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Some aspects of current State of Knowledge on Triassic series on both sides of the Central Atlantic Margin / *Quelques aspects de l'état des connaissances des séries triasiques de part et d'autre de la Marge Atlantique*

Sedimentological and sequence stratigraphy analyses of the syn-rift Triassic series of the Mohammedia–Benslimane–ElGara–Berrechid basin (Moroccan Meseta)

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Abstract. Sedimentological analysis has shown that during the syn-rift phase (Upper Triassic) the Mohammedia–Benslimane–ElGara–Berrechid basin (MBEB) is characterized by detrital and evaporite sediment filling. A gradual decrease of palaeoslope over time led to the evolution of paleoenvironments of proximal alluvial fans system to braided rivers and then to an anastomosing system. These environments evolve finally to an alluvial plain associated with a coastal plain where playa lakes, mudflats and lagoons had developed.

We have identified fourteen genetic sequences which are included in four progradational-retrogradational minor cycles that are themselves grouped in one major cycle. These cycles are related to the variations of the base level. The dominance of the retrogradation phases giving an asymmetrical appearance to the cycles is related to the predominance of the base level rise. These variations are probably of allocyclic origin: tectonic and probably climatic, in relation with the Tethys and the Atlantic Ocean being opened.

Keywords. Sedimentology, Paleoenvironment, High resolution sequence stratigraphy, Rifting, Triassic.

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1. Introduction

The Moroccan Triassic basins are characterized by two sedimentary episodes (detrital and evaporitic). The deposition of the detrital episode started during (1) the Early Triassic in the Argana Valley, [e.g. Hofmann et al., 2000, Tourani et al., 2010]; (2) the Middle Triassic in the Central High Atlas [e.g. El Arabi et al., 2006] and in the Oujda mountains [e.g. Courel et al., 2003, Crasquin-Soleau et al., 1997,

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Oujidi and Elmi, 2000], and during (3) the Upper Triassic in the Middle Atlas basins [e.g. Baudelot et al., 1990, Lachkar et al., 2000] and in the Moroccan Atlantic margin (Essaouira basin, e.g. Hafid, 2000, Slimane and El Mostaïne, 1997; Doukkala basin, e.g. Hminna et al., 2013; Khémisset basin, e.g Et-Touhami, 1994, Taugourdeau-Lanz, 1978; Mohammedia–Benslimane–ElGara–Berrechid basin (MBEB), Afenzar, 2018).

The Moroccan salt series (evaporitic episode) are formed during the Upper Triassic as in the other Triassic continental basins, whether in the North of Gondwana (Algeria, e.g. Aït Salem et al., 1998, Bourquin et al., 2010, Courel et al., 2003; and Tunisia, e.g. Soto et al., 2017, Soussi and Ben Ismaïl, 2000, Soussi et al., 2001) or in Europe (Portugal, Alves et al., 2006, Ramos et al., 2017, Soto et al., 2017; Spain, e.g. Barrón et al., 2006, Bourrouilh et al., 1995, Ferrer et al., 2012, Gonzàlez de Aguilar, 2015, Ortí, 2004, Reolid et al., 2014, Roca et al., 2011; France, e.g. Bourquin and Guillocheau, 1993, 1996; Germany, e.g. Aigner and Bachmann, 1992, Kozur and Bachmann, 2008) or in Canada [Leleu et al., 2016, Miall and Balkwilla, 2019, Olsen, 1997, Wade et al., 1995, Welsink and Tankard, 2012].

In Morocco, existing data for the Triassic salt successions are scarce [e.g. Peretsman and Holser, 1988, Salvan, 1974]. In the Atlasic domain, the saliferous series is more reduced and is represented in outcrop by gypsum levels (Central High Atlas, e.g. Biron, 1982, Benaouiss et al., 1996, Courel et al., 2003, El Arabi, 2007, Baudon et al., 2012, Vergés et al., 2017; Argana Valley, e.g. Hofmann et al., 2000; Middle Atlas, e.g. Lorenz, 1976, Laville et al., 1995, Ouarhache et al., 2012). Towards the Mesetien domain and the Moroccan Atlantic margin domain, these successions become much more important. In all Triassic basins belonging to these two domains, the saliferous successions are similar. They are subdivided into two large parts recognized in borehole: (1) the lower part attributed to the Upper Triassic and (2) the upper part dated from the Lower Liassic, separated by the Central Atlantic Magmatic Province, i.e. CAMP basalt (Essaouira Basin, Echarfaoui et al., 002b, Hafid, 2000; Doukkala Basin, Echarfaoui et al., 002a, Salvan, 1984; Khémisset Basin, Et-Touhami, 1994, 1996, 1998, Salvan, 1982; MBEB Basin, Afenzar, 2018, Lyazidi, 2004, Salvan, 1984).

The MBEB Basin consists of a detrital and evaporitic sedimentary series of about 1500 m [Afenzar, 2018, BRPM, 1973]. This sedimentary series is subdivided into two main formations: a sandy-conglomeratic formation at the base (Formation A) and argillaceous-saliferous formation in the middle and top of the series (Formation B) [Afenzar, 2018, Afenzar and Essamoud, 2017] recovered by Triassic-Liassic basalts [Peretsman, 1985].

The aim of this study, from a detailed sedimentological analysis is (1) to reconstruct palaeoenvironment and (2) for the first time, to propose sequence stratigraphy analyses to constitute a basis of a stratigraphic correlation with other Triassic Atlantic basins. Moreover, the correlations in terms of sequence stratigraphy allow to constrain the spatial and temporal evolution of salt series and could guide the exploration and thus have an economic impact.

2. Geological setting

At the early Mesozoic, the Pangea continent was affected by an initial break-up associated with the early stages of the opening of the Central Atlantic Domain. During this phase, the Moroccan and North American Margins were subjected to an extensive tectonic regime that led to the opening of a set of rift basins [e.g. Courel et al., 2003, Hafid, 2000, Leleu et al., 2016, Le Roy and Piqué, 2001, Medina, 1995, Olsen, 1997, Piqué and Laville, 1995, Piqué et al., 1998]. The Moroccan basins are placed geographically in the central segment of Central Atlantic Domain and are laterally equivalent to the Nova Scotian basins [Hafid, 2000, Leleu et al., 2016]. The MBEB basin is a part of a Moroccan margin like the Khémisset, Doukkala, Essaouira, Souss and Tarfaya basins (Figure 1). Among these basins, the closest to MBEB Basin are Khémisset Basin in the north (separated by the Paleozoic basement of central Morocco) and Doukkala Basin in the south (separated by the Paleozoic of Casablanca block).

The MBEB basin is located in the North-West of the Moroccan coastal Meseta, about twenty kilometers northeast of Casablanca (Figure 2). The structure of this basin has been interpreted several times. The interpretations of El Wartiti et al. [1992] were based on the boundary with the Hercynian basement, which are unconformity contacts materialized by border faults controlling the

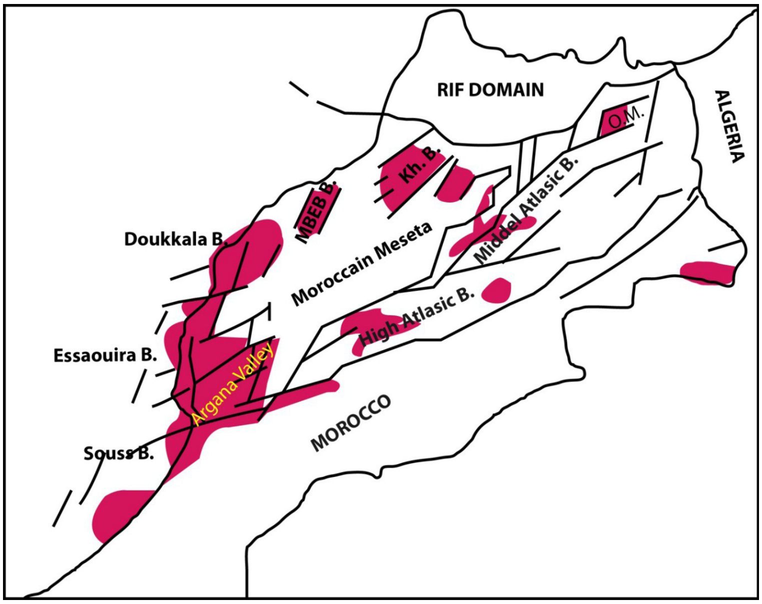

Figure 1. Paleogeographical location of Moroccan Triassic basins in the Late Norian (synthetic map based on Courel et al., 2003 and Leleu et al., 2016).

individualization of the basin and conditioning its filling.

Usually, this basin is presented as an immense shallow depression which seems to have originated from N–S to NE–SW half-graben structure [Afenzar, 2018, El Wartiti et al., 1992]. At the end of the Paleozoic and the early Mesozoic, this half-graben is developed and filled by an important detrital and evaporitic syn-rift sedimentary series; with a magmatic activity belonging to the CAMP [Manspeizer and Cousminer, 1988, Peretsman, 1985].

This basin was subjected to a NW–SE extension with a slight deformation component [El Wartiti et al., 1992]. The structure is controlled by a deep detachment, which is probably an ancient Hercynian weakness zone, and which plunges slightly towards the NNW. This is related to the opening of the proto-Atlantic domain [El Wartiti et al., 1992, Medina, 1994].

3. Lithostratigraphic framework

According to the old nomenclature, the lithostratigraphic series of the MBEB basin was subdivided into five main zones attributed to Permo-Triassic deposits [BRPM, 1973]: (1) Zone argileuse inférieure; (2) Zone salifère inférieure; (3) Zone basaltique; (4) Zone salifère supérieure; (5) Zone argileuse supérieure (Figure 3A).

According to the latest works, the sedimentary series in the MBEB basin is subdivided into two major series: Lower argillaceous-salt series attributed to Triassic and Upper argillaceous-salt series attributed to Liassic [Hssaida et al., 2012, Lyazidi, 2004]. The two parts are separated by a basaltic complex (Figure 3B).

This basalt was dated Late Triassic-Early Liassic (200 Ma) and belonged to the CAMP by several works based on radiometric dating data [Peretsman, 1985]. Subsequently the infra-basaltic series can be attributed to the Upper Triassic [Afenzar, 2018, El Wartiti et al., 1992, Lyazidi, 2004, Salvan, 1984].

In this study, we have subdivided this Upper Triassic part into two main formations: the sandy-conglomerate Formation (A) at the base of the series and the argillaceous-saliferous Formation (B), subdivided into two members, (1) Mudstone-siltstone Member and (2) Argillaceous-saliferous Member (Figure 3C).

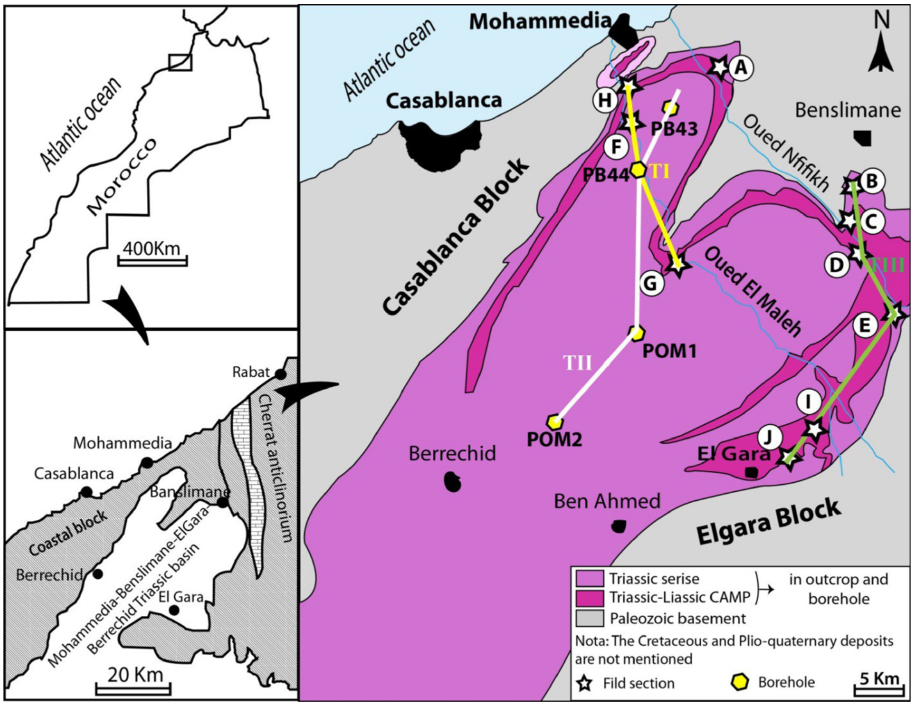

Figure 2. Geological map of the MBEB basin with the sections and boreholes analyzed as well as correlation transects in genetic stratigraphy (A: Chaâbat Al Hamra section, B: Chaâbat Lhmira, C: Assikriat section, D: Tlet Ziaida, E: Sidi Amour, F: Sidi Bouchaibe, G: Barrage Oued El Maleh, H: Sidi Bou Amar, I: Ouled Jhaich J: ElGara, TI, TII, TIII: correlation transects).

4. Method

This sedimentological study consists in a detailed analysis of the field sections (outcropping in the northeastern part of the basin) and drill cores of four boreholes (PB43 (712 m), PB44 (650 m), POM1 (1070 m) and POM2 (1350 m), Figure 2) for a better view of the sedimentary bodies and their spatial arrangements. This allows to characterize different facies and their associations as well as the architectural elements [Allen, 1983, Miall, 1985, 1996] which allow us to reconstruct the depositional environments and their evolutions over time and space.

In fact, the vertical and horizontal arrangement of these facies give birth to the characterized architectural elements according to several criteria determined by Allen [1983] and Miall [1985, 1996], which are: the nature of the upper and lower bounding surfaces, the external geometry, the scale, and the internal structures. The last step is the determination of paleoenvironment which is based on the nature and types of lithofacies already characterized and also on types of architectural elements.

The genetic stratigraphy applied in this study consists of a high-resolution correlation of all the field sections as well as the boreholes in the basin, which makes it possible to individualize isochronous markers separated by a few tens to hundreds of thousands years [e.g. Bourquin and Guillocheau, 1993, 1996].

After the characterization of sedimentary facies, deduction of depositional processes, identification of facies association and interpretation of depositional environments, and setting up a sedimentological model, the genetic unit are characterized and then stacking pattern showing the evolution over time of the depositional environment are established.

The second step consists in correlation of the genetic sequences according to three transects and based on reference levels which can serve as isochronous markers. For this objective four

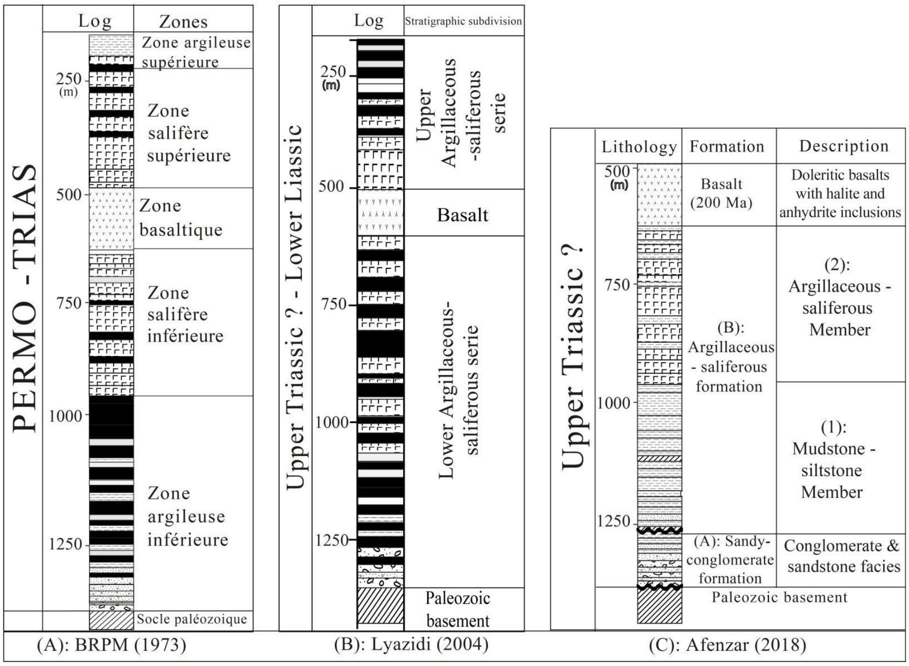

Figure 3. Lithostratigraphic subdivision of the detrital and evaporite infra-basaltic series of the Mohammedia–Benslimane–ElGara–Berrechid basin (A: BRPM, 1973; B: Lyazidi, 2004 C: Afenzar, 2018).

levels have been identified: (1) unconformity between the Hercynian basement and the first facies deposited in the basin; (2) contact between the siltstone-mudstone member and the basal part of the argillaceous-saliferous member; (3) contact between the top part of the argillaceous-saliferous member and the basal part of the member containing pure halitic facies; (4) the lower part of the basalt formation considered as the limit between the Upper Triassic and Lower Liassic [Peretsman, 1985]. A cartography of the genetic sequences was carried out below in order to obtain 2D and 3D geometries for a better interpretation of the evolution of these genetic units as well as the lateral passages of the facies.

5. Facies analysis

5.1. *Identification of lithofacies*

Fourteen facies were identified, described and interpreted in terms of depositional processes based on lithology, grain sizes and sedimentary structures [Miall, 1978, 1996] (Figures 4, 5 and 6, Table 1).

5.2. *Architectural elements*

In this study and according to architectural elements of [Miall, 1996, 2016] we used the abbreviation AE (Architectural Element) for the coding of these elements. This analysis made it possible to characterize six architectural elements (noted AE1 to AE6, Figures 5a, 5b, 5c and 5d) and two facies associations (AFP and AFE).

Architectural element AE1

This constitutes the basis of the series, it was determined in the Chaâbat El Hmira area on a vertical extent from 4 to 5 m. AE1 is formed mainly by facies association Fc1 and Fc2 corresponding to facies Gms and Gm of Miall [1978, 1996]. It is at the base of the series (in contact with the Paleozoic basement) and associated with the architectural elements AE2 and AE3 (Figure 5a). It is formed by gravity flow deposits, mainly pebbles and gravels poorly sorted, formed in the proximal areas of alluvial fans. According to all the criteria, this element corresponds to the element SG (Sediment Gravity Flow) of Miall [1985, 1996, 2016].

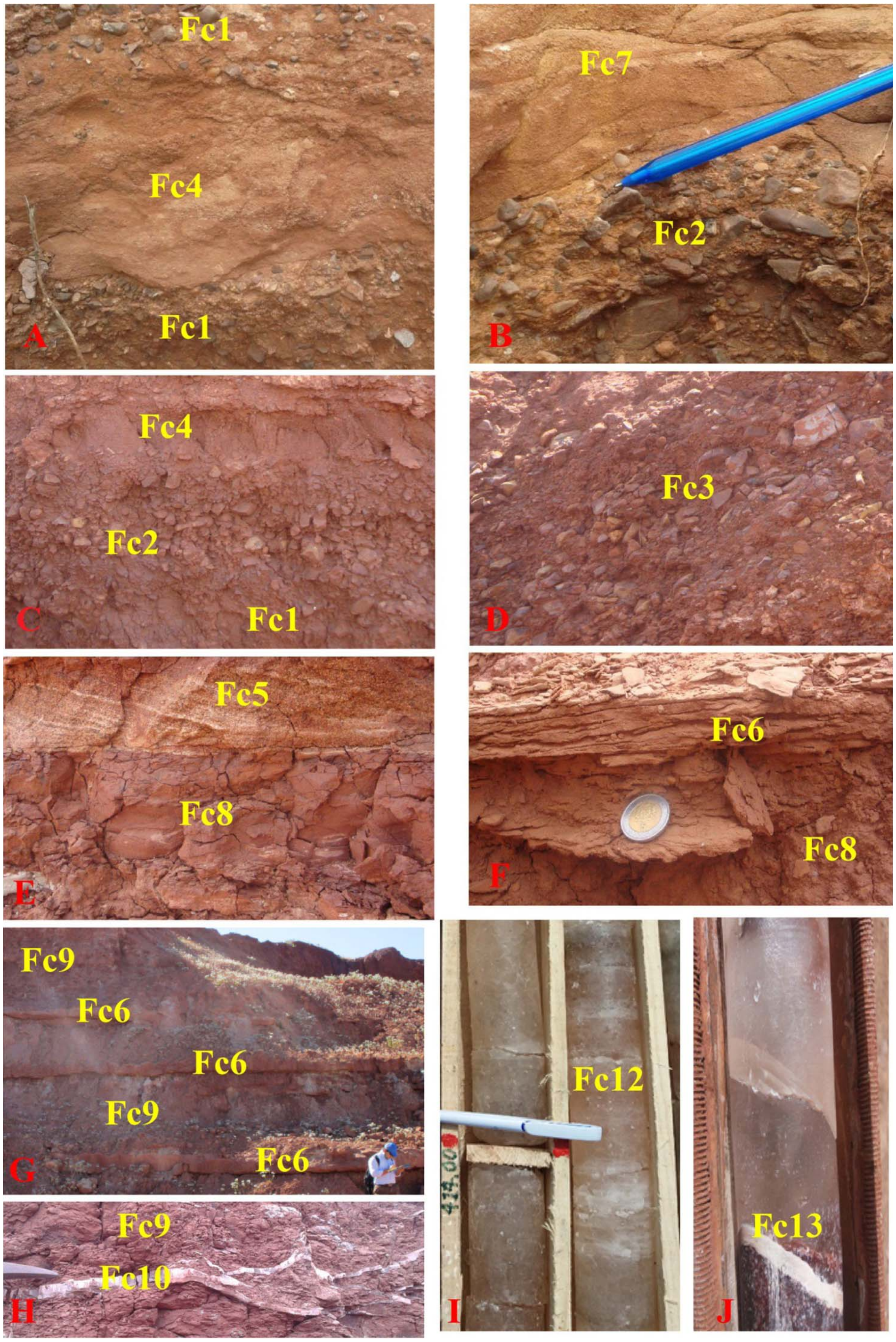

Figure 4. Illustration of the different facies identified in the basin. Description and interpretation in Table 1.

Architectural element AE2

AE2 (Figures 5a and 5b) is formed by lithofacies Fc2, Fc4, Fc5, Fc6 and Fc9. Regarding the internal structure, it is formed by poor matrix and imbricated pebbles facies (Fc2) showing channels lag and sieve deposits. In other cases, this element is formed by sandstone lithofacies characterized by horizontal planar bedding: upper flow regime (Fc6), and by some sandstone lithofacies showing the planar crossbeds (Fc5). Moreover, architectural element AE2 has fourth order basal boundary surfaces (4th: minor erosion) and over (5th: surface bounding generally flat to slightly concave-upward) [Miall, 1988]. These limits are sometimes erosive and slightly planar and in other cases erosive and concave to the top. Inside the element, and between the lithofacies, small boundaries can be identified. From these characteristics, we can say that AE2 resembles to the architectural element CH (Channels) of Miall [1985, 1996, 2016].

Architectural element AE3

It is formed mainly by assemblages of coarse lithofacies containing imbricated pebbles and gravels, showing horizontal stratification, sometimes planar crossbedding: Fc2 and Fc5 (Figure 5a). Sometimes minor lithofacies were identified between these major facies (Fc4 and Fc6). Most facies of this element are organized as tabular bodies of five to six meters thick. Also, it is formed from a 4% to 6% of fine to medium sandstones. AE3 corresponds to the architectural element GB (Gravel bars and bedforms). It is usually coarse deposits formed at gravels bars, these coarse deposits are sometimes intercalated by thin levels sandstones formed at low flows (speed decrease) [Massari, 1983, Miall, 1985, 1996, 2016].

Architectural element AE4

This architectural element (Figures 5b and 5c) is formed by medium to fine lithofacies assemblages: facies Fc5, Fc6 and Fc7 corresponding respectively to facies Sp, Sh and Sl of Miall [1978, 1996, 2016], but it is dominated by Fc7. The Fc6 and Fc7 facies are sometimes separated by a very fine facies: Fc8. Architectural element AE4 passes laterally into element OF. It is characterized by internal boundaries of second to third order, while its outer boundaries are fourth order. For this, AE4 has many similarities with the architectural element SB (Sand Bedform) of Miall [1985, 1996, 2016]. This architectural element characterizes in our case, crevasse channels and/or crevasse splays deposits.

Architectural element AE5

It is an assemblage of fine to very fine lithofacies. This element is presented as sandstone sheets with horizontal laminations from 40 to 80 cm thick: facies Fc6, it is intercalated with thin purplish siltstones and mudstones laminated: facies Fc8 and Fc9. This architectural element resembles to architectural element LS (sand laminated sheets) of Miall [1985] (Figure 5c). Lithofacies forming this architectural element have been interpreted as the product of flash floods [Miall, 1985, Rust, 1978, Sneh, 1983, Tunbridge, 1981, 1984]. The architectural characteristics of this element are well described by Tunbridge [1981] and Sneh [1983]. The sand sheets are deposited on flat surfaces slightly eroded, laterally, they can spread over hundreds of meters.

Architectural element AE6

Architectural element AE6 (Figures 5b and 5c) is considered as a major element in the basin, its thickness can reach forty meters. It is presented as large sheets (2 to 50 m thick), formed by purplish or red brick siltstones and mudstones, these siltstones and mudstones sometimes show a massive aspect with crude planar laminations indicating a quiet depositional setting. In other cases, they show horizontal laminations with very thin intercalations (5–15 cm) of fine sandstones. By these characteristics we can say that AE6 corresponds to the architectural element OF (Overbank fines) of Miall [1985, 1996, 2016].

According to Miall [1985, 1996], in most cases this element has a sheet geometrical form, reflecting its origin by vertical aggradation. In the vicinity of the active channels, these sheets are separated by crevasse splays. This architectural element may

Table 1. Description and interpretation of sedimentary facies of Triassic series of MBEB based on Miall (1978 and 1996), Bridge [2003] and Opluštil et al. [2005]

Facies code	Lithology and sedimentary structures	Depositional process	Interpretation
		Conglomeratic facies	
Fc1	Massive conglomerate (1 m to 4 m thick) with angular, disorganized and poorly sorted gravels. The matrix is formed by the fine sandstone. Without sedimentary structures (A, B Figure 4).	Gravity flows, Mass flow deposits	Equivalent to Gms of Miall [1996]. 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 flow at proximal alluvial fans environment [Miall, 1978, 1985, 1996, Opluštil et al., 2005].
Fc2	Clast-supported stratified conglomerates with centimeter to decimeter-sized pebble-gravels, showing angular to sub-angular shapes and horizontal bedding imbrication (B & C, Figure 4).	Aggradational deposit	Equivalent to Gm of Miall [1996]. This facies (0.4 m to 2.5 m thick) has been deposited at median to distal alluvial fans or longitudinal bars in the braided rivers system. It can also be interpreted as sieve and/or lag deposits [Miall, 1978, 1985, 1996].
Fc3	Planar crossbeds conglomerate (0.5 m to 3 m thick). The matrix is formed mainly by clastic materials (clast-supported) which are very fine sandstones (D, Figure 4).	Progradational deposit	Equivalent to Gp of Miall [1996]: Deposit of longitudinal bar in a braided rivers system with shallow channels [Miall, 1978, 1985, 1996]. This facies present a similarity with conglomerate of the lower part of Bigoudine formation (T6) in the Argana valley [Hofmann et al., 2000].
		Sandstone facies	
Fc4	Massive coarse sandstone (1 m to 3 m thick) without any sedimentary structures. Sometimes it presents isolated large fragments (A & C, Figure 4).	Rapid deposits Gravity flow deposits	Equivalent to Sm of Miall [1996]. The presence of isolated large fragments is probably related to their falling along the slope [Sohn et al., 1997], associated with the deposition mechanism itself or a movement in a high load flow [Postma and Cruickshank, 1988]. According to [Einsele, 1992, Miall, 1985, 1996], these facies occur in alluvial fans environment.
Fc5	Fine to coarse sandstone (0.4 m to 2 m thick), showing the planar crossbeds (E, Figure 4).	Progradational deposit	Equivalent to Sp of Miall [1996]: Linguoid or transverse bars deposits (lower flow regime) [Bridge, 2003, Miall, 1985, 1996, Todd, 1996]. It is similar to some sandstone beds of the lower part of Oukaïmeden sandstone [Benaouiss et al., 1996].

(continued on next page)

Table 1. (continued)

Facies code	Lithology and sedimentary structures	Depositional process	Interpretation
Fc6	Fine to coarse sandstone (0.2 m to 1.5 m) characterized by horizontal laminations with parting or streaming lineation (F, Figure 4).	Plane-bed flow	Equivalent to Sh of Miall [1996]. This structure is generated by small longitudinal vortices affecting the entire turbulent boundary layer. It results from upper flow regime deposits [Miall, 1985, 1996].
Fc7	Fine sandstone (0.5 m to 2 m thick) characterized by low angle (<10°) planar cross beds.	Scour fills	Equivalent to Sl of Miall [1996]. It is a crevasse channel and/or a crevasse splay deposit often formed in the floodplain at anastomosed fluvial system.
		Fine facies	
Fc8	Massive to horizontal laminated siltstone. They have a reddish appearance with grey to greenish levels of mottling (E & F, Figure 4).	Overbank deposit	Equivalent to Fl of Miall [1996]. Vertical accretion deposit showing a laminar flow of very low energy. This facies is interpreted as a flood plain, overbank or playa deposits [Miall, 1985, 1996].
Fc9	Massive reddish mudstone (0.1 m to 6 m thick) showing mottling spots (C & H, Figure 4).	Overbank deposit	Equivalent to Fm of Miall [1996]. These mudstones can be deposited in (1) an alluvial plain of a braided system, (2) floodplain and playas, and sometimes in (3) distal alluvial fans [Mader, 1985]. These mudstones are interpreted as lacustrine or overbank deposit [Miall, 1996]. This facies and Fc8 sometimes have cyclicity similar to that described by Hofmann et al. [2000] in the Argana valley (T4, T5 and T7).
		Evaporite facies	
Fc10	Gypsum beds facies (0.1 m to 0.5 m). It is presented in the form of centimeter banks alternating with the siltstones and the mudstones facies (H, Figure 4).	Evaporation in a hot and humid environment	These facies are formed in relatively hot and humid environments by the precipitation of sulfated ions in supersaturated solutions subjected to intense evaporation [Warren, 2006, 2010].
Fc11	Fibrous gypsum (0.1 m to 0.2 m thick)	Diagenetic facies	Diagenetic origin [Afenzar and Essamoud, 2017, Afenzar, 2018, Et-Touhami, 1994, 1996].

(continued on next page)

Table 1. (continued)

Facies code	Lithology and sedimentary structures	Depositional process	Interpretation
Fc12	Milky clean halite deposited as decametric to metric beds rarely associated with very fine anhydrite laminae (I, Figure 4).	Evaporation in a hot and humid environment	The rhythmicity of this facies with the mudstone facies is probably due to the interventions of the slightly turbid continental waters which propagate on the surface of the brine [Afenzar, 2018, Et-Touhami, 1994, 1996, Sonnenfeld and Hodec, 1985]. The alternation of this halite with detrital and sulphate levels indicates that it is probably deposited in saline mudflats or evaporite flats.
Fc13	Phenoblastic halite with limpid crystals (J, Figure 4). (0.5 m to 0.5 m thick)	Diagenetic facies	Filling of dissolution cavities. Diagenetic origin [Afenzar, 2018, Et-Touhami, 1994, 1996].
Fc14	Millimeter to centimeter veins of fibrous halite.	Diagenetic facies	Filling of pre-existing fractures in the mudstone levels. It is presented as thin fibers elongated perpendicularly to the walls of mudstones. This halite is formed probably during diagenesis in the mudstone [Dumas, 1988, Et-Touhami, 1994, 1996, Hovorka, 1983].

fill abandoned channels, provided it has concave-up basal contact and ribbon to lenticular geometry of the channel itself [Ethridge et al., 1981, Miall, 1985].

Facies association of Playa (AFP)

It is a lithofacies combination of 5 to 6 m thick. It is formed by siltstone and mudstone lithofacies assemblage (*Fc8, Fc9*) and by fine sandstones sometimes showing horizontal flat beddings (lithofacies Sh). The facies association AFP presents a cyclicity of the sandstone, siltstone and mudstone facies; which shows that it is deposited in Playa Lake. The presence of sandstone deposits also shows that these playa lakes are shallow [Liu and Wang, 2001].

Evaporite facies association (AFE)

It is an association of mudstone (Fm) and evaporite facies (Fc10: beds gypsum, Fc11: fibrous gypsum, Fc12: milky halite, Fc13: phenoblastic halite, Fc14: fibrous halite). The thickness of the facies varies between 1 and 1.5 m for the siltstone, between 10 and 20 cm for the gypsum and between 10 cm and 2 m for the halite. These evaporite facies are often of primary and in other cases diagenetic origin. They are formed by the evaporation of saline waters in mudflats and lagoons in a hot and humid climate in relation to a "pellicular" sea that covered the basin in the Upper Triassic.

6. Paleoenvironment reconstruction

6.1. *Proximal alluvial fans system*

This fluvial model is characterized by massive conglomerate with angular, disorganized and poorly sorted gravels, and by massive coarse sandstone (two to three meters thick without any sedimentary structures). These lithofacies are associated in two architectural elements: AE1 (Sediment gravity flow SG) and AE2 (Channels CH). AE1 units are interbedded with channelized beds of AE2. By these architectural element characteristics (facies assemblage, geometry, bounding surfaces...), we can deduce that this depositional environment is similar to the model

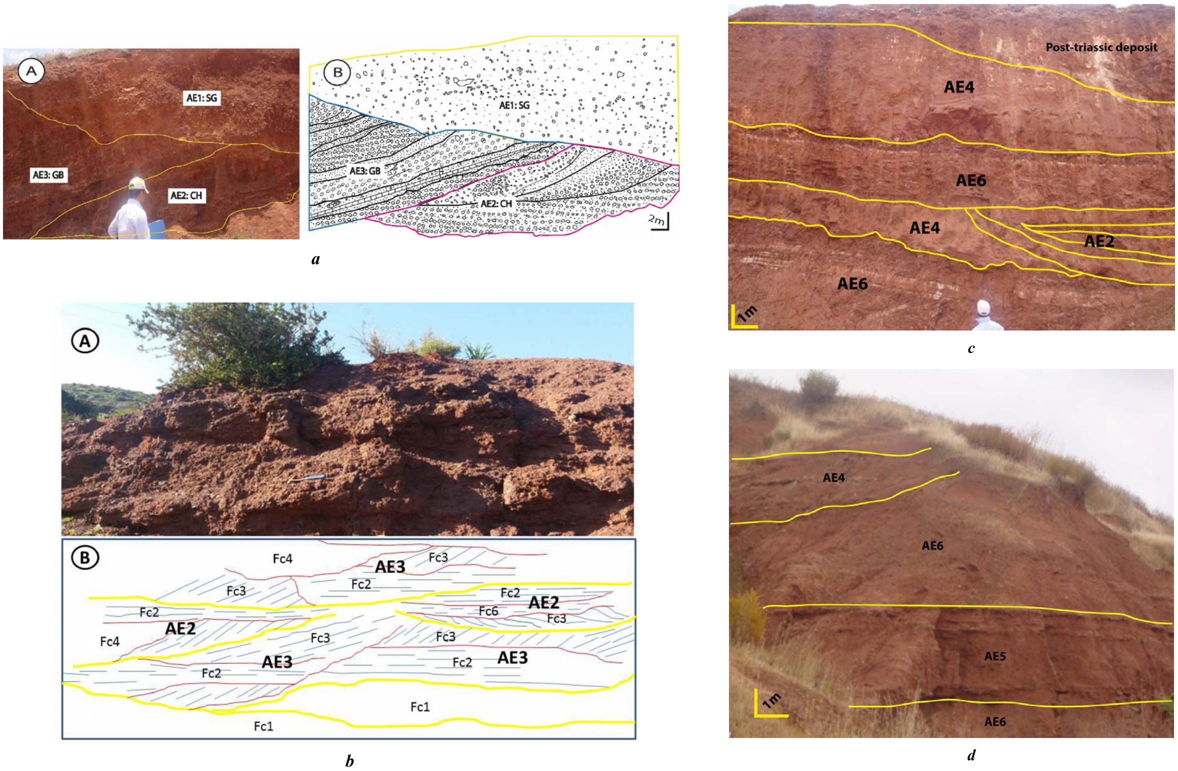

Figure 5. Architectural elements characterized in the basin (a: in Chaâbat Lhmira outcrop, b: in the Chaabat Al Hamra outcrop, c: in the top of Chaâbat Lhmira outcrop, d: in Assikriat outcrop).

No 1 of Miall [1985, 1996, 2016]. It is proximal alluvial fan with sediment gravity flows of gravelly rivers [Afenzar, 2018, Afenzar and Essamoud, 2017, Miall, 2016]. The frequency of debris flows depends strongly on source rock weathering characteristics, so that adjacent fans, the headwaters of which flow across contrasting bedrock units, may show quite different lithofacies assemblages [Hooke, 1967, Miall, 1996, 2016].

6.2. *Shallow channels of a braided rivers system*

The sediments characterizing this environment style are coarse to medium. It is a clast-supported stratified conglomerate with centimeter to decimeter-sized pebble-gravels, showing sub angular shapes and horizontal bedding imbrication (Fc2), and planar crossbeds conglomerate (Fc3). The medium to fine deposits are presented by massive coarse sandstone without any sedimentary structures (Fc4) and fine to coarse sandstone characterized by horizontal laminations with parting or streaming lineation (Fc6). The facies association of this style forms the architectural element AE2 (CH: channel) and AE3 (GB: gravel bars). In this environment, the architectural element AE3 is the most abundant. During the fluctuations stage, bar complexes become emergent, and are crossed by minor channels in which thin deposits of AE2 may form [Miall, 2016]. These fluvial style characteristics resemble to those of model No 2 of Miall [1985, 1996, 2016]. It is a proximal braided rivers system characterized by shallow channels and gravel bars.

6.3. *Floodplains in anastomosed rivers system*

This depositional environment is characterized essentially by fine to very fine deposits with a large thickness. In that case, these facies are organized into

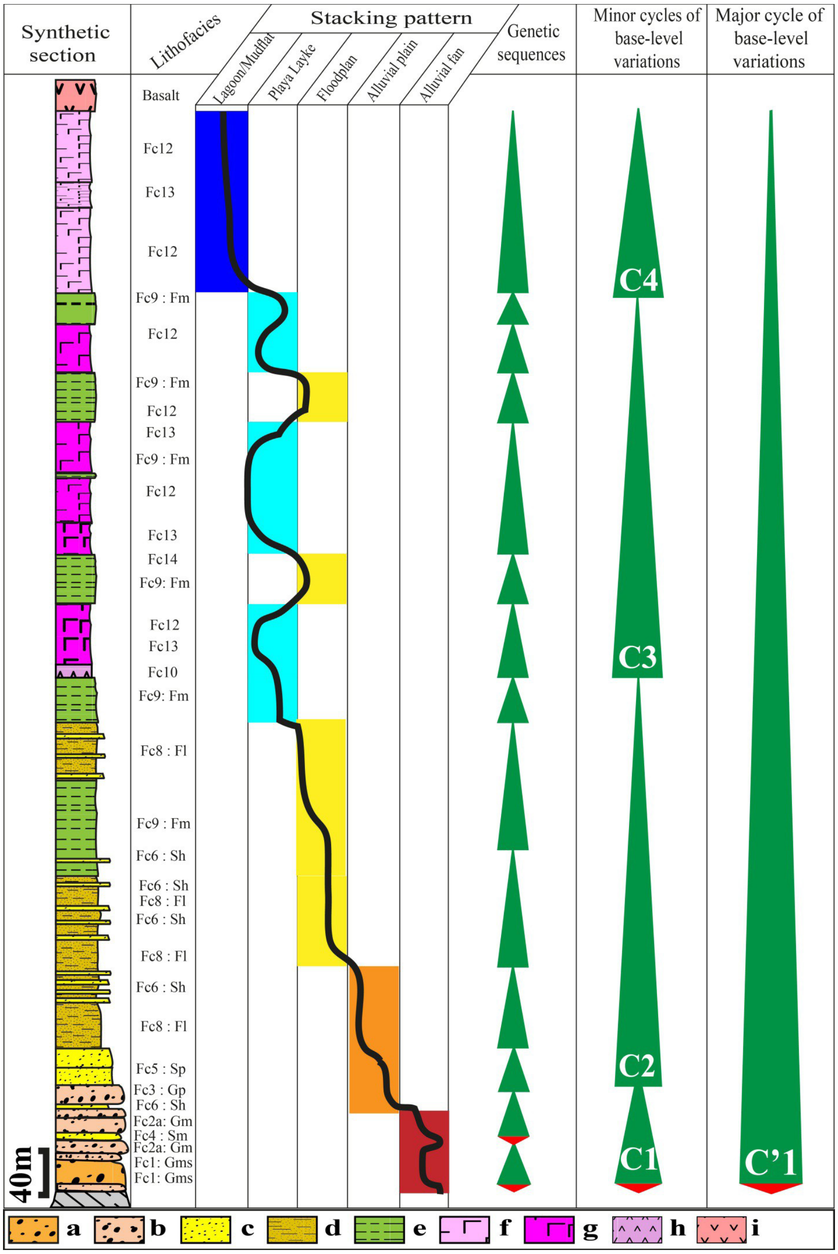

Figure 6. Synthetic sedimentary log of the basin with minor and major cycles of base-level variations. a and b: conglomerate; c: sandstone; d: siltstone; e: mudstone; f: pure halite; g: argillaceous halite; h: gypsum; i: basalt.

two architectural elements: AE4 (SB: Sand Bedforms) deposited in the crevasse splays, and architectural element AE6 (OF: Overbank Fine) formed in flood plains and abandoned channels. The element AE4 has a limited lateral extent and passes laterally into AE6. This type of fluvial style is much less studied and interpreted, unlike other types of depositional environment [Farrell, 1987, Kraus and Bown, 1988, Miall, 1985, 1996, 2016]. However, it is linked to an anastomosed environment characterized by low-energy floods with crevasse channels and crevasse splays.

6.4. *Coastal plains, playa lakes, mudflats and lagoons system*

This is a set of more distal deposit environments. They are characterized by deposits recorded in the middle and top part of the argillaceous-saliferous formation (B) and which is finally capped by Triassic-Liassic basalts. This system is characterized by massive to horizontal laminated siltstone, massive reddish mudstone showing mottling spots, gypsum beds facies alternating with the siltstones and the mudstones facies, fibrous gypsum, milky clean halite deposited as decametric to metric beds rarely associated with very fine anhydrite laminae and phenoblastic halite with limpid crystals.

This system probably corresponds to the large coastal plain downstream characterized by the development of playa lakes, mudflats and lagoons where the evaporite facies are formed by the evaporation of marine waters [Peretsman, 1985, Peretsman and Holser, 1988] under a hot and humid climate and in relation to a pellicular sea that covered the domain during the Upper Triassic time.

7. Genetic stratigraphy and correlation

7.1. *Identification of genetic sequences*

In the continental domain, as in our case, the identification of genetic sequences is complicated. A genetic sequence is usually represented by a period of erosion, by pass or stacked of fluvial deposits linked to the base level fall (i.e. progradation) and a period of aggradation accompanied the base level rise (i.e. retrogradation). The periods of base level fall correspond to a weak preservation of the facies whereas the period of aggradation corresponds to a significant sedimentary preservation [Bourquin et al., 1998, 2009, Hamon and Merzeraud, 2005, Homewood et al., 1992, Merzeraud, 1992].

Genetic sequence UG1

It is a genetic sequence in which an alluvial fan system evolves to a braided system with an alluvial plain. The period of base level fall (progradation) is characterized by a weak preservation of the thin conglomerate facies without sedimentary structure with coarse, angular and poorly sorted elements limited by erosion surfaces indicating the base level fall. The base level rise period (retrogradation) is characterized by the important preservation of alluvial fan facies and the development of conglomeratic facies (showing horizontal stratifications with imbricated and well-sorted pebbles-gravels) and sandstone facies showing horizontal planar bedding. These facies are organized into architectural elements: AE1, AE2 and AE3 formed in channels and bars in a braided river system.

Genetic sequence UG2

The base level fall period is characterized by the deposition of coarse massive sandstone facies without sedimentary structures. The base level rise is marked by well-organized facies with horizontal stratifications and other conglomerate facies showing planar cross-beds organized into architectural elements AE2 and AE3 deposited at the channels and bars in a braided fluvial system.

Genetic sequence UG3

This genetic sequence formed during the increase of the base level (retrogradation), is characterized by the development of distal fine facies forming the architectural element AE6 and deposited in the floodplain. The basal boundary of this sequence is marked sometimes by the passage of coarse facies formed at the bars in a braided system to fine facies of the floodplain.

Genetic sequence UG4

This sequence is characterized by its formation during the rise of the base level marked by the deposition of sandstone, siltstone and mudstone facies. These facies are associated in two architectural elements (AE2: CH and AE6: OF) formed in anastomosed channels with an immense floodplain. This period of base-level rise is also characterized by a decrease of grain-size, passing from channel sandstone facies to the siltstone-mudstone facies of the floodplain.

Genetic sequence UG5

UG5 is characterized by a period of base level rise associated with the development of sandstone and mudstone facies organized into architectural elements AE4, AE5 and AE6 deposited in sand bars and crevasse splays at a floodplain related to an anastomosing fluvial system. The facies association is characterized by a gradual decrease of grain-size.

Genetic sequence UG6

This genetic sequence is formed during the base level rise period. It is represented by sandstone and siltstone-mudstone facies deposited in floodplains and probably in coastal plains characterized by architectural element AE6 and facies associations of playa (AFP).

Genetic sequence UG7

It is characterized by a period of base level rise, and formed by sandstone, siltstone, mudstone and evaporite facies. These facies form the association of Playa (AFP) and/or facies-association of evaporite (AFE) formed at playa lakes and at lagoons with an immense coastal plain.

Genetic sequences UG8 to UG14

The UG8 to UG14 genetic sequences are characterized by alternating siltstone, mudstone and evaporites facies (organized into architectural elements AE6, AFP and AFE) formed in a coastal plain associated with mud flats and lagoons. These genetic units have been identified mainly in boreholes at depths ranging from 500 m up to 1000 m. The maximum flooding surfaces of these sequences are between the mudstone facies and the evaporites facies.

7.2. *Genetic sequences correlations*

The genetic units are correlated from one section to the other (Figure 7) and from borehole to another (Figure 8). This correlation is based on the determination of reference levels. For this objective four limits have been identified:

- the first one is the unconformity between the Hercynian basement and the first facies deposited in the basin,
- the second reference level is the contact between the detrital facies and the first evaporites facies (gypsum) deposited in the basin and corresponds to the contact between the Mudstone-Siltstone Member and the basal part of the Argillaceous-Saliferous Member (Figure 3C),
- the third reference level concerns the contact between the upper part of the Argillaceous-saliferous Member and the basal part of pure halitic facies, located at the top of this Member,
- the fourth one is the beginning of the Basalt considered as the limit between the Upper Triassic and Lower Liassic [Peretsman, 1985].

For more precision, this correlation was carried out according to three transects: the first one (TI) N–S on Oued El Maleh river. The second transect (TII) N–S on the Oued Nfifikh and the last transect (TIII) N–S which links between the boreholes PB43, PB44, POM1 and POM2 (Figure 2). The stacking pattern of the genetic sequence allows the constitution of four minor cycles of base level variation (Figure 6).

The first cycle (C1) is characterized by conglomerate and sandstone deposits unconformably deposited on the Hercynian basement. The maximum flooding surface (MFS1) is marked by the passage of thin conglomerate facies without sedimentary structure with coarse, angular and poorly sorted elements limited by erosion surfaces to conglomerate facies, deposited in proximal alluvial fans and conglomerate and sandstone facies formed in a braided fluvial system with a progressive rise of base level (UG1 and UG2).

The second cycle (C2) (Figures 9, 10 and 11) has a remarkable base level increase. It is characterized by a vertical aggradation of the sandstone, siltstone and mudstone facies formed in an alluvial plain in braided system and/or in an anastomosing river system.

The third cycle (C3) (Figures 9, 10 and 11) was identified on the borehole (PB44). It is a retrogradational/aggradational cycle and is characterized by the appearance of the first evaporite facies. Its base is represented by gypsiferous mudstone and alternations of mudstone and bed gypsum. Then, there is a transition to alternations of halite (+/− closed lagoon) and mudstone formed in playa and mudflats.

The fourth and last cycle (C4) (Figure 11) is characterized by the rise of the base level, with the formation of pure halite facies, which shows a marine intervention stopped abruptly by basaltic effusions at the

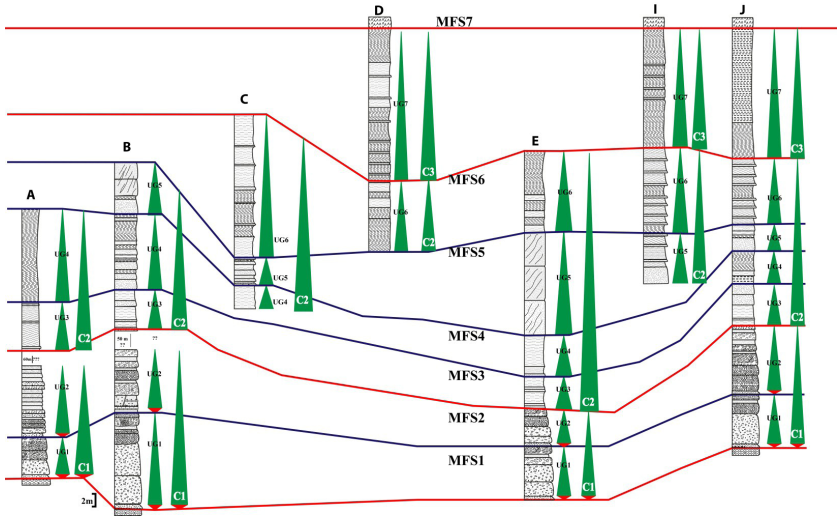

Figure 7. Correlation of genetic sequences based on the study of field sections on the Oued Nfifikh-ElGara axis (Transect II).

end of the Upper Triassic.

7.3. *Basin-wide genetic sequences cartography*

The identification of different orders of genetic sequence stacking and their correlation allow the cartography of their extent. The result is a paleogeographic reconstruction for each genetic sequence. This stratigraphic correlation makes it possible to study the distribution of facies in space within each sequence, and their evolution over time (Figures 9, 10 and 11).

At the base of MFS1, conglomerates have larger thicknesses in the center than at the ends for transect (TI) (Figure 9). For the transect (TII) (Figure 10), these conglomerates have significant thicknesses along the entire transect. At the north, some conglomeratic facies of the retrogradational part of the genetic sequence UG1 pass laterally to sandstone facies. The genetic sequence (UG1) of this cycle (C1) is formed in proximal deposition environments: alluvial fans, proximal braided system with remarkable variations of palaeoslope.

Between MFS1 and MFS2, an increase of base level leads to a change in the depositional environment to an alluvial plain characterized by sandstone and siltstone deposits. This rise of the base level is shown by well-developed braided channel facies and by a gradual decrease of grain size and then by the appearance of the well-sorted facies, with the disappearance of the angular elements and finally by the passage of the massive facies without sedimentary structure (Gms and Sm) at Planar cross-beds facies (Gp and Sp) then at Horizontal lamination facies (Gm and Sh) [Bourquin et al., 1998, 2009, Hamon and Merzeraud, 2005, Homewood et al., 1992, Merzeraud, 1992, Poli, 1997]. Lateral transition of facies is observed at the north of the transect (TI) (Figure 9) and the entire transect (TII) (Figure 10).

Between MFS2 and MFS4, we have noticed an appearance of evaporites facies that are concentrated in the middle of the transect (TI, Figure 9) and pass laterally to siltstone and mudstone at the same genetic sequence. For the transect (TIII, Figure 11), this interval (MFS2–MFS4) is characterized by a genetic sequence with purely saline facies. This passage of evaporites facies to mudstone facies is probably due either to the migration of deposition environment during the same time interval, or to the dissolution and erosion of these facies exposed in outcrop. The last cycle (C4) (Figures 10, 11) is characterized by a deposition of pure halite facies recovered by basalts, which shows the marine incursion before these basaltic effusions at the end of Triassic and early Jurassic.

These genetic sequences and progradational/retrogradational cycles show an evolution of the proximal fluvial environments (alluvial fans passing

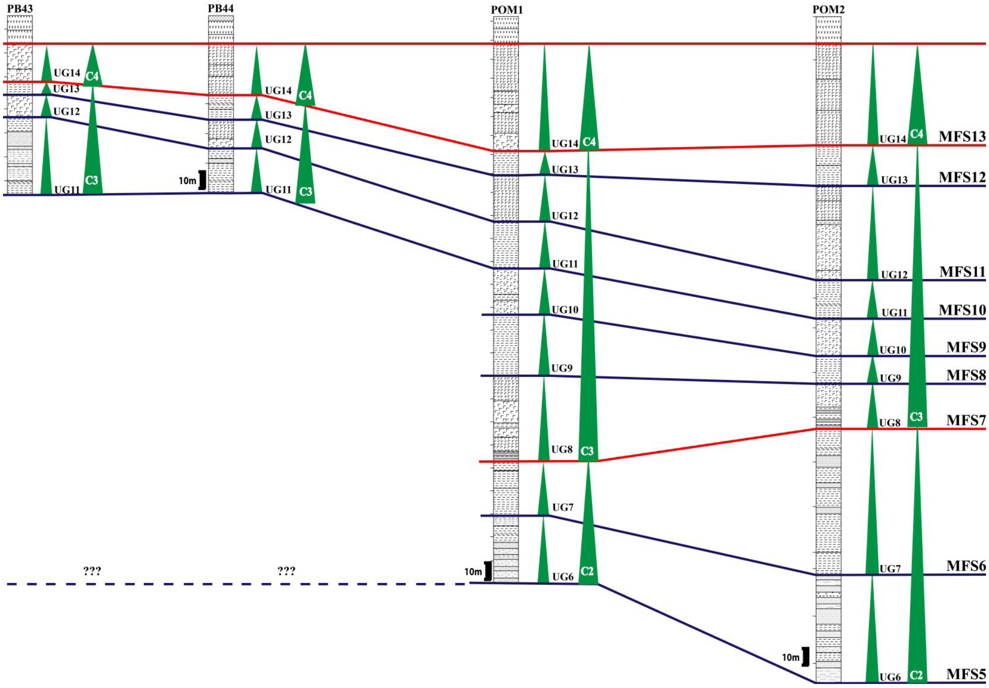

Figure 8. Correlation of genetic units based on the study of the central and northern boreholes of the basin (Transect III: N–S).

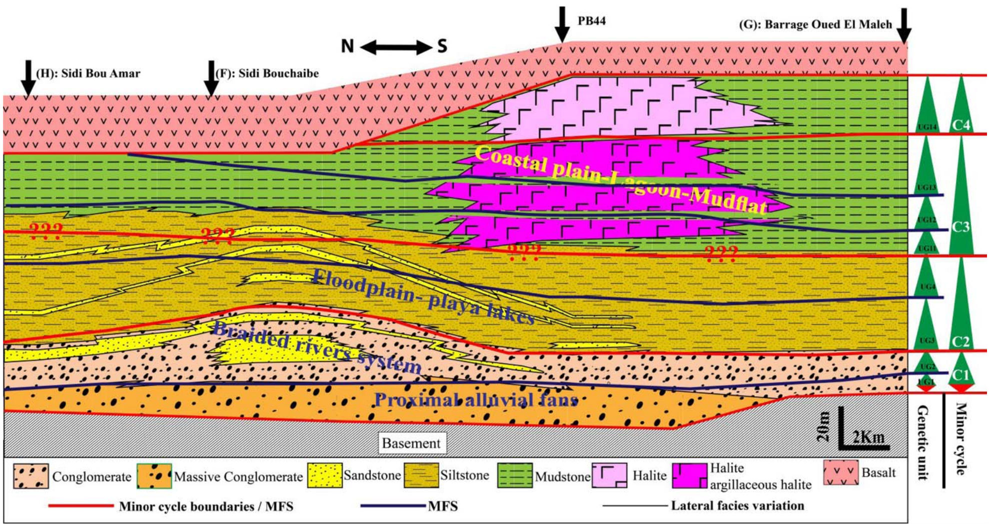

Figure 9. First transect (TI) N–S of correlation and cartography of genetic sequence and minor cycles of base-level variation.

laterally to braided system) at the base of the TI and TII (respectively Figures 9 and 10, orange and beige color) to a distal environments (anastomosed rivers and floodplains) in the middle of TI and TII and at the base of TIII (respectively Figures 9, 10 and 11, yellow and green color below MFS2), and then at a transition environment (coastal plain with lagoons and mudflats) at the top of the TI and TII and throughout

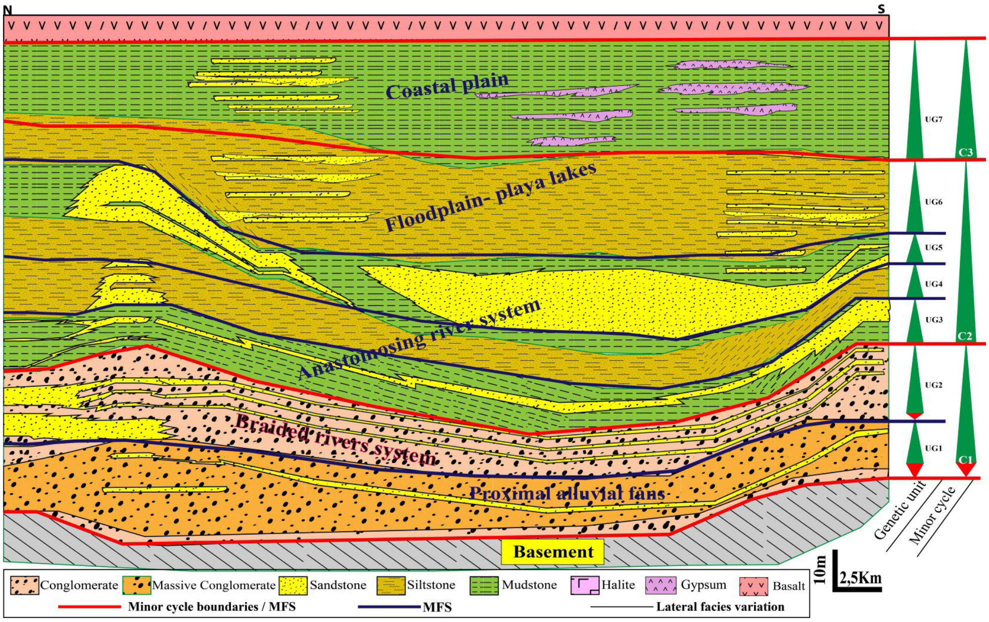

Figure 10. Second transect (TII) N–S of correlation and mapping of genetic sequence and minor cycles of base-level variation.

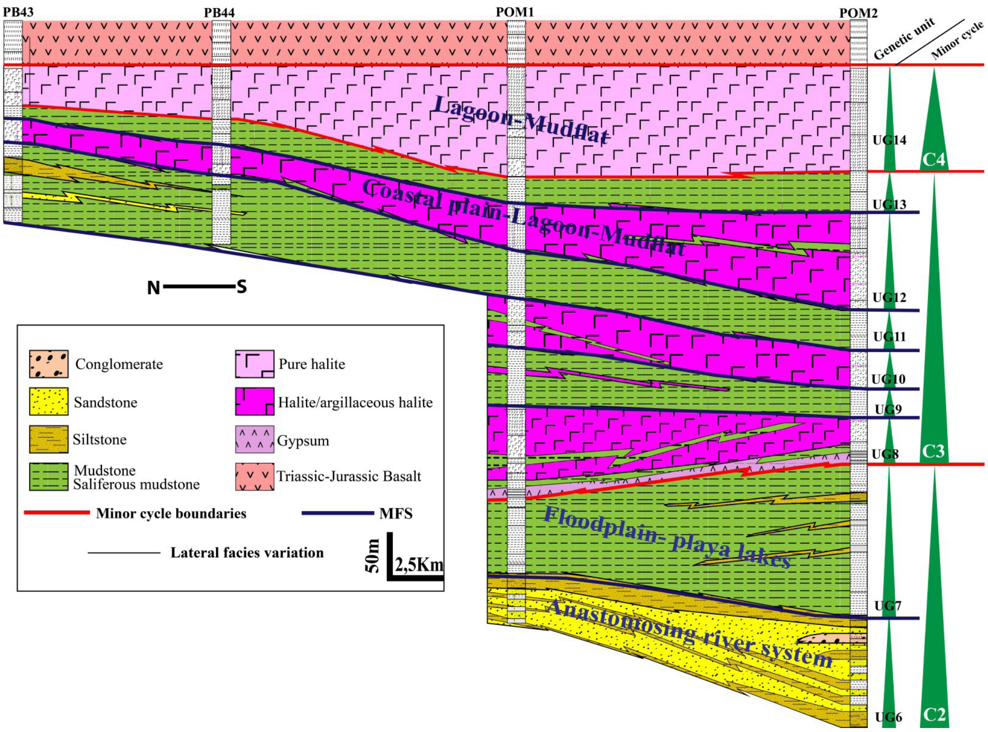

Figure 11. Third transect (TIII) N–S of correlation and mapping of genetic sequence and minor cycles of base-level variation.

the transect TIII (respectively Figures 9, 10 and 11, green and pink color).

8. Discussion

Paleoenvironmental evolution

Sedimentary analysis has shown that the studied basin is characterized by siliciclastic sedimentation at the beginning and then evaporitic at the end of the syn-rift sedimentary filling (Figure 6) [Afenzar, 2018]. First-cycle debris eroded from a mountainous source area are deposited at the edges of the basin in coarse alluvial fans, or transported to a coastal plain [Miall, 2016].

Based on the identified facies, and the characterized architectural elements and the alluvial styles, the depositional environments are evolved over time from:

- proximal alluvial fans system characterized by accumulation of gravity-flow sediments to a proximal braided system characterized by conglomeratic and sandstone bars;
- subsequently, the depositional environment has changed to an anastomosed system with a vast floodplain characterized by crevasse splays that pass laterally to overbank deposits (middle of the sedimentary series); these anastomosed systems occur in areas of active vertical aggradation, such as coastal systems during a time of rapidly rising base level;
- finally, these environments eventually evolve to a coastal plain where playa lakes, mudflats and lagoons have developed. In this phase, the syn-rift sedimentary series recorded a marine incursion at the Upper Triassic with saliferous sedimentation Afenzar [2018]. It is deduced from the presence of a thick saliferous series with a large lateral extension whose isotope ratios of sulfur and bromine contents indicate their marine origin [Peretsman, 1985, Peretsman and Holser, 1988]. These marine waters are probably of Tethyan origin and are also related to the opening of the Proto-Atlantic [Et-Touhami, 1994]. This marine incursion remains thin compared to the southwest European Triassic basins. In these cases, the well-developed marine domain is indicated by the presence of carbonates rich in marine species (e.g. Alpujarride carbonates in Betic Cordillera: Martin-Rojas et al., 2009). Leleu et al. [2016] specified that these marine ingressions from the Tethys domain are inferred from dolomite and marine fauna in Portugal and from thick salt deposits in Morocco and offshore Canada during the late Rhaetian.

Control factors

Detrital sedimentation in the MBEB basin can be interpreted as resulting from the filling of a ditch in the form of half-graben [El Wartiti and Fadli, 1985, El Wartiti et al., 1992], the replay of the Hercynian faults which caused the collapse of this ditch and the activation of erosion. According to Salvan [1984], distension and subsidence were localized in Meseta points (ex. MBEB basin), which led to the accumulation of salts deposits.

The MBEB basin is therefore an open continental zone, which has favored the registration of alluvial fans, high-energy fluvial systems, and then gradually filling up, we have moved to lakes, and to evaporites. It is a typical succession associated with geodynamic context of rift type.

In this basin, the silico-clastic sedimentation is the result of continental alteration, and therefore a good part of the budget of erosion will arrive in the basin. After the period of erosion (the ante-Triassic reliefs), the basin is an area of sedimentation. It is an extensive basin whose deposits are initially aggradational and then retrogradational.

The MBEB basin also recorded a budget of parameters (mainly tectonic, climate) that created accommodation and a parameter that fills this space: the sediment supply. The sediments are mostly red. This reflects the oxidizing conditions in which the sedimentation was carried out [Biron, 1982, Van Houten, 1973]. The evaporites indicate a relatively hot and humid climate that has favored their precipitation.

The palaeoenvironmental evolution was also controlled by the evolution of palaeoslope. The decrease of the latter is found in most Triassic rift basins belonging to the central Atlantic domain. Leleu and Hartley [2010] suggest that in the Fundy and Minas basins, the palaeoenvironmental transition is diachronous, such that it cannot be related to climatic controls of global or megaregional extent and the fining-upward profile can be explained by a decrease in source area relief by erosion within a hydrologically closed basin.

Paleogeography

The evaporitic deposits could correspond to a Late-Triassic transgression from the Tethys to the north and an epicontinental marine domain to the west [Beauchamp, 1988, Beauchamp et al., 1995, Oujidi et al., 2000]. A "pellicular" sea covered most of the Moroccan basins with intermediate facies, which was therefore a flat surface affected by localized subsidence (The MBEB basin is part of it) where the evaporitic thick layers accumulated. The marine character of the evaporites [Peretsman and Holser, 1988] denotes a first transgressive episode [Salvan, 1984] generalized throughout the Atlasic-Mesetien domain [Oujidi et al., 2000]. The detrital basins on either side of the future Atlantic Ocean are considered primarily purely continental, with the Newark Basin as a model [Smoot, 1991].

The idea of a secondary communication between the Tethyan marine domain and the proto-Atlantic via the basins of Khémisset, Roumani and MBEB, operating discontinuously is quite conceivable [Et-Touhami, 1994].

Relationship with Atlantic rifting

At the beginning of the Mesozoic, the northwestern part of the African continent was affected by an initial fracturing associated with the early stages of the opening of the central Atlantic (Atlantic rift).

Several authors consider that the opening of several Moroccan Triassic sedimentary basins (at least those in the southern edge of the Tethys) was initiated during this Triassic rifting. This opening was controlled by the reactivation of the preexisting weakness zones in the Paleozoic basement and inherited from the Hercynian orogeny [Courel et al., 2003, Hafid, 2000, Laville et al., 2004, Leleu et al., 2016, Le Roy and Piqué, 2001, Medina, 1994, Olsen, 1997, Piqué and Laville, 1995, Piqué et al., 1998].

The MBEB basin is part of the western province of Triassic deposits in Morocco, which correspond to all the basins of the Moroccan Atlantic margin (Doukkala, Argana, Essaouira…) in direct relation with the Atlantic rift [Beauchamp et al., 1985, Salvan, 1984, Van Houten, 1977]. The Triassic deposits are considered as syn-rift.

9. Conclusion

This sedimentological analysis carried out for the first time in this basin allowed the reconstruction of palaeoenvironments and thus the syn-rift sedimentary filling history during the Upper Triassic. During rifting, the MBEB Basin passed through three major phases of sedimentary filling. The first phase is purely continental. During this period, the first deposits arrived in the basin are of alluvial fan origin. Subsequently, the decrease in palaeoslope and the rise of the basal level resulted in paleoenvironmental changes (proximal fluvial system to a distal depositional environment). During the third phase, the syn-rift sedimentary series recorded a marine incursion at the Upper Triassic with saliferous sedimentation.

The correlation and cartography of the genetic sequences as well as the progradational/retrogradational cycles made it possible to obtain 2D/3D geometries of the basin according to the three correlation transects. This indicates a growth in the thickness of these sequences vertically (growth towards the top of the sandy-conglomeratic formation) and laterally (increase of the thickness of the genetic sequences while passing of borders to the center of the basin). These correlations also show lateral passages of the mudstone facies (NE-SE border) to the evaporite facies (basin center). The economic importance of these 2D/3D geometries lies in their orientation of the exploitation of pure halite facies whose thickness and quality increase towards the center of the basin.

From a paleogeographic point of view, the Mohammedia–Benslimane–ElGara–Berrechid Basin is part of the western Moroccan Triassic province, which corresponds to all the basins of the Moroccan Atlantic margin (Doukkala, Argana, Essaouira, Tarfaya) in relation to the rifting of Central Atlantic Domain. In this context, this study consists of a basic approach for all future studies concerning the stratigraphic correlations between this basin and the Triassic basins of the African Atlantic margin and Northeastern American margin.

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References

Afenzar, A. (2018). *Sédimentologie de faci'es, paléoenvironnements et interpretation en termes de stratigraphie séquentielle haute résolution de la série syn-rift triasique du bassin de Mohammedia–Benslimane–ElGara–Berrechid (Meseta occidentale, Maroc)*. PhD thesis, Univ. Hassan II de Casablanca (Maroc).

Afenzar, A. and Essamoud, R. (2017). Sédimentologie de faciès des dépôts triasiques de la région d'Oued el Maleh et ElGara (Meseta, Maroc). *Intl J. Adv. Res.*, 5(5):1938–1949.

Aigner, T. and Bachmann, G. H. (1992). Sequence-stratigraphic framework of the German Triassic. *Sedim. Geol.*, 80:115–135.

Aït Salem, H., Bourquin, S., Courel, L., Fékirine, B., Hellal, C., Mami, L., and Téfiani, M. (1998). Triassic series on the Saharan platform in Algeria; Peritethyan onlaps and related structuration. In Crasquin-Soleau, S. and Barrier, E., editors, *Stratigraphy and Evolution of Peritethyan Platforms*, volume 5 of *Peri-Tethys Mémoir 3*, pages 177–191. Mém. Museum Natl. Hist. Nat., Paris.

Allen, J. R. L. (1983). Studies in fluviatile sedimentation: bars, bar-complexes and sandstone sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders. *Sedim. Geol.*, 33:237–293.

Alves, T. M., Moita, C., Sandnes, F., Cunha, T., Monteiro, J. H., and Pinheiro, L. M. (2006). Mesozoic-Cenozoic evolution of North Atlantic continental-slope basins: The Peniche Basins, western Iberian margin. *AAPG Bull.*, 90(1):31–60.

Barrón, E., Gómez, J. J., Goy, A., and Pieren, A. P. (2006). The Triassic–Jurassic boundary in Asturias (northern Spain): Palynological characterisation and facies. *Rev. Palaeobot. Palynol.*, 138(3–4):187–208.

Baudelot, S., Charrière, A., Ouarhache, D., and Sabaoui, A. (1990). Données palynologiques nouvelles concernant l'Ordovicien et le Trias-Lias du Moyen Atlas. *Géol. Méditerr.*, 17:263–277.

Baudon, C., Redfern, J., and Driessche, J. V. D. (2012). Permo-Triassic structural evolution of the Argana valley impact of the Atlantic rifting in the High Atlas, Morocco. *J. Afr. Earth Sci.*, 65:91–104.

Beauchamp, J. (1988). Triassic sedimentation and rifting in the High Atlas (Morocco). In Manspeizer, W., editor, *Triassic-Jurassic Rifting: Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins*, Developments in Geotectonics 22, pages 477–497. Elsevier, New York.

Beauchamp, J., Benaouiss, N., and Courel, L. (1995). Où était donc le domaine marin dans le Maroc africain au Trias supérieur. *C. R. Acad. Sci. Paris, Ser. IIa*, 221:1033–1040.

Beauchamp, J., Ferrandini, J., and Ferrandini, M. (1985). La série mésozoïque du haut atlas de marrakech. Field trip guide IGCP183, october1985, 42 p.

Benaouiss, N., Courel, L., and Beauchamp, J. (1996). Rift-controlled fluvial/tidal transitional series in the Oukaimeden Sandstones, High Atlas of Marrakesh (Morocco). *Sedim. Geol.*, 107:21–36.

Biron, P. E. (1982). Le Permo-Trias de la région de l'Ourika (Haut-Atlas de Marrakech, Maroc): lithostratigraphie, sédimentologie, tectonique et minéralisations. Stratigraphy. Université Scientifique et Médicale de Grenoble.

Bourquin, S., Bourges, P., and Rigollet, C. (1998). High-resolution sequence stratigraphy of an alluvial fan-fan delta environment: stratigraphic and geodynamic implications – an example from the Keuper Chaunoy Sandstones, Paris Basin. *Sedim. Geol.*, 121:207–237.

Bourquin, S., Eschard, R., and Hamouche, B. (2010). High-resolution sequence stratigraphy of Upper Triassic succession (Carnian–Rhaetian) of the Zarzaitine outcrops (Algeria): A model of fluvio-lacustrine deposits. *J. Afr. Earth Sci.*, 58:365–386.

Bourquin, S. and 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. and 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.

Bourquin, S., Guillocheau, F., and Péron, S. (2009).

Braided river within an arid alluvial plain (example from the early Triassic, western German Basin): criteria of recognition and expression of stratigraphic cycles. *Sedimentology*, 56:2235–2264.

Bourrouilh, R., Richter, J. P., and Zolnai, G. (1995). The North Pyrenean Aquitaine basin, France: Evolution and hydrocarbons. *AAPG Bull.*, 79:831–853. 491P.

Bridge, J. S. (2003). *Rivers and Floodplains: Forms, Processes, and Sedimentary Records*. Blackwell, Oxford.

BRPM (1973). Rapports inédits de fin de sondages concernant les recherches de sels potassiques dans le bassin salifère de berrechid–elgara. Bureau de Recherches et de Participations Minières (BRPM), Maroc.

Courel, L., Ait Salem, H., Benaouiss, N., Et-Touhami, M., Fekirine, B., Oujidi, M., Soussi, M., and Tourani, A. (2003). Mid-Triassic to Early Liassic clastic/evaporitic deposits over the Maghreb platform. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 196:157–176.

Crasquin-Soleau, S., Rakus, M., Oujidi, M., Courel, L., Et-Touhami, M., and Benaouiss, N. (1997). Découverte d'une faune d'ostracodes dans le Trias des monts d'Oujda (Maroc); relations paléogéographiques entre les plates-formes nord et sud de la Téthys. *C. R. Acad. Sci. Paris, Ser. IIa*, 324:111–118.

Dumas, D. (1988). *Le Paléogène salifère du bassin de Valence (Sud-Est de la France): géométrie et sédimentologie des dépôts, synthèse de bassin*. PhD thesis, Université Claude Bernard, Lyon.

Echarfaoui, H., Hafid, M., and Aït Salem, A. (2002a). Structure sismique du socle paléozoïque du bassin des Doukkala, Môle côtier, Maroc occidental. Indication en faveur de l'existence d'une phase éovarisque. *C. R. Geosci.*, 334:13–20.

Echarfaoui, H., Hafid, M., Aït Salem, A., and Aït Fora, A. (2002b). Analyse sismo-stratigraphique du bassin d'Abda (Maroc occidental), exemple de structures inverses pendant le *rifting* atlantique. *C. R. Geosci.*, 334:371–377.

Einsele, G. (1992). *Sedimentary Basins: Evolution, Facies and Sediment Budgets*. Springer, New York, NY.

El Arabi, E., Bienvenido Diez, J., Broutin, J., and 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.

El Arabi, E. H. (2007). La série permienne et triasique du rift haut-atlasique: nouvelles datations; évolution tectono-sédimentaire. Thèse d'Etat, Faculté des sciences Aïn Chok. Université Hassan II de Casablanca, Maroc, page 225.

El Wartiti, M. and Fadli, D. (1985). Relations socle-couverture au cours du Trias dans la zone de BenSlimane-ElGara (Maroc nord mesetien). *Bull. Sci. Terre, Rabat*, 1:54–66.

El Wartiti, M., Medina, F., and Fadli, D. (1992). Effects of the Central Atlantic early *rifting* in the northern border of the Berrechid–ElGara basin (Morocco). *Gaia*, 4:31–38.

Et-Touhami, M. (1994). Le Trias évaporitique du bassin de Khémisset (Maroc central). *Notes Mem. Serv. Geol. Maroc, Rabat*, 373:211.

Et-Touhami, M. (1996). L'origine des accumulations salifères du Trias marocain : apport de la géochimie du brome du sel du bassin de Khémisset (Maroc Central). *C. R. Acad. Sci. Paris, Ser. IIa*, 323:591–598.

Et-Touhami, M. (1998). Le Trias salifère marocain: typologie des cristaux de l'halite et faciès halitiques. *Afr. Geosci. Rev.*, 5(1–2):107–115.

Ethridge, F. G., Jackson, T. J., and Youngberg, A. D. (1981). Flood-basin sequence of a fine-grained meander belt subsystem: the coal-bearing Lower Wasatch and Upper Fort Union Formations, southern Powder River Basin, Wyoming. In Ethridge, F. G. and Flores, R. M., editors, *Recent and Ancient Nonmarine Depositional Environments, Models for Exploration*, volume 31 of *Special Publication*, pages 191–209. SEPM Society for Sedimentary Geology.

Farrell, K. M. (1987). Sedimentology and facies architecture of overbank deposits of the Mississippi River, False River region, Louisiana. In Ethridge, F. G., Flores, R. M., and Harvey, M. D., editors, *Recent Developments in Fluvial Sedimentology*, volume 39 of *Special Publications*, pages 111–120. SEPM Society for Sedimentary Geology.

Ferrer, O., Jackson, M. P. A., Roca, E., and Rubinat, M. (2012). Evolution of salt structures during extension and inversion of the Offshore Parentis Basin (Eastern Bay of Biscay). In Alsop, G. I., Archer, S. G., Hartley, A. J., Grant, N. T., and Hodgkinson, R., editors, *Salt Tectonics, Sediments and Prospectivity*, volume 363 of *Special Publications*, pages 361–379. Geological Society of London.

Gonzàlez de Aguilar, J. P. (2015). *Salt tectonics in in-*

verted continental margins: Seismic interpretation in the Cantabrian Margin. PhD thesis, Granada: Universidad de Granada.

Hafid, M. (2000). Triassic-Liassic extensional systems and their Tertiary inversion, Essaouira Basin (Morocco). *Mar. Petrol. Geol.*, 17:409–429.

Hamon, Y. and Merzeraud, F. (2005). Nouvelles données sur le Trias de Sologne (Chémery, Sud-Ouest du bassin de Paris) : stratigraphie et environnements de dépôts. *Géol. France*, 176:3–22.

Hminna, A., Voigt, S., Klein, H., Saber, H., Schneider, J. W., and Hmich, D. (2013). First occurrence of tetrapod footprints from the continental Triassic of the Sidi Said Maachou area (Western Meseta *Morocco*). *J. Afr. Earth Sci.*, 80:1–7.

Hofmann, A., Tourani, A., and 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.

Homewood, P. W., Guillocheau, F., Eschard, R., and Cross, T. A. (1992). Corrélation hautre definition et stratigraphie génétique: une demarche intégrée. *Bull. Centres Rech. Explor. Prod. Elf Aquitaine*, 16:357–381.

Hooke, R. L. (1967). Processes on arid-region alluvial fans. *Geology*, 75:438–460.

Hovorka, S. D. (1983). Sedimentary structures and diagenetic modifications in halite and anhydnte, Palo Duro Basin. In *Geology and Geohydrology of the Palo Duro Basin, Texas Panhandle*, Geological Circular 83-4, pages 49–57. Bureau Economic Geology, Austin.

Hssaida, T., Zahour, G., Oulmach, F., Youssfi, Z., Chahaldi, S., and Habid, A. (2012). Nouvelles datations des argilites post-basaltiques du bassin de l'Oued Mellah (Meseta occidentale, Maroc). *Notes Mem. Serv. Geol. Maroc*, 575:131–137.

Kozur, H. W. and Bachmann, G. H. (2008). Updated correlation of the Germanic Triassic series within the Tethyan scale and assigned numeric ages. *Beri. Geologischen Bundesanstalt*, 76:53–58.

Kraus, M. J. and Bown, T. M. (1988). Pedofacies analysis; a new approach to reconstructing ancient fluvial sequences. *Geol. Soc. Am. Spec. Paper*, 216:143–152.

Lachkar, G., Ouarhache, D., and 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.

Laville, E., Charroud, A., Fedan, B., Charroud, M., and Piqué, A. (1995). Inversion négative et *rifting* atlasique ; l'exemple du bassin triasique de Kerrouchèn (Maroc). *Bull. Soc. Geol. France*, 166:364–374.

Laville, E., Piqué, A., Amrhar, M., and Charroud, M. (2004). A restatement of the Mesozoic Atlasic Rifting (Morocco). *J. Afr. Earth Sci.*, 38:145–153.

Le Roy, P. and Piqué, A. (2001). Triassic-Liassic Western Moroccan synrift basins in relation to the Central Atlantic opening. *Mar. Geol.*, 172:359–381.

Leleu, S. and Hartley, A. J. (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, A. J., Oosterhout, C. V., Kennan, L., Ruckwied, K., and 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.

Liu, Z. and Wang, C. (2001). Facies analysis and depositional systems of Cenozoic sediments in the Hoh Xil basin, northern Tibet. *Sedim. Geol.*, 140:251–270.

Lorenz, J. C. (1976). Triassic sediments and basin structure of the Kerrouchen basin, Central Morocco. *J. Sedim. Petrol.*, 46(4):897–905.

Lyazidi, A. (2004). *Evolution géodynamique du bassin triasique de Berrechid–ElGara–Benslimane (Meseta Nord Occidentale, Maroc)*. PhD thesis, Université Mohammed V-Agdal Rabat, Maroc.

Mader, D. (1985). Braidplain, floodplain and playa lake, alluvial-fan, aeolian and palaeosol facies composing a diversified lithogenetical sequence in the permian and Triassic of South Devon (England). In Mader, D., editor, *Aspects of Fluvial Sedimentation in the Lower Triassic Buntsandstein of Europe*, Lecture Notes in Earth Sciences, pages 15–64. Springer, Berlin/Heidelberg/New York/Tokyo.

Manspeizer, W. and Cousminer, H. L. (1988). Late Triassic–early Jurassic synrift basins of the U.S. Atlantic margin. In Sheridan, R. E. and Grow, J. A., editors, *The Atlantic Continental Margin. Geol. N. Am.*, volume I-2, pages 197–216. U.S. Geol. Soc.

Am., Boulder.

Martin-Rojas, I., Somma, R., Delgado, F., Estevez, A., Iannace, A., Perrone, V., and Zamparelli, V. (2009). Triassic continental rifting of Pangaea: direct evidence from Alpujarride carbonates, Betic Cordillera, SE Spain. *J. Geol. Soc. Lond.*, 16:447–458.

Massari, F. (1983). Tabular cross-bedding in Messinian fluvial channel conglomerates, southern Alps. In Collinson, J. D. and Lewin, J., editors, *Modern and Ancient Fluvial Systems*, volume 6 of *Special Publications of the international association of sedimentologists*, pages 287–300. John Wiley & Sons.

Medina, F. (1994). Evolution structurale du haut atlas occidental et des régions voisines du trias à l'actuel, dans le cadre de l'ouverture de l'atlantique central et de la collision afrique-europe. State Thesis, University Mohammed V, Rabat, Morocco.

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.

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.* PhD thesis, Université de Strasbourg.

Miall, A. D. (1978). Lithofacies types and vertical profile models in braided river deposits: a summary. *Can. Soc. Petrol. Geol. Mem.*, 5:597–604.

Miall, A. D. (1985). Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Sci. Rev.*, 22:261–308.

Miall, A. D. (1988). Architectural elements and bounding surfaces in fluvial deposits: anatomy of the Kayenta Formation (Lower Jurassic) Southwest Colorado. *Sediment. Geol.*, 55:233–262.

Miall, A. D. (1996). *The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis and Petroleum Geology.* Springer-Verlag, Germany, 4th edition.

Miall, A. D. (2016). Facies analysis. In *Stratigraphy: A Modern Synthesis*. Springer, Cham.

Miall, A. D. and Balkwilla, H. (2019). The Atlantic margin basins of North America. In Miall, A. D., editor, *The Sedimentary Basins of the United States and Canada*. Elsevier, Amsterdam, 2nd edition.

Olsen, P. E. (1997). Stratigraphic record of the Early Mesozoic breakup of Pangea in the Laurasia–Gondwana rift system. *Annu. Rev. Earth Planet. Sci.*, 2:337–401.

Opluštil, S., Martínek, K., and Tasàryovà, Z. (2005). Facies and architectural analysis of fluvial deposits of the Nýřany Member and the Týnec Formation (Westphalian D-Barruelian) in the Kladno-Rakovník and Pilsen basins. *Bull. Geosci.*, 80(1):45–66.

Ortí, F. (2004). Cordilleras Ibérica y Costero-Catalana. El rift Mesozoico Ibérico: 5.3.1.4 Últimas etapas de actividad del rifting. Sedimentos asociados. In Vera, J. A., editor, *Geología de España*, pages 492–495. Sociedad Geológica de España e Instituto Geológico y Minero de España, Madrid.

Ouarhache, D., Charrière, A., Chalot-Prat, F., and El Wartiti, M. (2012). Chronologie et modalités du *rifting* triasico-liasique à la marge sud-ouest de la Téthys alpine (Moyen Atlas et Haute Moulouya, Maroc) ; corrélations avec le *rifting* atlantique : simultanéité et diachronisme. *Bull. Soc. Geol. France*, 183(3):233–249.

Oujidi, M., Courel, L., Benaouiss, N., El Mostaine, M., El Youssi, M., Et Touhami, M., Ouarhache, D., Sabraoui, A., and Tourani, A. I. (2000). Triassic series of Morocco: stratigraphy, paleogeography and structuring of the Southwestern Peri-Tethyan platform. An overview. In Crasquin-Soleau, S. and Barbier, E., editors, *Peri-Tethys Memoir: 5. New Data on Peri-Tethyan Sedimentary Basins*, volume 182, pages 11–22. Mem. Mus. Natl. Hist. Nat., Paris.

Oujidi, M. and Elmi, S. (2000). Evolution de l'architecture des Monts d'Oujda (Maroc oriental) pendant le Trias et au début du Jurassique. *Bull. Soc. Geol. France*, 171:169–179.

Peretsman, C. G. (1985). A geochemical and petrographic analysis of early mesozoic evaporites from morocco: implications for the history of the north atlantic. Ms. Thesis, University of Oregon.

Peretsman, C. G. and Holser, T. W. (1988). Geochemistry of Moroccan evaporites in the setting of the North Atlantic rift. *J. Afr. Earth Sci.*, 7(2):375–383.

Piqué, A. and Laville, E. (1995). L'Ouverture initiale de l'Atlantique central. *Bull. Soc. Geol. France*, 166(6):725–738.

Piqué, A., Le Roy, P., and Amrhar, M. (1998). Transtensive synsedimentary tectonics associated with ocean opening; the Essaouira-Agadir segment of the Moroccan Atlantic margin. *J. Geological Soc. Lond.*, 155:913–928.

Poli, E. (1997). *Stratigraphie séquentielle haute-*

résolution, modèles de dépôt et géométrie 2D-3D des séquences triasiques de la marge téthysienne ardéchoise. PhD thesis, Université de Bourgogne-Centre des Sciences de la Terre.

Postma, G. and Cruickshank, C. (1988). Sedimentology of a late Weichselian to Holocene terraced fan delta, Varangerfjord, northern Norway. In Nemec, W. and Steel, R. J., editors, *Fan Deltas: Sedimentology and Tectonic Settings*. Blackie, London.

Ramos, A., Fernàndez, O., Muñoz, J. A., and Terrinha, P. (2017). Impact of basin structure and evaporite distribution on salt tectonics in the Algarve Basin, Southwest Iberian margin. *Mar. Petrol. Geol.*, 88:961–984.

Reolid, M., Pérez-Valera, F., Benton, M. J., and Reolid, J. (2014). Marine flooding event in continental Triassic facies identified by a nothosaur and placodont bonebed (South Iberian Paleomargin). *Facies*, 60:277–293.

Roca, E., Muñoz, J. A., Ferrer, O., and Ellouz, N. (2011). The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogeny: Constraints from the MARCONI deep seismic reflection survey. *Tectonics*, 30. (TC2001).

Rust, B. R. (1978). Depositional models for braided alluvium. In Miall, A. D., editor, *Fluvial Sedimentology*, volume 5 of *Memoir*, pages 605–625. Canadian Society of Petroleum Geologists.

Salvan, H. M. (1974). Les séries salifères du Trias marocain; caractères généraux et possibilités d'interprétation. Service de la Carte géologique du Maroc. Rabat-Chellah. *Bull. Soc. Geol. France*, 7(6).

Salvan, H. M. (1982). Les évaporites triasiques du Maroc : Caractères généraux-répartition-interprétation. *Colloque Permo-Trias marocain Fac. Sci. Marrakech*, 1:73–84.

Salvan, H. M. (1984). Les formations évaporitiques du Trias marocain. Problèmes stratigraphiques, paléogéographiques et paléoclimatiques. Quelques réflexions. *Rev. Geogr. Phys. Geol. Dyn., Paris*, 25:187–203.

Slimane, A. and El Mostaïne, 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*, page 54.

Smoot, J. P. (1991). Sedimentary facies and depositional environments of early Mesozoic Newark Supergroup basins, eastern North America. *Palaeogeogr, Palaeoclimatol. Palaeoecol.*, 84:369–423.

Sneh, A. (1983). Desert stream sequences in the Sinai Peninsula. *J. Sediment. Petrol*, 53:1271–1280.

Sohn, Y. K., Kim, S. B., Hwang, I. G., Bahk, J. J., Choe, M. Y., and Chough, S. K. (1997). Characteristics and depositional processes of large-scale gravelly Gilbert-type foresets in the Miocene Doumsan fan delta, Pohang Basin, SE Korea. *J. Sedim. Res.*, 67(1):130–141.

Sonnenfeld, P. and Hodec, P. P. (1985). Origin of clay films in rock salt. *Sediment. Geol.*, 44(1–2):113–120.

Soto, J. I., Flinch, J. F., and Tari, G. (2017). Permo-triassic basins and tectonics in Europe, North Africa and the Atlantic margins: a synthesis. In Soto, J. I., Flinch, J. F., and Tari, G., editors, *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins: Tectonics and Hydrocarbon Potential*, pages 3–41. Elsevier, Amsterdam.

Soussi, M. and Ben Ismaïl, M. H. (2000). Platform collapse and pelagic seamount facies: Jurassic development of central Tunisia. *Sedim. Geol.*, 133:93–113.

Soussi, M., Cirilli, S., and Abbes, C. (2001). Nouvelles données palynologiques sur la formation Rhéouis: Conséquences sur les corrélations et la paléogéographie de la Tunisie au Trias supérieur. *Notes du Service Géologique Tunisie*, 67:87–105.

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.

Todd, S. P. (1996). Process deduction from fluvial sedimentary structures. In Carling, P. A. and Dawson, M. R., editors, *Advances in Fluvial Dynamics and Stratigraphy*, pages 299–350. Wiley, Chichester.

Tourani, A., Benaouiss, N., Gand, G., Bourquin, S., Jalil, N. E., Broutin, J., Battail, B., Germain, D., Khaldoune, F., Sebban, S., Steyer, J. B., and 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.

Tunbridge, I. P. (1981). Sandy high-energy flood sedimentation some criteria for recognition, with an example from the Devonian of S.W. England. *Sediment Geol.*, 28:79–96.

Tunbridge, I. P. (1984). Facies model for a sandy ephemeral stream and clay playa complex, the Middle Devonian Trentishoe Formation of North Devon. *U.K. Sedimentology*, 31:697–715.

Van Houten, F. B. (1973). Origin of red beds: a review - 1961–1972. *Ann. Rev. Earth Planet. Sci.*, 1:39–61.

Van Houten, F. B. (1977). Triassic-Liassic deposits of Morocco and eastern North America: comparison. *AAPG Bull.*, 61(1):79–99.

Vergés, J., Moragas, M., Martín-Martín, J. D., Saura, E., Casciello, E., Razin, P., Grelaud, C., Malaval, M., Joussiame, R., Messager, G., Sharp, I., and Hunt, D. W. (2017). Chapter 26: Salt Tectonics in the Atlas Mountains of Morocco. In Soto, J. I., Flinch, J. F., and Tari, G., editors, *Permo-triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*, pages 563–576. Elsevier, Amsterdam, the Netherlands.

Wade, J. A., MacLean, B. C., and Williams, G. L. (1995). Mesozoic and Cenozoic stratigraphy, eastern Scotian Shelf: New interpretations. *Can. J. Earth Sci.*, 32:1462–1473.

Warren, J. K. (2006). *Evaporites: Sediments, Resources and Hydrocarbons*. Springer, Berlin.

Warren, J. K. (2010). Evaporites through time: Tectonic, climatic and eustatic controls in marine and nonmarine deposits. *Earth-Sci. Rev.*, 98:217–268.

Welsink, H. and Tankard, A. (2012). Extensional tectonics and stratigraphy of the Mesozoic Jeanne d'Arc basin, Grand Banks of Newfoundland A2 - Roberts, D. G. In Bally, A. W., editor, *Regional Geology and Tectonics: Phanerozoic Rift Systems and Sedimentary Basins*, pages 336–381. Elsevier, Boston.