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Microfacies, biostratigraphy, and geochemistry of the hemipelagic Barremian–Aptian in north-central Tunisia: Influence of the OAE 1a on the southern Tethys margin

M. Heldt *, M. Bachmann, J. Lehmann

University of Bremen, FB 5 - Geosciences, P.O. Box 330 440, D-28334 Bremen, Germany

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Abstract

Upper Barremian–lower Upper Aptian hemipelagic deposits of the Hamada Formation in the Djebel Serdj area, north-central Tunisia were studied in detail with regard to microfacies, biostratigraphy, $\delta^{13}C$ stratigraphy, and geochemistry. Our data provide insights into the palaeoenvironmental evolution and sea-level fluctuations of the Tunisian shelf. The unusually expanded deposits consist of mud-, wacke-, and packstones which reflect mid- and outer-ramp depositional environments. Planktonic foraminifer and $\delta^{13}C$ stratigraphy allowed us to establish a detailed time-frame and the recognition of the Lower Aptian Oceanic Anoxic Event 1a (OAE 1a) as well as time-equivalent deposits of shallow-marine carbonate-platform drowning. Based on our microfacies studies, we subdivide the studied sections into four genetic intervals: a pre-OAE 1a interval, an OAE 1a and platform-drowning-equivalent interval, and a post-platform-drowning interval. We present a 3rd-order sea-level curve for the Tunisian shelf, deriving from the results of our microfacies studies.

Deposits of the OAE 1a in the sections investigated are characterised by bioclastic wacke- and packstones with high abundances of poorly preserved radiolarians and moderately to well preserved planktonic foraminifers, suggesting a transgression and an eutrophication of the upper water column. Scarceness of benthic macrofossils, low abundances of small benthic foraminifers and ostracods possibly suggest dysoxic conditions at the seafloor. Mudstones of the platform-drowning time-equivalent deposits, directly overlying the OAE 1a, are partly showing a pronounced drop in carbonate content and are scarce of macrofossils.

Keywords: Aptian; OAE 1a; Platform drowning; Microfacies

1. Introduction

Marine sediments of the Late Barremian–early Late Aptian interval provide information about significant changes in the ocean/climate system and several major palaeoceanographic and palaeobiological events (e.g. Leckie, 2002 and references therein). Especially the late Early Aptian has been focused by many authors in last and recent years, due to a prominent episode of globally increased organic carbon burial (Oceanic Anoxic Event 1a) (Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Jenkyns, 1980; Arthur and Sageman, 1994; Menegatti et al., 1998; Bralower et al., 1999; Leckie, 2002; Erba, 2004), which is associated with increased marine productivity, a sea-level rise, and significant changes in marine flora and fauna: e.g. an appearance of widespread radiolarian blooms and crises in carbonate producing biota (e.g. Haq et al., 1988; Erbacher et al., 1996; Hochuli et al., 1999; Jenkyns, 1999; Erba, 2004). Geological evidence (e.g. trace metal peaks and pronounced strontium isotope excursions) suggest a direct link of this event with increased submarine volcanism in the Pacific ocean, related to the emplacement of the Ontong Java–Manihiki plateau (e.g. Larson, 1991; Bralower et al., 1997; Larson and Erba, 1999; Jones and Jenkyns, 2001; Jahren, 2002). Many authors suggested, that outgassing of high amounts of

* Corresponding author.
E-mail address: mheldt@uni-bremen.de (M. Heldt).

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CO_2 into the atmosphere was responsible for temporarily intensified greenhouse conditions, which in turn led to several processes (e.g. increased coastal runoff, intensified wind velocities, and upwelling) causing a eutrophication of neritic and pelagic environments as well as distinct perturbations in carbonate production (e.g. Weissert, 1989; Caldeira and Rampino, 1991; Weissert et al., 1998; Jones and Jenkyns, 2001; Weissert and Erba, 2004). It has been critically noted, that these mechanisms alone cannot explain the high productivity documented from remote parts of large oceans (Erba, 2004). Another explanation for the OAE 1a is a direct stimulation of marine productivity by hydrothermal input of biolimiting metals (e.g. Fe, Zn) during plateau construction (e.g. Sinton and Duncan, 1997; Larson and Erba, 1999; Walczak, 2006). Furthermore, the results of a study by Heimhofer et al. (2004) suggest that variations in CO_2 concentrations during the OAE 1a have only been of minor importance. These authors found no evidence for major climatic disturbances during OAE 1a in the Vocontian Basin, France.

Initially, investigations of the OAE 1a concentrated on pelagic deposits (e.g. Schlanger and Jenkyns, 1976; Jenkyns, 1980; Coccioni et al., 1987; Bréhéret, 1988; Bralower et al., 1994). In more recent years, attention has been also paid to the hemipelagic or shallow-marine time-equivalent deposits (e.g. Jenkyns, 1995; Aguado et al., 1999; de Gea et al., 2003; Immenhauser et al., 2005; Föllmi et al., 2006), which play an important role in understanding the processes leading to the OAE 1a.

In addition, an episode of shallow-water carbonate-platform drowning, which coincides in the initial part with the OAE 1a but lasts up to 4 my (Weissert et al., 1998; Föllmi et al., 2006), is recorded from the northern and southwestern Tethyan margin and from circum-Atlantic regions (e.g. Jansa, 1993; Föllmi et al., 1994; Grötsch et al., 1998; Weissert et al., 1998; Föllmi et al., 2006). Hypotheses to account for this event concentrate on eutrophication of marginal environments either by increased continental runoff and/or by upwelling (e.g. Weissert et al., 1998; Föllmi et al., 2006).

The onset of both events is characterised by a short-lived negative $\delta^{13}C$ excursion, which has been attributed to dissociation of CH_4-hydrates (Jahren and Arens, 1998; Opdyke et al., 1999; Jahren et al., 2001; Beerling et al., 2002). They are followed by pronounced positive $\delta^{13}C$ excursions, which reflect changes in the marine carbon partitioning probably as consequence of nutrient-enhanced productivity (e.g. Menegatti et al., 1998; Weissert et al., 1998; Erba, 2004).

This study focuses on the microfacies, geochemistry, and biostratigraphy of a Late Barremian–early Late Aptian succession cropping out at Djebel Serdj in north-central Tunisia (Fig. 1). The good exposure and expansion of the deposits (330 m) provide the excellent opportunity to study the palaeoenvironmental evolution of hemipelagic, mid- to outer-ramp deposits situated on the southern edge of the Tethyan ocean in detail. Respect is paid to the local sedimentary expression of the OAE 1a, which is more than 45 m thick in the studied area. The main goal of this study is to enhance our knowledge on the largely unknown impact of this event on the southern Tethys margin.

2. Geological setting

Central Tunisia is part of the eastern Atlassic domain; it consists of Mesozoic and Cenozoic sedimentary rocks deposited in several basins. Two major tectonic cycles affected this area, which is characterised by NE–SW trending folds, strike-slip faults and diapirism (Burollet, 1990; Bouaziz et al., 2002). The first tectonic cycle was related to the NE–SW to N–S opening of the Tethys in the Late Permian to Early Cretaceous and led to the formation of rifts, tilted blocks, horsts and grabens by extensional tectonics. The second tectonic cycle was characterised by NW–SE compression in the Cenozoic and caused an inversion of normal faults, reactivated uplifts and diapirs of Triassic evaporites (Ben Ferjani et al., 1990; Grasso, 1999; Bouaziz et al., 2002).

During the Late Barremian–early Late Aptian, central Tunisia was dominated by shallow-marine sedimentation in a mosaic of intrashelf basins. A stable high ("Kasserine Island") was located in the eastern part (Fig. 1). Typical deposits of this shallow-marine domain are limestones and sandstones (e.g. M'Rabet, 1987; Ben Ferjani et al., 1990, Chekhma et al., 1990; Chaabani et al., 1992; Chaabani and Razgallah, 2006). The northern part of Tunisia ("Tunisian Trough") was characterised by basinal sedimentation; typical deposits are claystones and marlstones, partly with intercalations of turbidites (e.g. Turki, 1985; Memmi, 1989; Ben Haj Ali and Ben Haj Ali, 1996).

The studied area is located about 25 km north of Kasserine Island, in a hemipelagic transition zone between the shallow-marine domain and the Tunisian Trough (Fig. 1). The deposits

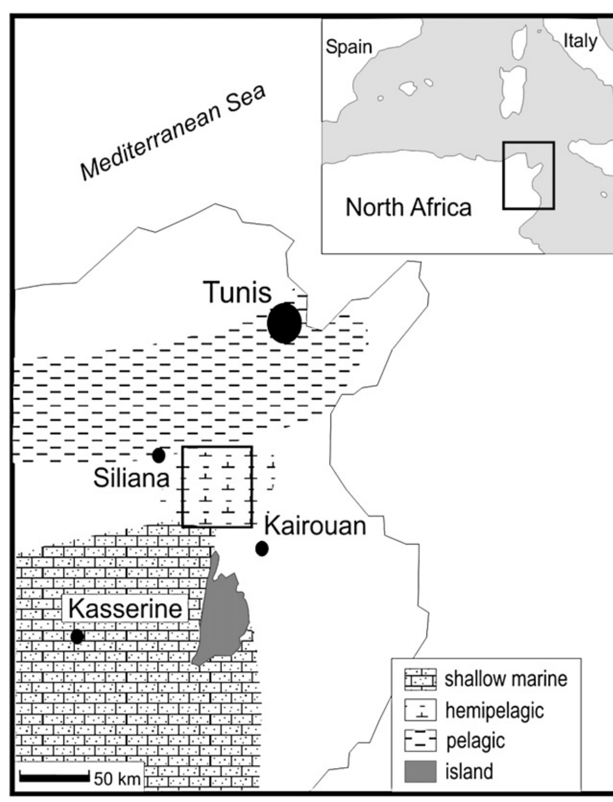

Fig. 1. Palaeogeographic map of Tunisia (see upper inlay) for the Lower Aptian. The lower black rectangle marks the studied area (Fig. 2). After Tlatli (1980) and M'Rabet et al. (1987).

investigated are mainly assigned to the 305 m thick hemipelagic Hamada Formation (Fig. 3), which consists of a 82 m thick limestone/marlstone-alternation dominated lower member, a marlstone-dominated 154 m thick middle member, and a marlstone-dominated 70 m thick upper member. The uppermost part of the studied deposits additionally include the 24 m thick limestones of the lowermost unit (S1) of the Serdj Formation, which is mainly composed of shallow-marine carbonates. Tlatli (1980) introduced lithological units and proposed an Early Aptian to early Late Aptian age for the Hamada Formation and an early Late Aptian age for the base of the Serdj Formation by using planktonic and benthic foraminifers for biostratigraphy.

3. Materials and methods

The study is based on two sections (A and B; 60 m and 270 m thickness, respectively) located in the Djebel Serdj region (Fig. 2). The sections were chosen for their good exposure and low tectonic overprint. A composite section is shown in Fig. 3.

Our detailed microfacies, biostratigraphical, and geochemical study presented in this paper are based on 145 samples (Fig. 3). In the lowermost part of the section and throughout the OAE 1a the spacing of samples was <1 m, whereas the homogenous marlstones in the upper part of the section were sampled at 2 to 10 m intervals. One-hundred fourteen thin sections were prepared from indurate samples (marlstones, limestones and siltstones). Thirty-one marlstone samples were disaggregated in clay dispersion (Rewoquat) and subsequently washed through sieves of 630, 100, 63, and 20 μm-screen. In both thin sections and washed samples, we determined microfacies composition and rounding of components. Depositional textures, relative abundances, and sorting of components were determined in thin sections. Relative abundances were obtained by using percentage estimation charts (e.g. Flügel, 2004). Components with abundances below 20% of the thin-section surface area are classified in: rare (few individuals), common (few individuals—10%), and abundant (10–20%). Abundances higher than 20% are plotted as percentages. Field observations and the results of the microscope analyses are summarized in 7 facies associations (A–G).

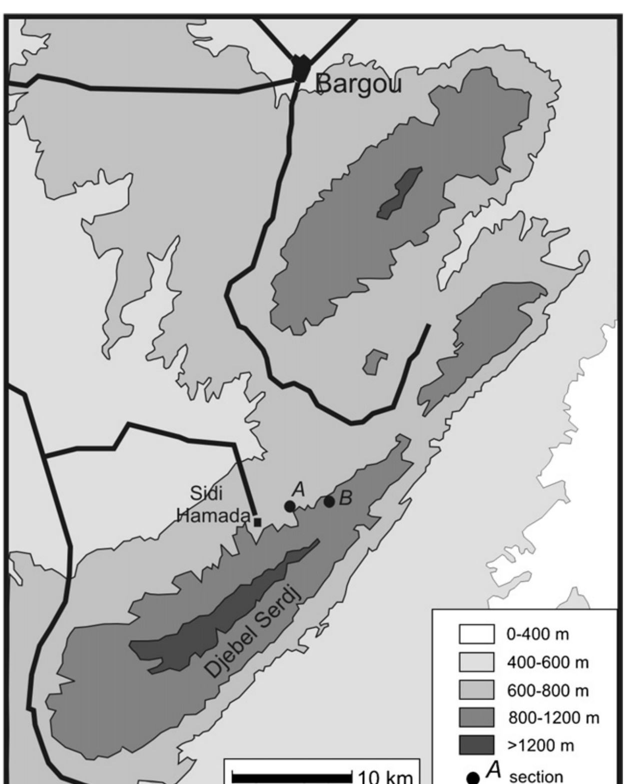

Fig. 2. Map of the Djebel Serdj area with locations of the sections investigated.

Biostratigraphy is based on planktonic foraminifers, which were picked from residues of washed material (60–100 specimen each sample). Taxonomic classifications, based mainly on shell texture and morphology, refer to Verga and Premoli Silva (2002) and Premoli Silva and Sliter (2002). The planktonic foraminifer zonal scheme is based on the standard low-latitude zonal schemes of Premoli Silva and Sliter (1999).

Carbon isotope data, additionally used for stratigraphy, has been obtained from 50 bulk rock samples which were measured in the RCOM, Bremen with a Finnigan MAT 251 mass spectrometer (accuracy +/−0.07‰). The δ^{13}C curve is divided into segments, as invented by Menegatti et al. (1998) for time-equivalent deposits in the pelagic Roter Sattel and Cismon sections (Swiss Préalps and southern Alps of northern Italy). These segments, C1–C8, are often applied as a chronostratigraphic tool in global successions (e.g. Bralower et al., 1999; Luciani et al., 2001; de Gea et al., 2003; Immenhauser et al., 2005). They include: an increase in δ^{13}C values (C1 segment), followed by a decrease (C2) and a δ^{13}C minimum (C3), a significant increase in values (C4), a stable interval (C5), followed by a further increase (C6), then variable, but overall high values (C7), followed by decreasing δ^{13}C values (C8).

The $CaCO_3$ content of 130 samples (Fig. 3) was derived from the measurement of C_{total} with a Leco CNS-200 elemental analyzer (accuracy +/−0.05%). The TOC content of the same samples was measured with a Leco CS-125 analyzer (accuracy +/− 0.02%). The measurements were carried out in the Alfred Wegener Institute, Bremerhaven.

4. Geochemical data and carbon isotope stratigraphy

4.1. $CaCO_3$ content

The carbonate content of the composite section ranges from 0 to 91% (Fig. 3). Values fluctuate considerably from 0 to around 70% in the marlstone/limestone alternation forming the first 45 m of the succession. Low values reflect the occurrence of siltstone beds. Values between 70 and 80% characterise the overlying marlstone/limestone alternation and limestone dominated deposits between 45 and 87 m. The marlstones between 87 and 142 m show a distinct decline in $CaCO_3$ content, two minima of 30.7% and 42.7% are observed at 116 and 140 m. Values at around 60 to 70%, rarely up to 90% characterise the overlying marlstone and limestone deposits (from 142 to 305 m) until the uppermost, limestone dominated part of the succession, where the $CaCO_3$ content rises up to over 90% (from 305 to 315 m).

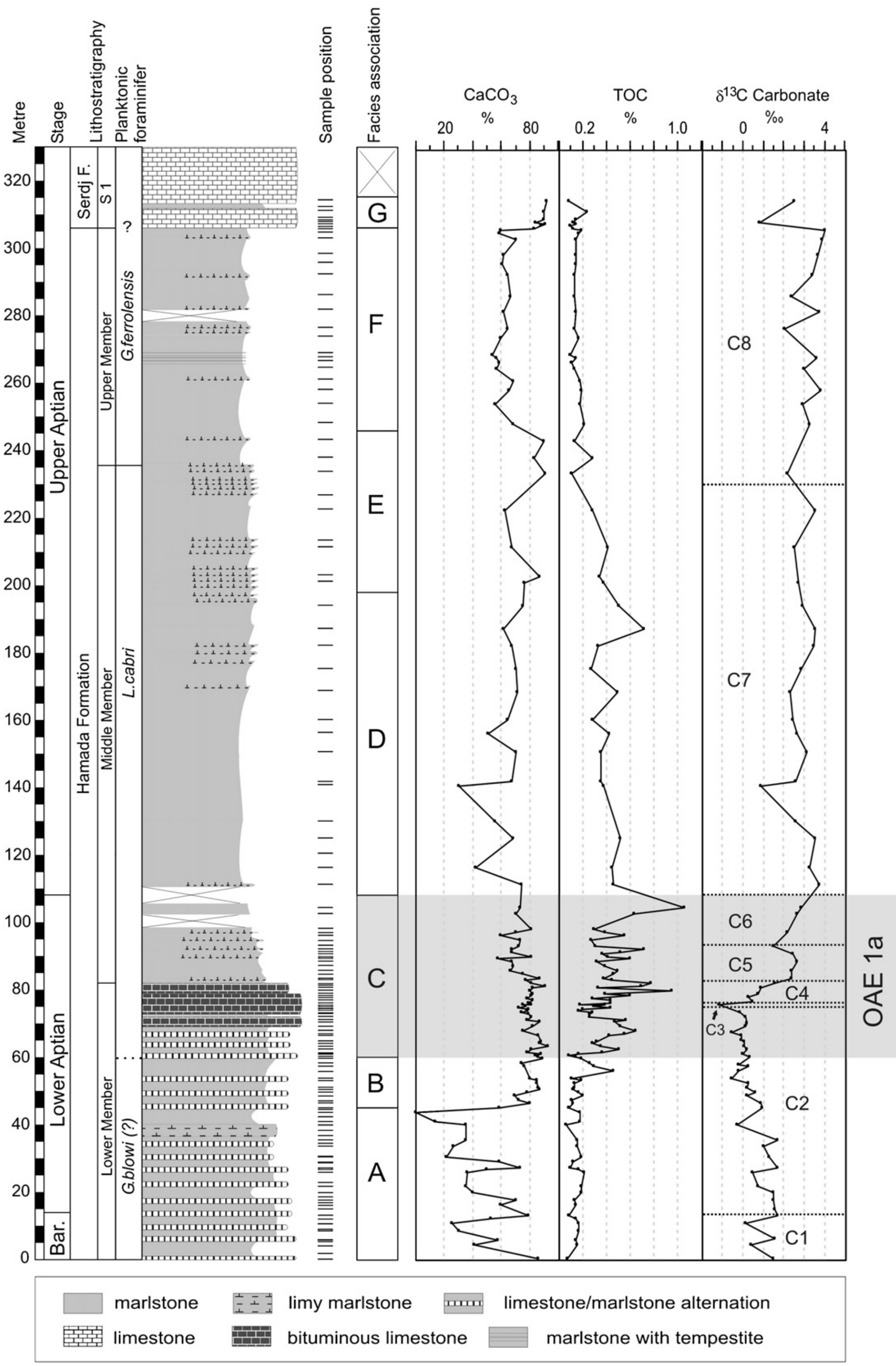

Fig. 3. Composite section of Djebel Serdj with geochemistry and biostratigraphy. The shaded area marks the OAE 1a interval. Based on two sections (A = 1–60 m, B = 60–330 m). For locations see Fig. 2.

4.2. TOC content

The total organic carbon (TOC) content of the composite section is generally low, values range from 0.1% to 1.1% (Fig. 3). Samples in the lower 55 m of the succession contain less than 0.2% TOC. The deposits between 55 and 108 m are characterised by fluctuations in values between 0.2 and 0.6%. A TOC maximum is reached at 105 m with 1.1%. The deposits from 108 to 218 m show values between 0.3 and 0.5%, exceptionally 0.7% at 187 m. The TOC content gradually decreases from 218 to 265 m, followed by more/less constant values between 0.1 and 0.2% in the uppermost part of the studied section (from 265 to 315 m).

4.3. Carbon isotope ratio and stratigraphy

δ^{13}C values of the Serdj section range between −1.2‰ and 4‰.

Our δ^{13}C curve of the studied section (Fig. 3) exhibits excursions, which closely correlate with those described by Menegatti et al. (1998) and other authors for Upper Barremian–lower Upper Aptian deposits worldwide (e.g. Jenkyns, 1995; de Gea et al., 2003; Takashima et al., 2004; Immenhauser et al., 2005). We exclude a strong diagenetic overprint of the deposits and attribute a Late Barremian–Early Aptian age for the Hamada Formation. This age is additionally confirmed by the results of our biostratigraphic studies on planktonic foraminifers (see Section 5).We divide the δ^{13}C curve into 8 segments (Fig. 3) as suggested by Menegatti et al. (1998) (see Section 3). From the base of the section upwards, the changes in δ^{13}C values are characterised as follows:

The lowermost part of the section (first 14 m) shows fluctuating values between 0.1 and 1.7‰ (C1 segment). It is followed by an overall negative shift with fluctuations in values (C2). A δ^{13}C minima is observed at 75 m (C3, −1.2‰). A positive excursion (C4) characterises the deposits between 75 and 83 m. It is followed by an interval with more/less stable δ^{13}C values (C5, 83–92 m) around 2.4‰ and a second positive shift (C6) between 92 and 111 m. Fluctuating, but predominantly high positive δ^{13}C values (ranges from 0.9 to 3.5‰) characterise the deposits between 111 and 228 m (C7). The upper part of the succession is characterised by fluctuating values between 0.81 and 4‰ (C8, 228–315 m). In coeval Tethyan successions, the whole C8 segment is marked by a pronounced negative shift (e.g. Menegatti et al., 1998; Weissert et al., 1998; de Gea et al., 2003).

5. Bio- and isotope stratigraphy

The biozonation of the Djebel Serdj composite section is based on planktonic foraminifers, which are present in the largest part of the studied succession. Their tests are recrystallised and moderately to well preserved. Zonal markers are missing in the lower part of the section (first 120 m). Here, δ^{13}C-stratigraphy (see Section 4) allows a global correlation and the tentative definition of the corresponding standard foraminifer zone (Fig. 3). From the base upward three biozones were identified (Figs. 3 and 4):

Globigerinelloides blowi (?) Zone (from 0 to 60 m): Defined as interval from the first occurrence of *G. blowi* to the first occurrence of *Leupoldina cabri*, following Premoli Silva and Sliter (1999). The zone was not identified by the use of planktonic foraminifers since *G. blowi* and other marker species are absent. Isotopic data (C1 to C3 segment) clearly define this part of the studied interval as being the uppermost part of the *G. blowi* planktonic foraminifer zone (e.g. Erba et al., 1999; Luciani et al., 2001; de Gea et al., 2003). Low diversity planktonic foraminifer assemblages are represented by hedbergellids and gorbachikellids. The upper boundary of the zone coincides with the onset of the OAE 1a interval (Premoli Silva and Sliter, 1999).

L. cabri Zone (from 60 to 235 m): Defined as acme zone of the nominal taxon, which can be applied at larger scale, then comprising the OAE 1a in the lowermost part (Premoli Silva and Sliter, 2002). We use this zone as total range zone, because rare specimens of *L. cabri* already appear during the OAE 1a interval.

Hedbergellids are the most common planktonic foraminifers in this biozone, accompanied by rare to common occurrences of leupoldinids (mainly *L. pustulans pustulans* and *L. cabri*), rare globigerinelloidids and rare gorbachikellids. Single large specimens of *Globigerinelloides ferrolensis* appear in the middle of this biozone (Fig. 4). The genera *Leupoldina* and *Gorbachikella* disappear at the upper boundary of the zone (Fig. 4). δ^{13}C data (C3–C7 segment) confirm a correlation with the *L. cabri* biozone.

G. ferrolensis Zone (from 235 m, the upper boundary is not defined): Partial range zone of *G. ferrolensis* from the last occurrence of *L. cabri* to the first occurrence of *G. algerianus*, according to Premoli Silva and Sliter (1999). Planktonic foraminifer assemblages in the *G. ferrolensis* Zone are dominated by hedbergellids, accompanied by rare large specimen of *G. ferrolensis*.

The scarcity of planktonic foraminifers in the uppermost part of the studied section prevents the identification of the planktonic foraminifer zone. δ^{13}C isotope data does not provide further stratigraphic information due to irregular isotopic values in most part of the C8 segment compared to other sections (see Section 4).

6. Depositional environments

Seven facies associations have been distinguished (A–G) on the base of main components, textures, macro-, and microfossil associations as well as lithological variations observed in the outcrops. Fig. 3 shows the ranges of the facies associations in our composite section. An overview of their characterisation and environmental interpretation is presented in Table 1. Relative abundances of selected components are illustrated in Fig. 4. A sea-level curve (Fig. 4) was established by using changes in the depositional settings (Fig. 4). From base to top, the facies associations are as follows:

6.1. Facies association A: silty bioclastic wackestone and packstone containing planktonic and small benthic foraminifers and ostracods, limestone/marlstone alternation

The 45 m thick facies association A is dominated by rhythmically alternating cm to dm thick olive green to grey marlstone and grey marly limestone beds. Grey to brownish marlstone (4–5 m thick) is intercalated in the lowermost and uppermost part. Few siltstone beds occur in the upper part. Bioturbation, thick lamination, and very thin bedding of marlstone is observed sporadically. Calcareous nodules appear in the lowermost part. Macrofossil assemblages in the first 25 m consist of rare to common

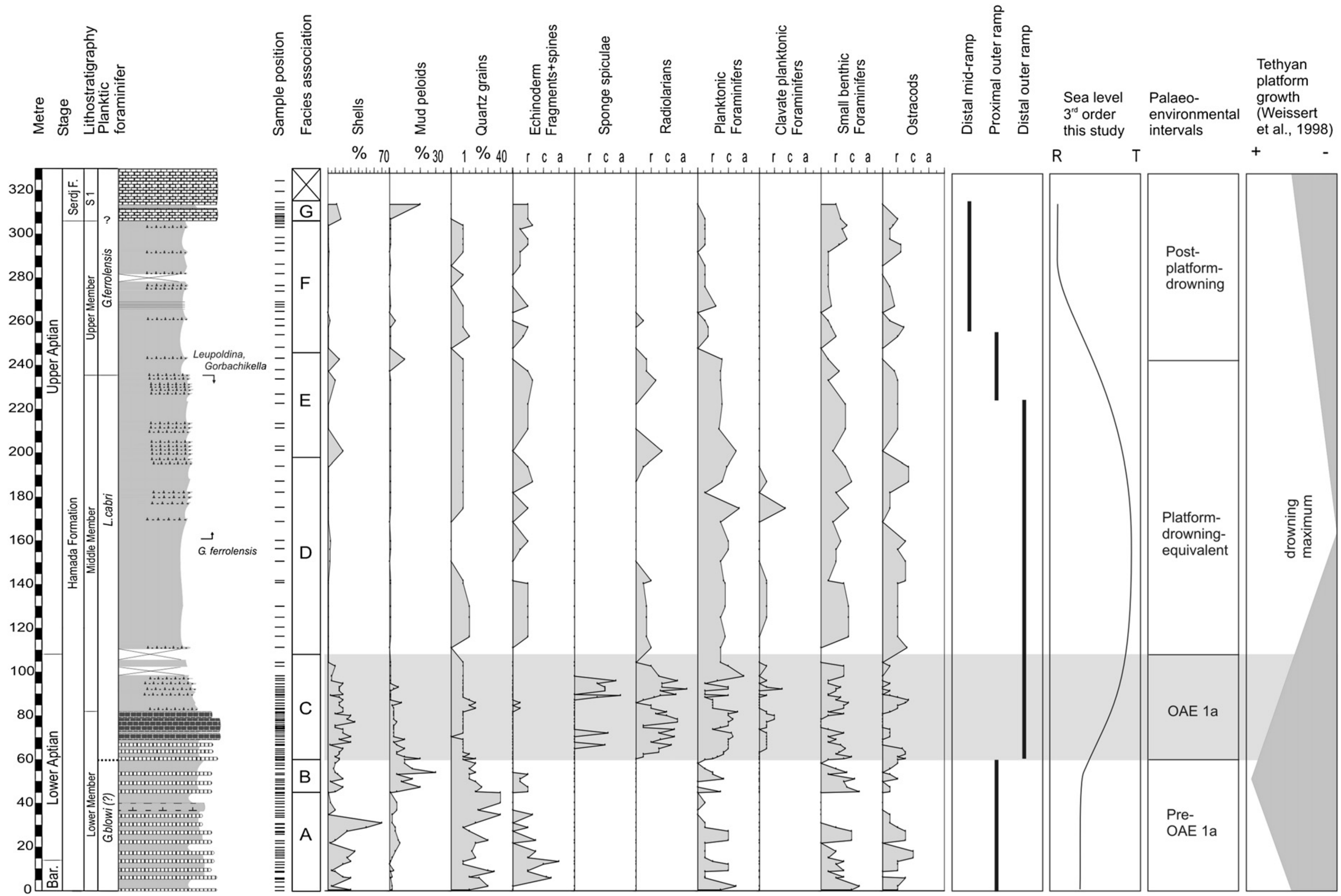

Fig. 4. Composite section of Djebel Serdj with components, depositional settings, sea-level changes, and palaeoenvironmental intervals. Abbreviations: r = rare, c = common, a = abundant; R = regression, T = transgression. The abundances of components are estimated (see Section 3). The shaded area marks the OAE 1a interval. For the description of the lithology see Fig. 3.

Table 1
Facies associations, lithology, microfacies, and palaeoenvironmental interpretation of the Serdj section

Facies association	Lithology	Microfacies/macrofossils	Environmental interpretation
A Silty bioclastic wacke- and packstone containing planktonic, small benthic foraminifers, and ostracods	Rhythmically alternating marlstone and limestone Siltstone beds appear in the upper part Nodular bedding, thick lamination and very thin bedding are observed sporadically	Components: fine-grained skeletal detritus, small shells, quartz grains, planktonic and small benthic foraminifers, ostracods and other components Macrofossils: echinoderms, brachiopods, bivalves, gastropods, shells Sorting/rounding: poorly to moderately sorted, angular to subrounded shapes	Proximal outer ramp (low-energy setting) Seafloor temporarily influenced by bottom currents
B Bioclastic to peloidal packstone containing planktonic, small benthic foraminifers, and quartz grains	Rhythmically alternating limy marlstone and limestone Nodular bedding is common in the lower part Thick lamination occurs sporadically	Components: fine-grained skeletal detritus, small shells, mud peloids, planktonic and small benthic foraminifers, quartz grains, and other components Macrofossils: brachiopods, echinoids, bivalves, gastropods, shells Sorting/rounding: poorly to moderately sorted, angular to subrounded shapes	Proximal outer ramp (low-energy setting) Oxic conditions at the seafloor
C Bioclastic wacke- and packstone containing radiolarians, planktonic foraminifers, and sponge spiculae	Alternating marlstone and limestone, bituminous limestone, and marlstone Nodular bedding and thin to thick lamination are observed sporadically	Components: fine-grained skeletal detritus, small shells, radiolarians, planktonic foraminifers, sponge spiculae, subordinated small benthic foraminifers, ostracods, and other components Macrofossils: ammonites, bivalves, gastropods, shells Sorting/rounding: poorly sorted/angular shapes orientation on bioclasts in the bedding plane	Distal outer ramp (low-energy setting) Meso- to eutrophic environment in the upper water column Possibly dysoxic conditions at the seafloor Seafloor influenced by bottom currents
D Mudstone containing planktonic, small benthic foraminifers, and ostracods	Marlstone, intercalations of limy marlstones beds Nodular and thin bedding is observed sporadically	Components: fine-grained skeletal detritus, small shells, planktonic and small benthic foraminifers, ostracods, and other components Macrofossils: – Sorting/rounding: poorly sorted/angular shapes	Distal outer ramp (low-energy setting)
E Mudstones and bioclastic wackestone, containing planktonic, small benthic foraminifers, and ostracods	Marlstone, intercalations of limestone beds Nodular bedding and thick lamination occur sporadically	Components: fine-grained skeletal detritus, small shells, planktonic and small benthic foraminifers, ostracods, and other components Macrofossils: – Sorting/rounding: poorly sorted/ angular shapes	Distal to proximal outer ramp (low-energy setting)
F Mudstone containing small benthic foraminifers	Marlstone, intercalations of limy marlstone beds Rare nodular bedding Silty limestone beds with hummocky cross-stratification are intercalated in the middle part	Components: fine-grained skeletal detritus, small shells, small benthic foraminifers, subordinated planktonic foraminifers, ostracods, and other components Macrofossils: oysters in the uppermost part Sorting/rounding: poorly sorted/angular shapes	Distal mid-ramp (low-energy setting) Deposition between fair-weather wave base and storm wave base
G Bioclastic to peloidal wackestone containing shells	Limestone beds marlstone is intercalated in the upper part Nodular bedding is common	Components: mud peloids, fine-grained skeletal detritus, small shells, small benthic foraminifers, larger shells and other components Macrofossils: oysters and shells at the base Sorting/rounding: poorly sorted/ angular shapes	Distal mid-ramp (low-energy setting)

The ranges of the facies associations in our composite section are plotted in Figs. 3 and 4.

echinoids (mainly *Toxaster*), brachiopods (Rynchonellida), bivalves (such as oysters), and gastropods. The upper 20 m is devoid of macrofossils (Fig. 5/A).

Bioclasts in the thin sections mainly consist of fine-grained skeletal detritus and smaller sized (mainly <1 mm, maximum 3–5 mm) fragmented shells. In the first 27 m, planktonic foraminifers (small hedbergellids and gorbachikellids), small benthic foraminifers (mainly *Protomarssonella praeoxycona*, *Patellina subcretacea*, and *Ataxophragmiides*), and ostracods are common, but scarce in the upper part. Larger fragmented shells (bivalves and gastropods), echinoderm fragments, echinoid spines, and small gastropods are common in the whole succession. Additional rare faunal elements are worm-tube fragments, remains of bryozoans, small indistinct calci-spheres, larger benthic foraminifers, such as *Choffatella*, and predominantly reworked orbitolines. Rounded cortoids with traces of microboring and bahamite peloids are present to common in few samples. Mud peloids and small mud

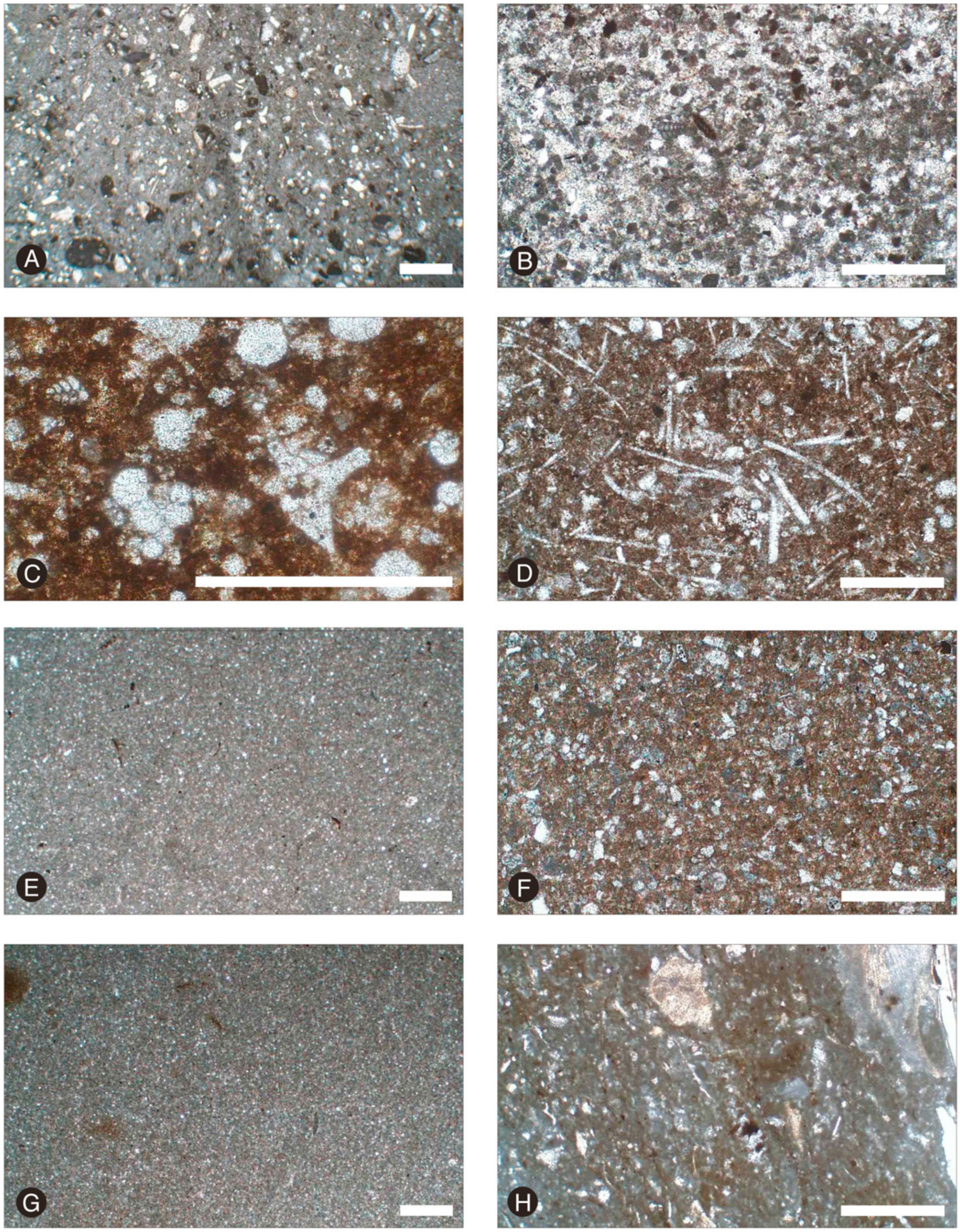

Fig. 5. Microfacies of the Serdj section. The scale is 1 mm for all images. (A) Facies association A, silty bioclastic wackestones and packstones containing planktonic and small benthic foraminifers and ostracods. (B) Facies association B, bioclastic to peloidal packstones containing planktonic and small benthic foraminifers and quartz grains. (C) Facies association C, bioclastic wackestones and packstones containing radiolarians, planktonic foraminifers, and sponge spiculae. A hedbergellid is seen in the lower left and a planktonic foraminifer of the genus *Leupoldina* in the lower right. (D) Facies association C, bioclastic wackestones and packstones containing radiolarians, planktonic foraminifers, and sponge spiculae. (E) Facies association D, mudstones containing planktonic and small benthic foraminifers and ostracods. (F) Facies association E, mudstones and bioclastic wackestones containing planktonic and small benthic foraminifers and ostracods. (G) Facies association F, mudstones containing benthic foraminifers. (H) Facies association G, bioclastic to peloidal wackestones containing shells.

intraclasts are rare. Most thin sections exhibit high amounts of quartz grains (<0.2 mm). All components are poorly to moderately sorted. In a couple of thin sections, a parallel orientation of bioclasts in the bedding plane has been observed. Fragmented bioclasts exhibit angular, subordinate subangular, and rounded shapes. Quartz grains exhibit angular shapes.

6.1.1. Interpretation

The diverse normal marine macro- and microfossil assemblages, which include planktonic organisms, and the muddy textures of the deposits suggest open marine conditions. Sorting and rounding of components indicates low-energy deposition. The occasional orientation of bioclasts in the bedding plane suggests an influence of bottom currents at times. The presence of rounded cortoids with traces of microborings, which are commonly associated with shallow-marine environments (e.g. Flügel, 2004), indicates transport from shallow-marine domains of the Tunisian platform. We suggest a proximal outer-ramp depositional environment with a strong detrital influx.

6.2. Facies association B: bioclastic to peloidal packstone containing planktonic and small benthic foraminifers and quartz grains, limestone/marlstone alternation (Fig. 5/B)

Facies association B (8 m thick) consists of rhythmically alternating grey limy marlstone and grey limestone beds (bedded at cm to dm scale) in the lower part and grey limy marlstone (7 m thick) in the upper part. Nodular bedding due to bioturbation is common in the lower part. Thick lamination and thin bedding of marlstone can be observed sporadically in the entire succession. The lower part of the deposits is characterised by high abundances of benthic macrofossils, especially well preserved brachiopods (Rynchonellida, Terebratulida) and echinoids (mainly *Toxaster*), common bivalves (such as oysters), gastropods, and large shells whereas poorly preserved ammonites (such as *Deshayesites*, *Pseudohaploceras*) and nautilids (*Heminautilus sanctaecrucis*) are rare. The upper part contains no macrofossils.

The biogenic assemblage in the thin sections is mainly composed of fine-grained skeletal detritus and smaller sized fragmented shells (predominantly <1 mm). Planktonic foraminifers (small hedbergellids and gorbachikellids) and small benthic foraminifers (mainly *P. praeoxycona* and *P. subcretacea*) are rare to common. Echinoderm fragments are common. Few samples contain rare ostracods, echinoid spines, worm-tube fragments, calcispheres of unknown origin, *Choffatella*, and small mud intraclasts. Rare rounded cortoids with traces of microborings and bahamite peloids are limited to the lowermost part of the deposits. Mud peloids often constitute a substantial part of the groundmass, their boundaries are often unclear in the micritic matrix. Quartz grains (<0.3 mm) are common in the lower part of the succession but become scarce in the upper part. All components are poorly to moderately sorted. The shapes of fragmented bioclasts are angular to subrounded. Sparite is present in some thin sections.

6.2.1. Interpretation

The diverse normal marine macro- and microfossil assemblages including planktonic organisms and the muddy textures suggest open marine conditions. Sorting and rounding of components suggest low-energy deposition. Facies association B differs from facies association A in slightly less diversified faunal associations, higher abundance of macrofossils, higher abundance of mud peloids, and a lower quartz content. High abundances of brachiopods and echinoids in the lower part of the succession suggest oxic conditions on the seafloor. A decrease in quartz content and absence of cortoids in the upper part could be related to a more distal deposition. We assume a proximal outer-ramp depositional environment for the lower part of the succession and a more distal outer-ramp depositional environment for the upper part.

6.3. Facies association C: bioclastic wackestone and packstone containing radiolarians, planktonic foraminifers, and sponge spiculae, limestone and marlstone (Fig. 5/C–D)

Facies association C (45 m thick) consists of alternating grey marlstone and limestone (7 m thick), partly rhythmically bedded dark grey bituminous limestone (15 m thick), and grey, partly splintery marlstone (23 m thick) with intercalations of grey limy marlstone beds. The uppermost part of the facies association is only partially exposed. All deposits are predominantly bedded at dm scale (rarely cm scale) and partially thin to thick laminated. Calcareous nodules are very rare. Macrofossils are scarce with the exception of two beds enriched in poorly preserved ammonites (*Pseudohaploceras*). Apart from these beds, only rare poorly preserved ammonites, rare gastropods, rare bivalves (such as oysters), and some larger fragmented shells have been observed.

The biogenic assemblage in the thin sections is composed of varying amounts of fine-grained skeletal detritus, indistinct small sized fragmented shells (mainly <1 mm), common to abundant calcified radiolarians and planktonic foraminifers (mainly hedbergellids, rarely globigerinelloidids, leupoldinids, and other clavate forms). Radiolarian species cannot be identified due to recrystallisation and dissolution. Sponge spiculae occur in highly variable amounts (absent to abundant). Additional biogenic elements are rare to common small benthic foraminifers (such as *P. praeoxycona*) and ostracods. Echinoderm fragments, echinoid spines, calcispheres of unknown origin, small mud intraclasts, and mud peloids are very rare. Quartz grains (<0.2 mm in diameter) are very rare to rare. Fine-grained skeletal detritus and fragmented bioclasts are poorly sorted and exhibit angular shapes. Quartz grains are angular to subangular shaped. Parallel orientation of bioclasts in the bedding plane is a common feature in the deposits, especially in planktonic foraminifer and radiolarian-rich layers.

6.3.1. Interpretation

Facies association C is thought to represent the local sedimentary expression of the OAE 1a. The pronounced increase in abundance of planktonic foraminifers compared to facies association A and B and appearance of high abundance of radiolarians suggest a change in the nutrient conditions in surface water and deepening, since no changes in preservation states have been observed. We suggest a deposition in a distal outer-ramp palaeoenvironment with low detrital input. Sorting and rounding of components indicate low-energy deposition. The seafloor was often influenced by bottom currents, as indicated by common orientation of bioclasts in the bedding plane. Scarce benthic macrofossils, low abundances of small benthic foraminifers and ostracods possibly suggest a dysoxic environment at the seafloor.

6.4. Facies association D: mudstone containing planktonic and small benthic foraminifers and ostracods, marlstone (Fig. 5/E)

Facies association D comprises 95 m grey, mainly structureless, sometimes splintery marlstone. Few limy marlstone beds (0.2–1 m thick) appear in the uppermost part of the deposits. No macrofossils have been observed and bioturbation is rare.

Bioclasts in the thin sections mainly consist of rare to common fine-grained skeletal detritus and small sized fragmented shells (mainly <1 mm), rare to common planktonic (mainly hedbergellids) and small benthic foraminifers (such as *Dorothia* and *Gavelinella*), as well as rare to common ostracods. Clavate planktonic foraminifers are rare, except for one thin interval near the boundary to the overlying facies association E when leupoldinids become abundant before the genus disappears completely. Echinoderm fragments and spines, radiolarians, small calcispheres, and mud peloids can be additionally recognised among the scarce components of the sequence. The sediment contains scarce quartz grains (<0.1 mm). Fragmented bioclasts and mud peloids are poorly sorted and exhibit angular shapes.

6.4.1. Interpretation

The muddy texture of these deposits, the poorly sorting and rounding of bioclasts and presence of plankton suggest an open marine depositional environment. Distinct similarities of this facies with the basinal facies described from the Tunisian Trough (northern Tunisia; Tlatli, 1980) suggest further deepening and possibly sea-level highstand. We assume a low-energy distal outer-ramp depositional environment with low detrital input. High abundances of leupoldinids have been interpreted as an adaptive response to low-oxygen levels in the upper water column by some authors (e.g. Boudagher-Fadel et al., 1997; Premoli Silva et al., 1999). Thus, the interval with increase in abundance of leupoldinids might reflect a significant change in palaeoenvironmental conditions.

6.5. Facies association E: mudstone and bioclastic wackestone containing planktonic and small benthic foraminifers and ostracods, limestone and marlstone (Fig. 5/F)

Facies association E is represented by 45 m of grey, sometimes splintery marlstone with common intercalations of dm-scale limestone beds. Nodular bedding or thick lamination is observed sporadically. Macrofossils are missing.

The biogenic assemblage in the thin sections is characterised by fine-grained skeletal detritus, small sized fragmented shells (mainly <1 mm), common planktonic foraminifers (mainly hedbergellids), rare to common small benthic foraminifers (such as *Dorothia* and *Gavelinella*), and ostracods. Additional bioclasts are echinoderm fragments and spines, rare radiolarians, and few calcispheres. Mud peloids are predominantly rare. Quartz grains (<0.1 mm) are very scarce. Components are poorly sorted, fragmented bioclasts exhibit angular, rarely subangular shapes.

6.5.1. Interpretation

Facies association E differs from facies association D predominantly in the occurrence of numerous limestone beds and higher contents of shells. The overlying deposits of facies F are characterised by mid-ramp deposition, which suggests a shallowing for facies association E. We suggest a distal to proximal outer-ramp low-energy depositional environment with little detrital input.

6.6. Facies association F: mudstone containing small benthic foraminifers, marlstone (Fig. 5/G)

Grey, splintery marlstone with few intercalations of limy marlstone beds (beds at dm scale) which exhibit a total thickness of 60 m characterise facies association F. Nodular and thin bedding is rarely observed. Few intercalations of small and sharp bedded yellow silty limestone beds (0.02–0.1 m thick) with hummocky cross-stratification or thin lamination are observed in the middle part (265–269 m). The deposits are devoid of macrofossils, only few oysters appear in the upper part.

Bioclasts in thin sections are mainly rare to common fine-grained skeletal detritus and small sized fragmented shells (mainly <1 mm). Small benthic foraminifers (such as *Praedorothia hyperconica*, *P. praeoxycona* and *Spiroplectinella gandolfi*) are rare except for the uppermost 10 m, where they are common. Ostracods and planktonic foraminifers (dominated by *Hedbergella*) are scarce. Further biogenic components are test fragments of echinoids and spines. Radiolarians are limited to rare specimens in the lowermost part of the succession. Mud peloids and quartz grains (<1 mm) are very rare to rare. Components are poorly sorted, fragmented bioclasts exhibit angular shapes.

6.6.1. Interpretation

The occurrence of storm related features (hummocky cross-stratification) suggest a depositional environment between fair-weather wave base and storm wave base with low detrital input. We assume a low-energy distal mid-ramp depositional environment.

6.7. Facies association G: bioclastic to peloidal wackestone containing shells, limestone (Fig. 5/H)

Facies association G consists of 10 m of massive grey to brownish limestone beds (bedded at dm to m scale) which are commonly nodular bedded. 1.5 m of brown marlstone with wackestone textures is observed in the upper part of the succession. Some oysters and large shells have been observed in the lower part. The studied sequence is the lower part of a massive cliff (30 m thickness), composed of limestone which is bedded at dm to m scale.

The microfacies is characterised by varying amounts of mud peloids (rare to abundant), fine-grained skeletal detritus and small sized fragmented shells (generally <1 mm). The boundaries of the peloids are often not recognisable. Larger shell fragments of bivalves and gastropods are common. Small benthic foraminifers, planktonic foraminifers, calcispheres, worm-tube fragments, echinoderm test fragments and spines are rare. Small mud intraclasts occur in a few samples. Quartz grains are rare to absent (diameter<1 mm). Some thin sections exhibit sparite. The sorting of the components is poor, fragmented bioclasts are angular, rarely subangular shaped.

6.7.1. Interpretation

Facies association G is characterised by low-energy deposition. Due to the scarceness of plankton we suggest a deposition in a distal mid-ramp environment.

7. Discussion

7.1. Biostratigraphy and $\delta^{13}C$ stratigraphy

Our integrated planktonic foraminifer and δ^{13}C stratigraphy dates the Hamada Formation at Djebel Serdj as late Late Barremian–early Late Aptian in age. The subdivision of the composite section by using the standard low-latitude planktonic foraminifer biozones (Figs. 3 and 4) (*G. blowi*, *L. cabri*, and *G. ferrolensis* Zone; Premoli Silva and Sliter, 1999) modifies and extends the biostratigraphic framework of Tlatli (1980), who interpreted the deposits as being Early Aptian–early Late Aptian in age. The position of the Lower/Upper Aptian boundary, which was formerly located at the base of the *G. ferrolensis* Zone (base of the upper member of the Hamada Formation; Tlatli, 1980), is now set on top of the OAE 1a in the lower part of the *L. cabri* Zone, in the lower part of the middle member of the Hamada Formation. The new position follows common use (e.g. Menegatti et al., 1998; Luciani et al., 2001; Bellanca et al., 2002).

Overall, the trends in δ^{13}C values in the Serdj composite section are consistent with other records worldwide, but the absolute values are generally 0.5–1.5‰ lower relative to some pelagic sections, e.g. sections from the Alpine Tethys (Menegatti et al., 1998) or from the Vocontian Basin (Herrle et al., 2004). The greatest discrepancy is observed in the C2 and C3 segments. The lighter values in general might be related to the hemipelagic setting of the Serdj section, thus being influenced by δ^{12}C enriched coastal water-masses.

The stratigraphical range of the OAE 1a in the studied section differs from some other investigations (e.g. Menegatti et al., 1998; de Gea et al., 2003; Föllmi et al., 2006). To date, authors apply different criteria to define the onset of the event. Menegatti et al. (1998) defined the OAE 1a chemostratigraphically as the interval ranging from the base of the C4 segment to the C6/C7-segment boundary, even if organic carbon-rich sediments crop out below. Some authors adapted the segments, but chose a part within the C2 segment or the C3 segment as onset (e.g. Bralower et al., 1999; Luciani et al., 2001; Bellanca et al., 2002; Danelian et al., 2004). Within these segments, significant changes in marine flora and fauna are already observed, e.g. an increase in abundance of radiolarians, a crisis of nannoconids, and eutrophication induced changes in shallow-water platform communities (e.g. Erba, 1994; Weissert et al., 1998; Danelian et al., 2004; Erba, 2004; Föllmi et al., 2006). In the Serdj section, a significant change in microfacies composition occurs in the upper part of the C2 segment. Here, radiolarians and planktonic foraminifers suddenly increase in abundance, indicating a transgression and eutrophication of the upper water column (see Section 6.3). Therefore, the OAE 1a in the Serdj section is thought to range from the upper part of the C2 segment to the C6/C7-segment boundary.

7.2. Sea-level changes

A 3rd-order sea-level curve for the Tunisian shelf (Fig. 4) was established by using changes in the depositional settings (Section 6). Our sea-level curve closely correlates with the global curve of Haq et al. (1988) and the curve of Haq and Al-Qahtani (2005) for the Arabian platform. Therefore, the sea-level changes on the Tunisian shelf are interpreted to reflect global sea-level changes and are not related to local tectonics. Microfacies data in the lower part of the Serdj composite section suggests a transgression, which started shortly before OAE 1a in the upper part of the *G. blowi* biozone. A sea-level highstand possibly extends over most part of the *L. cabri* Zone, followed by a regression in the transition interval to the *G. ferrolensis* Zone. A transgression and sea-level highstand associated with the *G. blowi*–*G. ferrolensis* Zones have been discussed in several other papers (e.g. Erbacher et al., 1996; Weissert et al., 1998; Jones and Jenkyns, 2001; Föllmi et al., 2006). It has been related to enhanced coastal nutrification during the OAE 1a by significantly expanding the areas of shallow banks and inland seas, thus increasing the area receiving large terrestrial nutrient influxes (e.g. Schlanger and Jenkyns, 1976; Jones and Jenkyns, 2001).

7.3. Palaeoenvironmental evolution of the Tunisian shelf

Our microfacies analyses in combination with field observations provide information on the palaeoenvironmental evolution and sea-level fluctuations of the Tunisian shelf during the Late Barremian–early Late Aptian interval. While Tlatli (1980) interpreted the deposits of the Hamada Formation predominantly as being basinal deposits, our new data suggest a deposition in mid- to outer-ramp palaeoenvironments (see Section 6). We suggest to subdivide the palaeoenvironmental evolution into four intervals (Fig. 4): 1) a pre-OAE 1a interval, 2) an OAE 1a interval, 3) a platform-drowning-equivalent interval, and 3) a post-platform-drowning interval. These intervals are discussed below with respect to the local sedimentary expression of the OAE 1a.

7.3.1. Pre-OAE 1a

The pre-OAE 1a interval comprises the lowermost part of the studied section (facies associations A and B) and is characterised by bioclastic wacke- and packstones which are interpreted as low-energy proximal outer-ramp deposits (see Sections 6.1 and 6.2). A moderate to high siliciclastic content especially in the upper part of facies association A probably originates from weathering on the stable uplift in the south (“Kasserine Island”, M’Rabet, 1987). High abundance of benthic macroorganisms in the lower part facies association B indicates oxic seafloor-conditions. A decrease in detrital influx and decline in transported shallow-water platform components (cortoids) possibly indicate the onset of the transgression, which is commonly associated with the OAE 1a (see Section 7.2).

7.3.2. OAE 1a

The deposits of facies association C, which are thought to represent the OAE 1a interval (see Section 6.3), are characterised by bioclastic wacke- and packstones and are interpreted as distal outer-ramp low-energy facies deposited under transgressive conditions. By comparison with other investigations, our studies on the microfacies of the event confirm some main observations, but also highlight some differences.

High abundance of radiolarians (Fig. 4) during the event are in agreement with previous studies on OAE 1a related deposits in pelagic successions (e.g. Erba et al., 1999; Premoli Silva et al., 1999; Danelian et al., 2002; Marsaglia, 2005). Recent radiolarian-rich deposits predominantly accumulate under areas of high fertility conditions in surface water, especially under upwelling conditions in which required nutrients and dissolved silica are provided (Racki and Cordey, 2000). Cretaceous radiolarian-rich deposits related to OAE 1a are also most probably indicative of high nutrient concentrations, because the increase in radiolarian abundance coincides with additional productivity-indicators (such as enhanced accumulation rates of organic matter, composition of nanno- and microfossil assemblages) (e.g. Erbacher et al., 1996; Jenkyns, 1999; Premoli Silva et al., 1999; Erba, 2004). An unusual observation is the co-occurrence of radiolarians and moderately to well preserved planktonic foraminifers (Fig. 4) during most part of the OAE 1a in the Serdj section. Both show similarities in their distribution pattern (Fig. 4). In pelagic successions, planktonic foraminifers are often scarce or absent and poorly preserved across the OAE 1a interval (e.g. Coccioni et al., 1992; Cobianchi et al., 1999; Premoli Silva et al., 1999; Marsaglia, 2005) and characteristically out of phase with radiolarian abundance (e.g. Coccioni et al., 1992; Cobianchi et al., 1999; Luciani et al., 2001). The temporary absence and poorly preservation of calcareous plankton in pelagic successions has been related to shoalings of the CCD as consequence of high productivity (e.g. Weissert et al., 1985; Bralower et al., 1994; Bralower et al., 2002; Danelian et al., 2002), and/or unfavorable conditions for calcareous plankton in surface waters (e.g. Cobianchi et al., 1999; Erba, 2004).

Planktonic foraminifer assemblages during the event at the Serdj section are mainly provided by hedbergellids (see Section 6.3), which have been also described for the OAE 1a from many other localities (e.g. Cobianchi et al., 1999; Premoli Silva et al., 1999; Luciani et al., 2006). Hedbergellids have been interpreted as being adapted to meso- to eutrophic conditions in the upper water column, they were probably capable of tolerating significant fluctuations in temperature, salinity, nutrients, and oxygen (e.g. Coccioni et al., 1992; Premoli Silva and Sliter, 1999; Luciani et al., 2001). Globigerinelloidids are very scarce within the planktonic foraminifer assemblage in the studied section, which is consistent with results from some other localities (e.g. Cobianchi et al., 1999; Premoli Silva et al., 1999; Luciani et al., 2006). This genus has been related to oligo- to mesotrophic conditions in surface waters (e.g. Coccioni et al., 1992; Premoli Silva et al., 1999). Leupoldinids, which are a consistent component of planktonic foraminifer assemblages in some other Tethyan hemipelagic or pelagic successions (e.g. Luciani and Cobianchi, 1994; Aguado et al., 1999; Premoli Silva et al., 1999) are also scarce in the studied section during OAE 1a. This group has been often interpreted as indicator for eutrophic conditions and low-oxygen levels in the upper water column (Boudagher-Fadel et al., 1997; Premoli Silva et al., 1999, Coccioni et al., 2006). Considering that ecological behaviour of Cretaceous planktonic foraminifera is still inadequately understood, planktonic foraminifer assemblages in combination with high abundance of radiolarians suggest meso- to eutrophic conditions in the upper water column of the studied area and possibly higher oxygen levels in comparison to pelagic palaeoenvironments.

Low abundance of benthic foraminifers in the Serdj section, which is a common feature in deposits of the OAE 1a interval (e.g. Coccioni et al., 1992; Premoli Silva et al., 1999; Cobianchi et al., 1999; Luciani et al., 2001), in combination with low abundance of ostracods and scarceness of benthic macroorganisms possibly indicates a dysoxic milieu at the seafloor.

The carbonate content of the OAE 1a interval in the studied section ranges from around 80% in the lower half of the OAE 1a to around 65% in the upper half (Fig. 3). Several pronounced drops in values, which have been described from coeval pelagic successions (e.g. Menegatti et al., 1998; Bralower et al., 1999), are missing at Djebel Serdj. Furthermore, some pelagic successions are even partially or entirely devoid of carbonate (e.g. Baudin et al., 1998; Danelian et al., 2002). These observations in pelagic sections have been related to shoalings of the CCD or unfavorable conditions for carbonate producing organisms in surface water, as already mentioned in relation with the temporary absence and poor preservation of planktonic foraminifers. Shoalings of the CCD would have not affected carbonate sedimentation in the hemipelagic Serdj area, thus explaining the high carbonate content as well as high abundance of planktonic foraminifers. The hemipelagic Cau section (SE Spain, Aguado et al., 1999) also shows predominantly high abundance of planktonic foraminifers. A lower nutrient content in the upper water column favored by carbonate producing biota cannot be excluded as reason for the observations at Djebel Serdj, but seems to be less probable considering the richness in radiolarians (up to 20% of thin-section surface area), which is consistent with pelagic sections.

Another explanation for the high carbonate content in the Serdj section, especially in the lower half of the OAE 1a (around 80%), could be carbonate export from shallow-marine areas with still-active shallow-water carbonate production. Shallow-water platform components (cortoids) in the lowermost part of the section (facies association A and B) indicate the studied area being adjacent to the shallow-marine domain of the Tunisian platform. Recent studies on shallow-marine successions in Oman and Egypt (Immenhauser et al., 2005; Thielemann, 2006) document an uninterrupted carbonate production during the event. We suggest that the pronounced perturbation of carbonate production during OAE 1a, as discussed by several authors for neritic as well as pelagic environments (e.g. Weissert et al., 1998; Wissler et al., 2003; Weissert and Erba, 2004; Föllmi et al., 2006), did not affect the southern Tethys margin or at least not to the same extent.

The TOC values during the OAE 1a interval in the Djebel Serdj section (between 0.2% and 1%) (Fig. 3) are very low in comparison to Tethyan pelagic sections (e.g. Menegatti et al., 1998; Danelian et al., 2002), which show values of up to 8% or more. Low values (about 0.8%) are also observed in the hemipelagic Cau section, SE Spain (Aguado et al., 1999), which was affected by a high subsidence rate, too. These authors interpreted the low contents as being a result of terrigenous dilution. The overall low values in the Serdj section can also be explained by dilution (here by terrigenous input and carbonate sedimentation), considering the extraordinary high sedimentation rate in the studied section.

7.3.3. Platform-drowning-equivalent

The platform-drowning-equivalent interval (Fig. 4) is characterised by mudstones and bioclastic wackestones (facies associations D and E) which are interpreted as low-energy distal outer-ramp facies deposited during further transgression, possibly sea-level highstand and regression (see Sections 6.4 and 6.5). Facies association D is time-equivalent with the maximum of the early Late Aptian shallow-carbonate-platform drowning (Fig. 4; Weissert et al., 1998). The corresponding deposits are characterised by mudstones in the Serdj section, being partly poor in $CaCO_3$ content and nearly devoid of macrofossils.

Studies on time-equivalent shallow-marine deposits on the Tunisian platform (e.g. Chekhma et al., 1990; Chaabani et al., 1992; Chaabani and Razgallah, 2006) do not add information on regional ecological changes in this time interval, because biostratigraphic markers for high resolution studies are missing in central Tunisian shallow-marine successions and $\delta^{13}C$ curves have not yet been established.

A small interval at the upper boundary of facies association D, which shows an increase in abundance of planktonic foraminifers of the genus *Leupoldina*, is probably related to a temporary change in palaeoenvironmental conditions. High abundances of leupoldinids have been interpreted as an adaptive response to low-oxygen levels in the upper water column, as discussed for the OAE 1a interval (facies association C). The interval in the upper part of the *L. cabri* Zone has not been described elsewhere, and therefore it is interpreted to reflect a local event.

7.4. Post-platform drowning

Mudstones and bioclastic wackestones of facies association F and G (see Sections 6.6 and 6.7) are interpreted to reflect the post-platform-drowning interval (Fig. 4). The deposits are predominantly characterised by low-energy deposition. Storm related features (hummocky cross-stratification) within facies association F indicate the establishment of a mid-ramp facies as consequence of a regression. The mid-ramp deposition probably prevails until the uppermost part of the studied section.

8. Conclusions

The Upper Barremian–lower Upper Aptian deposits of the Hamada Formation in the Djebel Serdj area, north-central Tunisia have provided excellent opportunity to study the evolution of a hemipelagic mid- to outer-ramp palaeoenvironment situated on the southern edge of the Tethyan ocean in detail. Altogether, four palaeoenvironmental intervals are subdivided: 1) a pre-OAE 1a interval, 2) an OAE 1a-interval, 3) a platform-drowning-equivalent interval, and 4) a post-platform-drowning interval. The results of the detailed microfacies, biostratigraphy, $\delta^{13}C$ stratigraphy, and geochemistry analyses concerning the OAE 1a confirm main observations in comparison to pelagic successions, but also highlight some differences. Our microfacies analyses show, that in the hemipelagic setting of the Tunisian shelf, the severe palaeoenvironmental perturbation related to the OAE 1a led to radiolarian blooms, which is consistent with results from pelagic successions worldwide. By interpreting high abundance of radiolarians as high fertility indicator, this study confirms the high-productivity model for the OAE 1a. Transgressive conditions during the event, which have been described by several other authors, can also be confirmed for the studied section. High abundance of moderately to well preserved planktonic foraminifers and a high carbonate content during OAE 1a are unusual observations in comparison to pelagic successions, which can be most probably explained by a better preservation. Considering the palaeobathymetry of the section, the studied area would have not been influenced by shoalings of the CCD, which probably led to intensified carbonate dissolution during pelagic sedimentation. The unusual high carbonate content at Djebel Serdj could be additionally related to carbonate export from shallow-marine areas of the Tunisian platform. Recent studies on shallow-marine successions of the southern Tethys margin suggest a high carbonate production during the event.

Time-equivalent deposits of the maximum of shallow-marine carbonate-platform drowning were identified on the base of biostratigraphy and $\delta^{13}C$ stratigraphy. They are represented by macrofossil-poor mudstones, deposited during further transgression and possibly sea-level highstand.

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