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Late Barremian eustacy and tectonism in the western High Atlas (Essaouira-Agadir Basin), Morocco

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ABSTRACT

The Barremian-Aptian interval is considered a turning point in the extensional evolution of the passive Atlantic margin of Morocco. The biostratigraphy and sedimentology study of the coarse-grained clastic deposits of the Essaouira-Agadir Basin (Bouzergoun Fm) indicates that they are entirely late Barremian (*Sartousiana p.p.* to *Sarasini p.p.* Zones) and suggests that most of them were deposited in a shallow marine environment, locally impacted by substantial fluvial influences. Facies evolution and the identification of discontinuity surfaces subdivide the unit into seven depositional sequences, two of which are marked by coarse-grained deposits and numerous indications of synsedimentary instability, and are interpreted as tectonically enhanced. These late Barremian tectonic events are interpreted as related to the abrupt uplift of the West Moroccan Arch, a long-lived, NNE-trending positive structure, located east of the Essaouira-Agadir Basin.

1. Introduction

Western and North Africa were influenced by Late Permian-Liassic Tethyan and Atlantic rifting followed by an mainly extensional tectonic regime. Around the Barremian-Aptian boundary, this tectonic regime is assumed to have evolved from a N–S to a NE–SW trending extensional regime, in response to the opening of the Equatorial Atlantic Ocean (Guiraud et al., 2005).

The passive Atlantic margin of Morocco experienced mainly marine sedimentation from late Triassic to Tertiary times. In the Essaouira area, Le Roy et al. (1998) mention a decrease in Early Cretaceous subsidence rates, a dominantly clastic sedimentation in the Barremian and an Early Aptian unconformity, which was not detected, however, by Ellouz et al. (2003). In the Essaouira-Agadir area, Piqué et al. (1998) describe synsedimentary deformation in the late Valanginian-earliest Aptian interval, as well as slumps and olistoliths in the Barremian-Albian sequence east of Agadir. In the Essaouira-Agadir Basin, the late Barremian-early Aptian period is marked by the deposition of coarse-grained sandstones, interpreted as the result of either tectonic movements (Ambroggi, 1963) or a drastic sea-level fall (Nouidar and Chellaï, 2001).

To the east, the West Moroccan Arch was active from the Early Jurassic through the Early Cretaceous (Frizon de Lamotte et al., 2008) and separates the Atlantic margin from the High Atlas. Following an interval of marine sedimentation related to Tethyan rifting, the High Atlas area became emergent in the Middle Jurassic and sediments derived from the uplift resulted in mainly continental, Late Jurassic-Early Cretaceous red beds. Recent studies documented that this sequence recorded an important tectonic event, marked by upper Barremian-lower Aptian basaltic flows and coarse-grained deposits (Frizon de Lamotte et al., 2000; Haddoumi et al., 2010; Ben Salah et al., 2013; Michard et al., 2013). In the Middle Atlas, Barremian conglomerates unconformably overly Middle Jurassic strata (Charrière, 1996), while a pronounced uplift is recorded in the Meseta at ~120 Ma (Saddiqi et al., 2009), thus confirming that the Barremian-Aptian period is a tectonically active period in Western Morocco.

The objectives of the present study are to refine the age and sedimentary evolution of the late Barremian-early Aptian

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sandstones and conglomerates of the Agadir-Essaouira Basin, to determine their depositional environment, and to assess and discuss their origin and tectonic significance.

2. Geological background

The Essouira-Agadir Basin (EAB, Fig. 1) belongs to the Moroccan Atlantic passive margin (Frizon de Lamotte et al., 2008). It records, therefore, the extensional tectonics related to Atlantic rifting (Late Triassic-Middle Liassic), followed by a drift period (Late Liassic-early Late Cretaceous) which was interrupted in the Late Cretaceous by incipient compressional tectonics, which culminated in the Eocene and Miocene (Le Roy et al., 1998; Frizon de Lamotte et al., 2008; Zühlke et al., 2004). After predominantly clastic-evaporitic sedimentation during the Triassic, Late Liassic to early Late Jurassic deposits were mainly shallow-marine carbonates. A marked Late Jurassic (Kimmeridgian-early Tithonian) regression was then followed by a late Tithonian marine transgression, which deposited a thick Cretaceous marine sequence (Ambroggi, 1963; Duffaud et al., 1966; Le Roy et al., 1998; Zühlke et al., 2004) (Fig. 2).

Above the Tithonian-Berriasian carbonate shelf deposits, the Valanginian is marked by the deposition of calcareous, then shaly and sandy strata (Ettachfini, 1991; Taj-Eddine et al., 1992; Wippich, 2003; Ettachfini, 2004). The thick Hauterivian sequence is chiefly comprised of shaly marls, interrupted by late early Hauterivian and latest Hauterivian shallow-marine sandstones or reefal limestones (Ferry et al., 2007; Mutterlose and Wiedenroth, 2008). Barremian sediments are dominantly marls and limestones overlain by clastic deposits (Witam, 1998; Company et al., 2008). These are in turn overlain by early Aptian limestones and marls, and then by late Aptian and Albian shaly marls (Witam, 1998; Bourgeoini et al., 2002; Peybernès et al., 2013; Hassanein Kassab, 2016; Luber et al., 2017). In the Agadir-Essaouira Basin, Early Cretaceous sedimentation culminates with a set of massive late Albian shelf limestones (Ettachfini, 1992) (Fig. 2).

The Barremian was first recognized in the EAB by Lemoine (1905), Gentil (1905) and Roch (1930). The latter subdivided the Barremian succession into a marly to calcareous lower part and a calcareous upper part. Ambroggi (1963) gave descriptions of some key sections; he identified alternating early Barremian marls and limestones as constrained by the ammonite genera *Paraspiticeras*, *Nicklesia*, *Barremites*, *Saynella* and *Karsteniceras*, overlain by late Barremian green marls, limestones and sandstone beds which contain *Heteroceras*, *Melchiorites*, *Ancyloceras* and *Hamulina*. He ascribed the overlying sandstones and variegated marls to the early Aptian. Duffaud et al. (1966) defined the early Barremian, marly Taboulouart Fm, and the late Barremian-early Aptian shaly and sandy Bouzergoun Fm (see also Rey et al., 1988; Canérot et al., 1986; Witam, 1998; Al Yacoubi et al., 2017) (Fig. 2).

More recently, Company et al. (2008) carried out a detailed study of the Barremian ammonite fauna of the western EAB (Taboulouart Fm). They identified hiatuses at the Hauterivian-Barremian boundary and in the early Barremian (*Hugii-Nicklesi* biozones), and a condensed section in the early late Barremian (*Vandenheckii-Sartousiana* biozones) (Company et al., 2008). These authors, however, did not study the massive sandstone that caps the Barremian succession. From a sedimentological perspective, Nouidar and Chellaï (2002) proposed that this late Barremian sandstone succession was deposited in a wave-dominated deltaic setting, while the overlying sandstone and conglomerates represent the tide-influenced, transgressive-regressive infilling of incised valleys carved during an early Aptian sea-level fall (Nouidar and Chellaï, 2001). Further east (Imi n'Tanout), Masrour et al. (2013) described dinosaur trackways from late Barremian variegated shales and interpreted the depositional environment as distal fluvial to very shallow-marine deposits. The late Barremian clastic

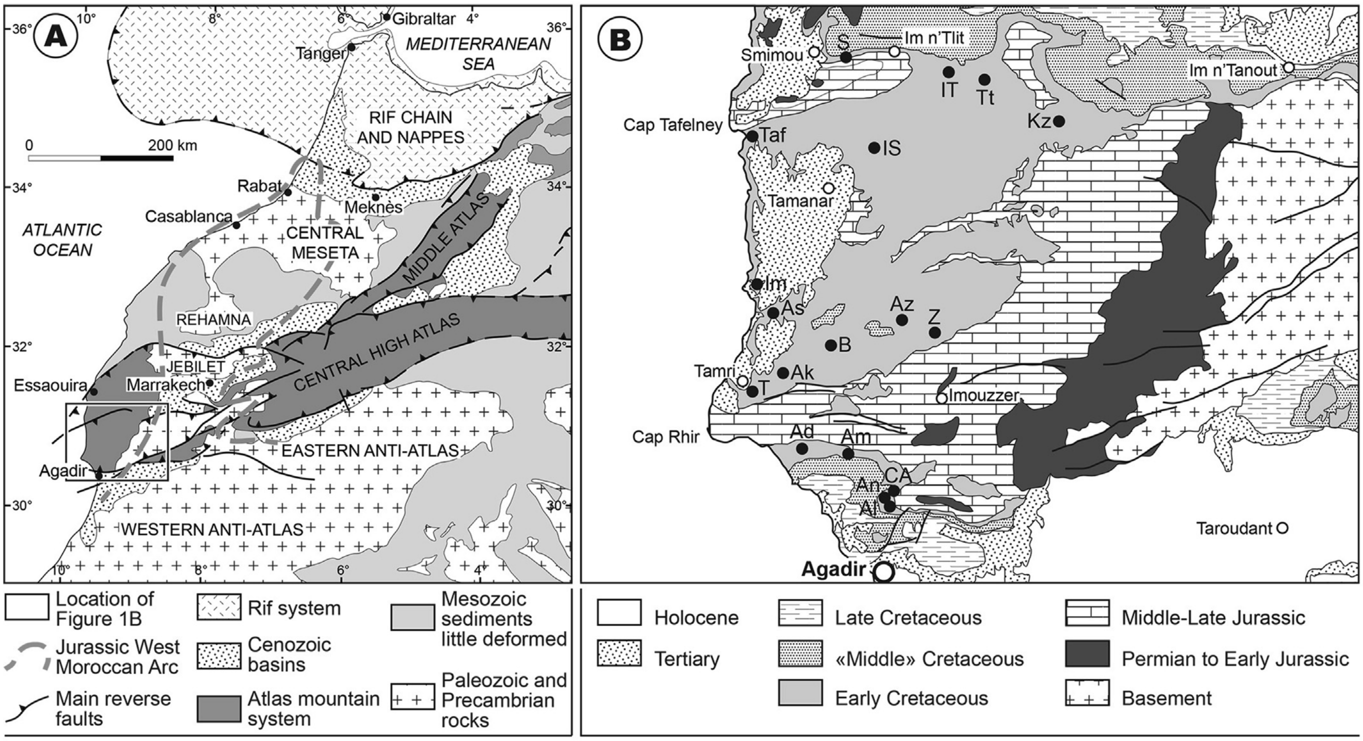


Figure 1. Location map. A: Structural sketch of Western Morocco and location of Fig. 1B, according to Frizon de Lamotte et al. (2008), simplified. B: Location of the studied sections: Ad: Addar; Al: Alma; Ak: Akarkour; Am: Amalou; An: Anzate; As: Assaka; Az: Aziar; B: Barrage; CA: Cluse Anzate; Im: Imsouane; IS: Ida w Shayq; IT: Tassila Ougadir; Kz: Kouzemt; T: Tamri, Taf: Tafadna; Tt: Takoucht; S: Smimou; Z: Zento.

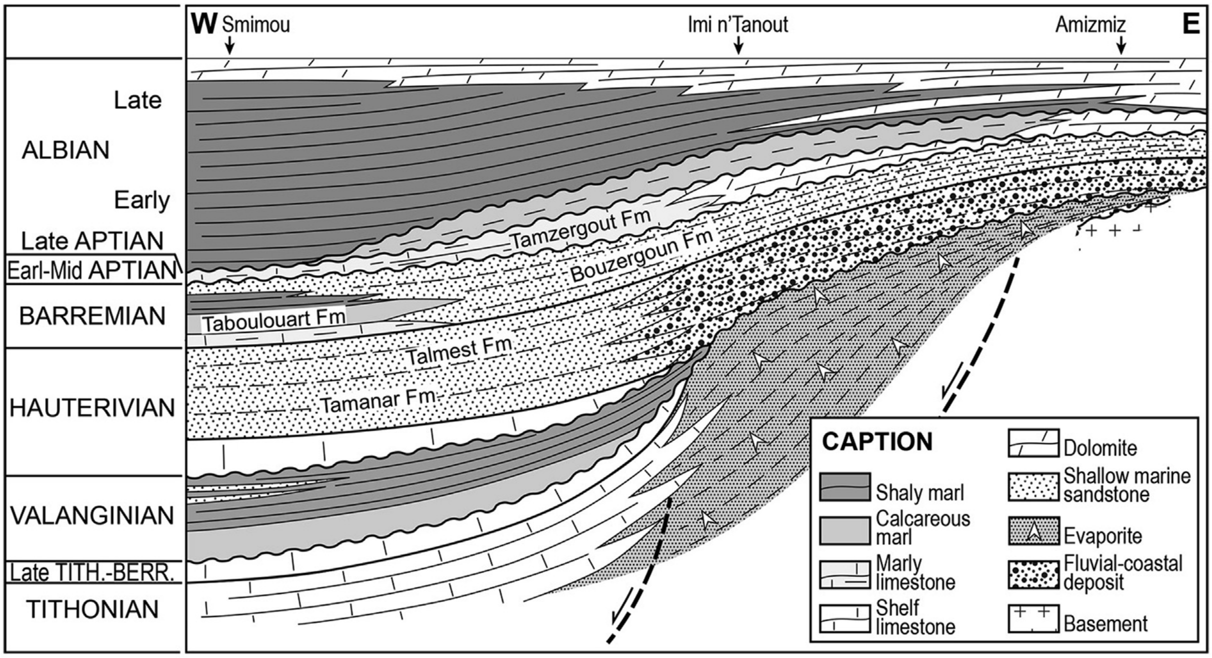


Figure 2. Sketch of the Early Cretaceous sedimentary succession in the northern part of the Essaouira-Agadir Basin, according to Rey et al. (1988), modified. The maximum thickness of the illustrated Cretaceous sequence is about 600 m.

deposits are then overlain by early Aptian limestones and marls (Tamzergout Fm; Ambroggi, 1963; Witam, 1998).

3. Material and method

Our study is focused on the coarse sandy series, which overlies the early to late Barremian sandy to calcareous succession. Stratigraphic columns of the sandy succession have been studied, which roughly follow the sidewalls of major anticlines (Fig. 1). These form three E-W transects across the EAB (Fig. 4 to 6), completed by a N–S profile (Fig. 7). Most sedimentological interpretations derive from field observations, augmented by petrographic and microfacies observations of thin sections. Field observations include lithology, grain size and sorting, sedimentary features, faunal content and accurate thickness measurements. The latter have been used to construct isopach maps. Several tens of ammonites have been collected by one of us (E.J.) along the studied sections and studied by two of us (S.R. and E.R.). However, because of the clastic nature of the sediments, ammonites are scarce and usually poorly preserved (internal molds), making their precise determination difficult.

4. Sedimentology

The late Barremian-early Aptian deposits contain both carbonates and siliciclastics. These distinct systems will be presented separately.

4.1. Facies description and interpretation

Facies 1 (F 1): Laminated, bioturbated sandstone

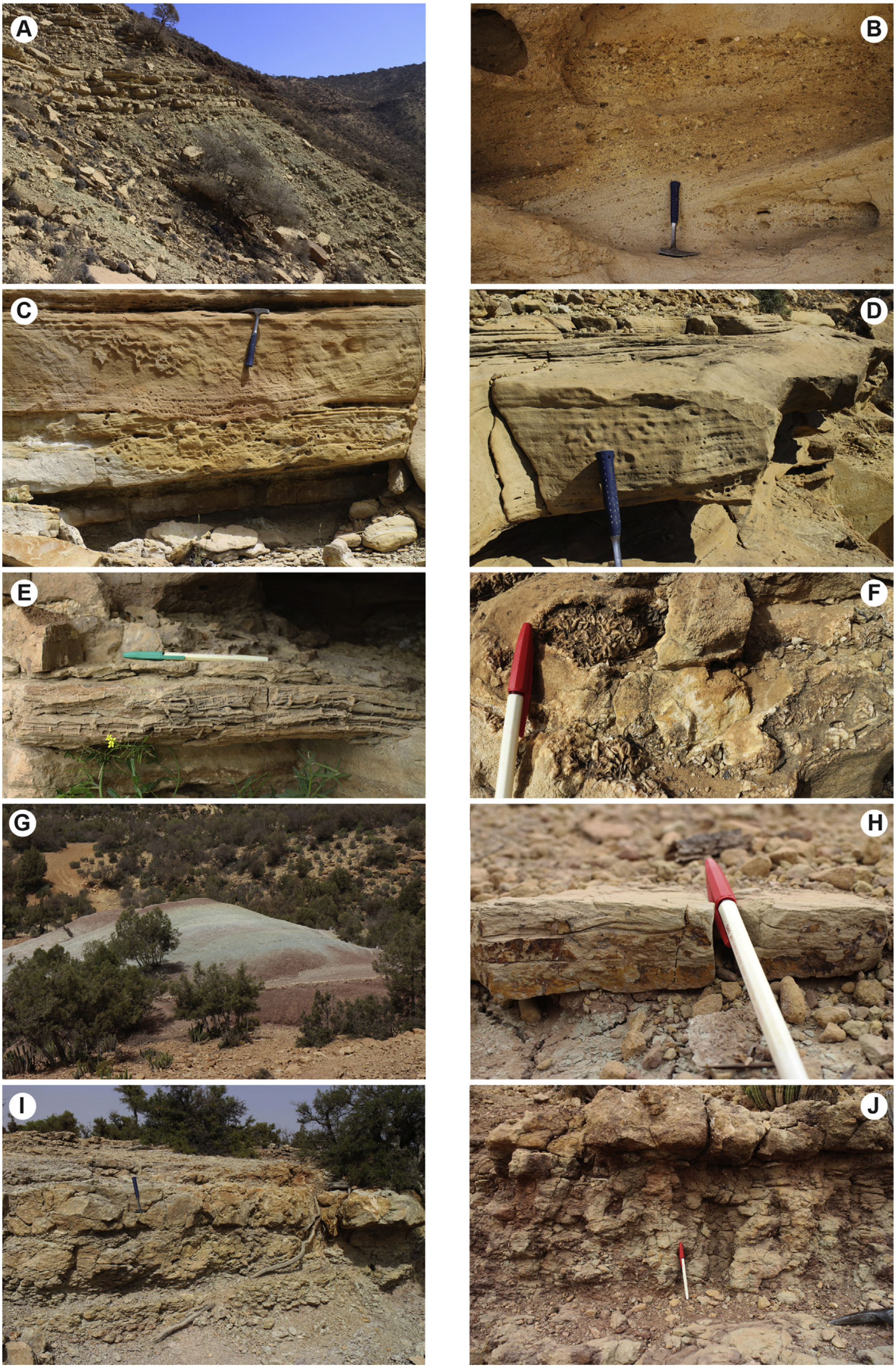
The western areas of the studied region are marked by fine- to medium-grained sandstone beds, exhibiting frequent parallel laminations, and, to a lesser extent, current or wave ripples and hummocky cross stratifications (HCS). Sandstones exhibit calcareous cement, usually dolomitized, and are intercalated with argillaceous, finer-grained, laminated sandstones. Sandstone proportion varies from 10 to 70% (Figs. 3A, 4 and 5). Evidence of biotic activity is very common, and mainly consists of large, vertical, oblique or horizontal burrows, as well as track molds and diffuse bioturbation. The fossil content consists of open-marine fauna (echinoids, ammonites, brachiopods, bivalves, gastropods) as well as plant fragments (stems and leaves). This facies usually evolves upward into thicker beds exhibiting cross bedding, associated with shallow-marine fauna (e.g. ostreids).

Interpretation. Sedimentary figures indicate a low to moderate energy of deposition, while the fauna predominantly indicates open-marine environments. Therefore, F 1 is interpreted as deposited in a moderately deep clastic shelf environment, mainly the transition zone. In some western areas (Akarkour, Tamri, Fig. 5) the lower part was deposited in the upper offshore zone, whereas the upper part may extend into the shoreface zone in some areas (Amalou, Fig. 4). The sedimentary features (laminations, ripples, some HCS) indicate the dominance of wave influences with sporadic storms. The local abundance of plant fragments (Barrage, Akarkour) indicates the proximity of emergent land areas.

Facies 2 (F 2): Homogeneous, fine-grained sandstone

This facies is mainly present in the northeastern part of the study area. It is represented by poorly consolidated, monotonous, very well-sorted, fine-grained sandstones, rich in shallow-marine fauna (gastropods, ostreids, trigonids and other bivalves). In some areas, fossiliferous limestone beds may be present. Because of abundant bioturbation, current-related sedimentary features are scarce; when preserved, they mainly consist of cross bedding and parallel laminations. Karst and tepee structures can be locally observed on top of some beds.

Interpretation. The homogeneous fine-grained sandstone is interpreted as deposited in a low-energy, shallow-marine, mainly siliciclastic shelf. Dominant processes seem to have been longshore currents, which distributed the fine-grained clastic material along the shore.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Facies 3 (F 3): Cross-bedded, thick sandstone

This facies is composed of thick beds of moderately to well-sorted, medium-to coarse-grained sandstones or conglomerates, exhibiting large-to medium-scale, planar or curved cross bedding (Fig. 3B); locally, the latter have a pronounced concave-upward shape (sigmoid). At certain sites, these beds may be lenticular, may display erosional bases (Fig. 3C), and their laminae may be defined by coarser grains. Although not common, HCS may be present. The top of the beds may contain irregular iron crusts or scattered rounded pebbles. In some cases, cross-bedded sandstones grade upwards into well-sorted sandstones, exhibiting very low-angle to planar laminations (Fig. 3D), locally cut by desiccation cracks (Akarkour, Fig. 3E) or containing pseudomorphs of desert roses (Assaka, Fig. 3F). Bioturbation is scarce and include mainly large, vertical burrows. The fossil content consists of shell fragments (usually bivalves, including trigonids and ostreids) and plant remains. Thick, cross-bedded sandstones may be intercalated with argillaceous, finer-grained sandstone, containing planar laminations, current or wave ripples, and diffuse bioturbation.

Interpretation. The cross bedding and coarse nature of these deposits indicate high-energy deposition. The good sorting and the fossil content imply a marine environment and the proximity of emergent areas. This facies is, therefore, interpreted as deposited on a shallow clastic shelf, most probably a shoreface environment. The occurrence of sigmoidal cross bedding, of planar lamination in the upper part of the beds and in some sections (Barrage, Akarkour, Fig. 5), of coarse-grained, moderately sorted, channelized or lens-shaped sandstone beds, suggests a strong influence of tidal currents, possibly amplified by the proximity of a river mouth. Sandstone beds with horizontal to very low-angle laminations, and/or the top of which contains scattered pebbles are interpreted as foreshore deposits. In some cases the latter are associated with desiccation features or anhydrite nodules (Fig. 3E, 3F). A comparable "cross-bedded sandstone" facies has been described by Nouidar and Chellaï (2001).

Facies 4 (F 4): Channelized conglomerates and sandstones

This facies consists of massive beds of poorly sorted, medium-to coarse-grained conglomerates, which may fill well-defined channels. Clasts may be calcareous, or more commonly siliceous or lithic fragments; they are subangular to well rounded. Beds always show an erosive basal contact; their base may contain rip up clasts (usually marl) reworked from underlying strata and a fining-upward trend; their upper part may grade into coarse-grained, locally pebbly, usually cross-bedded sandstone (see F 3). Sedimentary features are scarce, and include planar or curved cross bedding, and fluid-escape structures. Bioturbation is usually absent, although track molds may be present. This facies is restricted to some eastern sections (Aziar, Kouzemt, Alma, Anzate, Fig. 4 to 6) and usually underlies F 5.

Interpretation. The high depositional energy, the poor sorting of the clasts, and the fact that this facies infills channels suggest that conglomerates were deposited under strong fluvial influence. However, they commonly grade laterally and vertically into cross-bedded, well to moderately sorted, marine sandstones. This suggests either that the fluvial deposits are immediately reworked by marine processes, thus indicating a transgressive trend during a sea-level rise, or that the river mouth was associated with tidal influences (estuary). Moreover, the base of the conglomerate beds may include marine fossils (mainly ostreids), which may be reworked from underlying deposits. Whatever the case, this facies is interpreted as deposited in a distal fluvial environment, close to the shoreline and influenced by both fluvial floods and tidal currents. Nouidar and Chellaï (2001) described a comparable facies as "conglomerates and pebbly sandstones", and interpreted it in an identical manner.

Facies 5 (F 5): Variegated mudstones and siltstones

Variegated, red and green mudstones and siltstones are typical of the Bouzergoun Fm (Fig. 3G). They usually contain thin beds of laminated, fine-grained sandstone, exhibiting parallel laminations and current and wave ripples (Fig. 3H). Marine faunal elements are locally abundant (ostreids, trigonids, less frequently echinoids). Desiccation breccia can be observed. Bioturbation is common, and comprises small vertical burrows (*Skolithos* ichnofacies), as well as trackways and root traces. In some outcrops, red mudstones include remnants of green mudstones, suggesting that the original green deposit has been oxidized and reddened during diagenesis.

Interpretation. The variegated mudstone/siltstone facies is interpreted as a low-energy, very shallow subtidal to intertidal, marine deposit. In the study area, this facies is restricted to the eastern areas, where it overlies F 3 or F 4 (Alma, Fig. 4). Therefore, it may also correspond to low-energy bay-fill to delta-plain deposits. This facies has been previously described as "mudstones with intercalated sandstones and siltstones" and interpreted in the same way by Nouidar and Chellaï (2001).

Facies 6 (F 6): Fossiliferous marl

Fossiliferous marls are more abundant in the eastern sections, where they consist of dolomitized marl with abundant, often variegated limestone nodules. The abundant fauna consists of ostreids, trigonids, large bivalves, serpulids, bryozoans, gastropods, brachiopods, and ammonites; the composition varies regionally. In some sections, microkarstic cavities and root traces are observed in the upper parts of beds. Thin sandstone beds with parallel laminations or current ripples may be present.

Interpretation. The fossiliferous marls are interpreted as open-marine, outershelf deposits. To the south (Anzate, Alma, Fig. 4), the presence of bryozoans and brachiopods suggests a slightly deeper depositional environment than in the northern sections (Zento, Takoucht, Figs. 5 and 6), marked by root traces, karst and trigonids. The fossiliferous marls are usually capped by an erosional exposure surface, marked by reworked elements, root traces and mottling (Fig. 3J).

Facies 7 (F 7): Fossiliferous, dolomitized limestones

Fossiliferous dolomite underlies the upper Barremian sandstone units in the eastern and northern areas. There, they consist of fossiliferous dolostone with marly interbeds, highly dolomitized (Fig. 3I). The abundant fossil content comprises ammonites, nautiloids, ostreids, bryozoans, annelids, brachiopods, and scarce ammonites. Bioturbation is common. Some beds are affected by karstic dissolution, the caves of which are infilled by bioclastic calcarenites

Figure 3. Photographs of some facies on the upper Barremian-lower Aptian succession of the EAB. A. Alternating shales and sandstone (Facies 1), showing a thickening upward trend (Tamri). B. Large-scale cross bedding in conglomeratic sandstone beds (F 3, Barrage). C. Erosional surface in laminated sandstone (F 3, Assaka). D. Medium-grained laminated sandstone grading upward to fine-grained laminated sandstone, interpreted as lower to upper foreshore facies (F 3, Imsouane). E. Fine-grained, laminated sandstone, crosscut by desiccation cracks (F 3, Akarkour). F. Desert rose pseudomorphs in the upper part of a laminated sandstone (F 3, Assaka). G: Typical variegated siltstone (F 5, Alma). H: Thin sandstone bed bearing current ripples (F 5, Alma). I: Extensively dolomitized limestone beds (F 7, Zento). J: Mottled dolomitized marl with root traces (top of F 6, Alma).

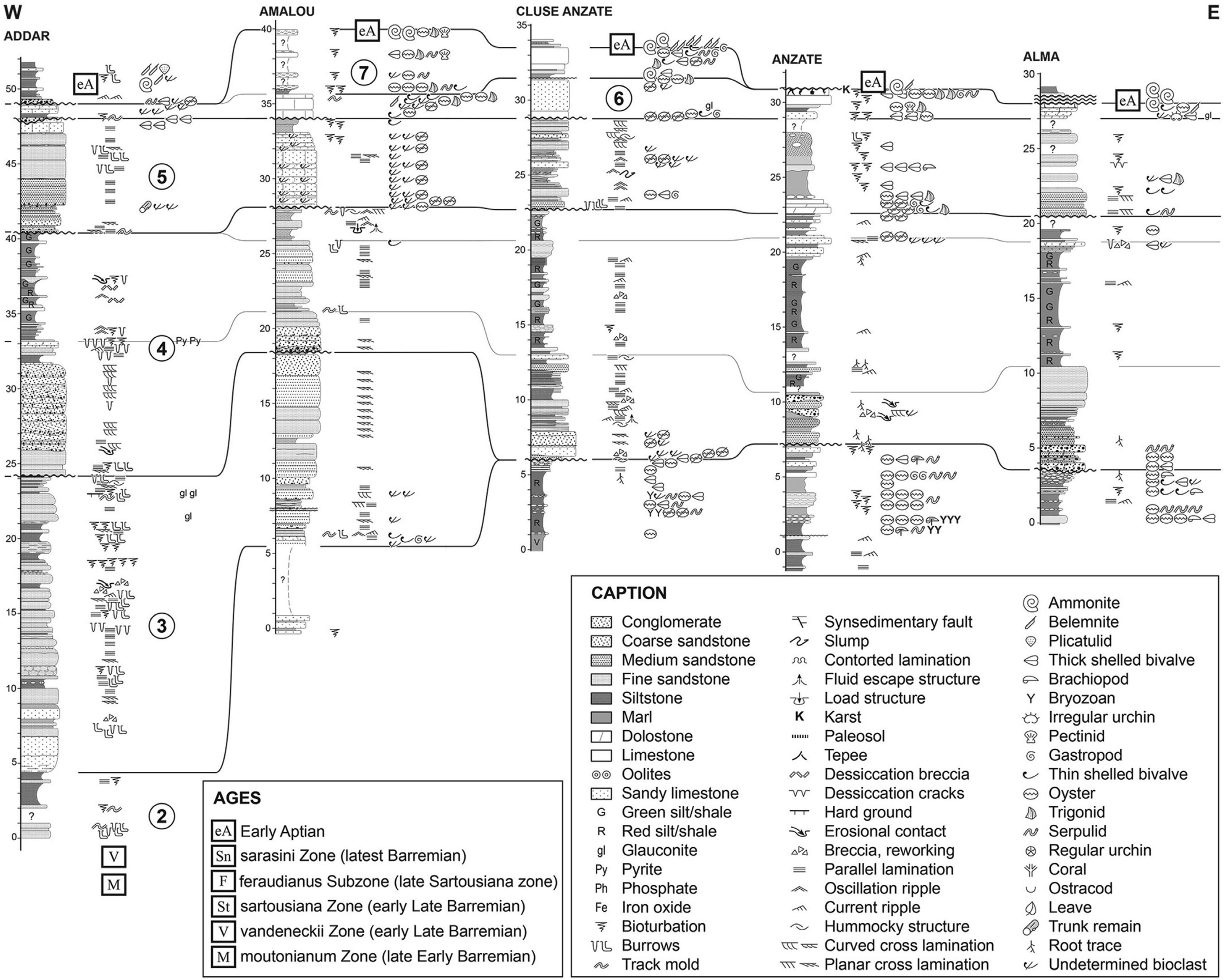

Figure 4. Sedimentary features and E-W correlation of upper Barremian sections in the southern part of the study area. Numbers refer to the units described in the text. See Figs. 1B and 5 for location.

or by the overlying sandstones. Intense dolomitization prevented microfacies analysis.

Interpretation. This facies represents a moderately deep carbonate shelf (Company et al., 2008). The faunal content indicates an open-marine environment, while the presence of emergence surfaces suggests a shallow environment, combined with pronounced eustatic oscillations or long-lasting emergence periods.

Facies 8 (F 8): Dolomitized, massive sandy limestone

Massive sandy limestone beds occur in the upper part of the studied succession. They are characterized by an abundant shallow-marine fauna (gastropods, serpulids, ostreids, trigonids, pectinids, other bivalves, and locally scleractinian corals) and by an abundant, fine-grained sandy content. Because of significant dolomitization, precise observations are difficult. However, bioturbation and current-related sedimentary features may be seen locally. Where observed, this facies terminates in a discontinuity surface, capped by an ammonite-rich horizon ("*Cheloniceras* bed").

Interpretation. The massive dolomitized limestone facies is interpreted as deposited in a shallow, open-marine, carbonate shelf environment. The significant clastic content suggests, either the proximity of a detrital source, or more probably, a transgressive trend, which favors the reworking of previously deposited sandstones from emergent areas.

4.2. Discontinuities and sedimentary evolution

The analysis of facies, their interpretation in terms of sedimentary environment, and the identification of discontinuity surfaces, allow the definition of sedimentary units. Because of numerous lateral changes in thickness, lithology and facies, southern, northern and central sections are described separately (Figs. 4 to 6). Seven lithologic units have been recognized, which may be identified across the whole area. From base to top, they will be referred to as Units 1 to 7.

4.2.1. Southern sections

The southern sections are presented in Figs. 4 and 9. To the east (Alma, Anzate, Cluse Anzate), coarse conglomerates and sandstones (F 3 and F 4) of Unit 4 abruptly overly marine marls (F 6) of Unit 1 or 2, through an erosional contact. This contact is marked by intense pedogenesis evidenced by abundant mottling and root traces (Fig. 3J), strong oxidization of the underlying marls (reddish color), and remarkable concentrations of bryozoans and other fossils. The latter are interpreted as resulting from the winnowing of the marine sediment due to the erosion-dissolution and removal of its fine-grained marly component, thus indicating a long-lasting, subaerial erosional hiatus. Conglomerates are composed almost exclusively of calcareous clasts, which are commonly subangular to rounded, and contain iron oxide coatings and pervasive dolomitization, thus supporting a long-lasting subaerial exposure prior to the resumption of deposition. The conglomerates and sandstones of Unit 4 grades upward into red and green, variegated siltstones and sandstones (F 5).

To the west (Amalou, Addar), Unit 4 abruptly overlies the coarsening- and thickening-upward succession of marine sandstones (F 1) of Unit 3, which expresses a prograding trend. Unit 3 is marked by cross bedding to the east (Amalou), whereas horizontal laminations, current ripples, and bioturbation dominate to the west (Addar), indicating a deepening trend to the west. Although no biostratigraphic data are available, Unit 3 is probably partly coeval with the hiatus locally identified in the eastern sections between Units 1 and 4.

In the same area, the massive, coarse-grained, locally pebbly sandstone of Unit 4 contains high-energy sedimentary features (large-scale planar or trough cross bedding). These deposits are tentatively correlated with massive, contorted, fine-to medium-grained sandstone beds of the Tamri section, which exhibit numerous, large-scale fluid-escape structures (Figs. 5 and 8). There, planar laminations, current and oscillation ripples, HCS, and plant fragments indicate a relatively shallow, open-marine environment. As a whole, Unit 4 is interpreted as a tide-dominated system, which recorded fluvial influences (F 4) to the east (Alma, Anzate), high-energy tidal currents (F 3 and 4) in Amalou and Addar, and open-marine shelf environment (F 1) to the west (Tamri, Fig. 5).

The overlying variegated siltstones of Unit 4 (F 5) exhibit laminated or fine-grained, rippled sandstones, desiccation breccia, bioturbation, typical shallow-marine sedimentary structures, such as oscillation ripples and HCS, as well as rare marine fauna (bivalves and isolated corals in Alma according to Ambroggi (1963)), indicating a low-energy, tidal-flat environment. In Tamri, Unit 4 is capped by submarine discontinuities marked by hard grounds and reworking surfaces (Fig. 5).

Unit 5 abruptly overlies the variegated Unit 4. Unit 5 consists of a fining-upward succession of fossiliferous, calcareous sandstones or sandy limestones (F 8). Bivalves (trigonids, ostreids) and sedimentary features (oscillation ripples, desiccation cracks) indicate a shallow-marine environment. This is further supported by the mature, clean, well-sorted nature of the sediment, which indicates a low to moderate energy regime. This succession is interpreted as a transgressive series, in a shallow, open-marine environment, influenced by significant siliciclastic input. In some cases (Cluse Anzate), the upper part exhibits a shallowing trend, expressed by high-energy sedimentary features in the upper part (planar or trough cross bedding, HCS), and a coarsening upward trend.

This unit is in turn overlain by a transgressive succession of marine sandy limestone and marl (Unit 7), which is capped, to the east, by the lower Aptian "*Cheloniceras* bed". In Alma, the "*Cheloniceras* bed" seems to directly overly the upper sandstone unit (Unit 5).

4.2.2. Central sections

The central sections are shown in Figs. 5 and 10. They are characterized by thick successions of coarse sandstone and conglomerate (F 3 and F 4). Except within the eastern portion (Aziar, Zento), facies 5 of Unit 4 is lacking.

To the west, Units 1 and 2 are open-marine, outer-shelf prograding sequences, which appear to grade eastward to shallower carbonate shelf deposits (Zento). They are separated from each other by a phosphate-rich, fossiliferous hard ground, which correlates with the top of the limestone sequence of the eastern area, as displayed in the Barrage section (Fig. 12G, 12H). Units 1 and 2 are tentatively correlated with outer shelf clastic deposits in the Tamri section (Fig. 5). Unit 3 is initially a thinning-upward, then thickening- and coarsening-upward series of marine sandstone (F 1). Eastward, it pinches out between Barrage and Aziar. The overall thickening-upward trend, interpreted as increasing-upward energy of deposition, suggests that this succession is a shallowing-upward, prograding succession deposited in a siliciclastic shelf environment. The clastic shelf deposition is locally interrupted by a thick sandstone intercalation (Imsouane, Akarkour, Barrage) indicative of reworking processes (Figs. 5 and 10).

Unit 4 abruptly overlies Unit 3 to the west, and directly overlies Unit 2 (Aziar) or 1 (Zento) to the east. In the western sections, the base of Unit 4 is marked by synsedimentary deformation and large-scale, fluid-escape structures, while in the eastern sections, the same level is marked by channelized conglomerates cut into underlying units. Except in the Zento and Imsouane sections (Figs. 5 and 7), fluid-escape structures as well as slumped and

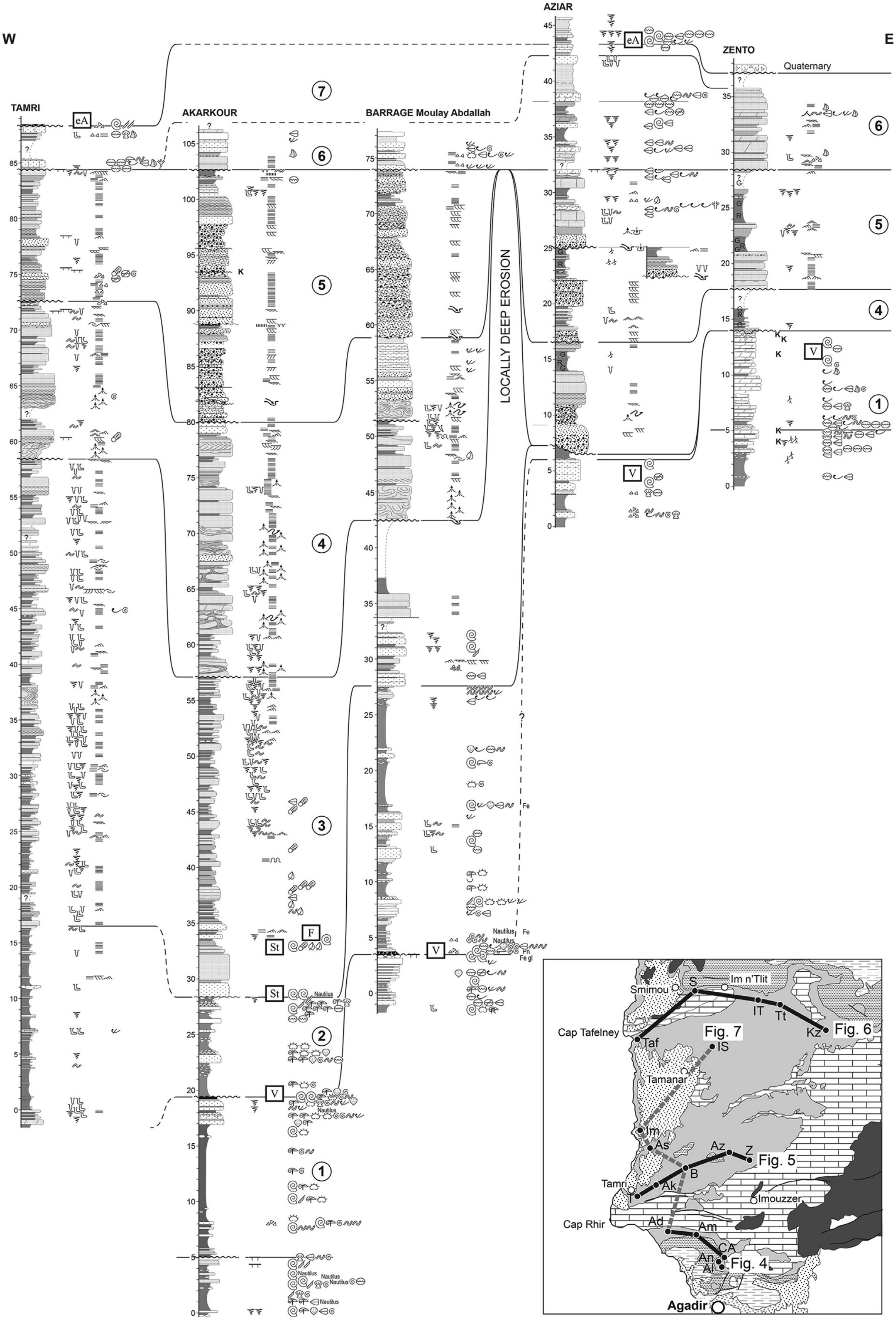
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Fig. 4
Agadir

disorganized beds are common, indicating significant tectonic instability. Such submarine slumps are especially spectacular in Akarkour, where they repeat part of the series and may explain the increased thickness of this section.

In the eastern sections, Unit 4 is sporadically intercalated with conglomeratic beds with erosional bases (Aziar) or by pebbly sandstones (Zento) suggesting that either clastic supply was irregular due to tectonic or climatic events, or to the migration of fluvial channels across the coastal plain. Whereas evidence for fluvial influences are strong in the Aziar section (deep channels, lack of marine fauna), the Zento succession bears evidence of shallow-marine to tidal-flat environments (low-angle planar laminations, oscillation ripples). Facies 5 of Unit 4 is not identified in the western sections (Barrage, Akarkour), where thick, coarse, conglomeratic intercalations are common, suggesting strong fluvial influences as also supported by abundant plant fragments. However, the exclusively sandy matrix, the frequent sigmoidal cross bedding, the alternating coarse- and fine-grained laminae (Fig. 3B) and the local occurrence of marine fauna indicate a marine environment. These sandstones and conglomerates are, therefore, interpreted as tidally influenced, Gilbert-type delta deposits, fed by a powerful river. Since the clasts are exclusively of crystalline origin, the source of the river is assumed to be the High Atlas region located to the East.

Unit 5 may be present in the Aziar section, and is tentatively correlated with the western sections. However, river-dominated, auto-cyclic processes seem to have been dominant during deposition of this unit, making difficult correlation of sedimentary discontinuities.

In the eastern sections, the upper Barremian coarse sandstones (Units 4 and 5) are overlain by a succession of clean, fine-grained, well-sorted marine sandstones (Unit 6), bearing abundant thick-shelled bivalves (trigonids, ostreids, and large bivalves); this succession is especially well developed in the northern sections (see below).

4.2.3. Northern sections

In the northern sections (Figs. 6 and 10), Units 1 and 2 are only present in the eastern sections (Smimou, Takoucht). To the west, Unit 4 rests directly on late lower Barremian karstified limestone (F 7, Tafadna) and is locally represented by a transgressive conglomerate (Smimou) bearing a shallow, open-marine fauna (bryozoans, ostreids and other bivalves). In Takoucht and Kouzemt, Unit 4 is represented by fine-grained, dolomitic sandstone beds, bearing moderate energy features.

Except in the eastern sections, the overlying Unit 4 bears an abundant marine fauna (ostreids, pectinids, trigonids), indicating a shallow, open-marine environment (F 5). Rey et al. (1986) mention the benthic foraminifera *Chofatella decipiens* south of Takoucht. Sedimentary features suggest a transgressive thinning-upward, then regressive thickening-upward evolution. To the west (Tafadna), this unit appears to grade laterally into massive, fossiliferous, shallow-marine calcareous sandstones.

In all sections, Unit 5 abruptly overlies Unit 4 and exhibits coarse-grained facies at its base (Fig. 10). In Takoucht, Tassila Ougadir and Tafadna, Unit 5 displays large-scale fluid escape structures suggesting significant tectonic movements. The presence of numerous echinoids, serpulids, ostreids and other bivalves, as well as desiccation features and breccia, indicate a shallow, open-marine environment. In most sections, the fining upward trend suggests a transgressive trend.

Unit 5 is in turn overlain by clean, fine-grained and well-sorted sandstones (F 2) of Unit 6, the base of which exhibits marine fauna (brachiopods, ostreids, trigonids and other bivalves). Because of the common occurrence of planar and trough cross bedding, this sandstone is interpreted as a set of submarine sand bars gently migrating on a shallow-marine clastic shelf.

Unit 7 consists of shallow-marine limestones, rich in serpulids, trigonids, ostreids and other bivalves (F 7). This unit is capped by the "*Cheloniceras* bed" and discontinuity.

4.3. Biostratigraphy

We use the standard biozonation as updated by Reboulet et al. (2014). All time units are interval zones; their lower boundary is defined by the first occurrence of the index-species, while their upper boundary is defined by the first occurrence of the next index-species. Stratigraphic position of the identified ammonites is given in Table 1.

The age of the beds overlain by Unit 4 varies spatially. In Tafadna (Fig. 6), *Barrancyloceras* sp., *B.* cf. *maghrebiense*, *Barremites* sp., and *Barre.* gr. *vocontius* indicate a late early Barremian age (*moutonianum* Zone). Few additional ammonites were collected from the Smimou (?*Barremites* sp.) and Takoucht ("*Emericiceras*" sp.) sections. In the central transect (Fig. 5), ammonites found below Unit 4 in the Aziar section consist of *B. barremense* and *Gassendiceras quelquejeui*, indicating an early late Barremian age (*vandenheckii* Zone). Farther east, ancyloceratids found below Unit 4 in Zento, are consistent with an early late Barremian age. In the Addar section (Fig. 4), the highest ammonites collected below Unit 3 are *B.* sp., *B. maghrebiense, Barre.* sp. and *Melchiorites* cf. *rumanus* of the *moutonianum* Zone.

In the western sections of the central transect, a phosphatic-glauconitic condensed level separates Unit 1 from Unit 2. This level yielded earliest late Barremian ammonites (*vandenheckii* Zone): *Barremites* sp., *Kotetishvilia* sp. and ?*Moutoniceras* sp. in Imsouane; *Heinzia* cf. *sayni, Barre.* sp., *Toxancyloceras vandenheckii, T.* cf. *ebboi* and *Toxancyloceras* sp. in Assaka; and *Nicklesia* sp. and *Barremites* sp. in Akarkour (Fig. 5).

In Unit 2 of Imsouane and Akarkour (Figs. 5 and 7), three successive ammonite assemblages have been recognized. The lower association probably corresponds to the *vandenheckii* Zone as it comprises, from base to top, *Macroscaphites* sp., *Lytoceras* sp. and *Toxancyloceras* sp. in Imsouane. In Addar, *Barrancyloceras barremense*, collected just below Unit 3, suggests the same age range. The next assemblage is characterized from base to top by *Camereiceras* sp., *C. limentinus*, and *Pachyhemihoplites* sp. in Akarkour, and may be ascribed to the *sartousiana* Zone. In the third assemblage, the occurrence of *Audouliceras* cf. *elephas* in Akarkour suggests the upper part of the *sartousiana* Zone (*feraudianus* Subzone). In Ida w Shayq (Fig. 7), sandy nodular limestones yielded an assemblage of *Gerhardtia provincialis*, *B.* sp. and *Gassendiceras* sp., which characterizes the *sartousiana* Zone.

Regarding the massive sandstone, the lowermost part of Unit 4 yielded *Macroscaphites* sp. in Tafadna, and *Spinocrioceras* cf. *polyspinosum* in Imsouane. The latter taxon indicates the *feraudianus* Subzone (Fig. 7).

In many sections, the massive sandstone unit (Unit 5) is capped by a condensed horizon rich in early Aptian ammonites (Ambroggi, 1963; Rey et al., 1988; Witam, 1998; Luber et al., 2017). However, in Smimou, the overlying alternating marl and limestone yielded *Pseudocrioceras* sp. and *Audouliceras* sp., while *Kutatissites* sp., *P.* sp.

Figure 5. Sedimentary features and E-W correlation of upper Barremian sections in the central part of the study area. Caption of lithologic symbols on Fig. 4. Numbers refer to the units described in the text.

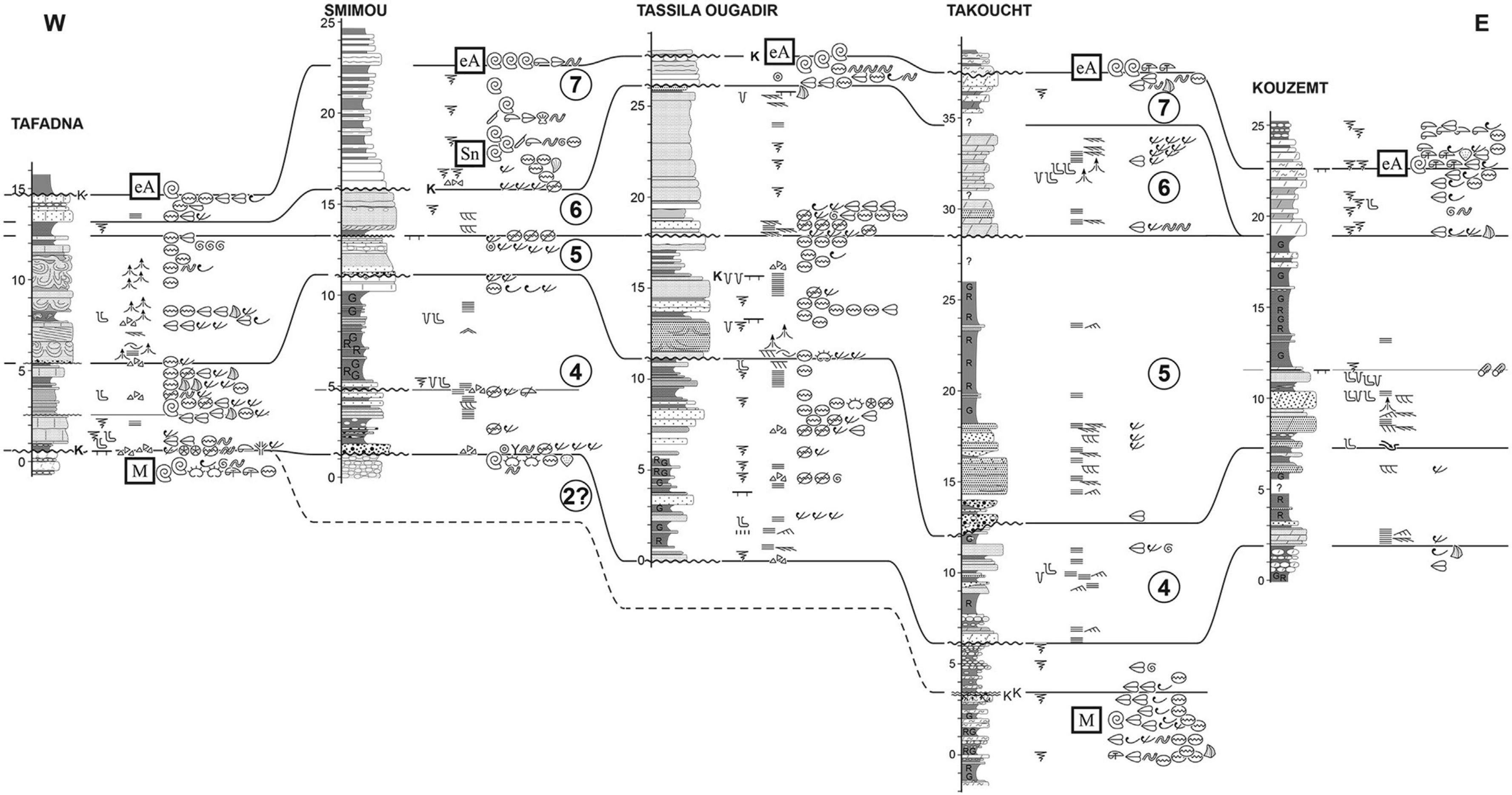

Figure 6. Sedimentary features and E-W correlation of upper Barremian sections in the northern part of the study area. Caption of lithologic symbols on Fig. 4. Numbers refer to the units described in the text. See Figs. 1B and 5 for location.

and *Ancyloceras* gr. *matheronianum* have been sampled 5.5 m above the top of Unit 6 in Ida w Shayq (Fig. 7). These findings demonstrate that Unit 7 is, at least partly, of latest Barremian age (*sarasini* Zone), and thus that Units 4 and 5 (Bouzergoun Fm s.s.) are entirely of late Barremian age (*feraudianus* Subzone to *sarasini p.p.* Zone).

In summary, Unit 1 is mainly of late early Barremian age (*moutonianum* Zone). In the southwestern area, a condensed level of early late Barremian age (*vandeneckii* Zone) separates Units 1 and 2. Unit 2 encompasses part of the *vandeneckii* and *sartousiana* Zones. Unit 3 spans the *sartousiana* zone, and the base of Unit 4 yielded ammonites from the *feraudianus* Subzone. Finally, Unit 7 is at least locally of latest Barremian age (*sarasini* Zone).

5. Sequence stratigraphy and tectonic interpretations

5.1. Sequence stratigraphy interpretation

In the eastern areas, the top of Unit 1 is characterized by evidence for subaerial exposure, including pedogenesis, karstification and erosion, and by a phosphatic-glauconitic, conglomeratic, ammonite-bearing condensed interval in western areas. As can be observed in the Barrage section, the emergence surface is directly overlain to the southwest by a phosphatic condensed level (Fig. 12G and 12H). These observations suggest that the exposure surface is a sequence boundary (SB), related to a significant sea-level fall that resulted in the emergence of most of the study area (Fig. 11), and that it is immediately overlain by a transgressive surface characterized by the phosphate bed.

Unit 2 overlies Unit 1 and is overlain by thick, glauconite-rich calcareous sandstone beds with erosional base, and local cross bedding and phosphate matrix. Numerous ammonites are concentrated both at the base and top of the sandy bed. These features suggest a submarine hiatus, followed by a transgression, which is interpreted as a SB. Unit 2 is therefore regarded as a second depositional sequence.

Offshore sandstones of Unit 3 are only known in the central western area (Figs. 5 and 13B) As Unit 3 overlies a phosphatic condensed level and was deposited while the eastern area was emergent, it can be interpreted as a lowstand systems tract of a depositional sequence subsequent to deposition of Unit 2. In this interpretation, Unit 4 would represent the transgressive systems tract (TST) and maximum flooding surface (MFS) of this sequence, as documented by the occurrence of marine fauna in some sections. Consequently, the major unconformity marked by the arrival of coarse siliciclastic deposits at the base of Unit 4 would be merged with the SB in the eastern areas, and with the transgressive surface in the western areas.

Alternatively, one may propose that the major unconformity at the base of Unit 4 is a SB. In this interpretation, Unit 3 would represent a third progradational depositional sequence restricted to the southwestern part of the study area, and Unit 4 would represent a fourth transgressive depositional sequence. The latter interpretation is preferred and illustrated in Fig. 11 as it is consistent with the transgressive-regressive trend indicated by sedimentary features in Unit 3, and since the basal unconformity of Unit 4 is of regional extent.

In all sections, deposits of Unit 5 are marked by a significant increase of grain size and show a deepening upward trend (Figs. 4 to 10). Unit 5 is, therefore, interpreted as the TST and possibly the MFS of a fifth depositional sequence (Fig. 11).

Unit 6 represents the TST and locally the MFS deposits of a sixth depositional sequence, deposited on an even topography, the depressions of which were infilled by the previous depositional sequences (4 and 5).

Finally, Unit 7 would correspond to at least one new depositional sequence of latest Barremian-early Aptian age, which is truncated by a discontinuity surface capped by the transgressive *Cheloniceras*-bearing strata of late early Aptian age. Poor exposures of this interval in most sections, as well as strong condensation in the western and southern areas, make difficult precise interpretation. However, in Ida w Shayq, Unit 7 contains latest Barremian ammonites, and karstic features are observed within and below the "*Cheloniceras* beds". This suggests that deposition of Unit 7 may be followed by a significant sedimentary gap related to the emergence of the area, consistently with the low sea level recorded in early Aptian times (e.g. Hardenbol et al., 1998; Haq, 2014).

5.2. Comparison with eustatic records

Haq et al. (1987) proposed that late Barremian and early Aptian times are a period of overall gradual sea-level fall. Synthetizing data on European basins, Hardenbol et al. (1998) identified moderate sea level falls and correlative sequence boundaries at the beginning of the late Barremian (Barr 5), in the late Barremian (Barr 6) and at the Barremian-Aptian boundary (Ap 1), and major sea-level falls at the Early-Late Barremian boundary (Barr 4), in the early Aptian (Ap 3) and at the beginning of late Aptian times (Ap 4). More recently, Haq (2014) refined these schemes and identified a minor sea-level fall at the boundary between the *moutonianum* and *vandeneckii* Zones (KBa 3), moderate sea-level falls at the boundary between the *vandeneckii* and *sartousiana* Zones (KBa 4) and close to the Barremian-Aptian boundary (KBa 5), and finally a major sea-level fall in the early Aptian (KAp 1).

Our biostratigraphic and sedimentological data which document an SB in the *vandeneckii* and *sartousiana* Zones (see also Company et al., 2008) are consistent with the eustatic sea-level falls proposed by Hardenbol et al. (1998, Barr 5) and Haq (2014, KBa 3 and KBa 4). Moreover, the major sea-level fall observed by these authors in early Aptian times is consistent with the condensed sedimentary record of the lower Aptian deposits in the EAB (*oglanlensis* to *furcata* Zones; Peybernès et al., 2013; Luber et al., 2017). The eustatic sea-level fall in the proximity of the Barremian-Aptian boundary (Hardenbol et al., 1998; Haq, 2014) has not been identified in this work, but it may correspond to a discontinuity within our poorly exposed Sequence 7, above the latest Barremian ammonites. The eustatic sequence boundary identified in the late Barremian (Barr 6 of Hardenbol et al., 1998) is also mentioned in southeastern France by Clavel et al. (2013) within their *giraudi* Zone and may correlate with the SB identified between our Sequences 4 and 5. However, no significant eustatic sea-level fall has been identified by Hardenbol et al. (1998) and Haq (2014) in the late *sartousiana* Zone or close to the *sartousiana-giraudi* zonal boundary. Therefore, the major basal unconformity of Sequence 4 is probably not of eustatic origin.

5.3. Synsedimentary tectonic activity

5.3.1. Sedimentary record

The appearance in Sequence 3 of abundant fine-grained marine sandstones may be interpreted as the evidence of a rejuvenation of erosion on some uplifted eastern areas. However, we did not find any evidence of coastal siliciclastics in the eastern areas, which would have supplied sediment to this clastic shelf. This can be due to the fact that large areas of the EAB were emergent at that time, or that the clastic material emenated from a source area located further to the south or north. Nevertheless, the intercalation of unusually thick sandstone beds in some sections (Imsouane, Akarkour, Barrage), locally exhibiting fluid escape structures (Tamri, Fig. 5), may represent distal evidence of some moderate

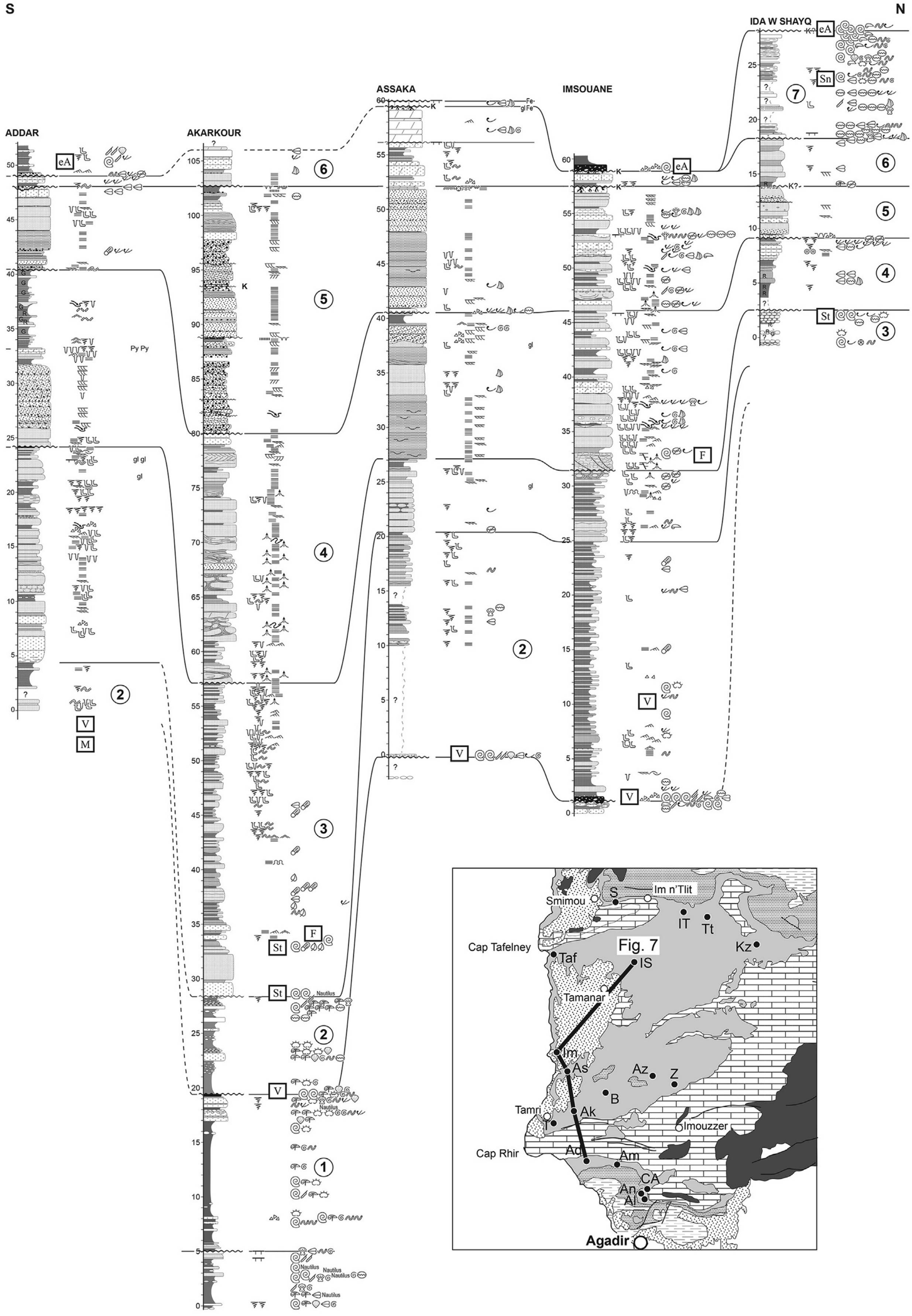
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Table 1
Identification and location, in meter, of the ammonites mentioned in the text.

Addar		Ida w Shayq	
Barrancycloceras maghrebiense (Immel)	≈ m -10	*Gherardtia provincialis* (d'Orbigny)	m 2
Barrancyloceras sp.	≈ m -10	*Barrancyloceras* sp.	m 2
Barremites sp.	≈ m -10	*Gassendiceras* sp.	m 2
Melchiorites cf. *rumanus* (Kilian)	≈ m -10	**Imsouane**	
Barrancycloceras barremense (Kilian)	≈ m -5	*Barremites* sp.	m 1
Akarkour		*Kotetishvilia* sp.	m 1
Nicklesia sp.	m 19.5	?*Moutoniceras* sp.	m 1
Barremites sp.	m 19.5	*Macroscaphites* sp.	m 9
Camereiceras sp.	m 27.5	*Lytoceras* sp.	m 11,5
Camereiceras limentinus (Thieuloy)	m 28.5	*Spinocrioceras* cf. *polyspinosum* Kemper	m 33
Pachyhemihoplites sp.	m 33	**Smimou**	
Camereiceras sp.	m 33	?*Barremites* sp.	m 1
Audouliceras cf. *elephas* (Anderson)	m 34	**Tafadna**	
Assaka		*Barrancyloceras* cf. *maghrebiense* (Immel)	m 0
Heinzia cf. *sayni* Hyatt	m 0	*Barrancyloceras* sp.	m 0
Barremites sp.	m 0	*Barremites* gr. *vocontius* (Lory & Sayn)	m 0
Toxancyloceras vandeneckii (Astier)	m 0	*Barremites* sp.	m 0
Toxancyloceras cf. *ebboi* Delanoy	m 0	*Macroscaphites* sp.	m 3
Toxancyloceras sp.	m 0	**Takoucht**	
Aziar		"*Emericiceras*" sp.	m 2
Barrancycloceras barremense (Kilian)	m 4	**Zento**	
Gassendiceras quelquejeui Bert, Delanoy & Bersac	m 6	Ancyloceratidae	m 11, 13

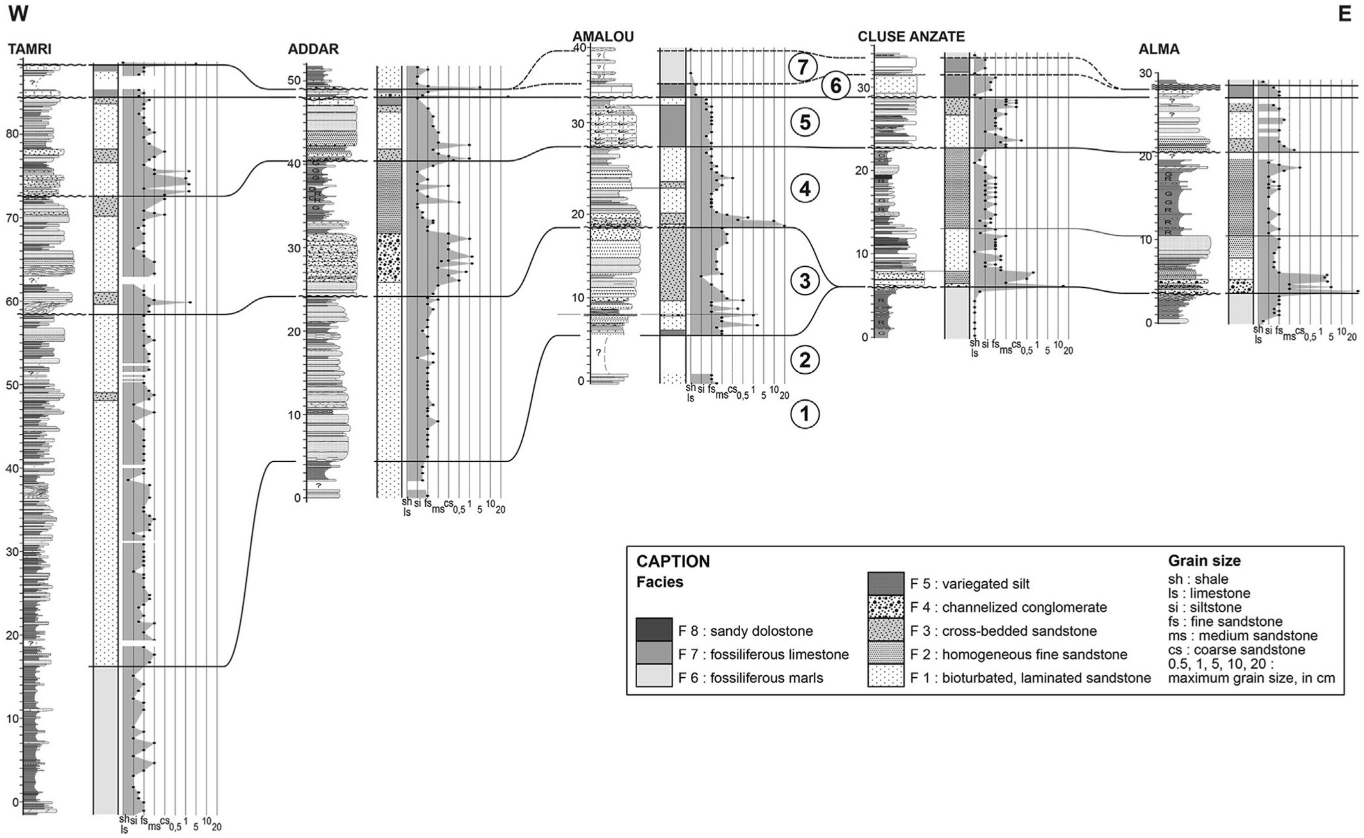

Figure 8. Grain size evolution and correlation of some upper Barremian sections in the southern part of the study area. See Figs. 1B and 9 for location.

tectonic movement, responsible for a renewal of erosion, and subsequent clastic supply.

In the northern and central sections, Sequence 4 overlies beds containing ammonites of the *moutonianum* (Tafadna, Fig. 6), the *vandeneckii* (Aziar, Zento, Fig. 5) or the *sartousiana* Zones (Ida w Shayq, Fig. 7). This indicates that significant erosion occurred in the northern and eastern areas between deposition of Sequences 3 and 4, which removed variable amounts of deposits, and/or that part of

Figure 7. Sedimentary features and N-S correlation of upper Barremian sections in the central and western parts of the study area. Caption of lithologic symbols on Fig. 4. Numbers refer to the units described in the text.

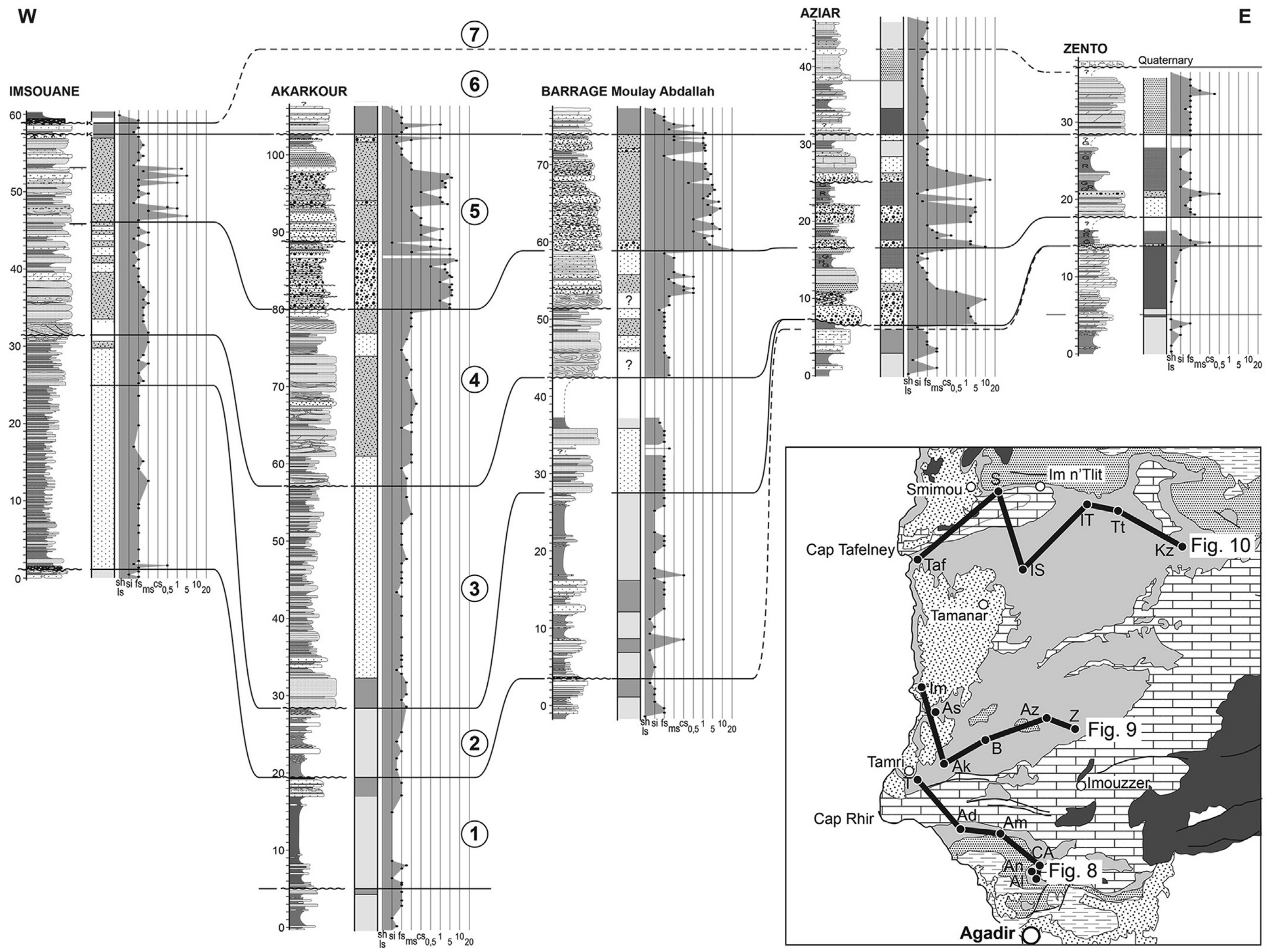

Figure 9. Grain size evolution and correlation of some upper Barremian sections in the central part of the study area. See Figs. 1B and 9 for location.

this region became emergent after the *moutonianum* or the *sartousiana* Zones, according to location. This suggests that some areas experienced a mild uplift at the beginning of the late Barremian.

At the base of Sequence 4, all western sections are marked by large-scale fluid escape and slump structures, while many eastern sections record channel incision. These features are associated with a substantial increase in the clastic grain size in all sections (Figs. 8 to 10) from medium sandstones to conglomerates with clasts as large as 20 cm, especially in eastern areas (Alma, Cluse Anzate, Aziar). This pattern indicates that an abrupt erosional increase occurred in the source areas.

A comparable situation is observed at the base of Sequence 5 (Figs. 8 to 10). In distal areas (Tafadna, Imsouane, Assaka), large-scale fluid escape structures are observed (Figs. 6 and 7). Where Sequence 5 rests on the fine-grained, variegated facies of Sequence 4, the grain size abruptly increases from fine-to medium grained sandstone to pebbly sandstone containing clasts up to 1 cm in diameter (Ida w Shayq, Cluse Anzate, Addar). Where conglomerates overly sandstones of Sequence 4 (Aziar, Barrage, Akarkour), they contain clasts up to 10–20 cm in diameter. This indicates that the coarse clastic input is limited to the central part of the study area, probably at the mouth of a large river, the course of which was controlled by the first tectonic event. Note that in the northern sections these two tectonic events are moderately expressed (Figs. 6 and 10).

In the overlying sequences (6 and 7), no such increase in the grain size of clastic sediments is observed. On the contrary, the grain size decreases gradually, until marly and calcareous sedimentation developed during the early Aptian (Ambroggi, 1963; Peybernès et al., 2013; Hassanein Kassab, 2016).

5.3.2. Field observations

Field observations support the mentioned interpretations. In the Barrage section, an angular unconformity is observed within dolomitized limestone of Sequence 1 (Fig. 12F). This indicates a northeastward downward tilt of the area in early late Barremian times.

At the base of Sequence 4, synsedimentary faults affecting soft sediments can be observed in Imsouane and Assaka (Fig. 12A), as well as spectacular fluid escape structures in the Tafadna, Akarkour and Barrage sections (Fig. 12B, 12C). Moreover, an angular unconformity is clearly visible in the Barrage section below Sequences 4 and 5, which onlap onto Sequence 1 to the Northeast (Fig. 12G and 12H); strata bearing early Aptian ammonites directly overly Sequence 1 near the Barrage (Left of Fig. 12H). This indicates that the area was again tilted down, now toward the southwest. This disposition may explain the wedging out of Sequence 3 toward the northeast (Figs. 11 and 13B) and the long-lasting hiatus observed between Sequences 1 and 4 in the uplifted northern and eastern areas (Fig. 11).

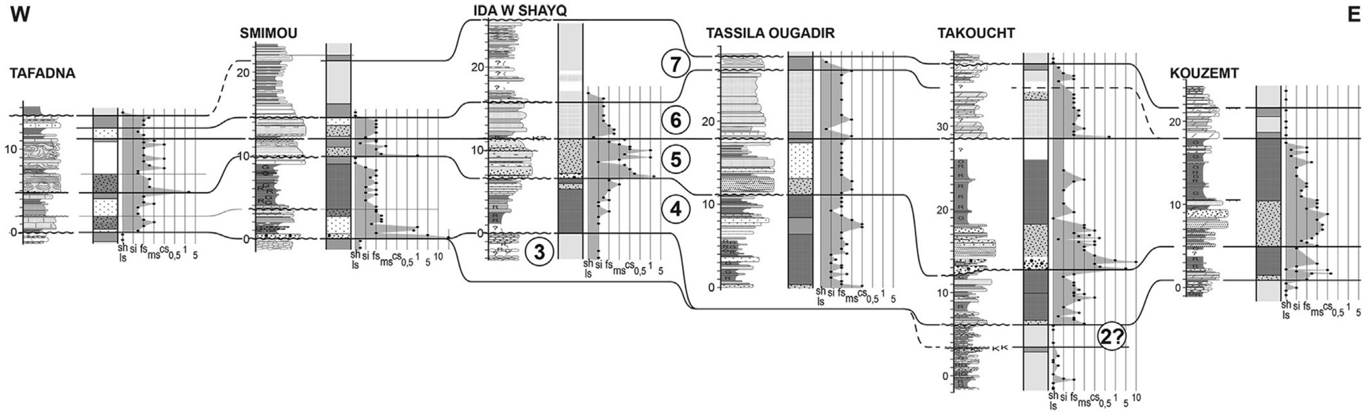

Figure 10. Grain size evolution and correlation of some upper Barremian sections in the northern part of the study area. See Figs. 1B and 9 for location.

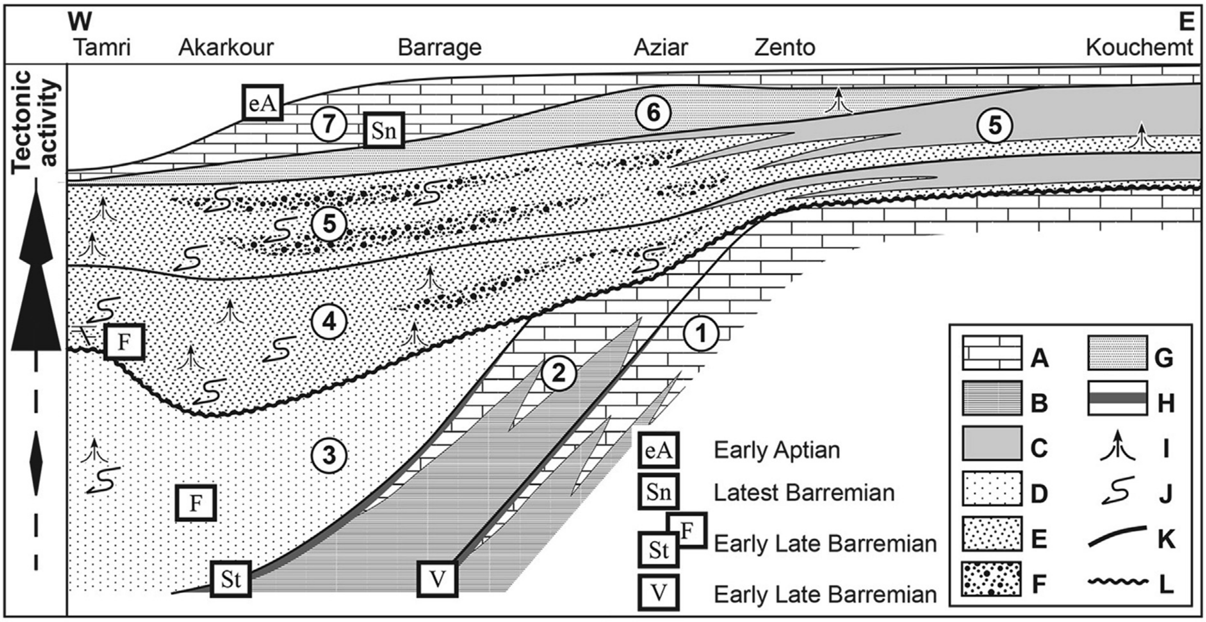

Figure 11. Sequence stratigraphy interpretation. Roman numerals refer to the depositional sequences described in the text. A: Shelf limestone; B: Marine marls; C: Variegated siltstones and sandstone; D: Fine-grained, shallow-marine sandstones; E: Coarse-grained, shallow-marine sandstones; F: Marine to fluvial conglomerates; G: Offshore sandstones; H: Phosphate-rich condensed level; I: Fluid escape structures; J: Slump; K: Sequence boundary; L: Tectonic unconformity.

During deposition of Sequence 5, more escape structures can be observed in Tafadna (Fig. 12C), Imsouane or Tassila Ougadir (Figs. 6 and 7). Yet, the most spectacular evidence for tectonic movements are found in Akarkour, where the upper part of the section (Sequence 5) is locally totally disorganized, and locally repeated by huge slumping structures (Fig. 12D, 12E). The channels filled by the slumped deposits seem to have a ≈NW-trend, i.e. orthogonal to the depocenter axis. Since slumps are commonly caused by the creation of slopes, this suggests that the depocenter was tectonically controlled by ≈ NE-trending faults.

Therefore, as previously mentioned by Ambroggi (1963), deposition of the Late Barremian sandstone (Units 4 and 5) is related to a strong tectonic activity. The latter caused the uplift of eastern sources areas, and controlled the shape of depocenters in the EAB. Tectonic movements may have begun during deposition of Sequence 3 (*vandenheckii* to lower *sartousiana* Zones). However, the main tectonic activity, locally expressed by large-scale tilting and erosion, slumps, as well as coarse siliciclastic sediment supply occurred during deposition of Units 4 and 5. Our biostratigraphic data indicate that these main tectonic events began during the *feraudianus* Subzone, and ended during part of the *sarasini* Zone, *i.e.* mainly during the late *sartousiana* and *giraudi* Zones of late Barremian age.

5.3.3. Paleogeography

Paleogeographic reconstructions are shown on Fig. 13. During deposition of Sequences 1 and 2, carbonate shelf deposits laterally grade westward to deeper shelf marl (Fig. 13A). Deposition of Sequence 3 recorded both the arrival of significant amount of sandy deposits in the western areas that represent a noticeable depocenter, and the probable emergence of most eastern areas (Fig. 13B). However, since significant erosion occurred prior to deposition of Sequence 4 in most eastern and northern areas, the exact date of emergence of these areas cannot be determined.

During deposition of Units 4 and 5, coarse-grained, siliciclastic sediments are localized along a ENE-to NE-trending area, which also represents the depocenter (Fig. 13C, 13D). This suggests, on one hand, that the supplying rivers were sourced by the High Atlas

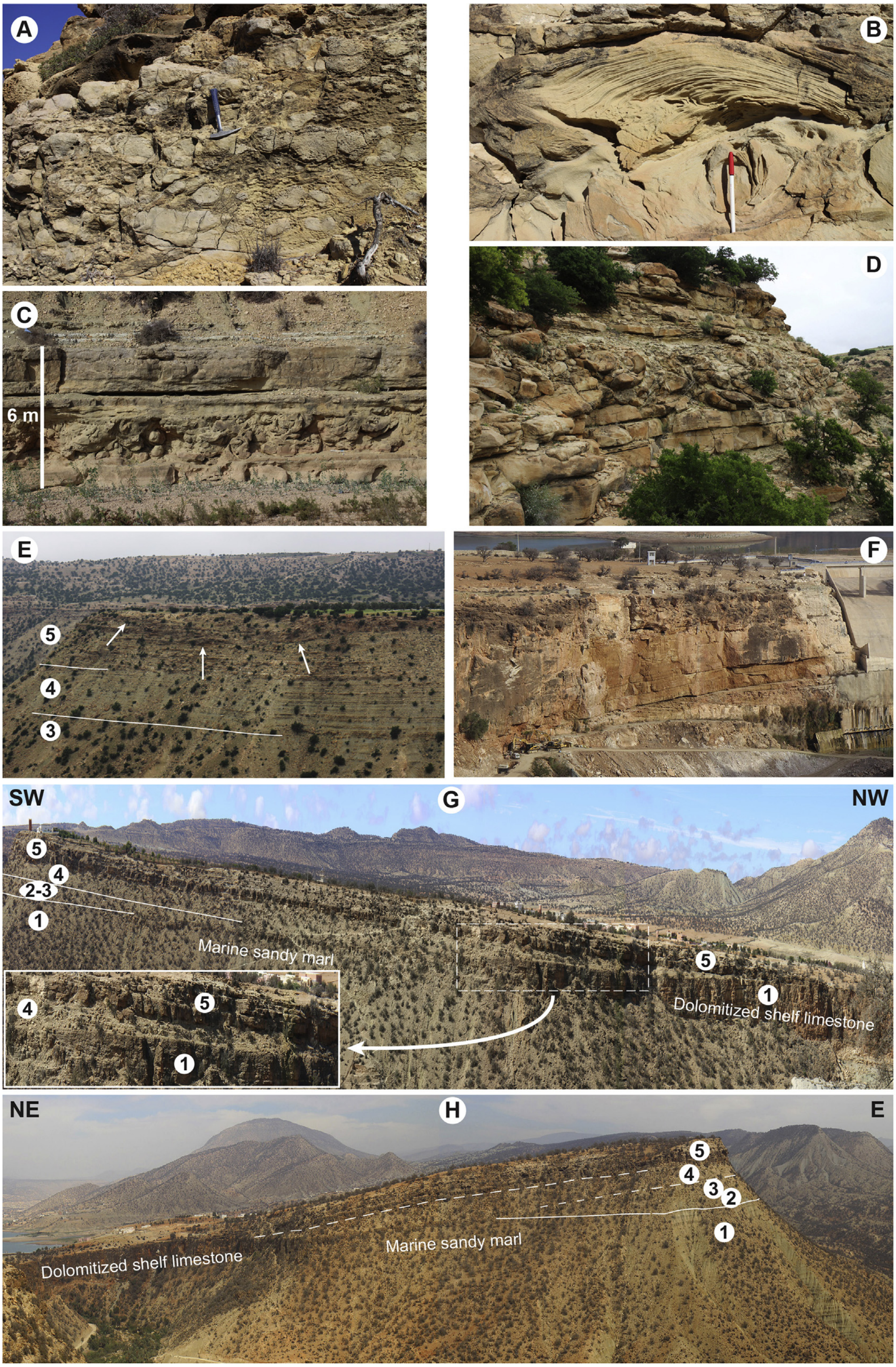

Figure 12. Photographs of some upper Barremian outcrops showing synsedimentary tectonic structures. A: Soft sediment deformation at the base of Sequence 4 (Imsouane). B: Slumped fluid escape structure in Sequence 4 (Barrage). C: Fluid escape structure in Sequence 5 (Tafadna). D: Slump structure in Sequence 5 (Akarkour). E: Large-scale erosive channel in Sequence 5 (arrows), infilled by slumped, redeposited sandstone (Akarkour). F: Angular unconformity within the dolomitized shelf limestone (Sequence 1 and below) of the Barrage section. This outcrop is located immediately to the right of Photograph 12G. Note construction vehicles in the foreground for scale. G: Angular

basement and/or its siliciclastic cover and was flowing southwestward, and, on the other hand, that their course was controlled by a NE-to ENE-trending structure. Although no evidence of synsedimentary faulting of this orientation have been found, it is worth noting that Mridekh et al. (2000) and Mridekh et al. (2009) mention NE-trending faults, which were active during the Mesozoic and Tertiary in the Agadir area, some of them acting as controls on salt diapir ascent. Moreover, Mehdi et al. (2004), Davison (2005), Hafid et al. (2006) and Tari and Jabour (2013) emphasize that the offset of inherited NE-trending faults influenced the Mesozoic salt tectonics and sedimentary evolution of the Essaouira area. At that time, the depocenter is surrounded to the east by more stable areas, which received finer grained deposits (Facies 5). To the west, the fine-grained clastic supply (quartz sandstones) seems to have been redistributed to the north along the coast, probably by nearshore currents, as indicated by the decreasing thickness of Units 4 and 5 from Tamri to Tafadna (Figs. 7, 13C, 13D). In the southern part of the EAB (Tamzergout, Alma), the basal conglomerates of Sequence 4 are marked by almost exclusively calcareous clasts, which denotes an ephemeral, distinct source area and drainage system.

During deposition of Sequences 6 and 7, little thickness variations are observed, and the isopach map is strongly oblique with respect to that of Sequences 4 and 5. The depocenters are N–S-trending, and the southwestern part of the EAB records a strongly condensed sedimentation, and probable temporary erosions. This pattern suggests on one hand, that the main tectonic activity that gave way to the uplift and erosion of the eastern basement rocks ceased by the deposition of Sequence 6, and on the other hand, that the southern and southwestern parts of the study area were slightly uplifted during deposition of Sequences 6 and 7.

6. Discussion

Ambroggi (1963) attributed the sandstone and variegated siltstones (our Units 4 and 5) to the lower Aptian, while Duffaud et al. (1966) considered these units as upper Barremian-lower Aptian in age. On the basis of scarce ammonites, Witam (1998) ascribed the massive sandstone series to the late Barremian and earliest Aptian. More recently, Nouidar and Chellaï (2001) considered the massive sandstone and conglomerates (our Sequences 4 and 5) deposition as associated with an early Aptian marine transgression. Our biostratigraphic data unequivocally indicate that Sequences 4 to 6 are late Barremian, since latest Barremian ammonites were found in Sequence 7 in Ida w Shayq and Smimou. As a consequence, the base of the Tamzergout Fm is locally uppermost Barremian, and not lower Aptian as assumed by Luber et al. (2017).

In Ida w Shayq, ammonites of the *sartousiana* Zone have been collected in nodular, marly limestone beds. This suggests that, although Sequence 3 is mainly sandy in the western areas, it may exhibit carbonate shelf facies in some little eroded eastern areas. As a consequence, the ammonite- and phosphate-rich discontinuity (SB + TS) that separates Sequences 1 and 2 in the western areas locally grades eastward into a discontinuity (SB) within the carbonate shelf deposits (Fig. 11). More studies of the lower to early upper Barremian carbonate shelf deposits will be necessary to identify this discontinuity. In any case, this shows that Sequence 4 unconformably overlies variably eroded Barremian deposits.

From a sedimentological point of view, Nouidar and Chellaï (2002) interpreted Sequence 3 as deposited in a southwest-ward prograding wave-dominated delta. However, the only coeval deposits known in the eastern areas are fossiliferous marine marls at Ida w Shayq. Therefore, the source area may have been located further east, the feeding channel having been eroded prior to deposition of Sequence 4. Alternatively, the source area may be located either farther south, as exemplified by sandstones of Sequences 4 and 5 scattered northward by coastal currents.

Nouidar and Chellaï (2001) interpreted the massive sandstone units of the southern areas (our Units 4 and 5) as deposited in an estuarine environment, during a major marine transgression overwhelming incised valleys. Although tidal influences and local estuarine environment are supported by our observations, this interpretation is difficult to support. Major sea level falls occurred during the *sarasini* Zone (latest Barremian) and *forbesi* Zone (early Aptian), while the base of Sequence 4 (*feraudianus* Subzone) is a period of rising sea level (Hardenbol et al., 1998; Haq, 2014). Therefore, no eustatic sea-level fall can account for the incision of valleys before deposition of Sequence 4. The localized deposition of coarse-grained deposits (Fig. 13C, 13D) suggests the creation of a topographic depression guiding the course of the feeding river. This, combined with the abundant evidences of tectonic activity at the base of Sequence 4, supports the occurrence of a significant tectonic event, responsible for both the renewal of erosion of part of the High Atlas crystalline basement, and the creation of a tectonic driven depression acting as an estuary during deposition of Sequences 4 and 5.

The calcareous clasts in the basal conglomerate of Sequence 4 in the southeastern part of the EAB (Alma, Cluse Anzate) may either represent remnants of limestone beds in the Barremian deposits eroded before deposition of Sequence 4 or derived from the erosion of the tectonically uplifted Imouzzer area consisting of Jurassic limestones. As a matter of fact, since the present-day Imouzzer-Cap Rhir anticline is cored by a diapir derived from Triassic evaporites (Mridekh et al., 2000), the late Barremian tectonic event may have initiated halokinetic movements of the Imouzzer diapir which resulted in the area's uplift. However, the lack of calcareous clasts in the rest of Sequence 4 in this area rather supports the first interpretation.

Slumps are commonly due to rapid accumulation on slopes or to the creation of slopes, while fluid escape structures are usually ascribed to high sedimentation rate or to basement destabilization (seismites). Since Sequences 4 and 5 were accumulated in estuarine to shallow-marine clastic systems, sedimentary slopes should have been more shallowly dipping than in a classical delta. On the other hand, the 15 to 80 m-thick late Barremian sandstones were deposited in ≈1–2 My, which does not represent a rapid accumulation in average (<0.8 mm/yr). Therefore, since the average accumulation rate was low, fluid escape structures and slumps were due either to the abrupt deposition of significant volumes of clastic sediments, or to movements of the basin basement. Significant tectonic activity can account for all of the observations including the sudden arrival of large amounts of detrital material, the development of slopes, and for earthquakes. This view is supported by the occurrence of large-scale tilting which resulted in angular unconformities (Fig. 12F, 12G, 12H) and by the observation of soft-sediment deformation due to normal faults (Fig. 12A).

One may argue that sea-level lowering in the late Barremian may have enhanced erosion of the hinterland and production of clastic deposits. However, the lowest sea level is reached in latest

unconformity below Sequence 4, causing the wedging out of Sequences 2 and 3 and the onlap of Sequences 4 and 5 onto Sequence 1 (Barrage, right bank) (vertical exaggeration: x 2). Numbers correspond to the sequences described in the text. H. Angular unconformity below Sequence 4 (Barrage, left bank, opposite to photographs 12G) (vertical exaggeration: x 1.5).

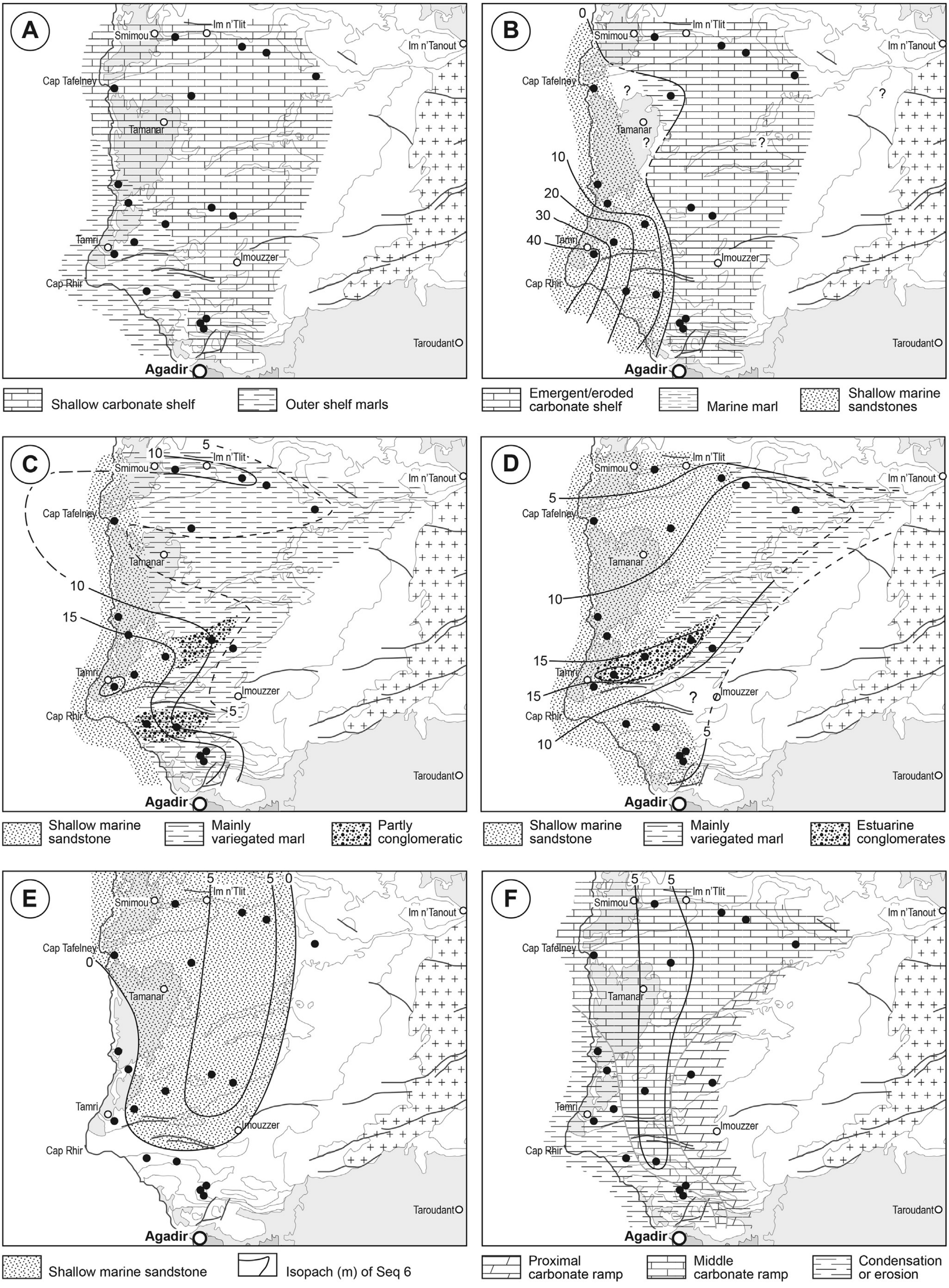

Figure 13. Paleogeographic sketches of the upper Barremian sedimentary sequences. A: Facies of Sequences 1 and 2. B: Facies and isopach map (in meter) of Sequence 3. C: Facies and isopach map of Sequence 4. D: Facies and isopach map of Sequence 5. D: Facies and isopach map of Sequence 6. F: Facies and isopach map of Sequence 7.

Barremian and early Aptian times, which are marked by fine-grained sandstone (Sequence 6) and calcareous or marly deposits (Sequence 7) without any evidence of synsedimentary tectonic instability. Moreover, the eastern and northern areas were emergent and significantly eroded before deposition of Sequence 4, whereas part of them received sediments during the latest Barremian and early Aptian times (Sequences 6 and 7 in Smimou, Ida w Shayq), thus indicating that there were significantly uplifted before deposition of Sequence 4. Finally, a climate change marked by rapid rainfall increase may provoke rapid sedimentation accumulation due to strengthened transport capacity of streams. However, the occurrence of desiccation cracks, desiccation breccias and desert rose pseudomorphs in sequences 4 and 5 suggest that the climate was rather dry. Therefore, the occurrence of large-scale slumps, fluid escape structures, soft deformation, angular unconformities and very coarse-grained deposits are viewed in as evidence for an abrupt, significant and short-lived tectonic activity of late Barremian age.

In the Central High Atlas (Fig. 1), the Late Jurassic-Early Cretaceous, mainly subaerial deposits recorded a short marine ingression in the early Barremian (Charrière et al., 2005), followed by an important tectonic event, marked by basaltic flows (Frizon de Lamotte et al., 2009; Ben Salah et al., 2013; Michard et al., 2013) and deposition of thick, coarse-grained, upper Barremian-lower Aptian deposits (Haddoumi et al., 2008, 2010). Further north in the Middle Atlas, Bathonian-Callovian red beds are directly and unconformably overlain by Barremian conglomerates and marine Aptian deposits, which divide the Mesozoic sedimentation into two distinct tectonic-sedimentary cycles separated by a long-lasting hiatus (Charrière, 1996). Northeast of the EAB, Saddiqi et al. (2009) record an exhumation peak ~120 Ma (early Aptian) in the Rehamna and Jebilet massifs (Fig. 1), through paleogeographic and apatite fission-track analyses (see also Leprêtre et al., 2015). Therefore, the area uplifted in the late Barremian is most probably centered on the Rehamna and Jebilet massifs, and located between the EAB to the west and the Central High Atlas and Middle Atlas to the east, since the latter recorded the deposition of coarse-grained conglomerates of Late Berremian age. This uplifted area, therefore, corresponds to the NNE-trending West Moroccan Arch (WMA, Fig. 1), which is assumed to have been a positive topographic feature from the Early Jurassic through to Early Cretaceous times (Frizon de Lamotte et al., 2008). Frizon de Lamotte et al. (2009) interpreted the uplift of the WMA as the result of a thermal doming. Our observations, however, suggests that this uplift has been abrupt and short-lived, which is not consistent with the thermal-doming interpretation. The available observations rather support an abrupt fault-controlled uplift of the WMA, associated with the play of NE-trending faults within the EAB, which controlled the location of both the depocenters and the drainage pattern. More studies would be necessary to specify the nature of this tectonic event and the geometry of the resulting faults and structures, although this will be made difficult by the scarcity of upper Barremian outcrops in the eastern part of the EAB and by the usually late diagenesis of sandstone and clay that hampers preservation of brittle deformation.

7. Summary

- The coarse-grained, “upper Barremian-lower Aptian sandstone cliff” of the EAB Basin is late Barremian in age (late *sartousiana* to ≈ *giraudi* Zones).
- Late Barremian tectonic activity is evidenced by numerous sedimentary features: channelized coarse-grained conglomerates, large-scale fluid-escape structures and slumps, synsedimentary plastic faults, local angular unconformities and correlative significant erosions.
- The coarse-grained part of the upper Barremian massive sandstone appears to have been deposited during two depositional sequences, both being probably tectonically enhanced.
- The source area of the upper Barremian clastic deposits were mainly the crystalline basement of the High Atlas, which supplied huge volumes of siliciclastic material mainly deposited in a NE-trending depocenter that seems to be controlled by inherited faults.
- Because grossly coeval late Barremian tectonic events have been recognized in the Central High Atlas and in the Middle Atlas areas, the uplifted area most likely corresponds to the NNE-trending West Moroccan Arch, which recorded an exhumation phase at ≈ 120 Ma.

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