de la série syn-rift triasique du bassin de Mohammedia-Benslimane-ElGara-Berrechid (Meseta occidentale, Maroc). Thèse de Doctorat, Université Hassan II de Casablanca, Faculté des sciences Ben M'Sick (Maroc), pp 65–77
- Afenzar A, Essamoud R (2020) Sedimentological and sequence stratigraphy analyses of the syn-rift Triassic series of the Mohammedia-Benslimane-ElGara-Berrechid basin (Moroccan Meseta). *CR Acad Sci Paris* 352(issue 6–7):417–441.
- Allen JRL (1983) Studies in fluvial sedimentation: bars, bar-complexes and sandstone sheets (low sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders. *Sediment Geol* 33:237–293. [https://doi.org/10.1016/0037-0738\(83\)90076-3](https://doi.org/10.1016/0037-0738(83)90076-3)
- Amghar M (1995) Apport des méthodes d'analyse de la tectonique cassante à l'histoire alpine du Haut Atlas occidental: structures, instabilités tectoniques et magmatisme liés à l'ouverture de l'Atlantique central et B la collision Afrique-Europe. Université Cadi Ayyad Marrakech, Maroc, Thèse Etat, p 253p
- Arche A, López-Gómez J, García-Hidalgo JF (2002) Control climático, tectónico y eustático en depósitos del Carniense (Triasico Superior) del SE de la Península Ibérica. *J Iberian Geol* 28:13–30. <http://hdl.handle.net/10261/5525>
- Arche A, López-Gómez J, Marzo M, Vargas H (2004) The siliciclastic Permian–Triassic deposits in Central and Northeastern Iberian Peninsula (Iberian, Ebro and Catalan Basins): a proposal for correlation. *Geologica Acta* 2:305–320. <http://hdl.handle.net/10261/5022>
- Baudelot S, Charrière A, Ouarhache D, Sabaoui A (1990) Données palynologiques nouvelles concernant l'Ordovicien et le Trias-Lias du Moyen Atlas. *Géol Méditerran* 17:263–277
- Baudon C, Redfern J, Driessche JVD (2012) Permo-Triassic structural evolution of the Argana valley impact of the Atlantic rifting in the High Atlas, Morocco. *J Afr EarthSci* 65:91–104. <https://doi.org/10.1016/j.jafrearsci.2012.02.002>
- Beauchamp J (1985) Modalité de la transgression triasique au Maroc. Actes 110^{ème} congrès soc. Savantes Montpellier Sci Fasc VI:245–256.
- Beauchamp J, Benaouiss N, Courel L (1995) Où était donc le domaine marin dans le Maroc africain au Trias supérieur. *CR Acad Sci Paris t. 221, sér. II a*, :1033–1040.
- Bertrand H (1991) The Mesozoic province of North west Africa: a volcanic-tectonic record of the early opening of central Atlantic. In: Magmatism in extensional structural setting

- (Edited by Kampunzu A. B and Lubala R.T), pp 147–188. Springer-Verlag, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-73966-8_7
- Biron PE (1982) Le Permo-Trias de la région de l'Ourika (Haut Atlas de Marrakech, Maroc): Lithostratigraphie, sédimentologie, tectonique et minéralisations. Université Scientifique et Médicale de Grenoble, Stratigraphy
- Boggs S (2006) Principes de sédimentologie et de stratigraphie, 2e éd. Printice Hall, New York, 662 pages. ISBN 0-13-154728-3
- Bourges J (1987) Projet de Cachuela Esperenza. Etude sommaire des débits. Publ. PHICAB
- Bourquin S, Guillocheau F (1993) Géométrie des séquences de dépôt du Keuper (Ladinien à Rhétien) du Bassin de Paris : implications géodynamiques. C R Acad Sci Paris Ser II 317:1341–1348
- Bourquin S, Guillocheau F (1996) Keuper stratigraphic cycles in the Paris basin and comparison with cycles in other peritethyan basins (German basin and Bresse-Jura basin). *Sedim Geol* 105(3–4):159–182. [https://doi.org/10.1016/0037-0738\(95\)00153-0](https://doi.org/10.1016/0037-0738(95)00153-0)
- Bourquin S, Bourges P, Rigollet C (1998) High-resolution sequence stratigraphy of an alluvial fan-delta environment: stratigraphic and geodynamic implications – an example from the Keuper-Chaunoy Sandstones, Paris Basin. *Sedim Geol* 121(1998):207–237. [https://doi.org/10.1016/S0037-0738\(98\)00081-5](https://doi.org/10.1016/S0037-0738(98)00081-5)
- Bourquin S, Bercovici A, López-Gómez J, Diez JB, Boutin J, Ronchi A et al (2011) The Permian-Triassic transition and the onset of Mesozoic sedimentation at the northwestern peri-Tethyan domain scale: palaeogeographic maps and geodynamic implications. *Palaeogeogr Palaeoclimatol Palaeoecol* 299:265–280. <https://doi.org/10.1016/j.palaeo.2010.11.07>
- Bridge JS (2003) Rivers and floodplains: forms, processes, and sedimentary records. Blackwell, Oxford., p 491
- Collinson JD (1978) Alluvial sediments. In: Reading HG (ed) *Sedimentary Environments and Facies*. Blackwell, London, pp 15–60
- Collinson JD, Mountney N, Thompson DB (2006) *Sedimentary structures*. Terra Publications, Hertfordshire, England, p 292
- Courel L, Ait Salem H, Benaouiss N, Et-Touhami M, Fekirine B, Oujidi M, Soussi M, Tourani A (2003) Mid-Triassic to early Liassic clastic/evaporitic deposits over the Maghreb platform. *Palaeogeogr Palaeoclimatol Palaeoecol* 196:157–176. [https://doi.org/10.1016/S0031-0182\(03\)00317-1](https://doi.org/10.1016/S0031-0182(03)00317-1)
- Cula P, Courel L (1987) Les grès inférieurs du Trias Cévennois: systèmes fluviaux et laguno-marins *Geol. Alp Mere Hors Série* 13:103–111
- Deleplancque B (2016) Caractérisation des hétérogénéités sédimentaires d'une plaine alluviale: Exemple de l'évolution de la Seine supérieure depuis le dernier maximum glaciaire. Thèse de Doctorat, Université Paris Sciences & Lettres, Paris, p 275p
- Diez JB, Bourquin S, Brotin J, Ferrier J (2003) The Iberian Permian Triassic 'Buntsandstein' of the Aragonian Branch of the Iberian range (Spain) in the West-European sequence stratigraphical framework: a combined palynological and sedimentological approach. *Bulletin De la Société Géologique De France* 178(3):173–195. <https://doi.org/10.2113/gssgfbull.178.3.179>
- Einsle G (2000) Sedimentary basins: evolution, facies, and sediment budget. Springer, 792 <https://doi.org/10.1017/S0016756801256234>
- EjiUba C, Heubeck C, Hulka C (2005) Facies analysis and basin architecture of the Neogene Subandean syn orogenic wedge, southern Bolivia. *Sed Geol* 180(3):91–123. <https://doi.org/10.1016/j.sedgeo.2005.06.013>
- El Arabi E, Bienvenido Diez J, Broutin J, Essamoud R (2006) Première caractérisation palynologique du Trias moyen dans le Haut Atlas; implications pour l'initiation du rifting téthysien au Maroc. *C R Geosci* 338:641–649. <https://doi.org/10.1016/j.crte.2006.04.001>
- El Arabi EH (1988) Le Permo-Trias du flanc sud du Haut-Atlas de Marrakech. Etude sédimentologique, cartographique et paléogéographique. Thèse Doct Univ Grenoble, 184
- El Arabi EH (2007) La série permienne et triasique du rift haut atlantique : nouvelles datations ; évolution tectonosédimentaire, unpubl. Thesis (thèse d'état) université hassan II casablanca, faculté des sciences Ain chok (Maroc), p 225
- Escudero-Mozo MJ, Márquez-Aliaga A, Goy A, Martín-Chivelet J, López-Gómez J, Márquez L et al (2015) Middle Triassic carbonate platforms in eastern Iberia: evolution of their faunal and palaeogeographic significance in the western Tethys. *Palaeogeogr Palaeoclimatol Palaeoecol* 417(1):236–260. <https://doi.org/10.1016/j.palaeo.2014.10.041>
- Et-Touhami M (1994) Le Trias évaporitique du bassin de Khémisset (Maroc central). *Notes Mem Serv Geol Maroc Rabat* 373:211
- Fambrini G, Neumann V, Acioli J, Filho M, Wellington F, Filho S, Oliveira E (2017) Facies architecture of the fluvial Missão Velha formation (Late Jurassic-Early Cretaceous), Araripe Basin, Northeast Brazil: paleogeographic and tectonic implications. *Acta, Geol, Polonica* 67(4):515–545. <https://doi.org/10.1515/agp-2017-0029>
- Frizon de Lamotte D, Raulin C, Mouchot N, Wrobel-Daveau JC, Blanpied C, Ringenbach JC (2011) The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: initial geometry and timing of the inversion processes. *Tectonics* 30:TC3002. <https://doi.org/10.1029/2010.TC002691>
- Frizon de Lamotte D, Zizi M, Missenard Y, Hafid M, El Azouzi R C, Maury R, Charrière A, Taki Z, Benammi M & Michard A (2008) The Atlas system In: Michard A, Saddiqi O, Chalouan A, Frizon de Lamotte D. Eds, *Continental evolution: the geology of Morocco*. – Lecture Notes Earth Sci, Springer Verlag, Berlin, 116:133–202. https://doi.org/10.1007/978-3-540-77076-3_4
- Gary N (2009) *Sedimentology and stratigraphy*. Wiley -Blackwell., 2nd ed., 419 p.
- Gustavson TC, Hovorka SD, Dutton AR (1994) Origin of satin spar veins in evaporite basins. *J Sediment Res* A64(1):88–94. <https://doi.org/10.1306/D4267D1B-2B26-11D7-8648000102C1865D>
- Hafid M (1999) Influence de l'évolution du Haut Atlas Occidental et de son avant-pays septentrional sur la dynamique Mésocène-Cénozoïque de la marge Atlantique (entre Safi et Agadir); apport de la sismique réflexion et des données de forages. Université Ibn Tofail, Kenitra, Maroc, p 283
- Hafid M (2000) Triassic-Liassic extensional systems and their tertiary inversion, Essaouira Basin (Morocco). *Mar Petrol Geol* 17:409–442. [https://doi.org/10.1016/S0264-8172\(98\)00081-6](https://doi.org/10.1016/S0264-8172(98)00081-6)
- Harms JC, Southard JB, Spearing DR, Walker RG (1975) Depositional environments as interpreted from primary sedimentary structures and stratification sequences. *Soc Econ Paleontol Mineral. Short Course 2* (Dallas, 1975), p 161
- Hjellbakk A (1997) Facies and fluvial architecture of a high-energy braided river: the Upper Proterozoic Segloden Member, Varanger Peninsula, northern Norway. *Sed Geol* 114:131–161. [https://doi.org/10.1016/S0037-0738\(97\)00075-4](https://doi.org/10.1016/S0037-0738(97)00075-4)
- Hminna A, Voigt S, Klein H, Saber H, Schneider JW, Hmich D (2013) First occurrence of tetrapod footprint from the continental Triassic of the Sidi Said Maachouarea (Western Meseta Morocco). *J Afr Earth Sci* 80:1–7. <https://doi.org/10.1016/j.jafrearsci.2012.11.003>
- Hofmann A, Tourani A, Gaupp R (2000) Cyclicity of Triassic to lower Jurassic continental red beds of the Argana valley, Morocco: implications for palaeoclimate and basin evolution. *Palaeogeogr Palaeoclimatol Palaeoecol* 161:229–266
- Holser WT, Clement GP, Jansa LF, Wade JA (1988) Evaporite deposits of the north Atlantic rift. In: Manspeizer W (ed) *Triassic-Jurassic*

- rifting: Continental breakup and the origin of the Atlantic Ocean and passive margins. Elsevier, pp 525–556
- Kamoun F, Peybernès B, Ciszak R, Calzada S (2001) Triassic palaeogeography of Tunisia. *Palaeogeogr Palaeoclimatol Palaeoecol* 172:223–242. [https://doi.org/10.1016/S0031-0182\(01\)00283-8](https://doi.org/10.1016/S0031-0182(01)00283-8)
- Kendall AC (1978) Facies model II. Continental and Supratidal (Sabkha) Evaporites. *Geosci Canada*, 5(No. 2):66–78.
- Klein H, Voigt S, Hminna A, Saber H, Schneider JW, Hmich D (2010) Early Triassic archosaur-dominated footprint assemblage from the Argana basin (Western High Atlas, Morocco). *Ichnos: Int J Plant Animal Traces* 17(3):215–227. <https://doi.org/10.1080/10420940.2010.510030>
- Krueger HW, Reesman RH (1983) Paleogeographic interpretation of strontium and sulfur isotopes in Moroccan gypsums (abs). *Geol Soc Am Abstr Programs* 15:619
- Lachkar G, Ouarhache D, Charrière A (2000) Nouvelles données palynologiques sur les formations sédimentaires associées aux basaltes triasiques du Moyen Atlas et de la Haute Moulouya (Maroc). *Revue Micropal* 43(4):281–299. [https://doi.org/10.1016/S0035-1598\(00\)90147-8](https://doi.org/10.1016/S0035-1598(00)90147-8)
- Laville E, Piqué A, Amrhar M, Charrout M (2004) A restatement of the Mesozoic Atlasic Rifting (Morocco). *J Afr Earth Sc* 38(2):145–153. <https://doi.org/10.1016/j.jafrearsci.2003.12.003>
- Le Roy P, Pique A (2001) Triassic-Liassic Western Moroccan synrift basins in relation to the Central Atlantic Opening. *Mar Geol* 172(3–4):359–381. [https://doi.org/10.1016/S0025-3227\(00\)00130-4](https://doi.org/10.1016/S0025-3227(00)00130-4)
- Leleu S, Hartley AJ (2010) Controls on the stratigraphic development of the Triassic Fundy basin, Nova Scotia: implications for the tectonostratigraphic evolution of Triassic Atlantic rift basins. *Geol Soc Lond J* 167:437–454
- Leleu S, Hartley AJ, Oosterhout CV, Kennan L, Ruckwied K, Gerdes K (2016) Structural, stratigraphic and sedimentological characterization of a wide rift system: the Triassic rift system of the Central Atlantic Domain. *Earth Sci Rev* 158:89–124. <https://doi.org/10.1016/j.earscirev.2016.03.008>
- Liu Z, Wang C (2001) Facies analysis and depositional systems of Cenozoic sediments in the Hoh Xil basin, northern Tibet. *Sed Geol* 140:251–270. [https://doi.org/10.1016/S0037-0738\(00\)00188-3](https://doi.org/10.1016/S0037-0738(00)00188-3)
- López-Gómez J, Galán-Abellán B, de la Horra R, Barrenechea J, Arche A, Bourquin S et al (2012) Sedimentary evolution of the continental Early-Middle Triassic Canizar formation (Central Spain): implications for life recovery after the Permian-Triassic crisis. *Sed Geol* 249:26–44. <https://doi.org/10.1016/j.sedgeo.2012.01.006>
- Lorenz JC (1988) Synthesis of Late Paleozoic and Triassic red bed sedimentation in Morocco. In V.H. Jacobshagen (ed), *The Atlas system of Morocco studied on its geodynamic evolution. Lectures en Notes in Earth Sci* 15:139–168.
- Malaza N, Liu K, Zho B (2013) Facies analysis and depositional environments of the late Palaeozoic coal-bearing Madzaringwe formation in the Tshipise-Pafuri basin, South Africa. *ISRN Geology*. <https://doi.org/10.1155/2013/120380>
- Massari F (1983) Tabular cross-bedding in Messinian fluvial channel conglomerates, Southern Alps, Italy. In: J.D. Collinson and J. Lewin (Eds.), *Modern and Ancient Fluvial Systems*. *Int Assoc Sediment Spec Publ* 6:287–300.
- McKee ED, Weir GW (1953) Terminology for stratification and cross-stratification in sedimentary rocks. *Bull Geol Soc Am* 64:381–389. [https://doi.org/10.1130/0016-7606\(1953\)64\[381:TFSACI\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1953)64[381:TFSACI]2.0.CO;2)
- Medina F (1988) Tilted-blocks pattern, paleostress orientation and amount of extension related to the Central Atlantic early rifting in the Amzri area (Argana basin, Morocco). *Tectonophysics* 148:229–233. [https://doi.org/10.1016/0040-1951\(88\)90131-X](https://doi.org/10.1016/0040-1951(88)90131-X)
- Medina F (1995) Syn- and post-rift evolution of the El Jadida-Agadir basin (Morocco): constraints for the rifting model of the central Atlantic. *Can J Earth Sci* 32:1273–1291. <https://doi.org/10.1139/e95-104>
- Merzeraud G (1992) Géométrie et signification géodynamique des séquences de dépôts en domaine continental et marin restreint: exemple du Lias inférieur du Sud-Ouest du bassin de Paris (applications aux potentialités de stockage de gaz naturel en nappes aquifères). Université de Strasbourg, Thèse de Doctorat, p 164
- Miall AD (1977) A review of the braided-river depositional environment. *Earth Sci Rev* 13:1–62. [https://doi.org/10.1016/0012-8252\(77\)90055-1](https://doi.org/10.1016/0012-8252(77)90055-1)
- Miall AD (1978) Lithofacies types and vertical profile models in braided river deposits: a summary. *Can Soc Petrol Geol Mem* 5:597–604
- Miall AD (1981) Alluvial sedimentary basins: tectonic setting and basin architecture. In: A.D. Miall (Editor), *Sedimentation and Tectonics in Alluvial Basins*. *Geol Assoc Can Spec Pap* 23:1–33
- Miall AD (1984) Variations in fluvial style in the Lower Cenozoic synorogenic sediments of the Canadian Arctic Islands. *Sed Geol* 138:499–523. [https://doi.org/10.1016/0037-0738\(84\)90091-5](https://doi.org/10.1016/0037-0738(84)90091-5)
- Miall AD (1985) Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Sci Rev* 22:261–308. [https://doi.org/10.1016/0012-8252\(85\)90001-7](https://doi.org/10.1016/0012-8252(85)90001-7)
- Miall AD (1987) Recent developments in the study of fluvial facies models. In: Ethridge FG, Flores RM (eds) *Recent developments in fluvial sedimentology*. *Soc Econ Paleontol Mineral Spec Publ* 39:1–9
- Miall AD (2006) *The geology of fluvial deposits: sedimentary facies, basin analysis, and petroleum geology*. Springer, Berlin
- Miall AD (1996) *The geology of fluvial deposits, sedimentary facies, basin analysis, and petroleum geology*. Springer-Verlag, Germany
- Opluštil S, Martinek K, Tasáryová Z (2005) Facies and architectural analysis of fluvial deposits of the Nýrany Member and the Týnec Formation (Westphalian D-Barruelian) in the Kladno Rakovníkand Pilsen basins. *Bull Geosci* 80(1):45–66
- Orti F (2004) Cordilleras Ibérica y Costero-Catalana. El rift Mesozoico Ibérico: 5.3.1.4 Ultima etapas de actividos del rifting. *Sedimentos asociados*, *Geologia de Espana*. In: Veara JA (ed) *Sociedad Geologica de Espana e Instituto Geologico y Minero de Espana*, Madrid, pp 492–495
- Ouarhache D, Charrière A, Chalot-Prat F, El Wartiti M (2012) Chronologie et modalités du rifting triasico-liasique à lamarge sud-ouest de laTéthysalpine (MoyenAtlas et Haute Moulouya, Maroc); corrélationsavecleriftingatlantique: simultanété et diachronisme. *Bull. Soc Geol France* 183(3):233–249. <https://doi.org/10.2113/gssgf>
- Oujidi M, Courel L, Benaouiss N, El Mostaine M, El Youssi M, Et Touhami M, Ouarhache D, Sabaoui A, Tourani A I (2000) Triassic series of Morocco: stratigraphy, palaeogeography and structuring of the Southwestern Peri-Tethyan Platform. An overview. In: Crasquin-Soleau S, Barrier E (Eds) *Peri-Tethys Memoir 5: New Data on Peri-Tethyan Sedimentary Basins*. *Mé'm Mus Natn Hist nat* 182:23–38. Paris
- Oujidi M, Et-Touhami M (2000) Stratigraphy of the Permian and Triassic systems in Morocco: an overview. In: Oujidi M, & Et-Touhami M, (eds) *Le Permien et le Trias du Maroc*. *Actes de la Première Réunion du Groupe Marocain du Permien et du Trias*, Hilal Impression, Oujda, pp 1–13
- Oujidi M, Elmi S (2000) Evolution de l'architecture des Montsd'Oujda (Maroc oriental) pendant le Trias et au debut du Jurassique. *Bull. Soc Geol France* 171:169–179
- Oujidi M, Courel L, Benaouiss N, EL moustaine M, EL Youssi M, EL Touhami M, Jalil N, Ouariacié D, SabaouiA, Tourani A,

- (1997) La marge peritéthysienne marocaine pendant le Trias. In : Les marges téthysiennes d'Afrique du Nord. Abstract, séance spécialisée Soc Géol Fr, Paris, pp 34–35
- Peretsman CG (1985) A geochemical and petrographic analysis of early Mesozoic evaporites from Morocco: implications for the history of the north Atlantic. Thesis, University of Oregon, Ms
- Peretsman CG, Holser TW (1988) Geochemistry of Moroccan evaporites in the setting of the North Atlantic rift. *J African Earth Sci* 7(2):375–383. [https://doi.org/10.1016/0899-5362\(88\)90082-6](https://doi.org/10.1016/0899-5362(88)90082-6)
- Poli E (1997) Stratigraphie séquentielle haute résolution, modèles de dépôt et géométrie 2D-3D des séquences triasiques de la marge téthysienne ardéchoise. Thèse, Université de Bourgogne-Centre des Sciences de la Terre. EAN13: 9782715908697
- Postma G, Cruickshank C (1988) Sedimentology of a late Weichselian to Holocene terraced fan delta, Varangerfjord, northern Norway. In: Nemeč W, Steel RJ (eds) Fan deltas: sedimentology and tectonic settings. Blackie, London, pp 144–158
- Quarbous A, Medina F, Hoepffner C (2003) Le bassin de Tizi n'Test (Haut Atlas, Maroc): exemple d'évolution d'un segment oblique au rift de l'Atlantique central au Trias. *Ca J Earth Sci* 40:949–964. <https://doi.org/10.1139/e03-029>
- Raulin C, Frizon de Lamotte D, Bouaziz S, Khomsi S, Mouchot N, Ruiz G et al (2011) Late Triassic-early Jurassic block tilting along E-W faults, in southern Tunisia: new interpretation of the Tebaga of Medenine. *J Afr Earth Sc* 61:94–104. <https://doi.org/10.1016/j.jafrearsci.2011.05.007>
- Reineck HE, Singh IB (1973) Depositional sedimentary environments. Springer-Verlag, Berlin. Heidelberg, New York. 439. <https://doi.org/10.1002/iroh.19780630125>
- Rust BR (1978) Depositional models for braided alluvium. In: Miall AD (ed) Fluvial sedimentology. *Can Soc Petrol Geol Mem* 5:605–625
- Rust BR (1979) Facies models 2. Coarse alluvial deposits. In: Walker, R.G (Ed.) Facies Models. *Geosci Can Rept Ser* 1:9–21.
- Saber H, El Wartiti M, Hmich D, Schneider J W (2007) Tectonic evolution from the Hercynian shortening to the Triassic extension in the Paleozoic western High Atlas (Morocco). *J Iber Geol* 33(1):31–40. ISSN (imprimé): 1698–6180. ISSN (enligne): 1886–7995
- Salvan HM (1984) Les formations évaporitiques du Trias marocain. Problèmes stratigraphiques, paléogéographiques et paléoclimatologiques. Quelques Reflexions *Rev Geol dyn Géogr Phys* 25(3):187–203
- Schlische RW, Olsen PE (1990) Quantitative filling model for continental extensional basins with applications to early Mesozoic rifts of eastern North America. *J Geol* 98:135–155
- Shettima B, Abubakar M B, Kuku A, Haruna A I (2018) Facies analysis, depositional environments and Paleoclimate of the Cretaceous Bima Formation in the Gongola Sub – Basin, Northern Benue Trough, NE Nigeria. *J Afr Earth Sci* 137:193–207. <https://doi.org/10.1016/j.jafrearsci.2017.10.001>
- Slimane A, El Mostaine M (1997) Observations biostratigraphiques au niveau des formations rouges de la séquence synrift dans les bassin des Doukkala et Essaouira. Première Réunion du Groupe Marocain du Permien et du Trias, Université Mohammed I, Faculté des Sciences, Oujda, Maroc. Oujda, Résumés p 54
- Smith DR, HaggardWarnemuen de BEEA, Huang C (2005) Sediment phosphorus dynamics for three tile fed drainage ditches in north-east Indiana. *Agricult Water Manage* 71:19–32. <https://doi.org/10.1016/j.agwat.2004.07.006>
- Sneh A (1983) Desert stream sequences in the Sinai Peninsula. *J Sediment Petrol* 53:1271–1280
- Sohn YK, Kim SB, Hwang IG, Bahk JJ, Choe MY, Chough SK (1997) Characteristics and depositional processes of large-scale gravelly Gilbert-type foresets in the Miocene Doumsan fan delta, Pohang Basin SE Korea. *J Sedi Research* 67(1):130–141
- Soualhine S, Julian TL, Christian H (2003) Les facies sédimentaires carbonifères de Tisdafine (Anti-Atlas oriental): remplissage deltaïque d'un bassin «pull-apart» sur la bordure méridionale de l'accident sud-atlasique. *Bull Ins Sci Rabat* 25:31–41
- Suárez J (2007) La Mancha Triassic and Lower Lias Stratigraphy, a well log interpretation. *J Iber Geol* 33(1):55–78
- Syamsir Z, Withjack MO, Durcanin MA, Schlische RW, Monteverde DH (2010) The Mesozoic Orpheus rift basin, offshore Nova Scotia and Newfoundland, Canada: Synrift and early post-rift evolution of a well imaged North Atlantic rift basin. II central & north Atlantic conjugate margins conference, Lisbon. V:279–283.
- Tanner LH, Brown DE (2003) Tectonostratigraphic evolution of the Orpheus graben, Scotian basin, offshore eastern Canada: Analogies to the Fundy rift basin. In: Le Tourneau PM, Olsen PE (Eds) the Great Rift Valleys in Eastern North America-Sedimentology, Stratigraphy and Paleontology, vol. 2. New York, Columbia University Press, p 59–68
- Taugourdeau-Lanz J (1978) Pollens des niveaux sédimentaires associés aux basaltes du Trias sur la bordure septentrionale du Maroc Central: Précisions stratigraphiques *Notes Mem. Serv Geol Maroc* 40(275):135–146
- Tourani A, Benaouiss N, Gand G, Bourquin S JNE, Broutin J, Batail B, Germain D, Khaldoune F, Sebban S, Steyer JB, Vacant R (2010) Evidence of an Early Triassic age (Olenakian) in Argana basin (High Atlas, Morocco) based on new chirotherioid traces. *C R Palevol* 9:201–208. <https://doi.org/10.1016/j.crpv.2010.05.001>
- Tucker ME (2003) Sedimentary rocks in the field. 3rd Edition, John Wiley and Sons Ltd., Chichester, p 236. ISBN 0-470-85123-6
- Van Houten EB (1973) Meaning of molasse. *Geol Soc Am Bull* 84:1973–1975
- Van Houten FB (1977) Triassic-Liasic deposits of Morocco and eastern North America: comparison. *AAPG Bull* 61(1):79–99
- Vargas H, Gaspar-Escribano JM, López-Gómez J, Van Wees JD, Cloetingh S, de La Horra R, Arche A (2009) A comparison of the Iberian and Ebro Basins during the Permian and Triassic, eastern Spain: a quantitative subsidence modelling approach. *Tectonophysics* 474:160–183. <https://doi.org/10.1016/j.tecto.2008.06.005>
- Vaskou P (1981) Apports de la sédimentologie à la connaissance des dépôts alluviaux des terrasses de la Moselle entre Noiregoux et Toul. Thèse, Univ, Nancy I, p 145
- Vergès J, Moragas M, Martin-Martin JD, Saura E, Casciello E, Razin P, Grelaud C, Malaval M, Joussame R, Messager G, Sharp I, Hunt DW (2017) Salt Tectonics in the Atlas Mountains of Morocco. In Soto JI, Flinch J, Tari G (Eds) Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins: Tectonics and Hydrocarbon Potential. Earth and Planetary Sciences, Geology, Tectonics. Elsevier, pp 563–579
- Virgili C, Cassinis G, Broutin J (2006) Permian to Triassic sequences from selected continental areas of southwestern Europe. In S. G. Lucas, G. Cassinis, & J.W. Schneider (Eds.), Non-Mar Permian Biostratigraphy Biochronology 265:231–259. London Geological Society of London special Publications. <https://doi.org/10.1144/GSL.SP.2006.265.01.11>
- Walker RG (1975a) Conglomerate: sedimentary structures and facies models. In: Harms JC, Southard JB, Spearing DR, Walker RG (Eds) Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. *Soc Econ Palaeontol Mineral Short Course Notes* 2:133–161
- Walker RG (1975b) Generalized facies models for resedimented conglomerates of turbidite association. *Geol Soc Am Bull* 86:737–748

- Withjack MO, Callaway S (2000) Active normal faulting beneath a salt layer: an experimental study of deformation patterns in the cover sequence. *Am Assoc Pet Geol* 84:627–651
- Withjack MO, Schlische RW, Olsen PE (2012) Development of the passive margin of Eastern North America: Mesozoic rifting, igneous activity, and breakup (Chapter 13). In: Roberts DG, Bally AW (eds) *Regional geology and tectonics: phanerozoic rift systems and sedimentary basins*. Elsevier, Amsterdam, pp 301–335

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.