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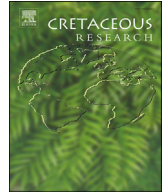
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Albian sedimentation in western Atlas, Morocco

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ABSTRACT

Detailed study of field sections and extensive ammonite collection allowed to specify the sedimentary evolution and age of the Albian series of the Western Atlas (Morocco). After a significant hiatus of earliest Albian age, the Albian transgression began in the late *Douvilleiceras leightonense* Zone with partly clastic deposits. A transgressive pulse gave way to clayey marl deposits (*Douvilleiceras mammillatum* Zone), which evolved upward to partly carbonate, laminated deposits of late early Albian to earliest middle Albian age (*Lyelliceras pseudolyelli* to early *Lyelliceras lyelli* zones). A major hiatus that encompassed most of the middle Albian, was followed by a new transgression marked first by sandy deposits (*Dipoloceras cristatum* and *Pervinquiria pricei* zones), and then by clayey marl and limestone nodules (*Pervinquiria inflata* Zone). A sharp sea level fall (late *Pervinquiria inflata* to early *Pervinquiria fallax* zones) led to the development of a shallow marine carbonate shelf (Kechoula Formation). A last transgressive pulse allowed deposition of outer shelf clayey marls (*Pervinquiria rostrata* to *Arrhaphoceras briacensis* (?) zones), interrupted near the Albian-Cenomanian boundary by a sea level fall and hiatus. Anoxic to disoxic conditions are recorded in the latest early Albian and the late Albian, which correlate with the Leenhardt and Breistroffer levels, respectively. Correlations with Albian successions in North Africa and southern Europe suggest a mainly eustatic origin for the most important sedimentary discontinuities, although the late Albian sea-level drop may be tectonically enhanced.

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1. Introduction

Albian times are marked by a major eustatic transgression and by a warm greenhouse climate, which will culminate in Cenomanian-Turonian times (Hancock and Kauffman, 1979; Hardenbol et al., 1998; Skelton, 2003; Haq, 2014). These conditions gave way to global anoxic events, in earliest Albian (OAE1b, Paquier event) and early late Albian times (OAE1c, Breistroffer event), as well as a less widespread anoxic period in the late early Albian (Leenhardt level) (e.g. Bornemann et al., 2005; Jenkyns, 2010; Sabatino et al., 2015). The equatorial Atlantic Ocean opened in early Albian times, which definitely separated Africa from South America (Moulin et al., 2010; Klingelhoefer et al., 2016; Dummann et al., 2023) and triggered syndepositional deformation in parts of Africa (Guiraud et al., 2005; Jaillard et al., 2013).

In large parts of the Tethys area, Albian deposits are dominantly made of monotonous marl deposits that make difficult the analysis of the sedimentary evolution, although the succession may be rich in ammonite fauna (Vocontian Basin, Rubino, 1989; Br  heret, 1995; Ferry et al., 2022). Moreover, the South-Tethyan margin is commonly marked by an endemic ammonite fauna (Latil, 2011; Latil and Jaillard, 2024) that hampers reliable correlation with the well-dated faunal succession of the North-Tethyan margin. The aim of this study is to refine the age of the Albian succession in Western Morocco through ammonite biostratigraphy, to decipher the sedimentary evolution of the Albian series, and to propose correlation of the sedimentary evolution with other Tethyan areas.

2. Geological context

2.1. Geological setting

The High Atlas chain is an ENE-trending mountain belt that crosses the whole Morocco country and extends to Algeria and Tunisia. The Western Atlas of Morocco is located between the

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Essaouira plain and Jebilet Paleozoic Massif to the Northeast, the High Atlas Paleozoic basement to the East and Southeast, and the Souss plain to the South (Frizon de Lamotte et al., 2008). It presents a complete Cretaceous succession that crops out widely between Essaouira, Agadir and Imi n'Tanout, forming the Essaouira-Agadir Basin (EAB; Fig. 1). Geologically, these deposits belong to the present-day passive margin of Central Atlantic, the evolution of which began in the late Permian with the Tethyan rifting (Zühlke et al., 2004; Hafid et al., 2008; Schettino and Turco, 2009). Following the opening of the Tethys (pre-Pliensbachian unconformity; Hafid, 2000), an extensional tectonic regime prevailed during the Jurassic and early Cretaceous. Marine, carbonate and marl deposition took place, interrupted by a middle to late Jurassic emergence period (Stets, 1992). Clastic input occurred sporadically during the Early Cretaceous (late Hauterivian, late Barremian; Canérot et al., 1986; Rey et al., 1986a, 1986b, 1988; Witam, 1998; Jaillard et al., 2019a). Albian to Coniacian times were marked by a mainly marly sedimentation, intercalated with carbonate shelf deposits (late Albian, Turonian, Coniacian p.p.; Ambroggi, 1963; Andreu, 1989; Bourgeois et al., 2002; Ettachfani et al., 2005; Jati et al., 2010; Essafroui et al., 2015). Clastic deposits during the Campanian (Algouti et al., 1999) indicate a tectonic instability, documented farther East by the folding of latest Cretaceous strata, sealed by Eocene deposits (Laville et al., 1977; Froitzheim et al., 1988; Guiraud and Bosworth, 1997; Frizon de Lamotte et al., 2008, 2011). This deformation preluded to the Atlas orogeny that culminated in Eocene and Miocene times (Frizon de Lamotte et al., 2011).

2.2. Previous works

After pioneer works by Gentil (1905) and Roch (1930), who studied the Albian section of Jebel Tiskatine, Ambroggi (1963) first proposed detailed sections of the Albian series of the EAB. He

distinguished (1) green marls and yellow sandstone (“grès chamois”) with numerous specimens of the genera *Hypacanthoplites* and *Beudanticeras* ascribed to the early Albian, (2) green clayey marls with quite scarce ammonites (*Knemiceras* and *Oxytropidoceras*) attributed to the middle Albian, and (3) marls and massive oyster-rich limestone beds containing scarce *Hysterocheras* and *Deiradoceras*, of late Albian, “pre-Vraconnian” age (Fig. 2). Then, Duffaud et al. (1966) subdivided the Albian succession into the Albian Oued Tidzi Formation (Fm) mainly made of marls, and the dolomitic limestones of the Kechoula Fm of “Vraconnian” (latest Albian) age. The latter is overlain by the Aît Lamine Fm, a thick series of marls ascribed to the Cenomanian (Duffaud et al., 1966) (Fig. 2). Wiedmann et al. (1978, 1982) proposed a little detailed, synthetic section of the whole Cretaceous series of the Agadir area, and mentioned altogether *Hysterocheras orbigny*, *Pervinqueria* (*P.*) *fallax*, *Paraturrilites* (*B.*) *bergeri* and *Stoliczkaia dispar*, at the top of the Kechoula Fm. Rey et al. (1986a, 1986b, 1988) were the first to study the northern and eastern parts of the EAB. They mentioned *Hypacanthoplites* gr. *jacobi*, “*Beudanticeras*” *dupinianum* var. *africana* and *Oxytropidoceras roissyanum* in the Oued Tidzi Fm, considered latest Aptian to middle Albian in age. Ettachfani (1992) proposed the first detailed biostratigraphic and sedimentological analysis of the late Albian-Turonian interval. He confirmed the late Albian age of the Kechoula Fm, and ascribed the lower part of the overlying Aît Lamine Fm to the late Albian-early Cenomanian.

More recently, Lubet et al. (2017, 2019), Jaillard et al. (2019b) and Giraud et al. (2020) identified the Aptian-Albian boundary as a major discontinuity, and dated the 20 to 50-thick overlying “grès chamois” of Ambroggi (1963) as belonging to the late *Douvilleiceras leightonense* and early *Douvilleiceras mammillatum* ammonite zones (earliest to early Albian; Szives et al., 2023). While studying the Cenomanian sedimentation along the Moroccan margin, Essafroui et al. (2015) mentioned *Mortonicerases* sp., “indicative of the Fallax to

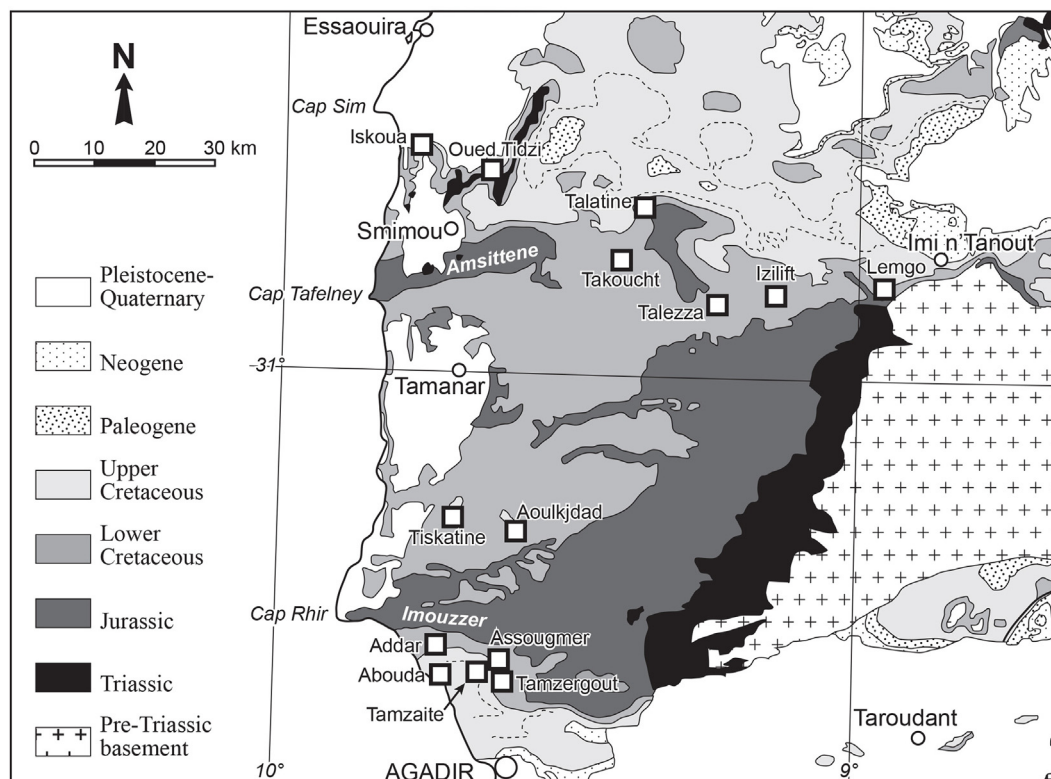


Fig. 1. Geological sketch of the Essaouira-Agadir Basin, and location of the studied sections.

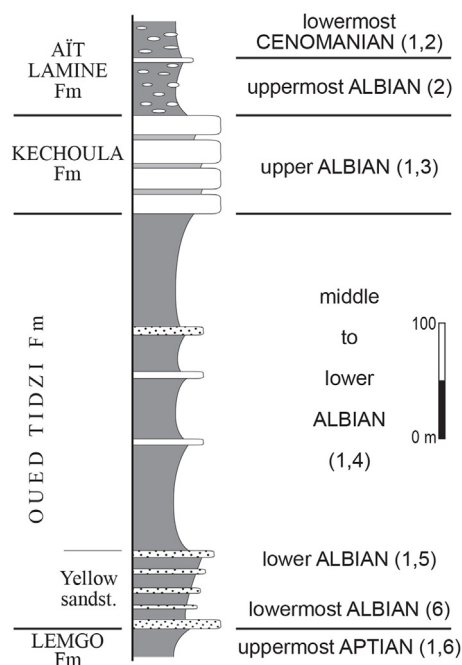


Fig. 2. Simplified Albian series of the EAB, according to previous works. (1) Ambroggi (1963); Duffaud et al. (1966). (2) Essafroui et al. (2015); Gale et al. (2020; 2021). (3) Wiedmann et al. (1978; 1982); Ettachfni (1992). (4) Wiedmann et al. (1978; 1982); Rey et al. (1986a; 1986b; 1988). (5) Jaillard et al. (2019b); Giraud et al. (2020). (6) Luber et al. (2017; 2019); Jaillard et al. (2019b); Giraud et al. (2020).

Rostratum zones" (late Albian), just above what seems to be the top of the Kechoula Fm. Finally, North of Agadir, Gale et al. (2020, 2021) identified precisely the Albian-Cenomanian boundary a few tens of metres above the Kechoula Fm, by the first occurrence of *Thalmaninella globotruncanoides*, and with the finding, from base to top, of the ammonites *Pervinquieria (S.) rostrata*, *Pervinquieria (S.) perinflata* and *Stoliczkaia (S.) clavigera* of latest Albian age, and of *Graysonites adkinsi* and *Mariella oehlerti sulcata*, of earliest Cenomanian age (Fig. 2). This biostratigraphic boundary roughly coincides with an important discontinuity marked by hard-grounds and bored surfaces (Gale et al., 2020, 2021; see also Ettachfni, 1992). Finally, Maatouf et al. (2020) provided a paleoenvironmental glimpse of the late Aptian-early Cenomanian environments, based on dinoflagellate cysts assemblages.

In this work, we present a detailed study of the poorly known Oued Tidzi Fm of the western part of the EAB, which had never been studied from a sedimentological point of view, and an overview of the Kechoula and lower Ait Lamine Fms. Thanks to significant ammonite findings, a reasonably precise chronological framework has been established. This, together with the identification of sedimentary discontinuities and facies evolution, allowed to refine the sedimentary evolution of the EAB, and to propose correlations and comparisons with other parts of the Tethyan realm.

The Albian series of the EAB can be subdivided into several units of highly variable thickness, from base to top:

- (1) a 30–60 m-thick, thickening-upward succession of green marl and yellow sandstone ("grès chamois" of Ambroggi, 1963),
- (2) 60–180 m of green to dark marls that ends up with thickening upward series of white, laminated micritic limestone,
- (3) 50–70 m of dark marls, intercalated with thickening upward sandstone beds,
- (4) 20–80 m of green-blue marl with nodular, laminated limestone interbeds,

- (5) 0–130 m of massive limestone or dolomite beds (Kechoula Fm),
- (6) 0–50 m of green marl with nodular limestone beds.

Units 1 to 4 constitute the Oued Tidzi Fm, Unit 5 corresponds to the Kechoula Fm of late Albian age, whereas Unit 6 corresponds to the base of the Ait Lamine Fm, dated as latest Albian (Essafroui et al., 2015; Gale et al., 2021) (Fig. 2).

3. Material and method

Good exposures and easy accesses in the Western Atlas provide excellent conditions to study the Cretaceous succession. The Albian marl series is usually exposed on the slopes of moderately elevated jebels topped by massive, often collapsed limestones (Kechoula Fm). This makes difficult, however, the study of the overlying marls, except where strata dips are high. Because of the abundance of marl, the sedimentological study was mainly carried out in the field, through observation of lithology, sedimentary features, key surfaces, bioturbation, faunal assemblages, mineral content, and vertical and lateral facies evolutions. These observations were complemented by the study of scarce thin sections from samples collected in carbonate beds. Precise location of the studied sections is given in Table 1.

Previous workers did not mention numerous ammonites in the Albian series. During this work, we found several fossiliferous levels, mainly in carbonate or sandy layers of the lower part of the succession, and in the central and western areas of the EAB. The southern and eastern sections proved poorly fossiliferous. In this respect, the well-exposed southern slope of Jebel Tiskatine can be taken as the type section of the Albian series of the EAB, although the Talatine and Takoucht sections yielded useful fauna. Two beds proved to be especially fossiliferous, the Tks10 bed of the Tiskatine section rich in pyritic specimens, and the condensed bed OT4 of the Iskoua section quite rich in phosphatic ammonites, that had been already mentioned by Duffaud et al. (1966, footnote p. 9 and 10). Paleontological description of the ammonite fauna will be published later.

4. Results

4.1. Sedimentology and sequence stratigraphy

4.1.1. Key-surfaces

Although discontinuities can be classified into typical surfaces, they may combine various of the characteristics (e.g. karstified surface overlain by reworked clasts, reworking of phosphatic clasts, abrupt facies change marked by reworked clasts, etc).

Karstified surfaces. The top of carbonate beds can be caved, voids of irregular shape being infilled by the overlying, often clastic and reddish, sediments (Fig. 3A, B). The shape of the voids differs from that of boring or burrows in that karstic voids are usually larger and deeper and their shape is irregular. Since karstification is related to dissolution by meteoric water, karstified surfaces are interpreted as representing emergence surfaces.

Erosional surface, reworking. These surfaces can show either an irregular topography, showing channel and relief forms of various size, or exhibit truncation of the underlying strata (Fig. 3D). As for karstified surfaces, they are often overlain by clastic deposits containing clasts of the underlying, eroded material (Fig. 3C). These surfaces indicate erosion periods, i.e. an interruption of sedimentation. Depending on the associated sedimentary features, erosion can be interpreted as having taken place in subaerial or submarine environments.

Table 1
Location of sections.

	Base	Top
Abouda	30°34'29"N; 9°44'33"W	30°34'31"N; 9°44'20"W
Addar	30°35'47"N; 9°42'54"W	30°35'32"N; 9°42'42"W
Aoulkjedad	30°45'05"N; 9°36'03"W	30°46'34"N; 9°35'53"W
	30°46'46"N; 9°34'15"W	30°46'38"N; 9°34'57"W
Assougmer	30°35'14"N; 9°36'29"W	30°34'51"N; 9°36'35"W
	30°35'13"N; 9°38'30"W	30°34'56"N; 9°38'01"W
Iskoua	31°19'51"N; 9°45'47"W	31°19'59"N; 9°45'50"W
Izilift	31°06'04"N; 9°08'16"W	31°06'34"N; 9°07'52"W
Lemgo	31°67'58"N; 8°56'40"W	31°08'20"N; 8°56'44"W
Oued Tidzi	31°17'02"N; 9°40'04"W	31°16'38"N; 9°39'49"W
Takoucht	31°09'57"N; 9°24'30"W	31°10'17"N; 9°24'30"W
	31°11'14"N; 9°26'14"W	31°11'26"N; 9°26'27"W
Talatine	31°15'21"N; 9°22'16"W	31°15'44"N; 9°22'29"W
Taleza	31°05'24"N; 9°15'17"W	31°05'50"N; 9°15'15"W
Tamzaite	30°34'37"N; 9°36'57"W	30°34'26"N; 9°35'05"W
Tamzergout	30°32'40"N; 9°34'06"W	30°32'37"N; 9°34'35"W
Tiskatine	30°46'44"N; 9°43'02"W	30°47'30"N; 9°42'17"W
TkS10 outcrop	30°46'54"N; 9°42'11"W	

Incised valley. A spectacular example is visible on a secondary jebel, south of Jebel Tiskatine (Fig. 3E). There, two lens-shaped layers of conglomerate and sandstone form a tabular promontory, and wedge out on either side of the latter, forming a bowl-shaped depression, interpreted as an incised valley. As a matter of fact, it is infilled first by a coarse-grained conglomerate containing mainly carbonate tube fragments, interpreted as broken sleeves precipitated around roots, coming from a reworked mangrove paleosol (Fig. 3F), then by marl, and finally by a finer-grained conglomerate. This 5 m thick succession is interpreted as made of two para-sequences of estuarine environment, emphasizing the transgression that follows an emergence and erosion period. Note that, where these lens-shaped strata are not visible, like in the southern slope of Jebel Tiskatine, no discontinuity can be detected.

Abrupt facies change. This kind of surface presents variable aspects. The most frequent are, on the one hand, the abrupt contact between outer shelf to hemipelagic marl, and overlying oyster-rich, or bioclastic, coarse-grained massive limestone. In case of Fig. 3B, karstified nodular outer shelf limestone are abruptly overlain by coarse-grained bioclastic limestone of nearshore environment. This facies change, from deep to shallow, is interpreted as related to a rapid fall of sea-level. On the other hand, marly sediments can also overly massive, usually thickening-upward limestone or sandstone beds (Fig. 3K). In this case, the top of the last massive bed is often marked by a hard-ground and by fossil concentration. The interpretation is that of a rapid transgression, after a period of progradation.

Hard-grounds and perforations. Firm grounds can be expressed in different ways. In some cases, a mineralized, often iron-rich crust (Fig. 3G) may coat the top of a massive bed. This means that a significant submarine hiatus occurred, which permitted the mineralization of the top of the bed. In other cases, the already lithified top of a bed is bored by lithophagous bivalves (Fig. 3H). This suggests that boring occurred after the diagenesis of the bed, i.e. after a sedimentary hiatus. Since boring organisms generally live in very shallow to intertidal environments, this surface may also represent an emergence period, boring occurring at the beginning of the subsequent transgression. Bored surfaces are mainly found in the late Albian shelf carbonate (Kechoula Fm).

Phosphatic crust and clasts. In the western part of the EAB, phosphate concentration during sedimentary hiatuses is frequent. Phosphate is often associated with glauconite. Phosphate may form dismembered crust, yielding locally numerous phosphatized fossils, among which ammonites (Fig. 3J), or may have phosphatized

carbonate clasts reworked at the base of the overlying bed (Fig. 3I). Beside special marine biochemical conditions, phosphate precipitation requires times; phosphate concentration is, therefore, interpreted as representing a submarine sedimentary hiatus or a period of condensation.

Onlap and toplap geometries. In special outcrop conditions, beds may be truncated below the overlying erosional surface, presenting a toplap pattern (Fig. 3D), or wedge out against the underlying surface, thus showing an onlap geometry (Fig. 3L). In Fig. 3M, onlapping beds are retrograding sandstone containing at their base reworked clasts from the underlying strata. In both cases, these geometric relations indicate a slight angular unconformity, and thus, a long-lasting sedimentary hiatus or a mild tilting related to differential subsidence or a tectonic event.

In this work, the main, correlatable discontinuity surfaces are labelled DAL 1 to DAL 11 and DCE1, thus defining 11 Albian sequences, named SAI 1 to SAI 11. Note that DAL 1 to DAL 4 of this work correspond to D4 to D7 defined in the lowermost Albian deposits by Jaillard et al. (2019b) and Giraud et al. (2020).

4.1.2. Depositional sequences

Depositional sequences of the studied sections are illustrated on Figs. 4–7.

SAI 1 to SAI 3 sequences (DAL 1 to DAL 4). These sequences have been described in previous works (Jaillard et al., 2019b; Giraud et al., 2020). They correspond to transgressive-regressive sequences deposited in proximal to distal ramp environments. DAL 1 to 4 are usually marked by an erosional surface overlain by dolomitic sandstone beds rich in phosphatized clasts and fossils. Transgressions are emphasized by sandstones rich in reworked litho- and bio-clasts and shallow marine fauna (oysters, annelids, locally corals ...), which grade upwards into thin-bedded sandstone and marl yielding deeper marine fauna (brachiopod, plicatulids, other bivalves, belemnites, ammonites). In the clayey middle part of the sequence, belemnites are dominant, associated with ammonites, plicatulids and brachiopods. The regressive part of the sequences is usually interrupted by the erosional surface of the overlying sequence boundary. As a whole, these three sequences display a thickening-upward evolution, reflecting an overall prograding and shallowing trend, well-marked in the Tiskatine and Tinfoul sections (Jaillard et al., 2019b). This succession corresponds to the “grès chamois” or “grès jaunes” (yellow sandstone) of Ambroggi (1963).

SAI 4 sequence (DAL 4 to DAL 5). These sequences are mainly made of green clayey marl with few sandstone interbeds. In almost all sections, SAI 4 is marked by green clayey marls. In some sections, thickening upward sandstone beds evidence a progradation in the upper part. The fauna is usually very rare, and consists mainly in annelids, fragments of oysters and plicatulids, and scarce ammonites. DAL 5 is clearly identified in the southwestern part of the EAB, either at the base of an incised valley indicating an emergence period (Tiskatine, Fig. 3E, F), or at the top of a slightly thickening upward sandstone succession (Tamzergout, Fig. 5), showing ripple marks, storm deposits and planar lamination of very shallow to shoreline environment.

SAI 5 sequence (DAL 5 to DAL 6). SAI 5 is mainly made of green clayey marl with few sandstone interbeds. In the western sections, (Tiskatine, Tamzergout, Talatine) carbonate nodules or beds are common. The upper part shows a thickening upward trend in clastic (centre) or carbonate (West) deposits (Figs. 4–6), expressing a shallowing upward evolution. Although lithology and fauna suggest an open marine, outer shelf environment, the depositional environment of the SAI 4 and SAI 5 sequences was not very deep, as shown by the very shallow marine to tidal deposits at the top of each sequence.

SAI 6 sequence (DAI 6 to DAI 7). DAI 6 is marked either by a karstified surface in the northern sections (Talatine, Takoucht, Fig. 6), or by an erosional surface at the top of a thin, thickening-upward succession (Figs. 4 and 5). SAI 6 is a rather thin, thickening-upward sequence, marked by nodular beds of white, laminated, micritic limestone with no visible fauna. The abundance of laminated, non-burrowed, non-fossiliferous micritic limestone suggests a low energy, disoxic to anoxic environment. Phosphate is more abundant to the West (Addar, Assougmer, Iskoua, Figs. 5, 6), suggesting that upwellings were active there, causing condensation. Conversely, sandstone is more common to the Northeast (Talatine, Takoucht, Fig. 6), thus indicating that clastic influx was provided by the High Atlas to the East. In the westernmost, external, section (Oued Tidzi, Fig. 6), no limestone or sandstone beds were observed, and discontinuity DAI 6 was not identified in the monotonous clayey succession, suggesting that the sequence boundary grades downdip to an elusive conformity within deeper-deposited marlstone. In some sections, minor discontinuities can be identified at the top of a massive sandstone bed that ends up a thickening-upward succession, or at the base of a massive sandstone bed marked by reworked, locally phosphatic clasts, and overlying karstified limestone beds.

SAI 7 sequence (DAI 7 to DAI 8). DAI 7 is a major surface marked by deep karsts and local phosphatisation, and by abundant reworked clasts and onlap geometries in the overlying sandstone beds (Fig. 3A, C, D, L, M). Overlying DAI 7, are three thickening-upward parasequences that end up with thick calcareous sandstone beds. The clayey lower parts of the parasequences contain rare outer shelf fauna (plicatulids, belemnites), while sandstone beds present shallow marine fauna (oysters, trigonids) and planar laminations. These features suggest that SAI 7 results from the progradation of a shallow marine clastic shelf system. The calcareous matrix of sandstones is more abundant in the southern sections.

SAI 8 sequence (DAI 8 to DAI 9). DAI 8 is usually marked by the abrupt contact between massive sandstones and outer shelf marls. In all studied sections, sequence SAI 8 is marked by green clayey marls with numerous nodular, white to yellow, laminated dolomitic limestone beds. Fauna is quite rare, and consists of scarce belemnites, plicatulids, annelids and isolated oysters, suggesting an outer shelf environment. In some sections, thickening- and thinning-upward trends can be detected, suggesting that parasequences exist within this sequence (e.g. Talatine, Takoucht, Tiskatine, Figs. 4 and 6). In some limestone beds, oblique laminations, ripples and Hummocky Cross Stratifications suggest that deposition occurred above the storm wave base. Although less micritic than the laminated limestone of SAI 7, the lack of bioturbation and scarcity of fauna suggest disoxic depositional conditions.

SAI 9 sequence (DAI 9 to DAI 10, Kechoula Fm). This sequence has not been studied in detail. Its base (DAI 9) is an erosional surface underlining an abrupt facies change, marked by oysters coquina, sandy biogenic limestone or massive bioclastic limestone beds that directly overly green marls and laminated carbonate nodules of SAI 8. This discontinuity is interpreted as resulting from a rapid sea level drop, which gave rise to the development of the Kechoula carbonate shelf. The abundance of tidal laminations, bored surfaces, desiccation features, oolithic beds and current figures indicates a very shallow marine environment (Figs. 5 and 6). On the other hand, limestone beds are interbedded with marl and locally sandstone, rich in oysters and other coquina, which suggests that, at least locally, the carbonate shelf deposited in mesotrophic conditions and received a noticeable terrigenous and nutrient influx.

SAI 10 and SAI 11 sequences (DAI 10 to DAI 11, Fig. 7). These sequences are thickening-upward successions of green marl and calcareous nodules. In Tamzaite (Fig. 7), SAI 9 ends up with very shallow marine to intertidal, oyster-rich limestone beds, which grade upward into nodular limestone beds rich in irregular urchins, of outer shelf environment, thus expressing a transgressive trend at the base of SAI 10. There, DAI 10 is marked by superimposed hardgrounds that cap nodular beds (Fig. 7). SAI 10 is then marked by clayey marl that grades upward into nodular limestone beds. The uppermost limestone bed shows tidal laminations, vertebrate remains and karstic caves (DAI 11) indicating an emergence period. Farther west, in Abouda, the succession is comparable, but the scarcity of limestone beds and nodules suggests a deeper depositional environment. SAI 11 is a thickening upward sequence of green clayey marl grading upward into nodular limestones, capped by calcareous nodules bearing well marked borings, indicating a sedimentary hiatus (Gale et al., 2020, 2021).

4.2. Biostratigraphy

Thanks to various ammonite findings, SAI 1 and the lower part of SAI 2 can be ascribed to the *Douvilleiceras leightonense* Zone (Szives et al., 2023) (former *Leymeriella tardefurcata* Zone earliest Albian; Giraud et al., 2020). According to Giraud et al. (2020), the upper part of SAI 2 and the whole SAI 3 sequence belong to the *Douvilleiceras mammillatum* Zone (early Albian). This is confirmed by the finding of *Tegoceras mosense* immediately above DAI 3 in Tiskatine (Fig. 8). In these deposits, Ambroggi and Breistroffer (1959) and Ambroggi (1963) mentioned *Beudanticeras revoili*, *Hypacanthoplites trivialis*, *H. gr. subelegans*, *Latidorsella latidorsata*, *Goretophylloceras (?) subalpinum* and *Puzosia provincialis*. The early Albian age of this assemblage is consistent with our data.

The SAI 4 sequence yielded *Parengonoceras* aff. *bussoni* at its base (Tamzergout, Tiskatine) and *Tegoceras* cf. *camatteanum*, *Roberticeras revoili* and *R. dupinianum* var. *africana* in its middle part (Takoucht). These indicate the upper part of the *Douvilleiceras mammillatum* Zone (Fig. 9). Note that *Roberticeras* replaced the name of *Beudanticeras* after revision of the latter genus by Latil et al. (2023).

The finding of *Parengonoceras* aff. *bussoni* in SAI 5 (Tiskatine) might indicate an age close to the base of the *L. pseudolyelli* Zone or Subzone (Latil, 2011; Szives et al., 2023) (Fig. 9).

In, SAI 6, the occurrence of *Oxytropidoceras* sp. (Tiskatine Est) and *Parengonoceras* sp. (Talatine) suggests a late early Albian to early middle Albian age.

DAI 7 yielded a phosphatized specimen of *Lyelliceras lyelli* (Tiskatine), which indicates the lower part of the middle Albian (Szives et al., 2023; Figs. 8, 9). Therefore, this major discontinuity can be correlated with a comparable surface identified in northeast Algeria and central Tunisia, which also contains *L. lyelli* (Masse and Thieuloy, 1979; Latil, 2011; Jaillard et al., 2021). In Tunisia, Robaszynski et al. (2012) found *L. lyelli* a few metres below this discontinuity, which indicates that an early middle Albian age for the top of the SAI 6 sequence cannot be ruled out, at least locally.

In the Tiskatine section, DAI 7 is immediately overlain by clayey marl that yielded a rich fauna of pyritic ammonites indicating undoubtedly the *Dipoloceras cristatum* Zone (base of late Albian). In the overlying marls and sandstones, *Pervinquieria* sp. (Addar), *Venezoliceras* cf. *bituberculatum* (Tiskatine), *Pervinquieria* cf. *pricei* (Tiskatine) and *Puzosia (Anapuzosia) hottingeri* (Talatine) indicate the *Dipoloceras cristatum* or *Pervinquieria pricei* zones, whereas the top of the SAI 7 sequence contains in Iskoua *Pervinquieria (Deiradoceras) cunningtoni* of the *Pervinquieria pricei* Zone (Figs. 8, 9).

In Iskoua, the phosphatic bed capping the DAI 8 contains, among others, *Pervinquieria* aff. *inflata*, *Pervinquieria (Deiradoceras)* sp., *Neophlyticeras* sp. and *Hypengonoceras chaberti*, which indicate the

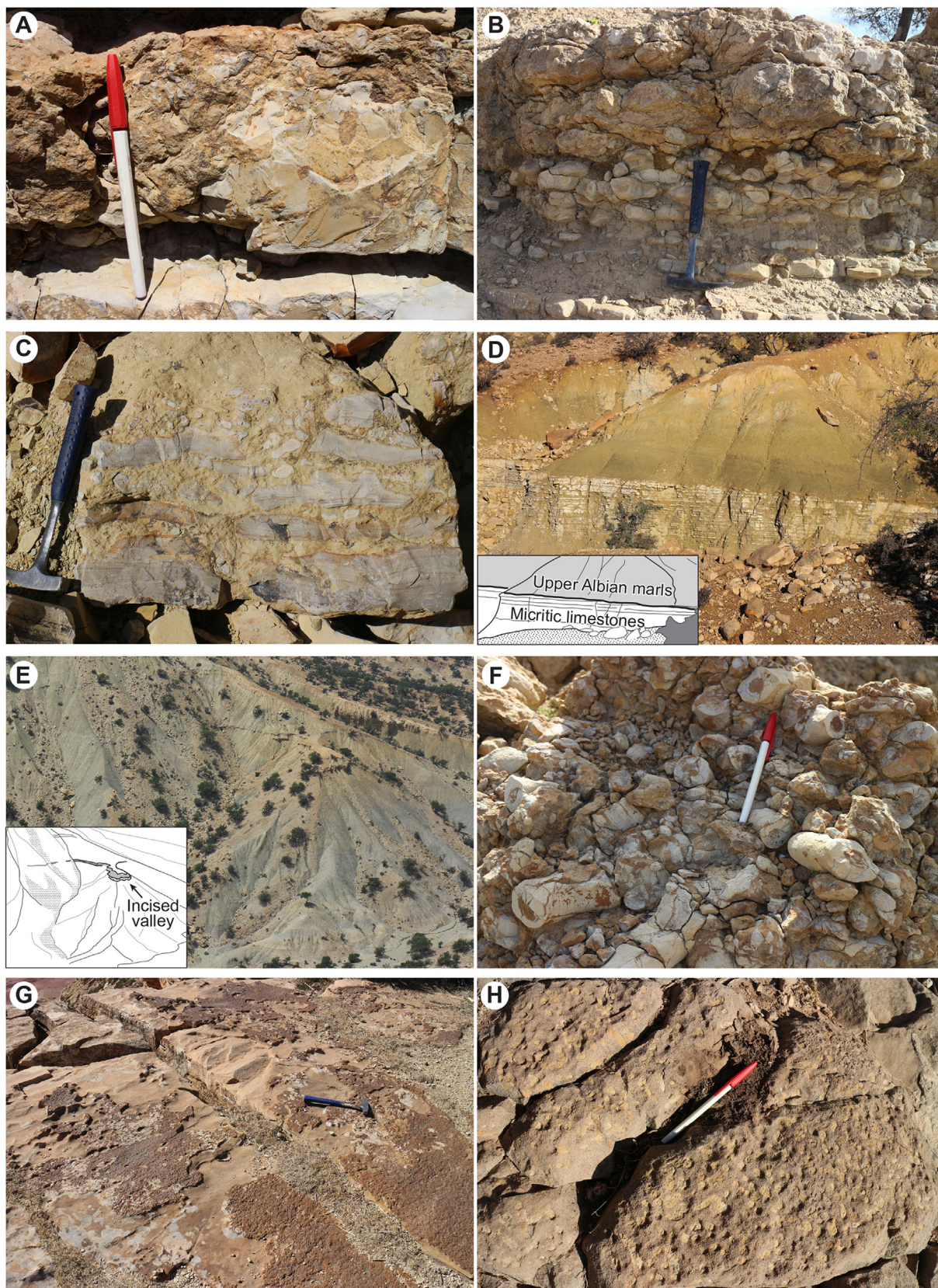


Fig. 3. Main types of discontinuity surfaces. **A.** Karstified limestone bed, Tiskatine, m 146. **B.** Karstified surface and abrupt facies change, Addar section, m 238. **C.** Reworked lithoclasts above a major erosional surface, Tiskatine section, m 146. **D.** Erosional truncation, Tiskatine setion, m 146. Erosion increases to the right (East). **E.** Infilling of an incised valley, forming promontory in a monotonous clayey succession, secondary jebel, south of Jebel Tiskatine, m 66. **F.** Conglomerate infilling the incised valley of picture E. All clasts are carbonate tubes interpreted as sleeves precipitated around mangrove roots. **G.** Iron-rich hard ground encrusting a limestone bed, Isk Izilift section, m 184. **H.** Bored limestone bed, Assougmer section, m 115. **J.** Phosphatic clasts reworked above an erosional surface, Assougmer section, m 5. **J.** The ledge on the right is a surface covered with phosphatic nodules and fossils, Iskoua section, m 28. **K.** Abrupt facies change, on top of a thickening-upward succession of yellow sandstone, Aoulkjdad section, m 0. **L.** Onlap geometry, Tiskatine section, m 146. The 1.5 m thick sandstone bed on the left disappears eastward (to the right) onto the major DAI 7 discontinuity surface. **M.** Erosional surface and transgressive sandstones retrograding to the East (right), Tiskatine section, m 146 (vertical scale $\times 2$).

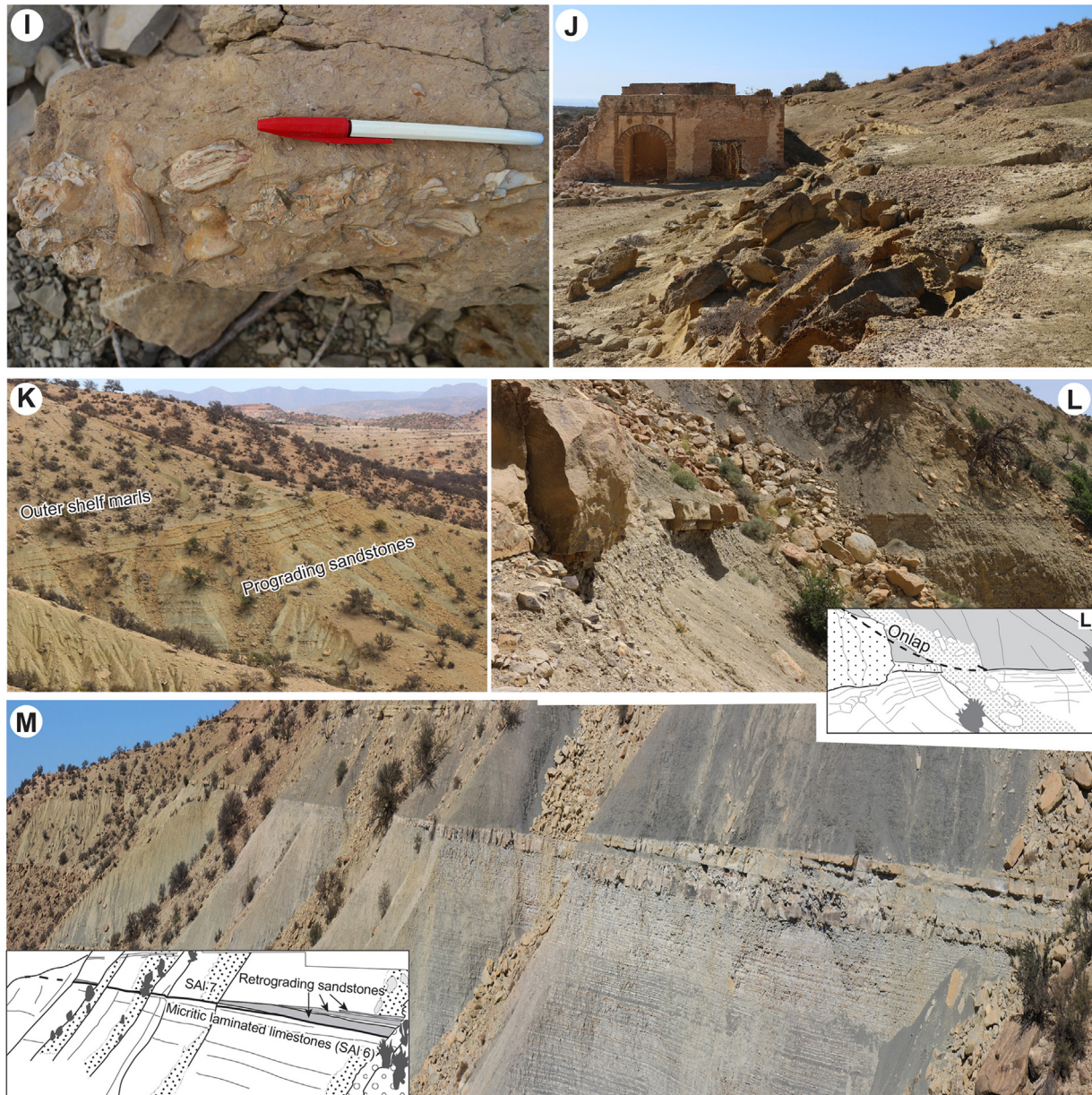


Fig. 3. (continued).

Pervinquieria inflata Zone, although reworked species from older strata (*P. pricei*, *Oxytropidoceras* spp., *Venezoliceras* spp.) are also present (Fig. 8). The base of SAI 8 yielded *Pervinquieria* sp. (Aoulkjdad) and *Hypengonoceras* sp. (Addar), which support this age.

In SAI 4 to SAI 8, Ambroggi and Breistroffer (1959, see also Ambroggi, 1963) collected *Oxytropidoceras* sp. gr. *mirapelianum*, *Knemiceras* sp. and *Pervinquieria* (*Deiradoceras*) sp., which indicate a middle to early late Albian age. The sample determined as *Knemiceras* sp. probably corresponds to a juvenile form of *Parengonoceras* sp.

At the base of the Kechoula Fm (SAI 9), Ambroggi (1963) mentions *Hysterocheras orbigny* of early late Albian age (Assougmer section). At the same level but from an undefined locality, Ambroggi and Breistroffer (1959) quoted *Protissotia madagascariensis*, indicative of the same age range. In Addar, we found

Pervinquieria cf. *inflata* (Figs. 8, 11), which indicates the eponymous zone (Szives et al., 2023) (Fig. 9).

According to Gale et al. (2021), SAI 10 comprises the *Pervinquieria rostrata* Zone and the lower part of the *Pervinquieria perinflata* Zone. In Abouda, we collected *Pervinquieria* sp. in SAI 10. The SAI 11 sequence would belong to the *Pervinquieria perinflata* Zone (and possibly the *Arrhaphoceras briacensis* Zone) of latest Albian age (Gale et al., 2021). The DCe 1 discontinuity (top of SAI 11) roughly corresponds to the Albian-Cenomanian boundary, since lower Cenomanian ammonites occur just above this surface, while the planktic foraminifera *Thalmaninella globotruncanoides* occurs immediately below DCe1 (Gale et al., 2021; Fig. 7). From “scarce limestone beds”, probably the Kechoula Fm (SAI 9), Wiedmann et al. (1982) mentioned “few ammonites”: *Stoczaika dispar*, *Paraturrilites* (*B.*) *bergeri*, *Pervinquieria* (*P.*) *fallax* and *Hysterocheras orbigny* of late Albian age (*Pervinquieria* (*P.*) *inflata* to *Pervinquieria*

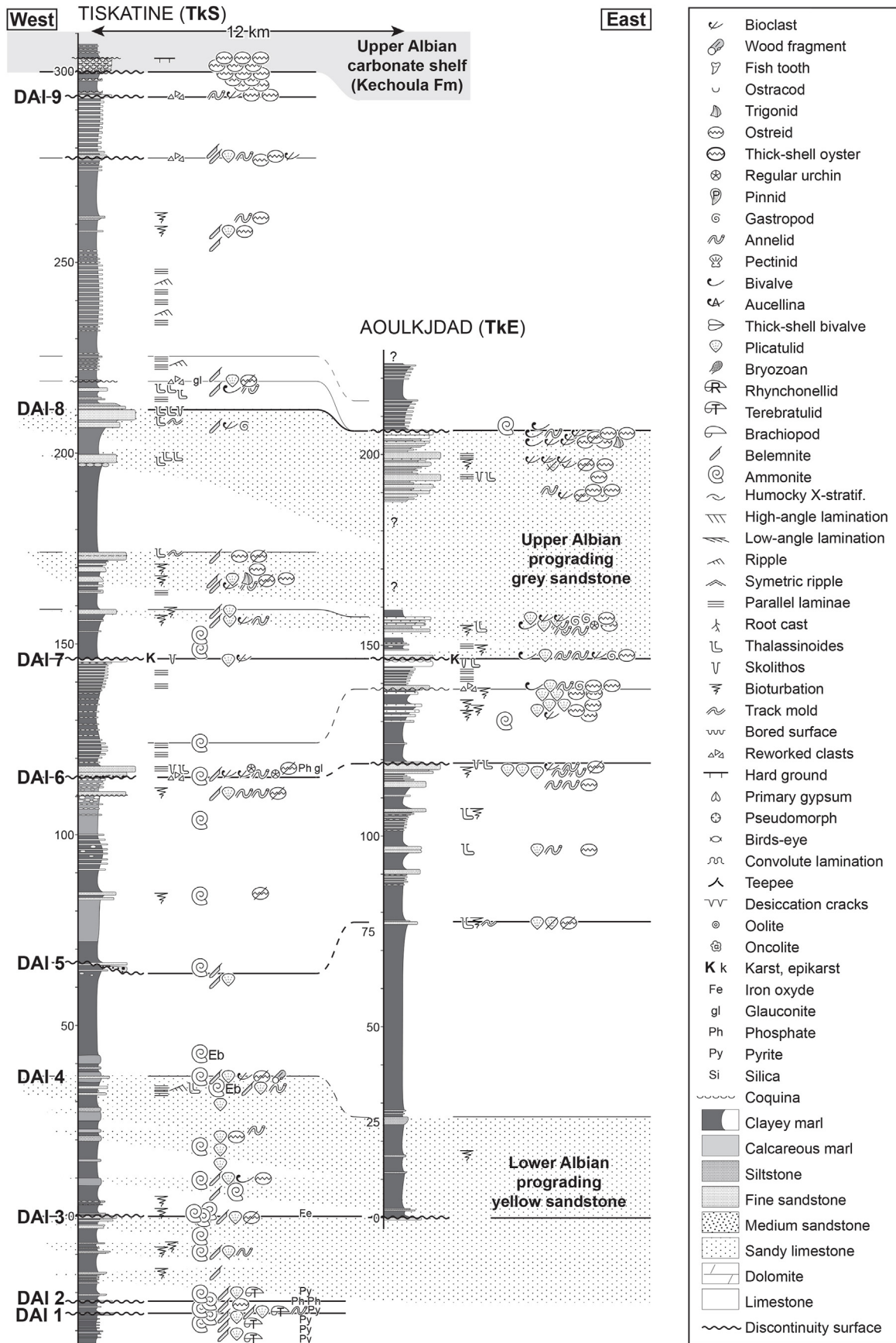


Fig. 4. Lithology and sedimentology of the Tiskatine and Aoulkjdad sections, central part of the Basin.

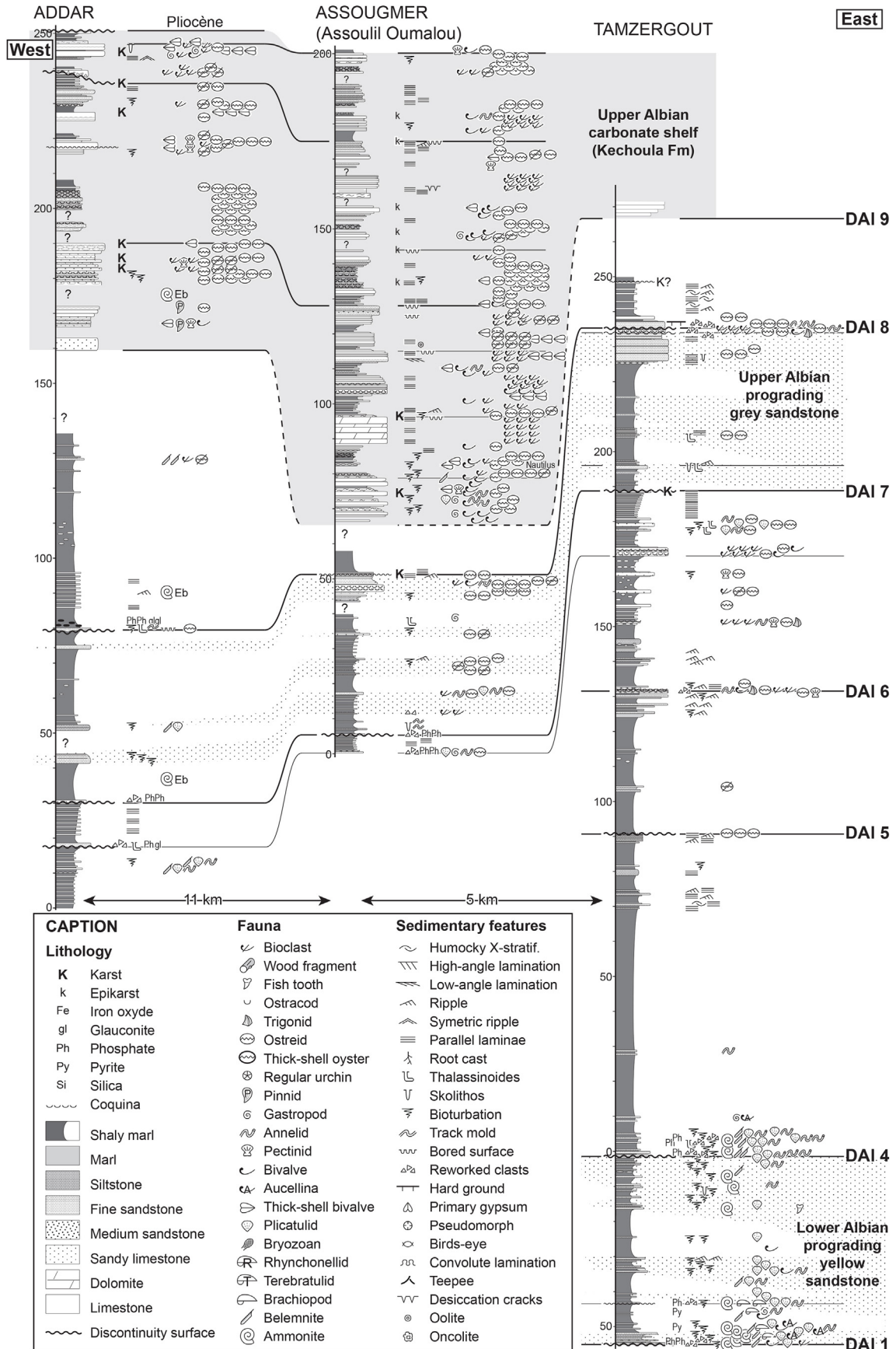


Fig. 5. Lithology and sedimentology of the Addar, Assougmer and Tamzergout sections, southern part of the Basin.

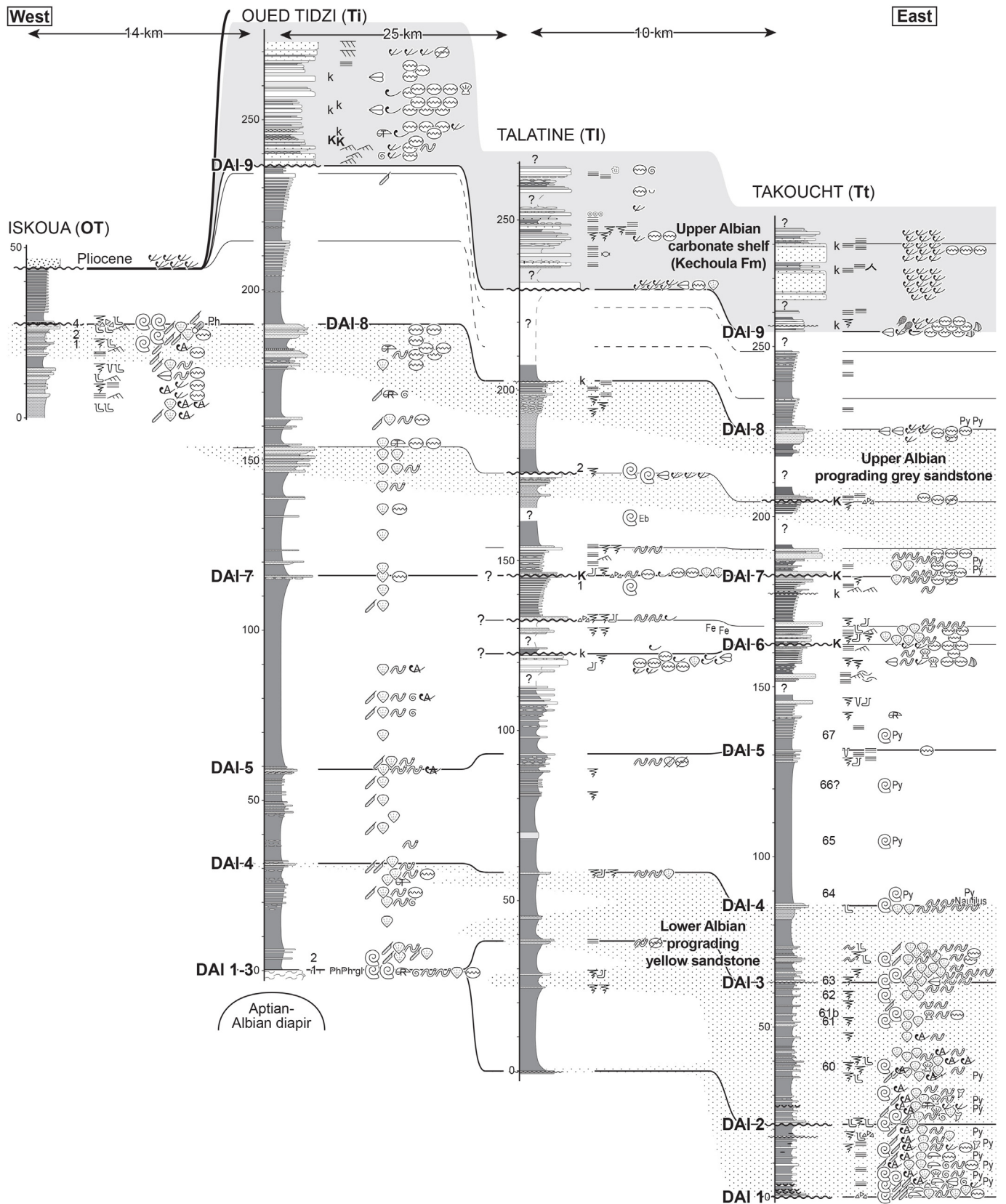


Fig. 6. Lithology and sedimentology of the Iskoua, Oued Tidzi, Talatine and Takoucht sections, north-western part of the Basin. Same caption as Fig. 5.

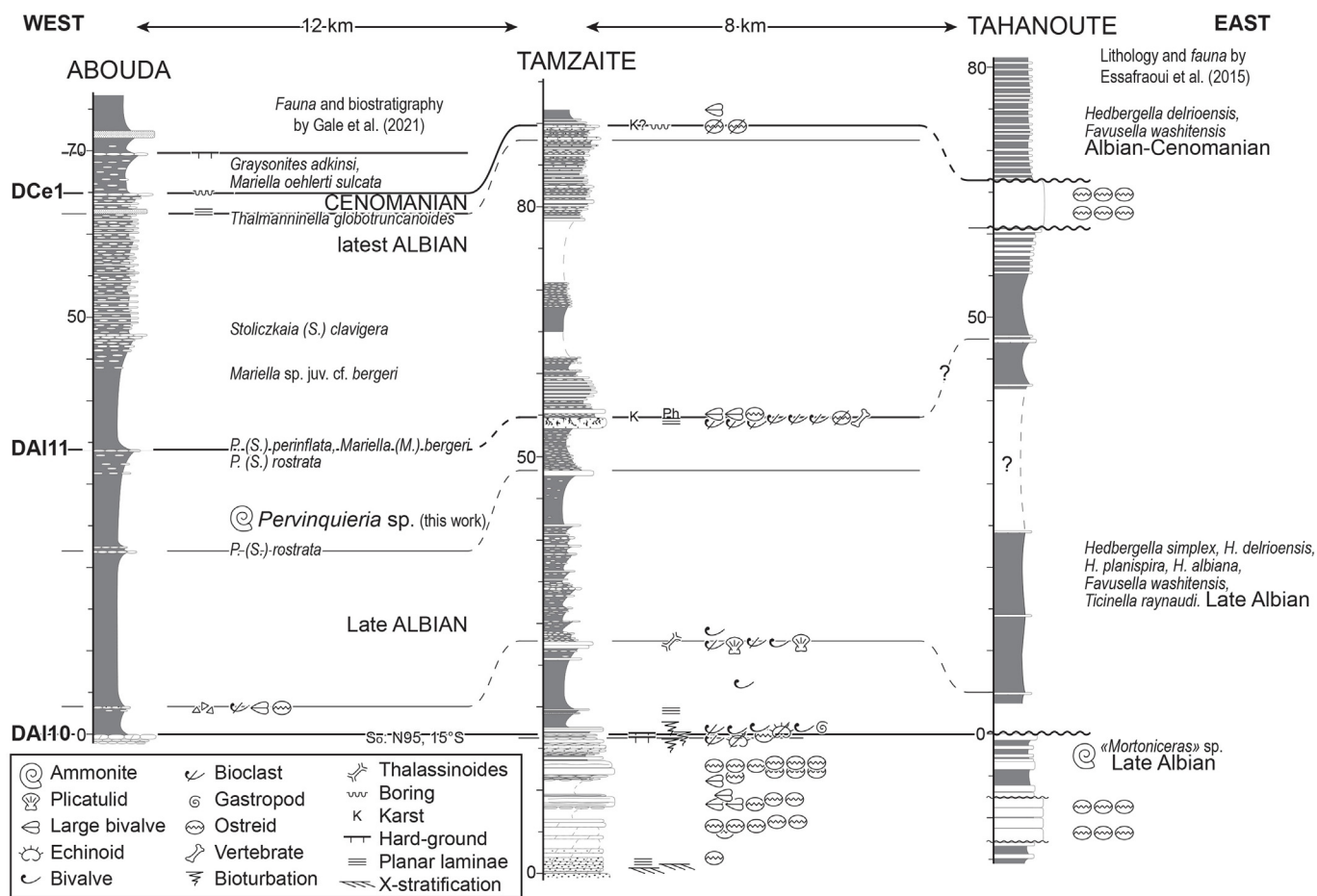


Fig. 7. Sedimentology and biostratigraphy of the Abouda (adapted from Gale et al., 2021), Tamzaite and Tahanoute (adapted from Essafroui et al., 2015) sections. Caption on Fig. 5.

(*Subschloenbachia*) *rostrata* zones). However, their little precise location in the lithologic succession makes difficult their biostratigraphic interpretation.

5. Correlation and comparison

5.1. Correlation with South-Tethyan areas

In the **Eastern part** of the **Essaouira-Agadir Basin**, the scarcity of diagnostic macrofauna and the rapid lateral variations make difficult correlation with the western part of the basin. Therefore, the proposed correlations are speculative and based mainly on lithological and sedimentological considerations, locally supported in the lower Albian, by few identifiable ammonites.

The earliest Albian sandstones (“grès chamois” of Ambroggi, 1963) are recognized at the base of easternmost sections (Fig. 10). In Lemgo, their base yielded *Mellegueiceras jaillardi* and a loose specimen of “*Hypacanthoplites*” cf. *buloti* (upper part of *D. leightonense* Zone, Latil, 2011), whereas we found *Roberticeras* sp. and *Paregonoceras* sp. in their upper part in Talezza. They may be correlated with our SAI 1 to SAI 3 sequences. The overlying succession mainly comprises marl, which may correlate with our SAI 6 sequence, since Rey et al. (1986a) mention “*Beudanticeras*” *dupinianum* var. *africana* at the base of the sequence in Lemgo; this species is common just below the *Lyelliceras pseudolyelli* subzone, and occasional at the base of this subzone in Tunisia (Latil, 2011). The major DAI 7 discontinuity (middle Albian) is tentatively placed

at the base of a limestone bed containing blocks of karstified white limestone (Talezza), or below a sandstone bed that contrasts with the underlying marl and limestone series (Isk Izilift, Lemgo, Fig. 10).

Above, the shallow marine, clastic SAI 7 sequence and the deeper marine SAI 8 sequence, are supposed to disappear eastward between Talezza and Isk Izilift (Fig. 10). Because of very high oyster content, the thin, overlying carbonate series is tentatively correlated with the shelf carbonates of the Kechoula Fm (SAI 9) of the western areas (Andreu, 1989). However, since the latter is of very shallow marine environment in the western EAB, it may have disappeared eastward; in this case the carbonated series would rather correlate with the deeper marine SAI 10 sequence. Because of the presence of white dolomitic nodules in Isk Izilift and Talezza, the overlying clayey marl series is correlated with the latest Albian, nodule-bearing marls (our SAI 10 and SAI 11). According to Andreu (1989), to Ettachfni et al. (1989) and to the geological map (Imi n'Tanout sheet, 1/100 000), the overlying, gypsum bearing, shallow marine carbonate shelf deposits are tentatively ascribed to the Cenomanian (Isk Izilift, Lemgo) (Fig. 10).

In the South **Riffian Ridges** of northern Morocco, only the late Albian transgression is recorded (Benzaggagh et al., 2017a). Overlying sandy and dolomitic transgressive deposits, fossiliferous marl and limestone of outer shelf environment yielded ammonites of the *Pervinquieria pricei* and *Pervinquieria inflata* ammonite zones (Benzaggagh et al., 2017a). Then, *Pervinquieria fallax* occurs below oolitic and tidal limestone beds that indicate a much shallower marine environment, which would correlate with SAI 9 of the EAB

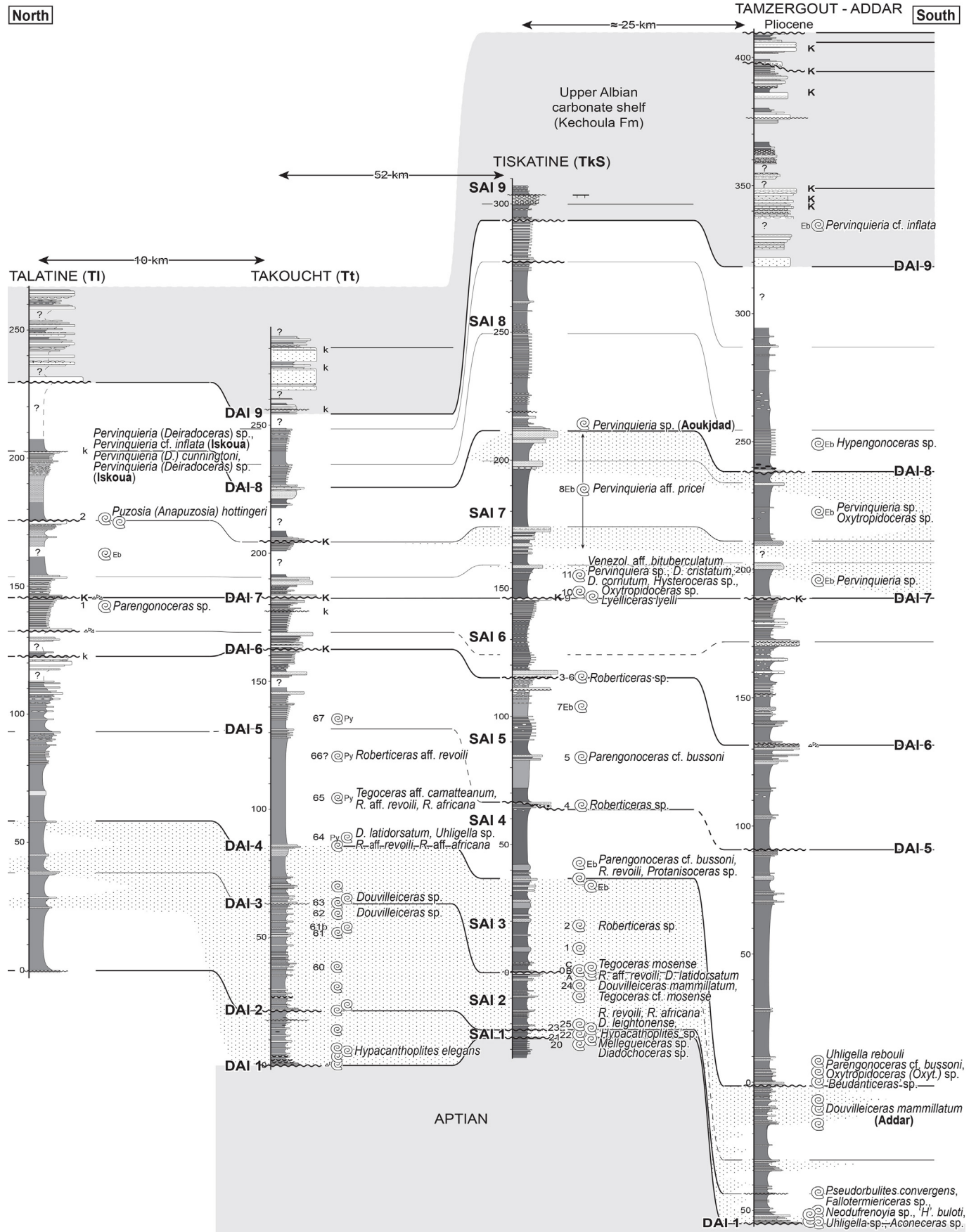


Fig. 8. Biostratigraphy and correlation of the Talatine, Takoucht, Tiskatine, and a composite southern section (Tamzergout between DAI 1 and DAI 8; Addar above DAI 8). Some ammonites collected in neighbouring sections are indicated.

AGE	MEDITERRANEAN (Szives et al., 2023)	MOROCCO	TUNISIA (Latil, 2011)
UPPER ALBIAN	CEN.	<i>Arrhaphoceras briacensis</i>	<i>Stoliczkaia (S.) africana</i>
	<i>Pervinquieria (S.) perinflata</i>		<i>Pervinquieria (S.) perinflata</i>
	<i>Pervinquieria (S.) rostrata</i>		<i>Pervinquieria (S.) rostrata</i>
	<i>Pervinquieria (P.) fallax</i>		<i>Pervinquieria (P.) fallax</i>
	<i>Pervinquieria (P.) inflata</i>		<i>Pervinquieria (P.) inflata</i>
	<i>Pervinquieria (P.) pricei</i>		<i>Pervinquieria (P.) pricei</i>
	<i>Dipoloceras cristatum</i>		<i>Dipoloceras cristatum</i>
MIDDLE ALBIAN	<i>Oxytropidoceras roissyannum</i>	<i>Oxytropidoceras (Mirapelia) sp.</i> <i>Oxytropidoceras (Oxytropidoceras) sp.</i>	?
	<i>Lyelliceras lyelli</i>	<i>Lyelliceras lyelli</i>	<i>Lyelliceras lyelli</i>
LOWER ALBIAN	<i>Lyelliceras pseudolyelli</i>		<i>Lyelliceras pseudolyelli</i>
	<i>Douvilleiceras mammillatum</i>	<i>Douvilleiceras mammillatum</i>	<i>Tegoceras camatteanum</i> <i>Bulotoceras radenaci</i> <i>Prolyelliceras gevreyi</i>
	<i>Douvilleiceras leightonense</i>	<i>Douvilleiceras leightonense</i>	<i>'Hypacanthoplites' buloti</i> <i>Mellegueiceras ouenzaensis</i>
	<i>Hypacanthoplites elegans</i>	<i>Hypacanthoplites elegans</i>	<i>'Hypacanthoplites' paucicostatus</i>
APT.	<i>Hypacanthoplites elegans</i>		<i>Mellegueiceras chihouaiae</i>

Fig. 9. Stratigraphic distribution of the main relevant ammonites mentioned in the text, following to standard (left) and local (right) zonation.

(base of Kechoula Fm). Overlying these beds are poorly dated marls (latest Albian, Cenomanian ?), overlain by Turonian massive limestones (Benzaggagh et al., 2017b).

In the **Middle and High Atlas** of Morocco, lagoonal to continental deposits are ascribed to the Albian or Albian-Cenomanian, without precise biostratigraphic constraints (Andreu, 1989; Ettachfni and Andreu, 2004; Charrière and Haddoumi, 2016; Haddoumi et al., 2019; Hadach et al., 2020; Adardor et al., 2021).

In **northern Central Tunisia**, the Albian transgression began with carbonate shelf deposits of earliest Albian age (Hameima Fm; Burolet, 1956; Chihaoui et al., 2010; Jaillard et al., 2021). A second transgressive pulse gave way to diachronous marls of outer shelf environment (Lower Fahdene Fm; Burolet, 1956; Chihaoui et al., 2010; Jaillard et al., 2021). The base of the latter yielded *Mellegueiceras jaillardi* and *Hypacanthoplites paucicostatus* (*H. paucicostatus* local Zone, Latil, 2011). The presence of *M. jaillardi*

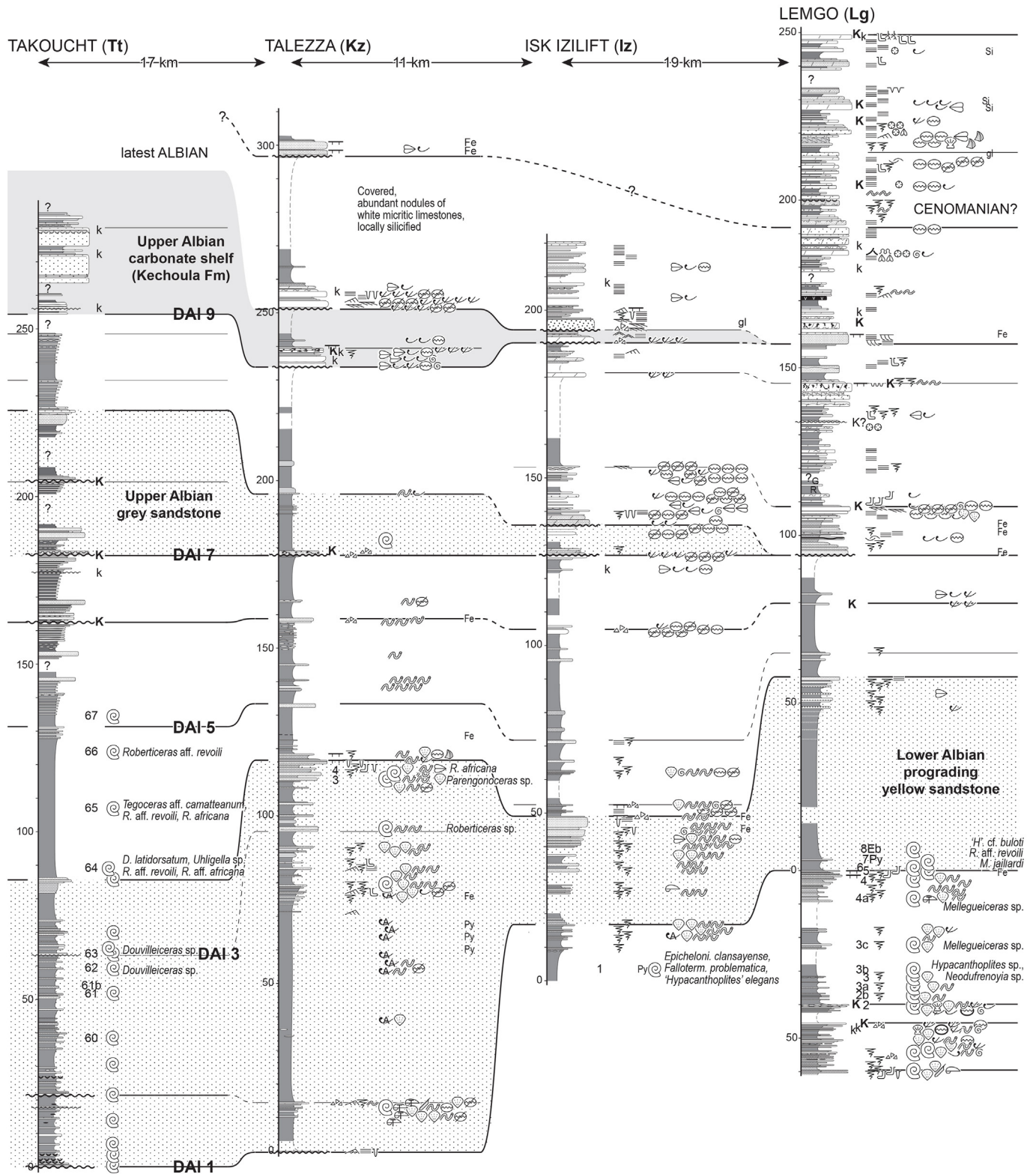


Fig. 10. Tentative correlation with the Eastern sections of the Essaouira-Agadir Basin.

and *H. paucicostatus* in SAI 1 (Tiskatine; see also [Giraud et al., 2020](#)) suggests a correlation with the transition between the lower part of the “Ammonite-rich horizon” (base of Fahdene Fm; [Fig. 11](#)). In the same way, the occurrence of *Douvilleiceras leightonense* and “*Hypacanthoplites*” *buloti* in SAI 2 evidence a correlation with the

upper part of the “Ammonite-rich horizon” (“*H. buloti* local Zone, upper part of *D. leightonense* Zone; [Latil, 2011](#)).

In SAI 3, the occurrence of *Douvilleiceras mammillatum*, *Tegoceras mosense* and *Prollyliceras gevreyi* (Takoucht) makes likely a correlation with the base of the Lower Shales of the Fahdene Fm of

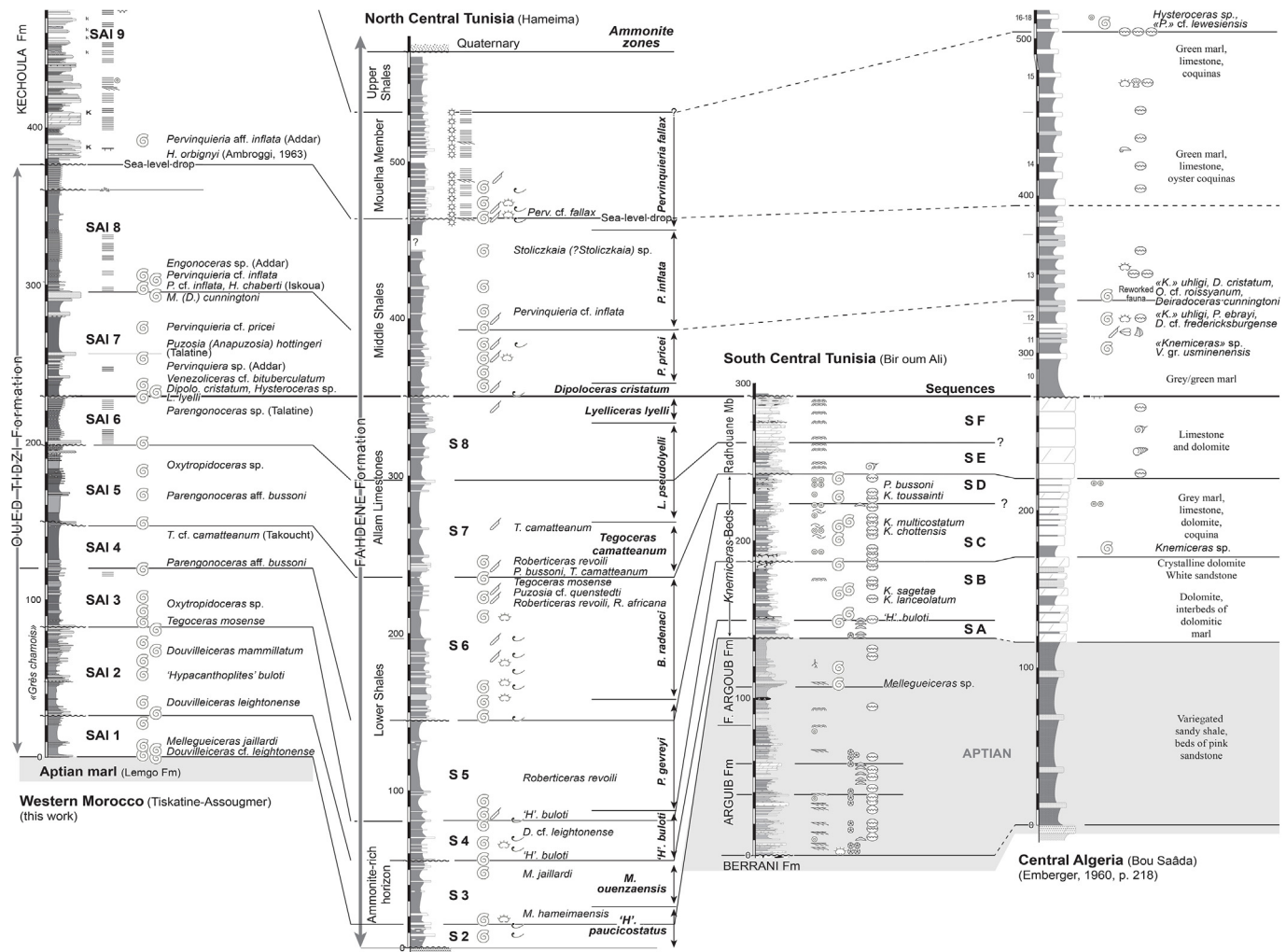


Fig. 11. Correlation between the studied area (Morocco), north central Tunisia (Jaillard et al., 2005, 2021; Chihaoui et al., 2010; Latil, 2011; Robaszynski et al., 2012), south central Tunisia (Jaillard et al., 2022; Latil and Jaillard, 2024) and Algeria (Bou Saâda area; Emberger, 1960). Only representative ammonites are mentioned.

Tunisia (Latil, 2011). The overlying sequence (SAI 4) is marked in Morocco by *Tegoceras cf. camatteanum*, which also occurs in Tunisia below the Allam limestones of Tunisia. The base of the latter yielded *Parengonoceras bussoni* (in jebel el Hamra, Latil, 2011), a close form of which occurs in our SAI 5 sequence. Therefore, we propose to correlate our SAI 4 sequence with the top of the Lower Shales, while our SAI 5 sequence would be equivalent with the lower part of the Allam Limestones (Fig. 11). The SAI 6 sequence lacks diagnostic fauna, and is correlated with the middle and upper part of the Allam Limestones, of latest early Albian (Latil, 2011) and early middle Albian age (Robaszynski et al., 2012). The major DAI 7 discontinuity is easily correlated with the major hiatus identified in Tunisia, which encompasses most of the middle Albian (Chihaoui et al., 2010; Latil, 2011; Jaillard et al., 2021).

Our SAI 7 sequence yielded *Dipoloceras cristatum* at the base, and *Pervinqueria cf. pricei* and *Pervinqueria (D.) cunningtoni* in its middle and upper parts, respectively. It is, therefore, correlated with the lower part of the Middle Shales of the Fahdene Fm of northern central Tunisia, which contains among others, *Venezoliceras sp.*, *Elobiceras sp.* and *Mortoniceras sp.* (Latil, 2011; Robaszynski et al., 2012). In the EAB, the overlying sequence (SAI 8) yielded *Pervinqueria cf. inflata*, which suggests it is coeval with the upper part of the Middle Shales of the Fahdene Fm that contains a

comparable fauna, although more abundant and diversified (Jaillard et al., 2005; Latil, unpubl.). DAI 8 roughly coincides with the boundary between the *Pervinqueria pricei* and *Pervinqueria inflata* zones. In Morocco, the base of the Kechoula Fm corresponds to a drastic decrease of the depositional depth, i.e. a significant sea level fall. The same is observed in Tunisia, where the Mouelha member of the Fahdene Fm presents numerous current features, indicating a much shallower marine environment than the underlying Middle Shales (Jaillard, et al., 2005). Since the Mouelha Fm yielded *Pervinqueria fallax* (Robaszynski et al., 2012; Latil, unpubl.), the Kechoula Fm of Morocco is probably of the same age. The SAI 10 and SAI 11 sequences of Morocco, are coeval with part of the Upper Shales of the Fahdene Fm of Tunisia, since they both contain *P. rostrata*, *P. perinflata* and *S. clavigera* (Jaillard et al., 2005; Robaszynski et al., 2012; Gale et al., 2020, 2021; Latil et al., 2021).

In southern Central Tunisia, the lower Albian series has been studied by Jaillard et al. (2022) and Latil and Jaillard (2024), who proposed correlations with northern Central Tunisia. Overlying the upper Aptian units (Arguib and Foul el Argoub Fms), the base of the "Knemiceras beds" yielded "*H.* buloti", which makes it coeval with SAI 3 of Morocco (Fig. 11). The occurrence of *P. bussoni* at the top of the "Knemiceras beds" allows a correlation with SAI 5. Therefore, the "Knemiceras beds" would correlate with SAI 3 and

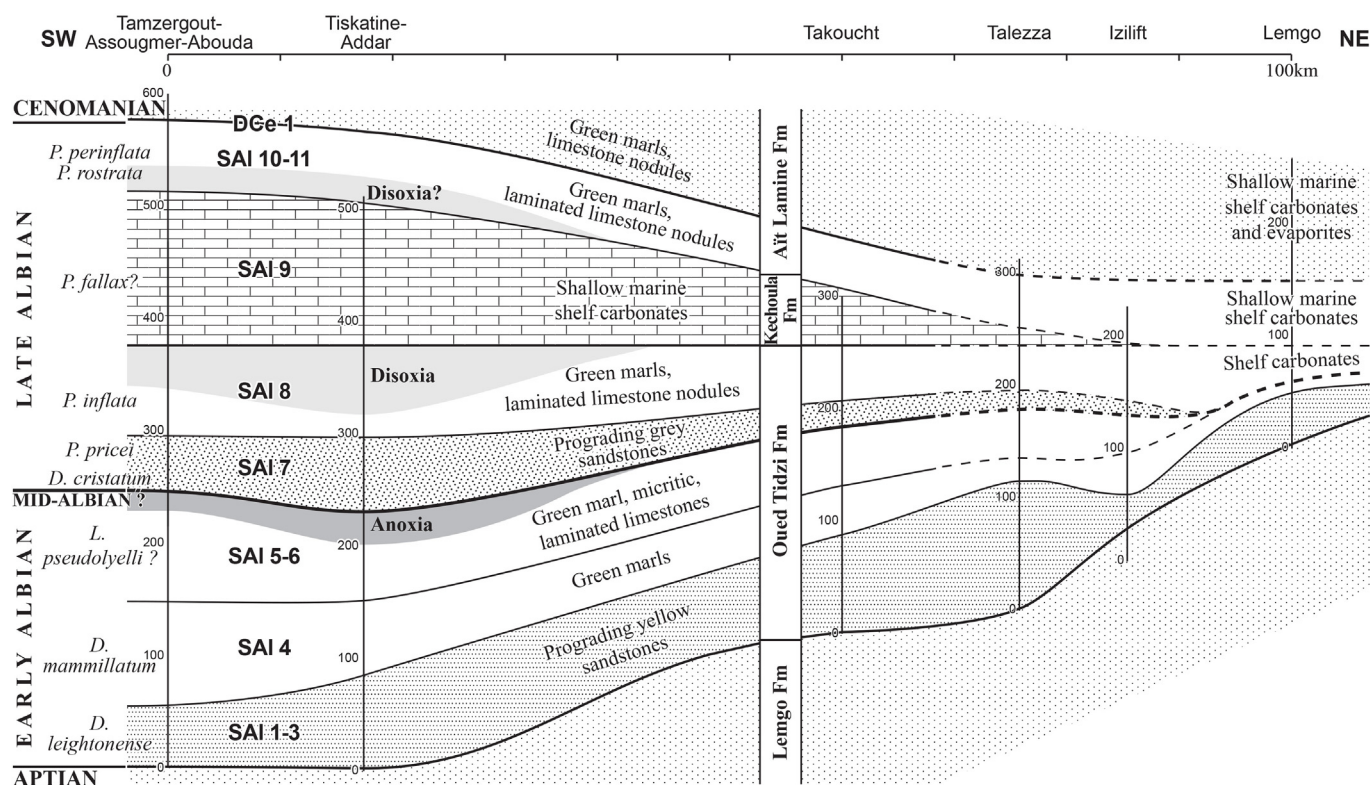


Fig. 12. Interpretative sketch of the Albian sedimentation across the Essaouira-Agadir Basin.

SAI 4. The overlying, restricted platform carbonates (Radhouane Mb) seems equivalent to the disoxic to anoxic Allam limestones of Tunisia and to the disoxic SAI 5 and SAI 6 sequences of Morocco.

In **Algeria** (Bou Saâda area), [Emberger \(1960\)](#) described an Albian section marked by variegated sandy shales at the base, overlain by dolomite and sandstone beds, comparable with the lower Albian succession of southern Central Tunisia ([Fig. 11](#)). The overlying marls and dolomites yielded a *Knemiceras* sp., and grade upward into massive limestone and dolomite, capped by a corroded and ferruginous surface, which we correlate with our DAI 7 major surface. As a matter of fact, overlying ammonites (*Diploceras fredericksburgense*, *Venezoliceras* gr. *usminensis*) indicate the *Diploceras cristatum* Zone (base of late Albian), as for the base of SAI 7 of the EAB. Higher up in the section, [Emberger \(1960; p. 218 to 220\)](#) mentioned a mixed fauna involving species of the *Diploceras cristatum* and *Pervinquieria pricei* zones ([Fig. 11](#)). This layer might, therefore, correspond to our DAI 8 discontinuity, where the same mixed fauna is observed (Iskoua). Further correlations are more speculative.

5.2. Correlation with the north Tethyan margin

The Aptian and Albian succession of the Vocontian Basin has been widely studied. Our DAI 1 can be correlated with the discontinuity identified in the latest Aptian or close to the Aptian-Albian boundary ([Fries and Rubino, 1988; Rubino, 1989; Bréhéret, 1995; Bréhéret and Brumsack, 2000; Joly and Delamette, 2008; Ferry et al., 2022](#)), which is also known in other parts of the world, as related to a drastic sea level drop (e.g., [Bulot and Ferry, 2007](#)). In SE France, a minor discontinuity is mentioned at the top of the Paquier level (top of *L. tardefurcata* Zone, [Bréhéret, 1995; Joly and Delamette, 2008](#)) locally marked by abundant baryte nodules ([Bréhéret and Brumsack, 2000](#)), which may correlate with our DAI 4

surface. The conspicuous discontinuity DAI 7 of Morocco corresponds to the $\Delta 8$ surface of [Bréhéret \(1995\)](#), who mentioned a change in the sedimentation and the absence of deposits in the shelf areas, thus indicating a marked sea level fall. The subsequent hiatus is identified in the Vocontian Basin (middle part of the middle Albian, [Rubino, 1989; Bréhéret and Brumsack, 2000; Joly and Delamette, 2008; Ferry et al., 2022](#)).

In the Vocontian Basin, the following discontinuity is placed close to the middle to late Albian boundary, and is followed by transgressive deposits ([Bréhéret, 1995; Bréhéret and Brumsack, 2000; Joly and Delamette, 2008](#)). This surface would correspond to our DAI 7, thus suggesting that in Morocco, the latter surface amalgamated various events of middle Albian age (see [Amédéo et al., 2023](#)). Another important surface is identified in SE France near the base of the *P. fallax* Zone ([Rubino, 1989; Ferry et al., 2022](#)), which corresponds to a marked reduction of depositional depth ([Bréhéret, 1995](#)). This surface bears the characteristics of the DAI 8 of the EAB, which underlines an abrupt contact of shelf carbonate above outer shelf marls.

Because of poor fossil record in the EAB, the latest Albian discontinuities are more difficult to correlate. The Moroccan DAI 10 surface may correspond to the discontinuity placed close to the *Pervinquieria fallax*-*Pervinquieria rostrata* boundary in SE France ([Rubino, 1989; Bréhéret, 1995; Joly and Delamette, 2008](#)), which marks an increase of the depositional depth ($\Delta 12$ of [Bréhéret, 1995](#)). The last Albian sedimentary discontinuity identified in the Vocontian Basin followed a progradation period; it occurred close to the Albian-Cenomanian boundary ([Rubino, 1989; Bréhéret, 1995; Bréhéret and Brumsack, 2000; Joly and Delamette, 2008](#)) and may correlate with our DCE 1 ([Gale et al., 2020, 2021](#)).

Farther North, in a platform domain (Jura of France and Switzerland), [Pictet et al. \(2019\)](#) also quote major discontinuities close to the Aptian-Albian boundary, in the middle Albian, close to

the base of the *P. fallax* Zone and at the Albian-Cenomanian boundary, which correlate with DAI 1, DAI 7, DAI 9 and DCE 1, respectively, of the EAB. In other parts of the north-Tethyan margin, the most conspicuous discontinuities are those of the Aptian-Albian boundary, of the middle Albian, of the *Pervinquieria inflata*-*Pervinquieria fallax* boundary, and of the Albian-Cenomanian boundary: Spalluto (2012) in Italy; Amédro et al. (2021, 2023) in the Paris Basin; López-Horgue et al. (2009), Poprawski et al. (2016) and Agirrezabala and López-Horgue (2017) in northern Spain; and Canérot and Médiavilla (2023) in the Pyrenees. In the two latter areas, the middle Albian discontinuity and hiatus are ascribed to a significant tectonic event (Poprawski et al., 2016; Agirrezabala and López-Horgue, 2017; Canérot and Médiavilla, 2023), as in Tunisia (Jaillard et al., 2013, 2021). However, no clear evidence of tectonic activity has been observed in the EAB.

6. General features of the Albian sedimentation in Western Morocco

6.1. Sea-level changes

The correlation of discontinuities presented above show that significant sea-level drops occurred in all mentioned areas close to the Aptian-Albian boundary, associated with a hiatus; in the early middle Albian marked by a regional hiatus; near the boundary between the *Pervinquieria inflata*-*Pervinquieria fallax* zones, which gave way to the development of a carbonate shelf (Kechoula Fm); and close to the Albian-Cenomanian boundary, marked by hardgrounds and bored surfaces (Gale et al., 2020, 2021), which indicate shallow marine conditions. This strongly suggests that these events are mainly related to eustatic variations. However, as mentioned before, the middle Albian hiatus may have been enhanced by tectonic events, as in Tunisia and Spain, although no clear tectonic features have been observed at that time in the EAB.

Some discontinuities identified in the EAB have not been correlated with other areas, probably due to the mainly clayey lithology. As a matter of fact, erosion related to emergence periods usually give way to erosion, followed by marine reworking during transgression. In good exposure conditions, reworking is marked by concentration of reworked fossils or clasts proceeding from the eroded sediments, or thanks to the infilling of channels or incised valleys. However, in case of unfossiliferous fine-grained sediments, clastic/fossiliferous lag may be not visible or covered by scree. Additionally, if channels of incised valleys are not exposed, discontinuity occurs between two clayey successions and cannot be identified, as illustrated in Fig. 3E. For this reason, lower Albian discontinuities could not be identified in the Oued Tidzi section (Fig. 6) or in some eastern sections of the EAB (Fig. 10).

The Albian evolution of the EAB is marked by three main periods of high relative sea level. The first one culminates in the early Albian (SAI 4, *Douvilleiceras mammillatum* Zone) and is followed by prograding anoxic/disoxic deposits. The second one is of early late Albian age (SAI 8, *Pervinquieria inflata* and possibly lower part of *Pervinquieria fallax* zones). The third period, of latest Albian age (SAI 10, *Pervinquieria rostrata* Zone), is interrupted by a significant sea level fall. This evolution appears comparable to that of the north-African and west-European areas described above. According to these interpretations, and in spite of poor biostratigraphic constraints for the eastern areas, we suppose that only the first and third of these transgressions reached the Lemgo section (Fig. 12). Correlatively, the shallow water deposits (SAI 6, SAI 7 and SAI 9) are assumed not to be recorded in the eastern sections (Fig. 12).

6.2. Synsedimentary tectonics

Few clear synsedimentary tectonic features have been observed in the Albian deposits. Actually, the predominance of marl deposits does not favour preservation of such structures. However, a mild angular unconformity is observed between SAI 6 and SAI 7 in Tiskatine (Fig. 3D, 3M), which may be related to mild tectonic movements. If so, the latter would be coeval with the middle Albian tectonic movements recorded in Tunisia (Jaillard et al., 2013). In other areas, previous workers mentioned slumps and synsedimentary normal faults in a poorly constrained “Barremo-Aptian” interval (Piqué et al., 1998), which might be roughly coeval with the early Albian opening of the Atlantic Ocean at equatorial latitude (Moulin et al., 2010; Dummann et al., 2023). Finally, Zühlke et al. (2004) mention breccias, arenites and ravinement at the base of the upper Albian Kechoula Fm (our SAI 9). In the sections studied in this work, the observed ravinement and erosional surfaces at the base of SAI 9 may be partly related to an abrupt fall of relative sea level. However, breccia levels and erosional channels have been observed at the base and in the lower part of the SAI 9 sequence in the southern sections (Addar and Anzate (west of Tamzergout section)). These features may additionally explain the significant erosion of SAI 8 in some southern sections (see Fig. 5). In this view, DAI 9 would be a tectonically enhanced discontinuity.

6.3. Paleoenvironment

Prograding sandy deposits are present at the base of the Albian (*Douvilleiceras leightonense* and lower part of *Douvilleiceras mammillatum* zones) and in the early late Albian (*Dipoloceras cristatum* and *Pervinquieria pricei* zones). In the first case, since sandstones are diluted westward (Fig. 6), the clastic input seems to originate from the East, i.e. from the High Atlas. In the second case, no massive sandstone deposits are known in the eastern sections, whereas they are still present in the westernmost sections. As a consequence, they might represent the distribution by longshore currents of clastic material deposited by a remote river or delta. Alternatively, the upper Albian sandstones may represent a shallow marine wedge that tapers eastward. In this case, they would represent lowstand deposits of the incipient, large-scale late Albian eustatic transgression. The second interpretation is favoured in this work (see Fig. 12).

Except in its upper part, the abundance of bioturbation, oysters and plicatulids suggests mesotrophic conditions during the early Albian. Because of the abundance of clay and sand deposits, nutrient would have proceeded from the continent. Comparable conditions prevailed during the early late Albian, dominated by sandy deposits. In spite of abundant clastic input, sedimentation seems to have been dominated by low to moderate energy conditions. As a matter of fact, dominant sedimentary features are planar laminations and small-scale current ripples, although bioturbation may have deleted other evidences.

6.4. Anoxia and disoxia

Anoxic or disoxic conditions are recorded during late early Albian times and during part of the late Albian (Fig. 12). Except in the eastern areas, the upper part of lower Albian deposits (SAI 6, *Lyelliceras pseudolyelli* subzone and part of *Lyelliceras lyelli* Zone) is marked by alternating marls and finely laminated micritic limestone beds, devoid of fauna and bioturbation, which suggest low energy, anoxic conditions (Figs. 4, 5, 6, 11). This interval would correlate with the Leenhardt level of the French Vocontian basin (Bréheret, 1995), and with organic-rich deposits known at the same

time in Tunisia (Allam limestone, [Burolet, 1956](#); [Khalifa et al., 2018](#); [Jaillard et al., 2021](#)) and in northwestern South America, such as the Villeta Fm in Colombia ([Blau et al., 1992](#); [Guerrero et al., 2021](#)) and the Pariatambo Fm in Peru ([Benavides, 1956](#); [Robert, 2002](#)). SAI 8 (\approx *Pervinquieria inflata* Zone) also presents thin beds of white laminated limestones in the western areas. However, scarce benthic fauna suggests disoxic conditions. Comparable facies is observed in the SAI 10 sequence (\approx *P. rostrata* Zone) and vanishes upward (Figs. 7 and 12). This time-interval (SAI 8 to SAI 10) corresponds to the OAE1d (Breistroffer event, [Bréhéret, 1995](#); [Bornemann et al., 2005](#)). In contrast, SAI 9 (\approx *P. fallax* Zone) is marked by shallow marine limestones including oolitic beds, shows moderate energy features and contains an abundant, yet little diversified fauna of oysters and other bivalves (Kechoula Fm). The fact that SAI 9 corresponds to period of low relative sea level suggests that in the EAB, the oxygen depleted water layer responsible for the Breistroffer event was located below the wave action base level.

7. Conclusion

New ammonite sampling along with detailed succession studies allowed to refine the stratigraphy of the Albian series of Western Morocco. The Albian transgression yielded ammonites of the late *Douvilleiceras leightonense* Zone, thus evidencing a long hiatus of earliest Albian age. After a progradation of late early Albian age, a major hiatus encompassed most of the middle Albian. The latter seems to be widespread in North Africa, since it has been recognized also in Algeria and Tunisia. Near the *Pervinquieria inflata*-*Pervinquieria fallax* boundary (middle late Albian), a sharp sea level fall gave way to the development of a shallow marine carbonate shelf. Latest Albian times (*Pervinquieria rostrata* Zone) are marked by a sea level rise, which is interrupted by a sea level fall near the Albian-Cenomanian boundary. The periods of highest sea level occurred in early Albian (*Douvilleiceras mammillatum* Zone), early late Albian (*Pervinquieria inflata* Zone) and latest Albian times (*Pervinquieria rostrata* Zone). Most of these events are known in the western Tethyan realm (North Africa, Western Europe), which suggest a eustatic origin. However, the mid-late Albian discontinuity may be tectonically enhanced.

Clastic deposits are observed in early Albian and early late Albian times. Detrital material is probably provided by the High Atlas region. Albian times seem to be marked by mesotrophic and low energy conditions in the EAB. However, anoxic deposits are recognized in late early Albian-earliest middle Albian times (*Lyellicerias pseudolyelli* subzone and *Lyellicerias lyelli* pars Zone), which correlate with comparable deposits in the South-Tethyan margin, from Tunisia to Peru, and in Southeast France (Leenhardt level). Disoxic deposits are also observed in mid-late Albian times (late *Pervinquieria inflata*- *Pervinquieria fallax* zones), which probably correspond to the Breistroffer event (OAE 1b).

CRedit authorship contribution statement

Etienne Jaillard: Conceptualization, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Emmanuel Robert:** Formal analysis, Writing – original draft. **Jean-Louis Latil:** Formal analysis, Writing – original draft, Writing – review & editing. **Moussa Masrou:** Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data were used for the research described in the article.

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