Stratigraphic framework and calcareous nannofossil productivity of the Essaouira–Agadir Basin (Morocco) during the Aptian–Early Albian: Comparison with the north-Tethyan margin

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ABSTRACT

In the southern Tethyan margin, the Essaouira–Agadir Basin (EAB), south of Morocco, exhibits well-exposed and fossiliferous sections of Aptian–Albian age. Biostratigraphy by ammonoids and sedimentological analysis have been realized for five sections located along an E-W transect in the EAB. The studied successions were dated from the latest Early Aptian to the Early Albian and are characterized by five major sedimentary discontinuities defining at least four main sedimentary sequences. The Late Aptian–Early Albian succession could be considered a gently westward-dipping ramp, marked by a deepening upward evolution. A quantitative study of calcareous nannofossils and calcium carbonate content has been performed on three of these sections. At this time, the EAB was located in the tropical-equatorial hot arid belt. The decrease in both calcium carbonate content and Nannococcus abundances at the Aptian–Albian transition could be the result of cooler climatic conditions recognized in the EAB, and/or of the associated increasing terrigenous input and nutrients, which hindered carbonate production. In the EAB, the nannofossil productivity is higher below the deposition of dark levels, which are coeval with the Niveau Paquier, recognized as the expression in southern France of the OAE 1b (Early Albian). During the Early Albian, the EAB was characterized by nannofossil fluxes two times lower than the upwelling-influenced Mazagan Plateau (southern Tethyan margin) and eight times lower than the Vocontian Basin (northern Tethyan margin). These results show that, with respect to the northern Tethyan margin, trophic conditions in sea surface waters of the pelagic realm of the southern Tethyan margin were lower. Comparable results obtained by Heldt et al. in the neritic realm of the southern Tethyan margin have been ascribed to more arid climatic conditions.

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1. Introduction

In terms of global changes, the Aptian–Early Albian time interval was a period of (1) increasing oceanic accretion with the opening of the Western Mediterranean sea and the rifting of the Central Atlantic Ocean, (2) eustatic sea-level rise, (3) deposition of black shales in oceanic settings, expression of two “Oceanic Anoxic Events” (OAEs, Schlanger and Jenkyns, 1976; Arthur et al., 1990; Bralower et al., 1994) and (4) climatic changes characterized by successive brief episodes (<1 my–5 my) of warming and cooling (Frakes and Francis, 1988; Weisert and Lini, 1991; Price, 2003; Pucéat et al., 2003; Weisert and Erba, 2004; Takashima et al., 2007; Wagner et al., 2008; Ando et al., 2008; Kuhnt et al., 2011). These OAEs are associated with major excursions of δ13C. The Early Aptian OAE 1a is marked by a major negative excursion, preceding the deposition of black shale, followed by a long-term δ13C positive shift (Menegatti et al., 1998). The OAE 1b is characterized by a distinct negative shift in various carbon reservoirs coincident with the black shale (Herrle et al., 2004; Wagner et al., 2007).

During this time interval, major changes in the carbonate production affected especially the (sub) tropical platforms located on the northern Tethyan passive margin both during climatic warmings, as the Early Aptian with the OAE 1a, and during climatic coolings as those recorded at the Late Aptian–Early Albian
transition (Weissert and Lini, 1991; Herrle and Mutterlose, 2003; Heimhofer et al., 2008; Mutterlose et al., 2009). Among different hypotheses, some authors proposed that enhanced terrigenous influx combined with sea-level rise would have brought more nutrients in the sea surface waters of the oceanic realm. The effects of eutrophication on the carbonate platforms are drastic changes in biological communities and a reduction of the carbonate productivity (Hallock and Schlager, 1986; Wood, 1993; Mutti and Hallock, 2003; Pittet et al., 2002). These biotic changes usually precede the drowning of carbonate platforms on the northern Tethyan margins.

Various studies show that the major carbonate crisis recorded on the carbonate platforms of the northern Tethyan margin during the Early Aptian (OAE 1a, Weissert et al., 1998; Wissler et al., 2003; Föllmi et al., 2006) is not recorded in the shallow paleoenvironments of the southern Tethyan margin (Oman, Immenhauser et al., 2005; Egypt, Thielemann, 2006; Tunisia, Heldt et al., 2008). The calcium carbonate content measured in the sediments of these platforms remains high even during intervals of major perturbations as the OAE 1a. Focusing on the Tunisian carbonate platform, Heldt et al. (2010) show that no widespread platform drowning is recorded at this time, possibly due to non-eutrophication of this platform located within the broad arid widespread platform drowning is recorded at this time, possibly due to non-eutrophication of this platform located within the broad arid

The rifting phase gave way to the deposition of thick red bed deposits of Late Permian–Triassic age, overlain by a thick series of shales and evaporites intercalated with basaltic flows dated as early Liassic (Hafid et al., 2000). The drifting period (from late Liassic onwards) coincides with the onset of low thermal subsidence of the margin (Bouatmani et al., 2007) and with the development of a widespread, shallow marine carbonate platform, and deeper marine carbonates to the West (Zühlke et al., 2004; Hafid et al., 2000).

The Cretaceous transgression followed a sharp regression of latest Jurassic age (Zühlke et al., 2004). A first cycle began with Berriasian shelf limestones and reached a maximum within Valanginian, open marine marls (Rey et al., 1988; Masrour et al., 2004). Hauterivian sediments are marked by shallowing upward deposits, which are overlain by inner shelf limestones or fluvial sandstones of Late Hauterivian–Barremian age (Canérot et al., 1986; Witam, 1998). A second cycle is represented at the base by Aptian shelf limestones that grade upwards into open marine shales of Albien age, which are in turn overlain by shallow marine marls and limestones, or even sandstones, of latest Albien age (Butt, 1982; Essafiouati et al., 2010). Upper Cretaceous times are then marked by two more transgressive-regressive cycles, one of Campanian–Turonian age, marked by a regional discontinuity at the Campanian/Turonian boundary (Ettachfini et al., 2005; Jati et al., 2010), and the other one of Senonian age, which is marked by a compressional teconic event of Campanian age (Algouti et al., 1999).

Salt tectonic and diapir activity began in the Jurassic and occurred repeatedly during the Cretaceous, controlling largely facies distribution in the distal, offshore part of the Basin (Tari et al., 2000; Mehdi et al., 2004; Zühlke et al., 2004).

Although parts of the Cretaceous succession have been studied in detail (e.g. Nouidar and Chellaï, 2001, 2002; Jati et al., 2010), the Late Aptian–Albian transgression is still poorly understood, because of the thick, monotonous and poorly fossiliferous shaly succession that represent most of the Albien stage. We studied five sections located along a roughly East-West transect of the margin, little North of the Agadir city. From East to West, these sections are: Tinfoul, Tamzergout, Alma, Addar and Tamri (Fig. 1B).
Fig. 1. Location maps (simplified from Zühlke et al., 2004). A: structural sketch of Western Morocco. B: Geological map of the Essaouira-Agadir Basin, and location of the sections discussed in the text.
3. Methods

3.1. Ammonites

In its present stage, our study includes about 1500 specimens of ammonites collected during the years 2008 and 2009 from eight Aptian—Early Albian stratigraphic sections in the EAB. Ammonites are unequally distributed throughout the studied interval: lowermost Early Aptian beds and upper Lower Albian marls yielded scarce material whereas the median part (uppermost Aptian to basal Albian) contains abundant material. The ammonite distribution has been studied through bed by bed sampling.

Collected material has been compared with specimens of the South Moroccan collections (Gentil, Killian, Roch, Breistroffer), and other historical private Aptian—Albian specimens of the Mediterranean provinces, deposited in the “Institut Dolomieu collection” (Observatoire des Sciences de l’Univers, Grenoble University). Ammonite specimens collected during the present study have been deposited and referenced in the same collection.

Ammonites are preserved either as small pyritized molds, very abundant in the calcareous and argillaceous marls, or as internal calcareous molds in the more massive and calcareous beds. Comparison of the ontogeny of both kinds of material is sometimes difficult, especially for the adult stages.

3.2. Calcimetry and calcareous nannofossils

Fifty-seven samples collected from the three sections of Alma, Addar and Tamzergout were analyzed for calcium carbonate content and for calcareous nannofossils. Samples are usually selected from more favorable lithologies (argillaceous marls, marls, calcareous marls) for nannofossil studies, with a number collected from limestones, in order to have a sampling representative of the various lithologies. Calcium carbonate content was determined using the carbonate bomb technique, which measures CO₂ emission during a hydrochloric acid attack. The calculation of the calcium carbonate percent is given in Appendix A.

Samples for nannofossil studies were prepared using the random settling technique of Geisen et al. (1999), a method adapted from Beaufort (1991) that allows calculate absolute abundances. This method is now applied in different studies focused on Cretaceous nannofossil assemblages allowing comparison of these assemblages between different settings (Herrle, 2002; Bormann et al., 2003, 2005; Herrle et al., 2003; Reboulet et al., 2003; Hardas and Mutterlose, 2007; Linnert et al., 2010). Nannofossils were observed under a light polarizing microscope, at 1560 magnification. 300 specimens were generally counted in a variable number of fields of view on the smear slide. In the poorest nannofossil samples, 150 specimens were counted following one longitudinal transverse. The taxonomic framework of Burnett et al. (in Bown, 1998) is followed. The nannofossil preservation was evaluated following the classes defined by Roth (1983). Relative abundances of each species were also calculated for each sample. In the calculation of the relative abundance, Nannococcos is excluded from the total sum of nannofossils because of their uncertain biological affinity. Buxson and Noël (1991) have compared the episodic proliferation of Nannococcos to those of extant dinoflagellates and proposed that they could be closely related groups. Aubry et al. (2005) in a reference work on the Mesozoic nannofossil size evolution did not take into account these nannolith because of their uncertain biological and ecological affinities. The nannofossil assemblage composition can also be described by means of the species richness, the Shannon Diversity Index and evenness defined by Shannon and Weaver (1949). Nannococcos are excluded from these calculations as explained before. The relationships between the different paleoenvironmental proxies (CaCO₃ %, nannofossil absolute abundance, species richness, diversity and evenness, percentage of Nannococcos) were investigated by linear correlation (Correlation coefficient of Pearson). This correlation coefficient can be used only with variables showing a gaussian distribution. To respect this criterion, the nannofossil absolute abundance is normalized, in calculating the logarithm10 of each absolute abundance value. For each correlation coefficient, r, a statistical test for significance is computed (“Fisher’s Z-transformation”, Fisher, 1921).

Nannofossil absolute abundances are usually biased by dilution. Therefore, we calculated nannofossil fluxes. In addition, sedimentation rates were estimated by using time duration proposed by Herrle (2002). The nannofossil fluxes are expressed as:

\[ F = \frac{AA}{p \times \text{sed. Rate}} \]

with AA: nannofossil absolute abundance; p: volume mass of calcite (2.7 g cm⁻³) and sed. Rate: sedimentation rate.

4. Results

4.1. Ammonite biostratigraphy

The Aptian and Albian ammonites of the EAB have been first reported respectively by Lemoine (1905) and Gentil (1905), Gentil (1905), Killian and Gentil (1906, 1907), and later Roch (1930), listed some faunas and proposed stratigraphic interpretations. Ambrogetti (1963) published the first regional synthesis, which remains until today the reference for the understanding of biological and sedimentological chronologies of the basin.

Our analysis of the distribution of the ammonite species identified in the Aptian—Albian of the EAB allowed us to establish a detailed faunal succession. The preliminary state of our study does not allow us to propose a local zonation; we will develop it in a forthcoming publication. However, thanks to the presence of numerous Tethyan species, our succession can be easily correlated with the Standard Mediterranean Zonation proposed by IUGS Lower Cretaceous Ammonite Working Group (“Kilian Group”; Reboulet et al., 2011).

We were able to correlate the ammonite succession with the four Late Aptian standard zones and with the first two zones of the Lower Albian. The Early Aptian and basal Late Aptian zones have also been identified but with much less accuracy because of condensed sedimentation and temporal hiatuses. The zones are assemblage or interval zones, the bases of which are determined some faunas and proposed stratigraphic interpretations. Ambrogetti (1963) published the first regional synthesis, which remains until today the reference for the understanding of biological and sedimentological chronologies of the basin.

Various new species and/or genus have been recognized in the ammonite faunas of the EAB. However, because the purpose of this section is to present our stratigraphic framework, these endemic species are not mentioned in the text and the table; they are only listed in Fig. 2.

Early Aptian

Resting on the Barremian massive sandy limestones, the Early Aptian to basal Late Aptian succession is marked by various sedimentary discontinuities and condensation levels. Ammonite specimens of Early Aptian age are scarce and poorly preserved, and ammonite zones are difficult to identify in this interval. They are not represented in the Tinfoul Section (Fig. 3).
Fig. 2. Ammonite occurrences and standard biostratigraphic interpretation of the reference regional Addar section (for lithology, see caption of Fig. 4).
Fig. 3. Regional biostratigraphic correlations with standard zonation nomenclature across the studied sections of the EAB (for lithology, see caption of Fig. 4).
However, in Addar (Fig. 2), the occurrence of *Cheloniceras* sp. (bed 1) and *Deshayesites* sp. indicates an uppermost Early Aptian age. These genera are possible markers of the *Deshayesites deshayesi* Zone. This assignment is supported by the occurrence of other representatives of the genus *Deshayesites* (Table 1).

The *Dufrenoyia furcata* Zone has been recognized in various sections. However, these species co-occur in the same beds with taxa indicative of the overlying *Epicheloniceras martini* Zone of basal Late Aptian age. This mixing of taxa corroborates the condensation of the succession and the amalgamation of discontinuities.

**Late Aptian**

The Late Aptian zones are better identified than the Early Aptian ones, except in the Tinfoul section, where only the *Hypacanthophilies jacobi* Zone is recognized.

Various ammonite species characteristic of the *Epicheloniceras martini* Zone are recognized (Table 1).

The identification of the *Parahoplites melchioris* Zone is more problematic; the index species is absent and other ammonites attributable to this zone are very scarce. As a consequence, the exact position of the lower boundary is uncertain (Fig. 3). We placed it at the first appearance of *Acanthohoplites* sp. (beds 9 in Addar and 10 in Alma), where it is associated with *Colombiceras discoidale* Sinzow.

The overlying *Acanthohoplites nolani* Zone is well recognized in all the studied sections; the “nolani” beds define a very characteristic horizon, known since early publications. Its lower boundary is placed at the first appearance of the index species, associated with other *Acanthohoplites* species (Table 1).

The *Hypacanthophilies jacobi* Zone has also been recognized in all sections, even though the index species is absent in our material; the genus *Hypacanthophilies* is moreover little represented in the ammonite assemblages of the zone, although *Acanthohoplitoidea* dominate. The lower boundary is also not well defined in the Alma and Tamzergout sections, and we conventionally placed it at the first appearance of *Pseudohaploceras* sp. (bed 16 in Addar).

**Earliest Albian**

The Aptian/Albian boundary is still in debate (e.g. Owen, 1984; Huber and Leckie, 2011). Partly due to the high provincialism, which prevents interregional correlations (Huber and Leckie, 2011), the ammonite fauna is of little help, so far, to define the base of the Albian stage, especially on the southern margin of the Tethys (Latil in Chihaoui et al., 2010; Latil, 2011). Nevertheless, the presence of cosmopolitan taxa in the Moroccan faunas can greatly improve correlations with the standard Western Europe ammonite biozonation and may provide new insights on the definition of the base of the Albian stage.

The *Leymeriella tardefurcata* Zone is identified in all the studied sections, even though the index species is absent as in the entire Mediterranean region. Characteristic species have been recorded for the zone (Table 1). Until now, the Aptian/Albian boundary cannot be determined accurately in the Tamzergout and Tinfoul sections (Fig. 3).

The *Douvilleiceras mammillatum* Superzone has been identified in the uppermost part of the studied successions, with the exception of the Alma Section where it has not been recognized (Fig. 3). Its lower boundary is difficult to determine in various sections, except in the Addar and Tinfoul sections, which record the respective occurrences of *Parenegonoceras hachourii* (Dubourdieu, 1953) and *Douvilleiceras mammillatum* aequinodum (Quenstedt). Ammonite assemblages comprising numerous specimens of the genus “*Beudanticeras*” (Table 1), define the very characteristic “*Beudanticeras beds*” horizon of the historical literature (Roch, 1930; Ambroggi, 1963).

The Aptian and Early Albian are reduced to a phosphatic crust in the Tamri area (Fig. 1B). This hardground yielded an ammonite assemblage comprising species characteristic of the Early Aptian (e.g. *Cheloniceras gr. cornuelainum* (d’Orbigny), *C. gr. meyendorfiseminosaurum*, Toxeroceratidae sp.), the Late Aptian (*Deshayesites* sp., *Dufrenoyia dufrenoyi* (d’Orbigny), *Colombiceras* sp., *Vectisites caprotnius* Casey), the Late Aptian—Early Albian interval (*Pseudobulbitidae* sp., *Puzosia* sp.) and the Albian (*Uhtiigella cf. rebouli* (Jacob) and *Engonoceras* sp.). (Fig. 3).

### 4.2 Sedimentary correlations

As a whole, the Late Aptian—Early Albian succession does not present any high energy and barrier facies and can be considered a westward, gently dipping ramp, marked by a deepening upward evolution that documents the Late Aptian—Early Albian eustatic transgression. Since detailed sedimentological analysis is not yet achieved, we will only describe the identified unconformities, which allow us to specify the biostratigraphic correlations.

Five main discontinuities have been recognized, which are correlatable in all the studied sections, thus defining at least four main sedimentary sequences (Fig. 4). Note, that in the westernmost Tamri section, these five discontinuities are contained within a single, 50 cm-thick, conglomeratic phosphatic hardground.

### Table 1 Ammonite associations identified in the studied sections (Essaouira-Agadir Basin), and correlations with the Early Aptian to Early Albian Standard Ammonite Zones.

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Ammonite standard zones</th>
<th>Ammonite associations</th>
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<tbody>
<tr>
<td><strong>Early Albian</strong></td>
<td></td>
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<tr>
<td><em>Douvilleiceras mammillatum</em></td>
<td>Beudanticeras dupinianum africana Pervinquière, Beudanticeras revoili Pervinquière, Uhligella rebouli Jacob, Parenegonoceras hachourii Dubourdieu, Douvilleiceras mammillatum aequinodum Quenstedt Phylloceras (Hypophylloceras) cf. cypris Fallot &amp; Termier, Phyllopachyceras baborene (Coquand), Egaudryceras (Eoestrigonites) cf. balmensis Breistroffer, Valdedorsella getulna (Coquand), Puzosia (Puzosia) quenstedti (Parona &amp; Bonarelli), Puzosia (Puzosia) quenstedti bonarelli Breistroffer in Besairie, “Uhligella” cf. tocazi (Jacob), “Beudanticeras” cf. revoili (Pervinquière), Oxytryploceras (Oxytryploceras) sp., Silestoides superbes (Jacob), Neosilestes palensis (Fallot &amp; Termier), “Hypacanthophilies” numidicus (Sornay), Hypacanthophilies elegans (Fritel), Hypacanthophilies gr. sarasini-nodosicostatus</td>
<td></td>
</tr>
<tr>
<td><em>Leymeriella tardefurcata</em></td>
<td></td>
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</tr>
<tr>
<td><strong>Late Aptian</strong></td>
<td><em>Hypacanthophilies jacobi</em></td>
<td>(Phylloceras) aptiense Sayn, Phyllopachyceras picturamen (d’Orbigny), Aconeceras aptiana (Sarasin), Pseudohaploceras convengens (Jacob), Diadococeras magni (Seunes), numerous Acanthohoplites, Hypacanthophilies nolaniiformis (Glaunova), Epicheloniceras clausayerace (Jacob) Aconeceras aptiana (Sarasin), Pseudohaploceras sp., Zuercharella sp., Acanthohoplites nolani (Seunes), Acanthohoplites bigoretti anhuali Breistroffer, Acanthohoplites bergeroni (Seunes), Epicheloniceras clausayerace (Jacob), Diadococeras sp.</td>
</tr>
<tr>
<td><em>Acanthohoplites nolani</em></td>
<td></td>
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<tr>
<td><em>Parahoplites melchioris</em></td>
<td></td>
<td>Acanthohoplites sp., Colombiceras discoidale (Sinzow)</td>
</tr>
<tr>
<td><strong>Early Aptian</strong></td>
<td><em>Dufrenoyia furcata</em></td>
<td><em>(Phylloceras)</em> (Sowerby), Tropeaena sp., Toxeroceratidae emericianum (d’Orbigny)</td>
</tr>
<tr>
<td><em>Deshayesites deshayesi</em></td>
<td></td>
<td><em>(Phylloceras)</em> (Sowerby), Tropeaena sp., Toxeroceratidae emericianum (d’Orbigny)</td>
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Fig. 4. Main discontinuities identified in the Late APT–Early Albian interval of the southern part of the Essaouira–Agadir Basin. Sections are located on Fig. 1B.
The first discontinuity is located at the top of the Barremian massive limestones or sandstones. It is marked, according to the sites, by a karstified surface (Tamzergout, Addar, Tinfoul), by an erosional surface (Alma), or by a simple, abrupt, lithological change (Tinfoul).

The second discontinuity is either amalgamated with the first one (Tamri, Alma, Tinfoul), or located 1 m, or less, above the first one. It consists of either an erosional surface (Tamzergout), or a karstified surface (Addar). The second unconformity overlies scarce ammonites that indicate a late Early Aptian age (Deshayesites deshayesi Zone (and Dufrenoyia furcata Zone)). Although observations are scarce and difficult (strong diagenesis), the associated fauna indicates a shallow marine depositional environment.

A third discontinuity seems to be located within the “Nolani Beds”. It is marked by an erosional surface overlain by reworked clasts (Alma) or by a condensed, bioturbated surface marked by ammonite accumulations (Addar). It has not been clearly observed as yet in the Tamri, Tamzergout and Tinfoul sections. Since it lies within the “Nolani Beds”, it is of Late Aptian age.

The fourth discontinuity is marked by a very constant layer of reddish sandstone that contains commonly green phosphatic, and reworked clasts (Addar, Alma, Tinfoul), and probably corresponds to a submarine hiatus. The underlying sequence is of latest Aptian age (Hypacanthoplites jacobi Zone), and was deposited in an open marine, deep outer shelf, as suggested by the scarce benthic fauna (brachiopods, pectinids and other bivalves).

The fifth discontinuity roughly coincides with the base of the “Beudanticaeras Beds”. It is marked by a constant bed of yellow sandstone that reworks white phosphatic clasts, ammonite fragments, and shaly flat pebbles, thus documenting a sedimentary hiatus and a period of submarine erosion. The underlying series is virtually devoid of benthic fauna in the western sections (Addar, Alma), and contains abundant brachiopods, pectinids and annelids in the eastern sections, thus documenting a basin to outer shelf environment. Overlying ammonite assemblages indicate an earliest Albian age (Leymeriella tarde-furcata Zone).

The overlying marly series contains several beds of sandstones with erosional base, which probably represent additional discontinuities. Available biostratigraphic data indicate an Early to Late Albian age (Ambroggi, 1963; Duffaud et al., 1966; Rey et al., 1988).

4.3. Calcium carbonate content and calcareous nannofossils

All nannofossil taxa observed in the studied sections are reported in Appendix B. The nannofossil total assemblage is composed of 78 species. Some taxa that exhibit similar morphology have been grouped. Biscutum spp. includes B. constans and B. ellipticum (they belong to the same morphological continuum as Bornemann and Mutterlose, 2006). The Cretarhabdus group includes all species of the genera Cretarhabdus and Retecapsa (Roth and Krumbach, 1986). Nannoconus are grouped into Nannoconus spp. (Roth and Krumbach, 1986; Herrle et al., 2003). Stauroolithites spp. include S. mutterloesi, S. seisseri, S. imbricatus and S. mitcheneri. All zeugrhabditos (including Z. erectus) with major axis smaller than 5 μm are combined under small Zeugrhabditos (Erba et al., 1992). Watznaueria barnesiae and W. fossincinctum are lumped together because they are believed to represent end-members of a morphological continuum (Lees et al., 2004, 2006; Bornemann and Mutterlose, 2006).

4.3.1. The Alma section

The Alma section presents the oldest sediments among the three sections selected for calcium carbonate and nannofossil analysis (Fig. 5). The carbonate content varies from 24 to 79% except in the three first samples of the succession, which present values below 10%. Six samples are barren of nannofossils. Eight samples display moderately preserved nannofossils with moderate etching and overgrowth (categories E2 and O2) and three samples show poorly preserved specimens with strong etching and moderate overgrowth or moderate etching and strong overgrowth (categories E3/O2 or E2/O3).

The nannofossil absolute abundance ranges from 2.75 x 10⁷ to 7.76 x 10⁶ specimens per gram of sediment. The species richness varies from 11 to 31. The Shannon index and evenness range between 2.93–3.96, and 0.732–0.849, respectively. Lowest values are associated with poorly-preserved samples. Nine species or group of species are well represented in the assemblages and display important abundance fluctuations; they are in decreasing order of abundance: Watznaueria barnesiae (average value (av. v.) of 28.8%, maximum value (max. v.) of 43.2%), small Zeugrhabditos (av. v. of 10%, max. v. 13.4%) Discorhabdus rotatorius (av. v. of 9%, max. v. of 14.3%), Biscutum spp. (av. v. of 6.7%, max. v. of 15.7%), Rhodoglossus asper (av. v. of 5.9%, max. v. of 10.7%), Watznaueria communis (av. v. of 3.9%, max. v. of 6.5%), Orastrum perspicuum (av. v. of 3.5%, max. v. of 8%), Nannoconus spp. (av. v. of 3.4%, max. v. of 7.8%), Lithraphidites carnioles (av. v. of 1.8%, max. v. of 4.6%), W. barnesiae and D. rotatorius generally do not present the same patterns for their absolute and relative abundances. Regarding the other taxa, their absolute and relative abundances follow the same trend. There is a decrease in both the absolute and relative abundances of Nannoconus spp. upward this short succession.

4.3.2. The Addar section

This section presents the most complete stratigraphic succession (Fig. 6). The calcium carbonate content varies between 30 and 56.5% at the base of the section, and progressively decreases upwards, to reach values around 10% (minimum of 7.6%).

Among the 27 selected samples, 6 samples are poorly preserved (categories E3/O2 or E2/O3), 13 samples are moderately preserved (categories E2 and O2) and 7 samples display well-preserved nannofossils with slight etching and overgrowth (categories E1 and O1). The nannofossil absolute abundance ranges from 3.81 x 10⁷ to 2.44 x 10⁶ specimens per gram of sediment. Highest abundances are recorded at the base of the section, and the absolute abundance decreases upward following the same trend as the carbonate content. Very low absolute abundances generally correspond to argillaceous sediments (carbonate content below 10%). The species richness varies from 15 to 35. The Shannon index and evenness fluctuate between 2.49–4.36, and 0.61–0.87, respectively. Variations of the nannofossil diversity are low except in the last 3 m of the succession. Ten species or group of species are well represented in the assemblages and display important abundance fluctuations; they are in decreasing order of abundance: W. barnesiae (av. v. of 26.2%, max. v. of 59%), small Zeugrhabditos (av. v. of 10.7%, max. v. of 15.1%), Biscutum spp. (av. v. of 8.8%, max. v. of 16.8%), D. rotatorius (av. v. of 6.5%, max. v. of 12.3%), R.asper (av. v. of 4.7%, max. v. of 9.8%), W. communis (av. v. of 4.6%, max. v. of 13.8%), Repagulan parvidentatum (av. v. of 3.08%, max. v. of 15.7%), L. carnioles (av. v. of 2.5%, max. v. of 5.8%), O. perspicuum (av. v. of 1.5%, max. v. of 9%), Nannoconus spp. (av. v. of 1.3%, max. v. of 5.5%). The relative abundances of W. barnesiae do not present the same pattern as their absolute abundances. For all other taxa, the absolute and relative abundances follow the same trend. The relative abundances of Biscutum spp. increase in the upper part of the section. W. communis is especially present at the base of the section. R. parvidentatum, which is not present in the Alma section, displays an increase in both absolute and relative abundances along the succession before to decrease gently at the top. The increase of
Fig. 5. Stratigraphic changes in calcium carbonate content, calcareous nannofossil total absolute abundance, species richness, diversity, evenness, and absolute and relative abundances of selected taxa for the Alma section. Position of samples is indicated by a small line.
Fig. 6. Stratigraphic changes in calcium carbonate content, calcareous nannofossil total absolute abundance, species richness, diversity, evenness, and absolute, and relative abundances of selected taxa for the Addar section. Position of samples is indicated by a small line.
R. parvidentatum is synchronous to the decrease in both absolute and relative abundances of R. asper. O. perspicuum is well represented in the first 10 m of the succession whereas it becomes rare or absent at the top. Nannoconus spp. are usually present at the base and at the top of the succession, and L. carniolensis is more abundant in the middle part of the succession.

4.3.3. The Tamzergout section

With respect to the other sections, the Tamzergout section presents a dark color interval of approximately 8 m dated as Early Albian (Fig. 7). Below this interval, the calcium carbonate displays values between 20 and 37%. These values sharply decrease within the dark interval, and reach a minimum of 4.7%. Above this interval, the carbonate content increases.

Among the 19 selected samples, 3 are poorly preserved (categories E3/O2 or E2/O3) and are located in the dark interval, 11 samples are moderately preserved (categories E2 and O2) and 5 samples are well-preserved (categories E1 and O1). Well-preserved assemblages are mostly observed at the base of the section. The nannofossil absolute abundance ranges from $4.57 \times 10^7$ to $1.58 \times 10^5$ specimens per gram of sediment. The absolute abundances are higher in the lower part than in the upper part of the succession. The species richness varies from 16 to 38. The Shannon index and evenness fluctuate between 3.59–4.34, and 0.74–0.89, respectively. Nine species or group of species are well represented in the assemblages and display important abundance fluctuations; they are in decreasing order of abundance: W. barnesiae (av. v. of 24.5%, max. v. of 34.3%), Biscutum spp. (av. v. of 9.1%, max. v. of 14.3%), small Zeyghanbotus (av. v. of 8.8%, max. v. of 14.8%), W. communis (av. v. of 6%, max. v. of 11.7%), D. rotatorius (av. v. of 5.4%, max. v. of 8.9%), R. parvidentatum (av. v. of 3.7%, max. v. of 6.2%), R. asper (av. v. of 3.1%, max. v. of 7.8%), L. carniolensis (av. v. of 1.9%, max. v. of 4.9%), and O. perspicuum (av. v. of 1.3%, max. v. of 3.3%). All taxa present a maximum in their absolute abundances at 57.5 m, which corresponds to a peak in the total absolute abundance. This level corresponds to a maximum flooding surface deduced from the sequence analysis of the section, and may, therefore, reflects a condensed level due to reduced sedimentation rate. The percentages of R. asper decrease from base to top of the section whereas those of R. parvidentatum generally present an opposite trend. This latter species presents the highest percentages within the dark interval, as does W. communis, of which the relative abundance is maximum at the base of the dark interval, and then sharply decreases until the top of this interval. The percentages of L. carniolensis decrease all along the succession, except in the dark levels where it increases. O. perspicuum is common in the lower part of the section until the base of the dark levels, and sharply decreases both in absolute and relative abundances above. Nannoconus are not represented in the Fig. 7, since their average percentages are generally below 1%.

5. Discussion

5.1. Calcareous nannofossil preservation

Three classes of nannofossil preservation have been identified in the sections of Alma, Addar and Tamzergout. Preservation state can control nannofossil abundance, species richness, and relative abundance of some species. Dissolution ranking of Cretaceous calcareous nannofossils has been proposed (Hill, 1975 (experimentation); Thierstein, 1980 (experimentation); Roth and Krumbach, 1986). Dissolution-resistant species are the large, thick placoliths with strongly imbricated elements (Hill, 1975) as W. barnesiae, which is considered the most resistant to dissolution (Hill, 1975; Thierstein, 1980, 1981; Roth, 1981; Roth and Bowdler, 1981; Roth and Krumbach, 1986). Thus, an increase of diagenetic alteration may imply an increase in the relative abundance of W. barnesiae and a concurrent decrease in the species richness of the assemblage. Conversely, B. constans, Z. erectus, Discorhabdus, are delicate taxa, considered to be very dissolution-susceptible forms (Hill, 1975; Thierstein, 1980; Roth, 1981; Roth and Bowdler, 1981; Roth and Krumbach, 1986), and an increase in diagenetic overprint may imply a decrease in their relative abundances. For all sections, we statistically tested the recognized effects of the different classes of preservation on nannofossil absolute abundance, species richness, relative abundances of W. barnesiae and of delicate taxa (Biscutum spp. + D. rotatorius + small Zeyghanbotus; Fig. 8). Higher mean nannofossil absolute abundance, species richness, relative abundance of delicate taxa and lower mean percentages of W. barnesiae are recorded in samples presenting a good preservation (class E1-O1) with respect to the other classes (moderate preservation: E2-O2 and poor preservation: E3-O2/E2-O3). However, there are no statistically significant differences for means of these different parameters between the different classes of preservation (Fig. 8). We can therefore conclude that in the EAB, nannofossils are only moderately affected by diagenesis and may reflect original assemblage composition.

5.2. Carbonate production during the Late Aptian–Early Albian transition in the EAB

Considering the most complete section of Addar, the calcium carbonate content decreases progressively during the Late Aptian–Early Albian interval (Fig. 6). The variations of nannofossil absolute abundance follow those of the carbonate content (Fig. 6). The statistical correlation calculated between these two proxies from the entire dataset (49 samples from the three sections, except 2 poorly-preserved samples and some sterile samples; Table 2) displays a low positive correlation ($r = 0.318$, Table 2). This indicates that part of the carbonate fraction results from autochthonous carbonate production by nannofossils. Carbonate content is also positively correlated with the relative abundance of Nannoconus spp. (Table 2). Nannoconus are the biggest and more calcified nannofossils recognized within the assemblage, and are, therefore, the major component of the carbonate fraction produced by nannofossils.

Strong fluctuations of Nannoconus abundances are recorded during the Late Aptian–Early Albian both in the Tethyan and Pacific realms. The Late Aptian is characterized by high abundances of N. truittii, recognized as the "Nannoconus truittii Acme" described by Mutterlose (1989, 1991) and observed in the Tethyan and Boreal realms (Mutterlose, 1989; Erba, 1994; Herrle and Mutterlose, 2003). This acme occurs in the martini ammonite Zone. This time interval is present in the three studied sections of the EAB, but was only studied for nannofossils in the Alma section. The base of this section, characterized by the highest abundances of Nannoconus spp., mainly represented by N. truittii, could correspond to the end of this acme (Fig. 5). Latest Aptian and Early Albian times display a sharp decrease of Nannoconus abundances in the North Sea (Rückheim et al., 2006a, b), North Germany (Mutterlose et al., 2003), Italy (Erba, 1994; Cobianchi et al., 1997), the Vocontian Basin (Herrle and Mutterlose, 2003), and the Atlantic, Pacific and Antarctic oceans (Herrle, 2002; Wise, 1983; Mutterlose et al., 2009; Mutterlose and Wise, 1990). In the EAB, abundances of Nannoconus spp. sharply decrease during the latest Aptian (Alma and Addar sections; Figs. 5 and 6), and this species becomes rare during the Early Albian (Addar section; Fig. 6). Ecological affinities of Nannoconus spp. for warm and oligotrophic surface waters have been shown by numerous studies (Table 3). The decrease in both calcium carbonate content and Nannoconus abundances at the Aptian–Albian transition could
Fig. 7. Stratigraphic changes in calcium carbonate content, calcareous nannofossil total absolute abundance, species richness, diversity, evenness, and absolute and relative abundances of selected taxa for the Tamzergout section. Position of samples is indicated by a small line. The gray interval corresponds to dark levels recognized in this section.
result from cooling climatic conditions and/or from associated increasing terrigenous input and nutrients, unfavorable to carbonate production. Mutterlose et al. (2009) suggest that the global cooling may have caused increased water circulation, leading to upwelling and increasing fertility of marine surface waters. However, in some places, as the south Atlantic margin, Late Aptian–Albian times correspond to a global “transgressive” period without significant terrigenous influx, and abundances of Nannoconus spp. remain low (B. Lambert, personal communication). After having dominated nannofossil assemblages in most Tethyan settings during the Lower Cretaceous (Bussen and Noël, 1991; Street and Bown, 2000), the nannoconid population shows an abrupt decline “Nannoconid crisis” in the Early Aptian (Erba, 1994). A short-lived return marks the Late Aptian “Nannoconus truitti Acme” (Mutterlose, 1989, 1991) that did not reach the former abundance, and is followed by a new drastic decrease of Nannoconus abundance in the middle Late Aptian (nannoconid crisis II; Herrle and Mutterlose, 2003). Locally, Nannoconus can be significant contributors in some upper cretaceous chalks (as for instance, the Turonian of the Paris basin, Aubry, 1970), but at a global scale, they are rare after the upper Aptian times, and became extinct in the Late Cretaceous (Burnett et al. in Bown et al., 1998).

So the reduction of nannoconids observed at the end of the Aptian could be the result of cooling at low latitudes, but the major decline is observed before with the two Aptian nannoconid crises, which seem synchronous with major drowning events of carbonate

Table 2
Correlation analyses between calcium carbonate content, nannofossil absolute abundance (specimens/gr. of rock), species richness, diversity and evenness, and the relative abundance of Nannoconus spp. The number of measurements is 49. The correlation coefficient of Pearson is in bold where it is statistically significant (p (probability) < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>CaCO₃ (%)</th>
<th>Nannof. abs. ab. (sp./g of rock)</th>
<th>Species richness</th>
<th>Shannon index</th>
<th>Evenness</th>
<th>Nannoconus spp. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃ (%)</td>
<td>1.000</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td>0.318</td>
</tr>
<tr>
<td>Nannof. abs. ab. (sp./g of rock)</td>
<td>0.318</td>
<td>1.000</td>
<td>0.479</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Species richness</td>
<td>-0.124</td>
<td>0.479</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shannon index</td>
<td>-0.157</td>
<td>0.484</td>
<td>0.717</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evenness</td>
<td>-0.116</td>
<td>0.285</td>
<td>0.170</td>
<td>0.807</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Nannoconus spp. (%)</td>
<td>0.652</td>
<td>0.241</td>
<td>-0.213</td>
<td>-0.203</td>
<td>-0.108</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Fig. 8. Mean nannofossil absolute abundance (specimens/gr. of rock), mean species richness, mean relative abundance of W. barnesiae and mean relative abundance of delicate taxa (Biscutum spp. + D. rotatorius + small Zeugrhabdotus) for different classes of preservation and for all the studied sections. In order to estimate the significance of the observed differences between the various classes of preservation, a Bonferroni/Dunn test is applied. It allows comparison of the calculated means for datasets with different sizes (here, the highly variable number of samples from one state of preservation to each other). Statistically significant differences were observed at p (probability) < 0.0167. Fifty-seven samples are considered in this analysis.
platforms, possibly reflecting a collapse in the marine carbonate system on a global scale (Herrle and Hemleben, 2001).

5.3. Climatic conditions during the Late Aptian—Early Albian transition in the EAB

The Aptian—Albian transition has been identified as a period of substantial climate cooling. Evidences for this cooling episode mainly proceed from high-latitude records and are supported by lithological, geochemical and palaeontological proxies (see Heimhofer et al. (2008) for a synthesis). Decreasing surface water temperatures are indicated by a first global decline of Tethyan nannofossils in the Late Aptian at both high and low latitudes, associated with increasing nannofossil boreal taxa in low latitudes during the latest Aptian to earliest Albian period (Herrle and Mutterlose, 2003; Mutterlose et al., 2009).

If we consider nannofossil taxa as indicators of changes in surface temperatures in the EAB, strong variations in both the absolute and the relative abundances of three taxa must be taken into account: Nannoconus spp. (already described in the preceeding section), R. parvidentatum and R. asper. R. parvidentatum is a high-latitude species (Table 3). Its occurrence in the Tethyan realm during the Aptian times (Haq et al., 1987). However, taxa with Tethyan affinities, like R. asper, indicative of warmer sea surface temperature (Table 3) decreased in the North Sea and North Germany during the Early Albian (Jeremiah, 1996, 2001; Rückheim et al., 2006a, b), as did Tethyan nannofossils.

R. parvidentatum is absent (Alma section; Fig. 5) or rare (Addar and Tamzergout sections; Figs. 6 and 7) during the Late Aptian, whereas it increases both in absolute and relative abundances during the Early Albian (Addar and Tamzergout sections; Figs. 6 and 7). These results evidence a decrease of sea surface temperature in the EAB at that time, allowing migration of nannoflora from high to low latitudes. The decrease in absolute and relative abundances of R. asper during the same time interval for the three sections (Figs. 5–7) supports this interpretation.

Our study shows, therefore, that the cooling episode identified elsewhere at the Aptian—Albian transition, is recognized in the EAB.

Table 3
Paleoecological significance of selected nannofossil taxa.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Fertility of surface waters</th>
<th>Paleoeceanography</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. constans</td>
<td>eutrophic&lt;sup&gt;a&lt;/sup&gt;, 2, 4, 6, 7, 8</td>
<td></td>
</tr>
<tr>
<td>B. ellipticum&lt;sup&gt;b&lt;/sup&gt;</td>
<td>eutrophic&lt;sup&gt;c&lt;/sup&gt;, meso-eutrophic&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Biscutum spp.</td>
<td>mesotrophic&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>D. rotatorius</td>
<td>meso-eutrophic&lt;sup&gt;g&lt;/sup&gt;, 9, 11, 12, 13</td>
<td></td>
</tr>
<tr>
<td>L. carniolensis</td>
<td>eutrophic&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Z. erectus</td>
<td>eutrophic&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>R. parvidentatum</td>
<td>oligotrophic&lt;sup&gt;f&lt;/sup&gt;, 12, 17</td>
<td>warm waters&lt;sup&gt;g&lt;/sup&gt;, 15, 16</td>
</tr>
<tr>
<td>R. asper</td>
<td>warm waters&lt;sup&gt;g&lt;/sup&gt;, 11, 14, 15, 18</td>
<td></td>
</tr>
<tr>
<td>R. parvidentatum</td>
<td>high latitude&lt;sup&gt;g&lt;/sup&gt;, 14, 18, 19</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Roth, 1981; <sup>b</sup>Roth and Bowdler 1981; <sup>c</sup>Roth and Krumbach, 1986; <sup>d</sup>Premoli Silvá et al., 1989; <sup>e</sup>Roth, 1989; <sup>f</sup>Watkins 1989; <sup>g</sup>Williams and Bralower 1995; <sup>h</sup>Mutterlose and Kessels 2000; <sup>i</sup>Giraud et al., 2003; <sup>j</sup>Linnert et al., 2010; <sup>k</sup>Ebera, 1992; <sup>l</sup>Coccioni et al., 1992; <sup>m</sup>Herrle et al., 2003; <sup>n</sup>Ebera et al., 2007; <sup{o}</sup>Mutterlose, 1989; <sup>p</sup>Street and Bown 2000; <sup>q</sup>Ebera, 1994; <sup>r</sup>Crux, 1991; <sup>s</sup>Wise, 1988. 
<sup>a</sup>B. ellipticum is considered as a morphotype of B. constans (Bornemann and Mutterlose, 2006).
<sup>b</sup>Biscutum spp.: B. constans (abundant), B. ellipticum (common) (Linnert et al., 2010).

5.4. Nannofossil productivity during the Late Aptian—Early Albian transition in the EAB (Addar and Tamzergout sections)

Variations in nannofossil productivity are estimated in the EAB taking into account and comparing two proxies: the relative abundance of meso-eutrophic nannofossil taxa recognized in our samples (Biscutum spp., D. rotatorius, small Zeugrhodatus and L. carniolensis; their paleoecology are summarized in Table 3), and the nannofossil fluxes calculated for some well-calibrated time interval using the results of Herrle (2002). Only the Addar and Tamzergout sections, in which the same time interval has been studied for nannofossils, are considered for the calculation of fluxes and estimation of productivity.

The relative abundances of the meso-eutrophic taxa do not present strong fluctuations in the Addar section, whereas in the Tamzergout section, where dark levels are recognized, stronger variations in percentages are observed (Fig. 9). The abundances of meso-eutrophic taxa sharply decrease at the base of the dark levels, and then progressively increase in the upper part of the darker interval to reach values similar to those found in the rest of the section.

On the basis of biostratigraphic and chemosтратigraphic results, Herrle (2002) proposed a correlation between the Niveau Paquier recognized in the Vocontian Basin and the OAE 1b identified on the Mazagan Plateau. The Niveau Paquier, and the dark levels of the EAB are both dated from the tardefurcata amonite Zone, and can be considered synchronous. Therefore, although sedimentological and geochemical studies have not been carried out, it could be possible that the dark interval, only recognized in the median part of the EAB, represent the lithological expression of the OAE 1b.

Based on mean sedimentation rates calculated with biostratigraphic and cyclostratigraphic time control by Herrle (2002), the estimated duration of the tardefurcata amonite Zone is 1.08 my (Table 4).

Although the tardefurcata ammonite Zone time interval is only represented by 5 samples in the Addar section, the nannofossil fluxes seem to be higher in Tamzergout than in Addar (Fig. 9). In the Tamzergout section, the nannofossil flux sharply decreases just before deposition of the dark levels. Considering both the relative abundance of meso-eutrophic taxa and flux in the Tamzergout section, the nannofossil productivity is higher below the dark interval than within it. For the time interval corresponding to the tardefurcata Zone, the mean relative abundance of meso-eutrophic taxa is similar in the Addar and Tamzergout sections, whereas the mean nannofossil flux is higher in Tamzergout than in Addar (Table 4). So there are some discrepancies between results obtained from meso-eutrophic taxa percentages and fluxes. The results obtained from fluxes suggest that the nannofossil productivity is higher in Tamzergout than in Addar. This can be explained by the fact that since Tamzergout is located in a more proximal position with respect to Addar, more nutrients associated to runoff are expected to be available in more proximal environments.

5.5. Comparison of nannofossil productivity between the southern and northern Tethyan margins

In this section, we compare the mean nannofossil productivity between the southern Tethyan margin (EAB and Mazagan Plateau) and northern Tethyan margin (Vocontian Basin), using the data by Herrle (2002). For this comparison, we chose two proxies available for all settings, the relative abundance of meso-eutrophic taxa, and the nannofossil fluxes.

The comparison of nannofossil fluxes is possible since in the work by Herrle (2002) and in the present study, the same
random settling method of Geisen et al. (1999) was performed to prepare nannofossil smear slides and to calculate absolute abundance.

The mean nannofossil productivity was compared for the time interval corresponding to the taurefrurcata Zone (Early Albian), which is recovered for the EAB (Addar and Tamzergout sections), the Mazagan Plateau and the Vocontian Basin.

During the Early Albian, the mean relative abundance of the meso-eutrophic taxa was higher on the Mazagan Plateau than in the Vocontian Basin and in the EAB (Fig. 10). The Mazagan Plateau

<table>
<thead>
<tr>
<th>Meso-eutrophic taxa (%)</th>
<th>Nannofossil absolute abundance</th>
<th>Thickness of the tardefurcata Zone (m)</th>
<th>Duration of the tardefurcata Zone (my)</th>
<th>Sedimentation rate (cm/ky)</th>
<th>Nannofossil flux (nanno./m²/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addar</td>
<td>23.9</td>
<td>3.36E-08</td>
<td>19</td>
<td>1.08</td>
<td>1.76</td>
</tr>
<tr>
<td>Tamzergout</td>
<td>23.6</td>
<td>3.47E-08</td>
<td>41</td>
<td>1.08</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Fig. 10. Mean nannofossil fluxes and mean meso-eutrophic taxa percentages for the Agadir basin, the Mazagan Plateau (DSDP Site 545) and the Vocontian Basin for the earliest Albian (*tardefurcata* ammonite Zone). For the Vocontian Basin and the Mazagan Plateau, data are compiled from Herrle (2002). The Late Aptian paleogeographic map is modified from Heldt et al. (2010).
was submitted to upwelling conditions during this period. The presence of upwelling was suggested by Leckie (1984), based on the high abundance of radiolarians, the high benthic/planktonic foraminifera ratio and the high abundance of fish debris.

However, results obtained from the mean nannofossil fluxes data do not correlate with the relative abundances of meso-eutrophic taxa. The Vocontian Basin is characterized by nannofossil fluxes four times higher than those of the Mazagan Plateau, and height times higher than those of the EAB (Fig. 10). On the southern Tethyan margin, the nannofossil productivity is lower in the EAB than on the Mazagan Plateau. This indicates that our study area of the EAB was located outside the main upwelling area, without excluding totally the presence of upwelling in the EAB.

Our data show that the estimates of the nannofossil productivity are different, depending on the proxies we used. How can we explain these differences? As already discussed by Williams and Bralower (1995), the relative abundances data are affected by “closed-sum” problems and the high relative abundance of one species can be interpreted as a real increase in abundance of this species, or as a decrease in abundance of the other species. Considering the nannofossil fluxes, the comparison between the southern and the northern Tethyan margins shows that the nannofossil productivity is higher in the Vocontian Basin with respect to both the Mazagan Plateau and the EAB during the Late Aptian—Early Albian interval. The Vocontian Basin is located in the humid climatic belt of Chumakov et al. (1995) (Fig. 10), and more nutrients are associated to runoff. Moreover, Herrle (2002) and Herrle et al. (2003) showed that the Vocontian Basin was submitted to a monsoon climate-type during the Early Albian. However, the clay mineral assemblages from different low to mid palaeolatitudes, including the Algarve basin (Heimhofer et al., 2008), the EAB (SW Morocco; Daoudi and Deconinck, 1994) and the Vocontian Basin (SE France; Bréhéret, 1997), show very similar patterns with high abundances of illite, indicating high physical weathering rates. This is in agreement with an arid climate in both the northern and southern margins of the Tethys. Consequently, trophic conditions in sea surface were probably lower, both in neritic (results of Heldt et al., 2010) and pelagic realms on the southern Tethyan margin, with respect to the northern margin, likely due to more arid climatic conditions to the South.

6. Conclusions

A high resolution ammonite biostratigraphy and recognition of major sedimentary unconformities allowed good correlation of five sections located on a proximal (Tinfoul section) — distal (Tamri section) transect in the EAB encompassing the Aptian—Early Albian interval. Dark levels are recognized in the Tamzergout section; they are dated from the tardefurcata ammonite Zone and could be synchronous with the black shales of the Niveau Paquier in the Vocontian Basin, a lithological expression of the OAE 1b.

A decrease in carbonate productivity, is revealed by the calcium carbonate content and nannofossils abundances, at the Aptian—Albian transition. It could result from cooler climatic conditions recognized in the EAB, as well as in other basins, and/or from the associated increasing terrigenous input and nutrients, which hindered carbonate production. In the EAB, the nannofossil productivity is higher before deposition of the dark levels, in the earliest Albian. The nannofossil productivity in two sites of the southern Tethyan margin (EAB, this study; DSDP site 545, Mazagan Plateau submitted to upwelling conditions, Herrle, 2002) and one site of the northern Tethyan margin (Vocontian Basin, Herrle, 2002) has been compared. This comparison shows that the nannofossil fluxes and percentages of meso-eutrophic taxa are not correlated.

During the Early Albian, the Vocontian Basin is characterized by nannofossil fluxes four times higher than those of the upwelling-submitted Mazagan Plateau, and height times higher than those of the EAB. Conversely, the meso-eutrophic taxa are slightly more abundant on the Mazagan Plateau than in the Vocontian Basin. These data seem to corroborate the results of Heldt et al. (2010) and show that trophic conditions in sea surface waters were lower not only in the neritic, but also in the pelagic realm of the southern Tethyan margin with respect to the northern margin, probably due to more arid climatic conditions on the southern Tethyan margin.

Acknowledgments

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References


Appendix A

The calcium carbonate percent is calculated using the following equations.

Equation 1 (Measuring CO2 gas volume)

\[ V_{CO_2} = \left( V(P - Ps) / 273 \right) \times 760 \times (273 + T) \]

Where \( V \) is the volume of CO2 measured in milliliter (ml). 273 K = 0 °C and 760 mmHg (torr) = 1 atm are Standard temperature and pressure (STP).

\( P \): atmospheric pressure obtained using a laboratory barometer in mmHg.

\( Ps \): saturation pressure correction factor (function of temperature) in torr read from table of saturation pressure-temperature data.

\( T \): temperature in Celsius degree obtained using a laboratory thermometer.

Equation 2 (Weight percent CO2)

\[ CO_2\% = \left( V_{CO_2} \times 44 \times 100 \right) / 22,414 \times 4 \]

With 44 – molar mass of CO2 in g mol\(^{-1}\) and 100 – molar mass of CaCO3 in g mol\(^{-1}\).

At STP, 1 mol of an ideal gas occupies 22,414 ml.

\( M \) = weight of sediment powder used (g).

Equation 3 (Weight percent CaCO3)

\[ CaCO_3\% = CO_2\% / 2.273 \]


\( f \): the correction factor – average ratio between CaCO3invex/CaCO3inw obtained after 5 measurements of the calcium carbonate content (CaCO3invex) from a standard (CaCO3inw = 98).

Appendix B

List of nannofossil species recognized in this study

Anfractus harrisonii Meld, 1979
Biscutum constans (Gorka, 1957) Black in Black and Barnes, 1959
Biscutum ellipticum (Gorka, 1957) Grün in Grün and Alleman, 1975
Bravardospheara africana Stradner, 1961
Bravardospheara regularis Black, 1973
Braunioina signata (Noel, 1960) Noel, 1970
Bukrylithus ambiguus Black, 1971

Calcilites sp. Jakubowski, 1986
Chaozygys littorarius (Gorka, 1957) Manivit, 1971
Corollithus signum Stradner, 1962
Cretarhabdus conicus Bramlette and Martini, 1964
Cribrosphearea ehrbergii (Arkhangelsky, 1912) Deflandre in Piveteau, 1952
Crubiscibutum huyi (Black, 1973) Jakubowski, 1986
Crubiscibutum salesbroum (Black, 1971) Jakubowski, 1986
Cyclagelosphaera margerelii Noel, 1965
Diazomatolithus lehmanni Noél, 1965
Discorhabdus rotatorius (Bukry, 1969) Thierstein, 1973
Effeltush straitus Black, 1971
Eproliithus florialis (Stradner, 1962) Stover, 1966
Flabellites oblongus (Bukry, 1969) Crux in Crux et al., 1982
Gaarderellia granulifera Black, 1973
Grantorhabdus coronadventis (Reinhardt, 1966) Grün in Grün and Alleman, 1975
Haquis circumradiatus (Stover, 1966) Roth 1978
Hayesites albiensis Manivit, 1971
Hayesites irregularis (Thierstein in Roth and Thierstein, 1972) Applegate, et al., in 1978
Helena chiastia Worsley, 1971
Hemipodorhabdus gorkae (Reinhardt, 1969) Grün in Grün and Alleman, 1975
Lithugophites carnosensis Deflandre, 1963
Loxolithus armilla (Black in Black and Barnes, 1959) Noel, 1965
Manivitella pimmatoides (Deflandre in Manivit, 1965) Thierstein, 1971
Micrurhlabdites deflandrei and Fert, 1954
Microhlabdus deflandrei, 1959
Nannococcos inornatus Rutledge and Bown, 1996
Nannococcus quadriangularis Deflandre and Deflandre, 1967
Nannococcus truitii trottini (Mutterlose, 1955)
Oroslipus perspicuum Varol in Al-Raya et al. 1990
Perissocycus tayloriae Crux, 1989
Placozygus bifuriformis (Reinhardt, 1964) Hoffman, 1970
Polyhlabdus madingleyensis Black, 1968
Prediscosphaera columbiana (Arkhangelsky, 1912) Gartner, 1968
Prediscosphaera spinosa (Bramlette & Martini, 1964) Gartner, 1968
Radiolithus planus Stover, 1966
Rapagoullia parvidentatum (Deflandre and Fert, 1954) Forchheimer, 1972
Retecapula surirella (Deflandre and Fert, 1954) Grun in Grun and Allemann, 1975
Rhagodiscus achlyostaurion (Hill, 1976) Doeven, 1983
Rhagodiscus angustus (Stradner, 1963) Reinhardt, 1971
Rhagodiscus asper (Stradner, 1963) Reinhardt, 1967
Rotelapillus lafriter (Noel, 1975) Noel, 1973
Rucinolithus terebrodentarius Applegate, Bralower, and Wise, 1987
Scapholithus deflandrei, in Deflandre and Fert, 1954
Serrishabrithes guenthsleri Mutterlose, 1992
Sollasites horticus (Stradner et al., 1966) Cepenk and Hay, 1969
Staurolithites imbricatus (Gartner, 1968) Burnett, 1997
Staurolithites mitcheneri (Applegate and Bergen, 1988) Rutledge and Bown, 1998
Staurolithites mullerihesi Crux, 1989
Staurolithites siesseri Bown in Kennedy et al., 2000
Stoverites aechlyos (Stover, 1966) Persch-Nielsen, 1986
Tegumentum stradneri Thierstein in Roth and Thierstein, 1972
Tranolithus gabalus Stover, 1966
Tubodiscus Thierstein, 1973
Watznaueria bennosi (Black 1959) Persch-Nielsen, 1968
Watznaueria biperta Bukry, 1969
Watznaueria britannica (Stradner 1963) Reinhardt, 1964
Watznaueria communis Reinhardt, 1964
Watznaueria fossicanis (Black 1971) Bown in Bown and Cooper 1989
Watznaueria manivitae Bukry, 1973
Watznaueria ovata Bukry, 1969
Zyghzobdaius bicornescentus (Stover, 1966) Burnett in Gale et al., 1996
Zyghzobdaius diplogrumpus (Deflandre in Deflandre and Fert, 1954) Burnett in Gale et al., 1996
Zyghzobdaius elegans (Gartner, 1968) Burnett in Gale et al., 1996
Zyghzobdaius emmerbergeri (Noel, 1958) Persch-Nielsen, 1984
Zyghzobdaius erectus (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1965
Zyghzobdaius noeliae Rood et al., 1971
Zyghzobdaius scutaulis (Bergen, 1994) Rutledge and Bown, 1996
Zyghzobdaius streeitiae Bown in Kennedy et al. 2000
Zyghzobdaius trivectris Bergen, 1994
Zyghzobdaius xenotus (Stover, 1966) Burnett in Gale et al., 1996