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Increased terrigenous influx but no drowning: palaeoenvironmental evolution of the Tunisian carbonate platform margin during the Late Aptian

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ABSTRACT

During the Aptian, some carbonate platforms of the sub-tropical realm (for example, on the northern Tethys margin or in the Gulf of Mexico) were affected repeatedly by severe perturbations in the carbonate production factory and drowning, preferentially during global warming events such as the Early Aptian Oceanic Anoxic Event 1a and a prominent mid-Late Aptian warming interval. These platform growth crises have been explained mainly by strongly increased coastal runoff (for example, siliciclastics and nutrients) in combination with pronounced eustatic sea-level rises. In the last few years, increasing evidence suggests that carbonate platforms of lower latitudes were generally less or even not affected by environmental perturbations during these events. This raises the question as to the responsible factors that promoted platform growth or decline in different latitudinal areas. In this study, Upper Aptian (Middle Gargasian to Uppermost Clansayesian) inner-tropical carbonate ramp deposits of the Serdj Formation at Djebel Serdj, north-central Tunisia are studied in detail with regard to microfacies, lithology, biostratigraphy and chemostratigraphy. These data allow reconstruction of the palaeoenvironmental evolution of the Tunisian carbonate platform margin and investigation of its response to the prominent mid-Late Aptian warming interval. The unusually expanded, 600 m thick Serdj Formation consists of limestones, marlstones and siltstones, suggesting deposition within mid-ramp to inner-ramp palaeoenvironments. Deposits of the mid-Late Aptian are represented by quartz-rich platform carbonates and siltstones, probably resulting from increased coastal runoff on the Tunisian shelf as a response to global warming and accelerated water cycling. The siliciclastic input was accompanied by elevated nutrient levels as indicated by a partial decline in the abundance of oligotrophic biota and mass occurrences of orbitolines and green algae. Carbonate platform drowning during the mid-Late Aptian, as reported from the sub-tropical realm, has not been identified. A comparison with other tropical river-influenced platforms suggests that none of them drowned during the mid-Late Aptian. One important reason might be widespread arid to semi-arid climatic conditions within lower latitudes during that time, promoting platform growth due to comparably low nutrient runoff.

Keywords Aptian, biostratigraphy, carbonate platform, chemostratigraphy, global climate change, microfacies.

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INTRODUCTION

Carbonate platforms are sensitive recorders of changes in the ocean/climate system and have attracted much attention as a means of evaluating the Mid Cretaceous Greenhouse Earth (Aptian to Turonian, 120 to 90 Ma). The carbonate platforms latitudinally extended during this period, characterized by globally averaged sea-surface temperatures possibly 6° to 14 °C warmer than at present (Barron, 1983; Pucéat *et al.*, 2003; Steuber *et al.*, 2005). Although their maximum expansion was reached in the Late Albian and Santonian (Johnson *et al.*, 1996; Skelton, 2003), the latitudinal limits during the Late Aptian possibly already exceeded those of the preceding time intervals (Takashima *et al.*, 2007). During the Aptian, the carbonate platforms were colonized extensively by characteristic biota, including rudist bivalves, scleractinian corals, stromatoporids, benthonic foraminifera (including miliolids and orbitolinids) and nerineacean gastropods, as well as dasycladacean algae and calcareous red algae (Masse, 1992; Kiessling *et al.*, 2003).

The climate during the Aptian was far from stable. Several brief global cooling and warming episodes (1 to 5 Myr-scale) have been identified (Weissert & Lini, 1991; Price, 2003; Weissert & Erba, 2004; Takashima *et al.*, 2007). The warming episodes are associated with accelerated water cycling, increased terrigenous influx (for example, siliciclastics and nutrients) on the sub-tropical/tropical shelves and widespread carbonate platform drowning during eustatic sea-level rises (Weissert, 1990; Weissert *et al.*, 1998; Wortmann *et al.*, 2004; Föllmi & Gainon, 2008). One of these warming intervals, which has been linked to a major platform demise (Föllmi *et al.*, 1994; Weissert *et al.*, 1998), as well as biotic changes in boreal/tropical open marine environments (Weissert & Lini, 1991; Mutterlose, 1992, 1998; Herrle & Mutterlose, 2003; Takashima *et al.*, 2007) has been ascribed to the mid-Late Aptian (*Hedbergella trocoidea/Ticinella bejaouensis* planktonic foraminiferal zone) and was termed 'Aptian Greenhouse Earth 2' by Weissert & Lini (1991). This 3 to 4 Myr lasting warming interval is associated with a globally traceable positive carbon isotope excursion (Föllmi *et al.*, 1994; Bralower *et al.*, 1999; Jenkyns & Wilson, 1999; Herrle *et al.*, 2004) and is reflected in a negative oxygen isotope excursion (Clarke & Jenkyns, 1999; Weissert & Erba, 2004). Hypotheses to account for the global temperature elevation concentrate on increased levels of CO_2 in the atmosphere related to the Kerguelen Plateau volcanism in the Indian Ocean (Bralower *et al.*, 1997; Coffin *et al.*, 2002; Takashima *et al.*, 2007).

Until now, the hypothesis of widespread carbonate platform drowning during the warming intervals of the Aptian, such as the mid-Late Aptian warming event, has been verified for some areas of the northern Tethys margin and the Gulf of Mexico only (Funk *et al.*, 1993; Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Lehmann *et al.*, 2000; Wilmsen, 2005; Castro *et al.*, 2006). The most detailed investigations were carried out on platforms of the northern Tethys margin, where drowning is indicated by widespread phosphorite hardgrounds capping platform limestones, the occurrence of siliciclastics and hiatuses (Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Wortmann *et al.*, 2004). Elevated riverine nutrient loads are regarded as the most important trigger for the observed drowning (Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Föllmi & Gainon, 2008). The effects of excess nutrients (such as those derived from nitrogen and phosphorus) on carbonate platforms include reduced water transparency, destabilized oxygen levels and pH, leading to drastic changes in platform communities and reduced carbonate production (Hallock & Schlager, 1986; Wood, 1993; Mutti & Hallock, 2003). Platform community changes often preceded drowning on the northern Tethys margin: oligotrophic biotic communities were replaced by mesotrophic to eutrophic assemblages (Föllmi *et al.*, 1994, 2006; Föllmi & Gainon, 2008).

Some authors have suggested that the proposed carbonate platform drowning episodes during the warming intervals of the Aptian additionally were triggered by a rapid increase in the partial pressure of CO_2 (pCO_2) in the surface ocean, and thus sea water became more acidic (Herrle & Mutterlose, 2003; Wissler *et al.*, 2003; Weissert & Erba, 2004). However, the extent of the temperature rise during the warming events of the Aptian is controversial and extreme scenarios of widespread carbonate platform drowning caused by a global humidity and river runoff increase are not well-substantiated. Oxygen isotopes used as a palaeotemperature proxy are very sensitive to diagenesis and thus often are not reliable tools (Hudson, 1977; Brand & Veizer, 1981). Some more recent publications even suggest that climate variations during the Aptian were just a matter of a very few degrees or that pCO_2 changes were of minor importance only (Kuhnt *et al.*, 1998; Heimhofer *et al.*, 2004; Haworth *et al.*, 2005). In this case, one would assume less-intense environmental changes on the shelves than previously suggested.

The aim of this study is to reconstruct the palaeoenvironmental evolution of a tropical southern Tethys carbonate platform margin in the Serdj area, north-central Tunisia, by using detailed lithology and microfacies analyses as well as biostratigraphy and chemostratigraphy. Emphasis is given to palaeoecological changes on the Tunisian carbonate platform during the mid-Late Aptian. The results are compared to investigations on coeval carbonate platforms of the sub-tropical/tropical realm to test the hypothesis of widespread platform drowning during the mid-Late Aptian and to discuss the impact of global warming events during the Aptian on different latitudinal areas and climate zones.

GEOLOGICAL SETTING

Palaeogeography of the central Tunisian carbonate platform

The studied area was located on the northern platform margin of the central Tunisian carbonate platform, about 25 km north of a large island (Kasserine Island; Fig. 1). The platform was part of the broad inner-tropical carbonate platform system that extended over large parts of the southern Tethys continental margin during the Late Aptian (Kiessling *et al.*, 2003). Shallow marine carbonate sedimentation in Tunisia during this time took place in a relatively stable realm delimited to the south by the clastic, riverine sedimentation of the terrestrial Saharan platform and to the north by open, mainly deep marine sedimentation of the Tunisian Trough (Boltenhagen, 1985; M'Rabet, 1987; Lefranc & Guiraud, 1990). A mosaic of islands in the central part of the platform probably divided it into a more or less restricted southern part and a Tethys-connected northern part with a ramp-type platform margin (Tlatli, 1980; Marie *et al.*, 1982; M'Rabet, 1987). A north–south trending high zone ('North/South Axis') separated the platform from the eastern Tunsian shelf (Ben Ferjani *et al.*, 1990; Burollet, 1990).

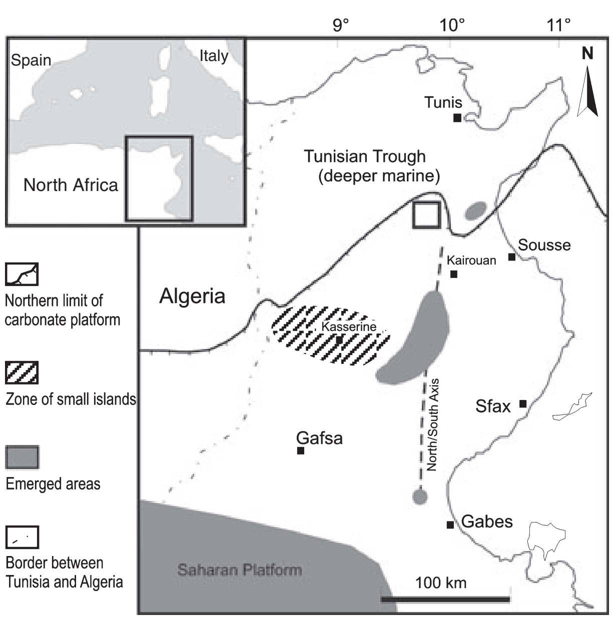

Fig. 1. Palaeogeographic map of Tunisia for the Late Aptian. The black rectangle in the main map marks the investigated area (Fig. 2); after Tlatli (1980) and M'Rabet (1987).

Lithostratigraphy

The Upper Aptian shallow marine carbonates of central Tunisia are represented by the Orbata Formation in the southern part of central Tunisia (Gafsa–Sidi Bouzid region) and by the Serdj Formation in the more northerly parts (Kasserine–Kairouan region) (Burollet, 1956; M'Rabet, 1987; M'Rabet *et al.*, 1995). Both formations are 450 to 660 m thick on average, but show considerably reduced thickness along the North/South Axis and the island-zone around the city of Kasserine (Burollet, 1956; Ben Ferjani *et al.*, 1990). The Orbata Formation mainly consists of inner shelf carbonates with intercalations of evaporites and is ascribed to the southern, more protected part of the Tunisian carbonate platform. It passes northwards into the Serdj Formation, which is characterized by inner shelf carbonates and deposits of the ramp-type platform margin, for example, reefal limestones (Tlatli, 1980; M'Rabet, 1981, 1987; Ben Ferjani *et al.*, 1990; Tandia, 2001; Chaabani & Razgallah, 2006). The upper boundary of both formations is marked commonly by an emergence surface, reflecting the exposure of the platform caused by tectonic movements in the Late Gargasian to Latest Clansayesian (Marie *et al.*, 1982; Ben Ferjani *et al.*, 1990; Chaabani & Razgallah, 2006). It has been suggested that the central parts of the platform were affected first, hence Upper Aptian platform carbonates in this region comprise the shortest time interval (M'Rabet *et al.*, 1995; Chaabani & Razgallah, 2006). However, the detailed ages of both formations are still a matter of debate, because biostratigraphic markers are scarce generally in Tunisian shallow marine successions and chemostratigraphic curves are not well-established.

Geological setting of the studied area

The Serdj Mountain is located in north/central Tunisia (Figs 1 and 2). The evolution of the massif has been ascribed to different tectonic movements during the Cretaceous–Tertiary. It is characterized by a SW–NE striking anticlinorium affected by a variety of faults, for example, faults with a SW–NE direction, a large normal fault at the NW-flank of Djebel Serdj, including dextral and sinistal strike-slip faults of several directions (with a magnitude of displacement between one and several tens of metres) (Turki, 1977).

Barremian to possibly Albian sediments (hemipelagic to shallow marine marlstone, limestone and siltstone) cropping out at Djebel Serdj (Fig. 3) have been studied by several authors over the years (Pervinquiére, 1903; Burollet, 1956; Turki, 1975; Tlatli, 1980; Heldt *et al.*, 2008; Lehmann *et al.*, 2009). These sediments belong to the Hamada Formation, Serdj Formation and, possibly, the Fahdene Formation (Tlatli, 1980; Heldt *et al.*, 2008). The Serdj Formation studied herein is characterized by 600 m thick limestones (for example, bioclastic and peloidal wackestone, packstone, grainstones, oolitic grainstones and coral framestones), marlstones and siltstones. The upper boundary of the formation is characterized by an emergence surface, reflecting the exposure of the north-eastern part of the carbonate platform probably in the Late Clansayesian (compare *Lithostratigraphy* section above). The emergence surface is overlain by limestone and marlstone, possibly of Lower and Middle Albian age (Fahdene Formation; Tlatli, 1980).

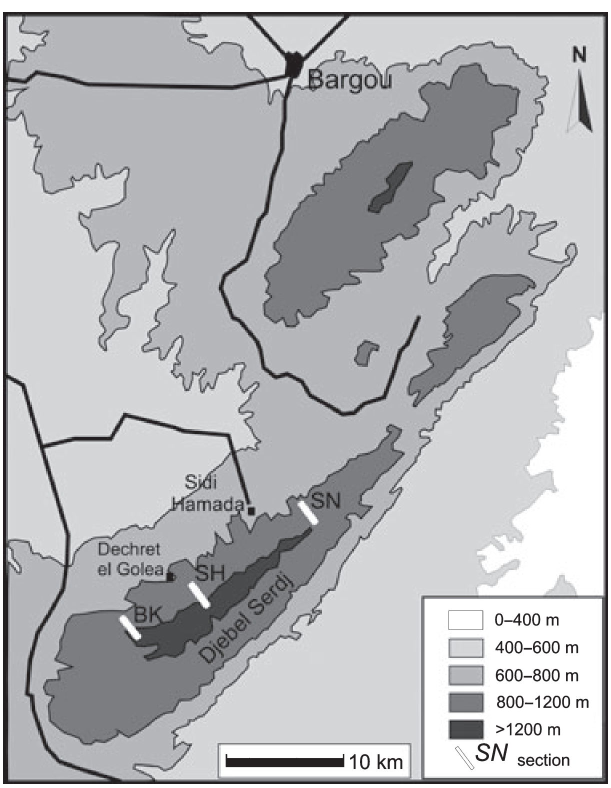

Fig. 2. Map of the Serdj area with locations of the sections investigated.

The facies of the Serdj Formation at Djebel Serdj has been investigated by Tlatli (1980) and dated as Middle Gargasian to Latest Clansayesian by planktonic and benthonic foraminifera. Some of the biostratigraphic markers used by this author are rather vague and refer to outdated regional zonal schemes, whereas others (planktonic foraminifera and orbitolines) can still be applied to date the sections (compare *Biostratigraphy* section below). Tlatli (1980) subdivided the Serdj Formation into five calcareous units (S1 to S5) separated by silty and marly levels (T1 to T4). Tlatli suggested that the deposits reflect inner to outer ramp palaeoenvironments close to the open marine domain of the Tunisian Trough and described a trend to more shallow marine environments upwards.

MATERIAL AND METHODS

This study is based on three sections (SN, SH and BK; 575, 515 and 220 m, respectively) along Djebel Serdj (Figs 2 and 3), together comprising nearly the entire Serdj Formation. The uppermost 50 to 70 m of the formation was not recorded for this study. All sections show low syn-sedimentary and post-sedimentary tectonic overprint.

The detailed microfacies, biostratigraphy and geochemical analyses presented in this study were carried out on 319 samples. In sections SN and BK, the microfacies samples were collected mainly between 1 and 5 m apart, whereas section SH was sampled at 5 to 10 m intervals. A total of 298 thin sections were prepared from indurated samples (limey marlstone, limestone and siltstone). Twenty-one marlstone samples were disaggregated in clay dispersion (Rewoquat) and subsequently washed through sieves of 630, 100, 63 and 20 micron-screen. Microfacies composition and rounding of components were determined in thin sections and washed samples. Depositional textures, relative abundances and

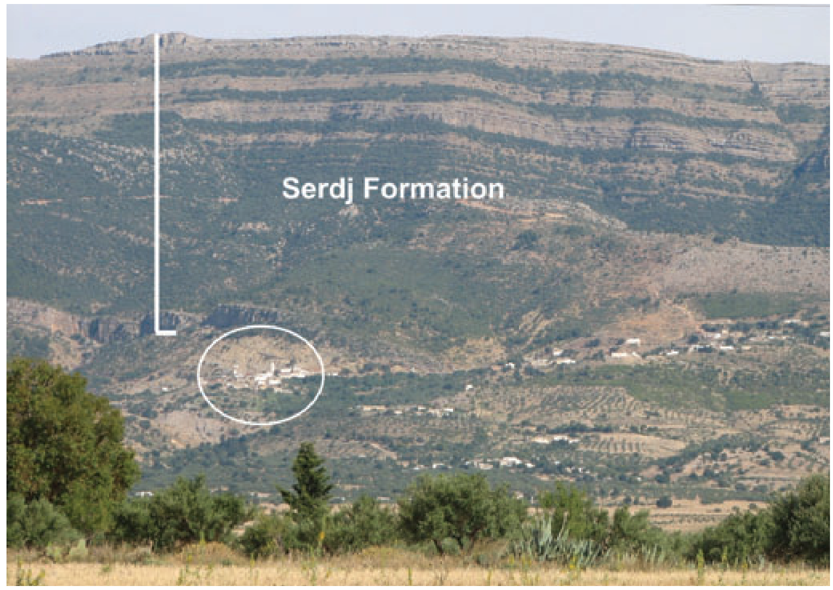

Fig. 3. View from the north-west of the sedimentary rocks of the Upper Aptian Serdj Formation cropping out in the central part of Djebel Serdj. The encircled village on the left is Dechret el Golea (for location see Fig. 2). The white line marks Section SN. The thickness of the Serdj Formation is *ca* 550 to 600 m in this area. The darker bandings (vegetation covering) that trace the bedding in the upper part of the deposits correspond to softer sedimentary rocks, including marlstones and siltstones.

sorting of components were determined in thin sections only. Field observations and the results of the microscope analyses led to a division of the successions into four facies zones (A to D), each being subdivided into two to five microfacies types. The palaeoenvironmental zonation of the Tunisian platform margin was established by adapting and modifying the division scheme for homoclinal carbonate ramps as suggested in Flügel (2004).

Stratigraphy is based on planktonic and benthonic foraminifera (orbitolines) as well as $\delta^{13}C$ isotopes. Planktonic foraminifera were picked from residues of washed material (60 to 100 specimens per sample). For taxonomic classifications, based mainly on shell texture and morphology, refer to Premoli Silva & Sliter (2002). The age of the observed zone is deduced from the standard low-latitude zonal schemes of Premoli Silva & Sliter (1999). For taxonomic identification of the orbitolines, internal structures, especially the embryonic apparatus, were analysed in the thin sections *sensu* Schroeder (1975). The stratigraphic ranges of the species were deduced from the compilation of Tethyan ranges by Bachmann & Hirsch (2006). The taxonomy of the ammonite fauna collected during the fieldwork is discussed extensively in Lehmann *et al.* (2009).

Carbon isotope data, additionally used for stratigraphy, has been obtained from 52 bulk rock samples of section SN. These data were measured in The Research Center Ocean Margins (University of Bremen) with a Finnigan MAT 251 mass spectrometer (accuracy ±0·07‰; Finnigan MAT GmbH, Bremen, Germany).

STRATIGRAPHY

Biostratigraphy

Microfossils suitable for dating have been observed in the lowermost and uppermost parts of the sections only (Fig. 4). In one horizon of section SN, recrystallized, moderately to well-preserved planktonic foraminifera allowed the determination of the *Globigerinelloides algerianus* biozone. The deposits below and above contain no or scarce planktonic foraminifera. Following Premoli Silva & Sliter (1999), the *Globigerinelloides algerianus* zone indicates the Middle Gargasian. Tlatli (1980) described planktonic foraminifera in several beds at Djebel Serdj and identified the ranges of the *G. ferrolensis zone* and *G. algerianus* zones, which were adopted for the present study.

Orbitolina (*Mesorbitolina*) *texana* is observed in most parts of all sections, but does not provide additional stratigraphical information, due to its long range (Late Aptian to Late Albian; Bachmann & Hirsch, 2006). The occurrence of *Orbitolina* (*Mesorbitolina*) *subconcava* in the uppermost parts of sections SN and BK suggests a Latest Clansayesian age. Following the range charts of Bachmann & Hirsch (2006), this species appears in the Latest Clansayesian and disappears in the lowermost Cenomanian. Tlatli (1980) addition-

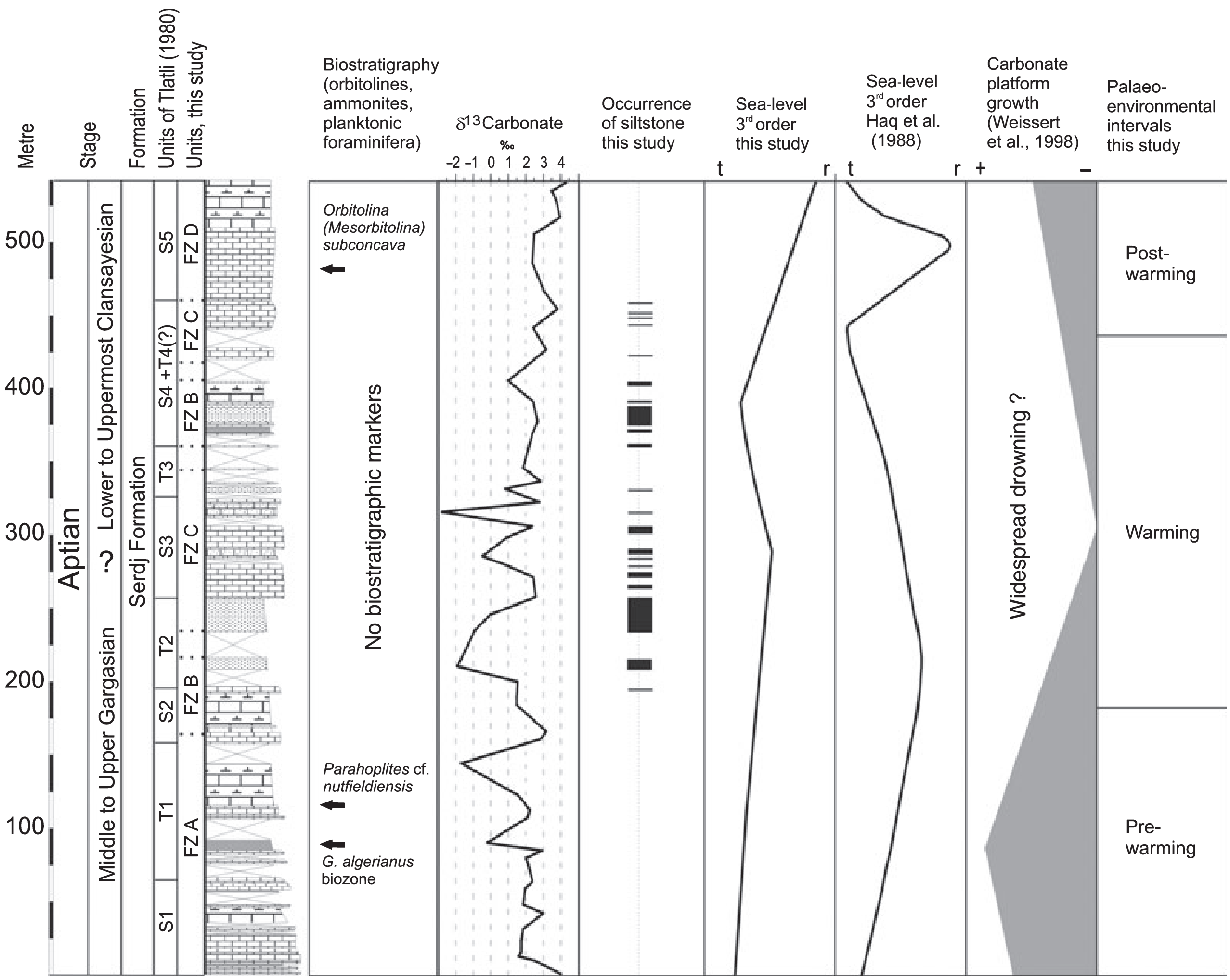

Fig. 4. Section SN with facies zones, biostratigraphy and $\delta^{13}C$ stratigraphy, occurrence of siltstones, sea-level changes, palaeoenvironmental intervals and carbonate platform growth as proposed by Weissert *et al.*, 1998 and others (see text). For the location of the section, see Fig. 2. For the description of the lithology, compare Fig. 6. This warming interval corresponds to the prominent mid-Late Aptian warming event (Weissert & Lini, 1991; Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Takashima *et al.*, 2007).

ally described *Orbitolina* (*Mesorbitolina*) *parva* from several horizons at Djebel Serdj. This species ranges from the Late Aptian to Late Albian and thus does not provide more detailed stratigraphic information. Tethyan range charts of *Ovalveolina reicheli*, occurring in the uppermost parts of sections SH and BK, have not yet been established. This species has been reported from the Late Gargasian and Clansayesian of the Tunisian carbonate platform (Masse & Thieuloy, 1979; Masse & Chiki-Aouimeur, 1982).

Few ammonites have been collected in the investigated successions (Lehmann *et al.*, 2009). *Parahoplites* cf. *nutfieldiensis* probably indicates the *P. nutfieldiensis* zone in the lower part of the successions, which is in agreement with the *G. algerianus* planktonic foraminiferal zone determined by Tlatli (1980; Figs 4 and 5). *Parahoplites laticostatus* dates the lowermost part of the Serdj Formation as Late Aptian, it is associated with an undetermined cheloniceratid.

Chemostratigraphy

New $\delta^{13}C$ data support the Middle Gargasian to Latest Clansayesian age of the investigated deposits deduced from the biostratigraphy (Figs 4 and 5). The $\delta^{13}C$ values of section SN (Fig. 4) range between 2·9‰ and 4·3‰. Stable values of *ca* 2 to 3‰ are observed in the lowermost part of the section (first 80 m). The overlying deposits (80 to 325 m) show fluctuations in $\delta^{13}C$ values between −2·9‰ and 3·1‰. A positive excursion with maximum values of *ca* 4‰ characterizes the

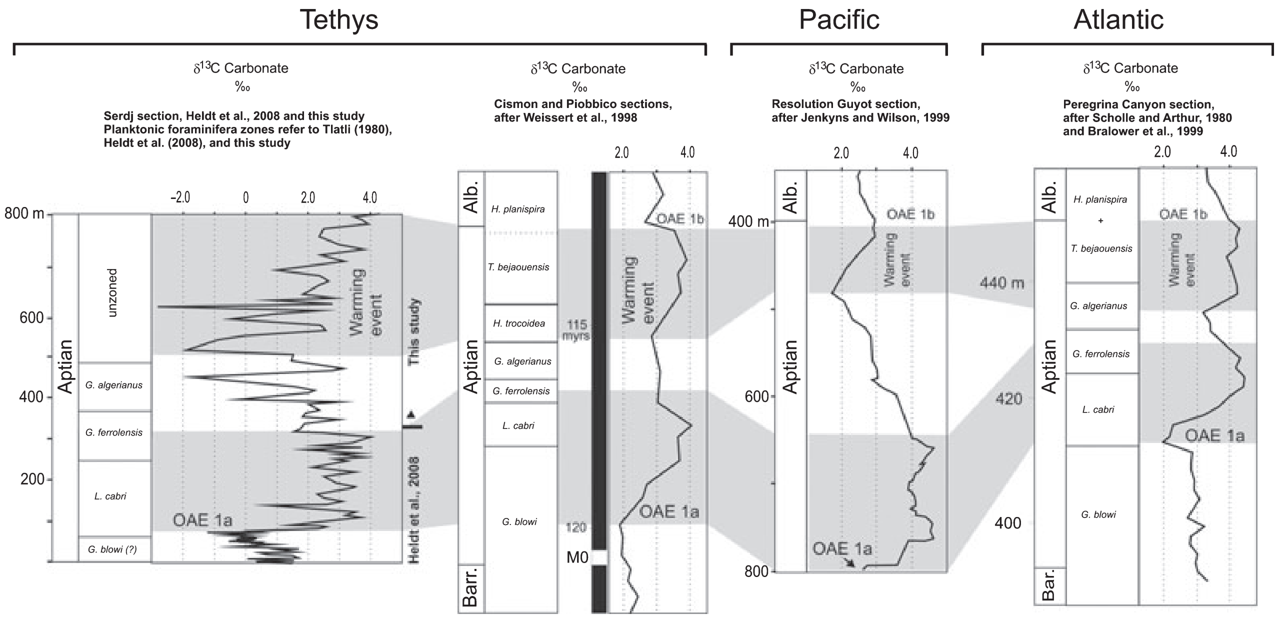

Fig. 5. Correlation of the Serdj δ^{13}C record (Heldt *et al.*, 2008 and this study) with δ^{13}C records from the Tethys, Pacific and Atlantic. The shaded areas mark prominent Aptian positive isotope excursions. Note that the planktonic foraminiferal zones refer to different zonal schemes (for example, the range of the *L. cabri* zone varies considerably). The Late Aptian warming event correlates with the upper positive isotope excursion according to Weissert & Lini (1991), Föllmi *et al.* (1994) and others.

deposits from 325 m onwards. In Fig. 5, the δ^{13}C-curve is plotted against reference curves of the Tethys, Atlantic and Pacific (Weissert *et al.*, 1998; Bralower *et al.*, 1999; Jenkyns & Wilson, 1999). These curves show positive δ^{13}C values of *ca* 2 to 4‰ in the *G. ferrolensis* to *G. algerianus* zone and a long-lasting positive excursion (to values *ca* 3 to 4‰) starting in the *G. algerianus* zone or lowermost part of the *T. bejaouensis* zone. The values of section SN (320 to 800 m) are consistent with the overall trends, but values fluctuate considerably in the *G. algerianus* zone and in the succeeding deposits (Fig. 5, 390 to 625 m). Minimum δ^{13}C values are up to 5‰ lower than those in the reference curves. Because of these fluctuations, the onset of the prominent Late Aptian positive excursion is hardly identifiable at Djebel Serdj. Considering that the biostratigraphic data indicate the Latest Clansayesian in the uppermost part of section SN, it is suggested that the δ^{13}C values of these deposits represent the termination of the Late Aptian positive excursion close to the Aptian/Albian boundary.

DEPOSITIONAL ENVIRONMENTS

Four facies zones (FZ A to D), which are subdivided into 12 microfacies types (MFT 1 to 12), are distinguished on the basis of their main components, textures, macrofossil and microfossil associations, as well as lithological variations observed in the outcrops. These facies zones represent different depositional environments and are clearly separated from each other. Figure 6 shows the distribution of the facies zones and the microfacies types in the investigated sections; their characteristics and environmental interpretations are given in detail in Table 1. Typical thin sections are illustrated in Figs 7 and 8. A palaeoenvironmental reconstruction with characteristic biota/components is illustrated in Fig. 9. The facies zones and microfacies types are:

Facies Zone A: Mid-ramp

Description

This 125 to 170 m thick unit is composed of grey limestones (mostly bedded at decimetre to metre-scale) and grey to brownish marlstones (Table 1, Fig. 7A). The base of facies unit A is marked by a vertical limestone cliff, 25 to 30 m high, which is regarded as the base of the Serdj Formation (Tlatli, 1980). Scarce macrofossils include bivalves, brachiopods, echinoids, nautiloids and ammonites. Two microfacies types are distinguished: *MFT 1 Bioclastic to peloidal wackestone and packstone* and *MFT 2 Marlstone*. The most

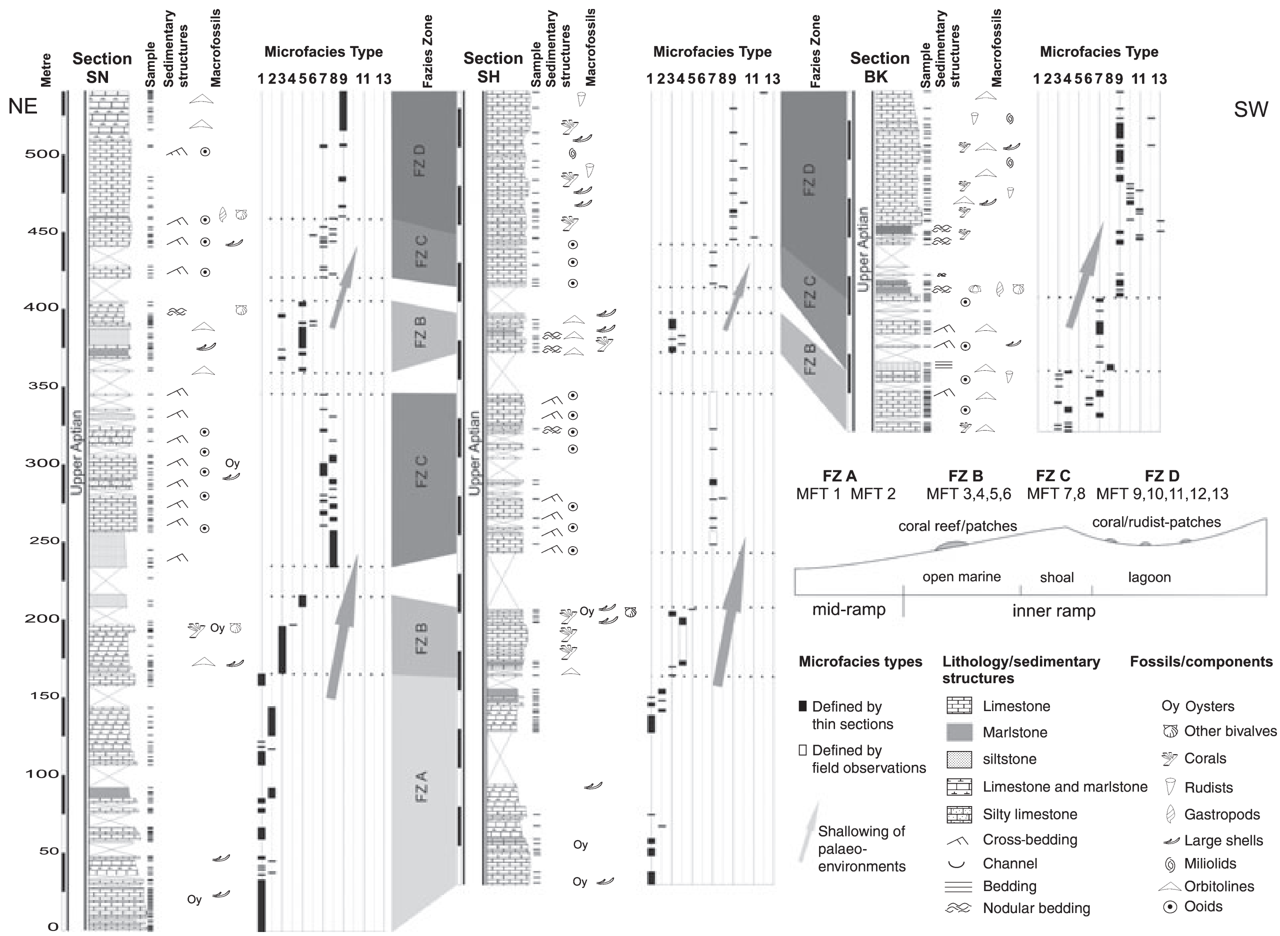

Fig. 6. The occurrences of facies zones and microfacies types in the sections investigated. For locations see Fig. 2.

common components in thin sections are mud peloids, fine-grained skeletal detritus and indistinct small fragmented shells (mainly <1 mm). Common completely preserved microfossils are planktonic foraminifera, small benthonic foraminifera and ostracods. Further skeletal grains are the remains of bivalves, echinoderms, worm tubes and gastropods. Orbitolines occur in the upper part of the facies zone, together with miliolids, cortoids (skeletal remains with micritic envelopes), bahamite peloids (small micritized skeletal remains) and quartz grains. All components are poorly to moderately sorted. Skeletal fragments exhibit angular to sub-angular shapes.

Palaeoenvironmental interpretation

The fully marine macrofossil and microfossil assemblages including common planktonic organisms suggest open marine conditions. Sorting and rounding of components suggest low hydrodynamic energy. Shallow water components (miliolids, cortoids and peloids) and increasing detrital input in the upper part of FZ A possibly suggest an upward shallowing. A distal mid-ramp palaeoenvironment is assumed for the lower part and a proximal mid-ramp environment is assumed for the upper part of FZ A. A mid-ramp setting is supported by Heldt *et al.* (2008), describing the occurrence of tempestites close below the base of the Serdj Formation.

Facies Zone B: Inner ramp/open marine

Description

Facies unit B is characterized by 25 to 50 m of grey limestones and grey to brownish siltstones (all bedded on a decimetre to metre-scale; Table 1, Fig. 7B to E). Nodular bedding of limestones is common. Few siltstone beds show cross-bedding. Channels filled with siltstone are rare. Common macrofossils are bivalves (especially oysters), colonial corals (often decimetre-scale *in situ* colonies or beds) and solitary corals. In section SN only, colonial corals form a 25 to 30 m thick prominent cliff (Fig. 10). Gastropods, encrusting red algae and rudists (rarely in life

Table 1. Facies zones, microfacies types, macrofossils, components, sedimentary structure/textures and palaeoenvironmental interpretation of the sections.

Facies Zone	Microfacies type	Macrofossils	Microfacies (components in order of abundance)	Sedimentary structures/textures	Environmental interpretation
A	MFT 1: Bioclastic to peloidal wackestone and packstone	Bivalves (e.g. oysters), rhynchonellid brachiopods, nautilids (*Cymatoceras neckerianum*), ammonites (*Cheloniceras* (*Cheloniceras*) sp., *Parahoplites laticostatus*, *Parahoplites* cf. *nutfieldiensis*), toxasterid echinoids	Fine-grained skeletal detritus, mud peloids, small shell fragments (mainly <1 mm), planktonic foraminifera (mainly hedbergellids, rarely globigerinelloidids), small benthonic foraminifera, ostracods, echinoderm remains, worm tube fragments; in the upper part of the FZ there are also orbitolines, miliolids, cortoids, bahamite peloids, quartz grains	Bedded at decimetre to metre-scale Components are poorly sorted, skeletal fragments exhibit angular to sub-angular shapes	Distal mid-ramp in the lower parts, proximal mid-ramp in the upper parts, low-energy setting
	MFT 2: Marlstone	No macrofossils	Fine-grained skeletal detritus, smaller-sized shell fragments (mainly <1 mm), planktonic foraminifera (mainly hedbergellids, rarely globigerinelloidids); small benthonic foraminifera (such as *Praedorothia praeoxycona*, *Lenticulina* spp.), echinoderm fragments, ostracods, worm tube fragments, small gastropods, quartz grains	Predominantly homogenous sediments Bioclasts are angular shaped	
B	MFT 3: Bioclastic to peloidal wackestone and packstone	Bivalves (e.g. oysters), solitary corals, gastropods (e.g. *Natica sautieri*), encrusting red algae, rudists (rarely in life-position)	Shell fragments (<2 mm), mud peloids, cortoids, bahamite peloids, quartz grains, skeletal fragments of bivalves, gastropods, echinoderms, corals, bryozoans, green algae and others completely preserved; small benthonic foraminifera (e.g. miliolids), orbitolines (*Orbitolina* (*Mesorbilolina*) *texana*), large agglutinating foraminifera (*Ataxophragmides* sp.), ostracods	Bedded at decimetre to metre scale, nodular bedding occurs sporadically Components are poorly to moderately sorted, angular to sub-rounded shapes	Inner ramp/open marine, maximum water depth in more distal portions, a few tens of metres maximum, moderate energy setting, probably elevated nutrient levels at times

Table 1. Continued.

Facies Zone	Microfacies type	Macrofossils	Microfacies (components in order of abundance)	Sedimentary structures/textures	Environmental interpretation
	MFT 4: Coral framestone	Colonial corals (coral reef, *in situ* colonies and beds), encrusting red algae	Colonial corals (often recrystallized), layers of red algae, unknown micro-encrusting organisms; for additional components, see MFT 3	Nodular bedding is common For sorting and rounding of additional components, see MFT 3	
	MFT 5: Siltstone	No macrofossils	Quartz grains, mud peloids, shell fragments, small benthonic foraminifera; for additional components, see MFT 3	Rarely cross-bedded Usually beds, rarely as siltstone channels intercalated within MFT 3 quartz grains angular to sub-rounded	
	MFT 6: Orbitoline floatstone	Orbitolines, larger bivalve fragments	Completely preserved orbitolines, quartz grains; other components correspond to MFT 3	Homogenous sediments For sorting and rounding, see MFT 3	
C	MFT 7: Bioclastic to oolitic grainstone	Large bivalve shells only (especially oysters)	Ooids, quartz grains, skeletal fragments of: bivalves, gastropods, green algae (e.g. *Udoteacea* spp., *Arabicodium* and *Cylindroporella* sp.), echinoderms, bryozoans, large agglutinating foraminifera (e.g. *Ataxophragmides* sp.), small benthonic foraminifera (e.g. miliolids), ostracods, encrusting red algae, orbitolines, mud and bahamite peloids; many shells exhibit micritized rims (cortoids)	Cross-bedding is common, ripple marks and tidal channels are observed at few horizons Components are moderately to well-sorted and rounded, sometimes parallel orientation of bioclasts in the bedding plane	Inner ramp/high-energy shoals, water depths of a few metres, influence of tidal currents, high-energy setting, probably elevated nutrient levels
	MFT 8: Siltstone	Macrofossils correspond to MFT 7	Quartz grains (often with oolitic coating), mud and bahamite peloids; for additional components, see MFT 7	Same structures/textures as described for MFT 7, quartz grains angular to sub-angular shape	

Table 1. Continued.

Facies Zone	Microfacies type	Macrofossils	Microfacies (components in order of abundance)	Sedimentary structures/textures	Environmental interpretation
D	MFT 9: Bioclastic to peloidal wackestone and packstone	Oysters [e.g. *Rasteilum* (*Arcostrea*) *Macropterum*] and other bivalves, gastropods (e.g. Turrilitacea *Natica sautieri*), echinoids, solitary corals, rudists, rare ammonites (*Parahoplites maximus*, *Neodeshayesites nicholisoni*) and belemnites (*Neohibolites* sp.)	Fine-grained skeletal detritus, small shell fragments (mainly <3 mm), mud and bahamite peloids, skeletal fragments of: bivalves, gastropods, echinoderms, corals, rudists, worm tubes, red and green algae, bryozoans and others completely preserved: miliolids and other small benthonic foraminifera (such as *Patelina subcretacea* and *Pradorothia praeoxycona*), orbitolines [*Orbilotina* (*Mesorbitolina*) *texana*, *Orbitolina* (*Mesorbitolina*) *subconcava*], alveolinids (*Ovalveolina reicheli*) and ostracods; many shells exhibit micritized rims (cortoids)	Bedded at decimetre to metre scale, nodular bedding is rare Components are poorly sorted, shell fragments show angular to rounded shapes	Inner ramp/ lagoon water depth a few metres maximum, influenced by the tides and/or wave action at times, low to moderate energy setting, nutrient-depleted water conditions
	MFT 10: Bioclastic grainstone	No macrofossils	Cortoids and bahamite peloids, mud intraclasts, mud peloids, benthonic foraminifera (especially miliolids); for additional components, see MFT 9; components within the grainstones show strong signs of reworking	Bedded at decimetre to metre scale Well-sorted, sub-rounded to rounded shapes	
	MFT 11: Coral framestone	Colonial corals (*in situ* colonies or beds) encrusting red algae	Colonial corals, layers of red algae (*Rhodophycea*); for additional components, see MFT 9	Often nodular bedded For sorting and rounding of additional components, see MFT 9	
	MFT 12: Rudist bafflestone	Rudist colonies (*in situ* colonies)	Rudists; for additional components, see MFT 9	— For sorting and rounding of additional components, see MFT 9	
	MFT 13: Mudstone	No macrofossils	Small shell fragments (silt to sand-size), sponge spiculae, small benthonic foraminifera (mainly miliolids) and ostracods	Homogenous sediment Poorly sorted, angular shapes	

The ranges of the facies zones and microfacies types are plotted in Figs 4 and 6.

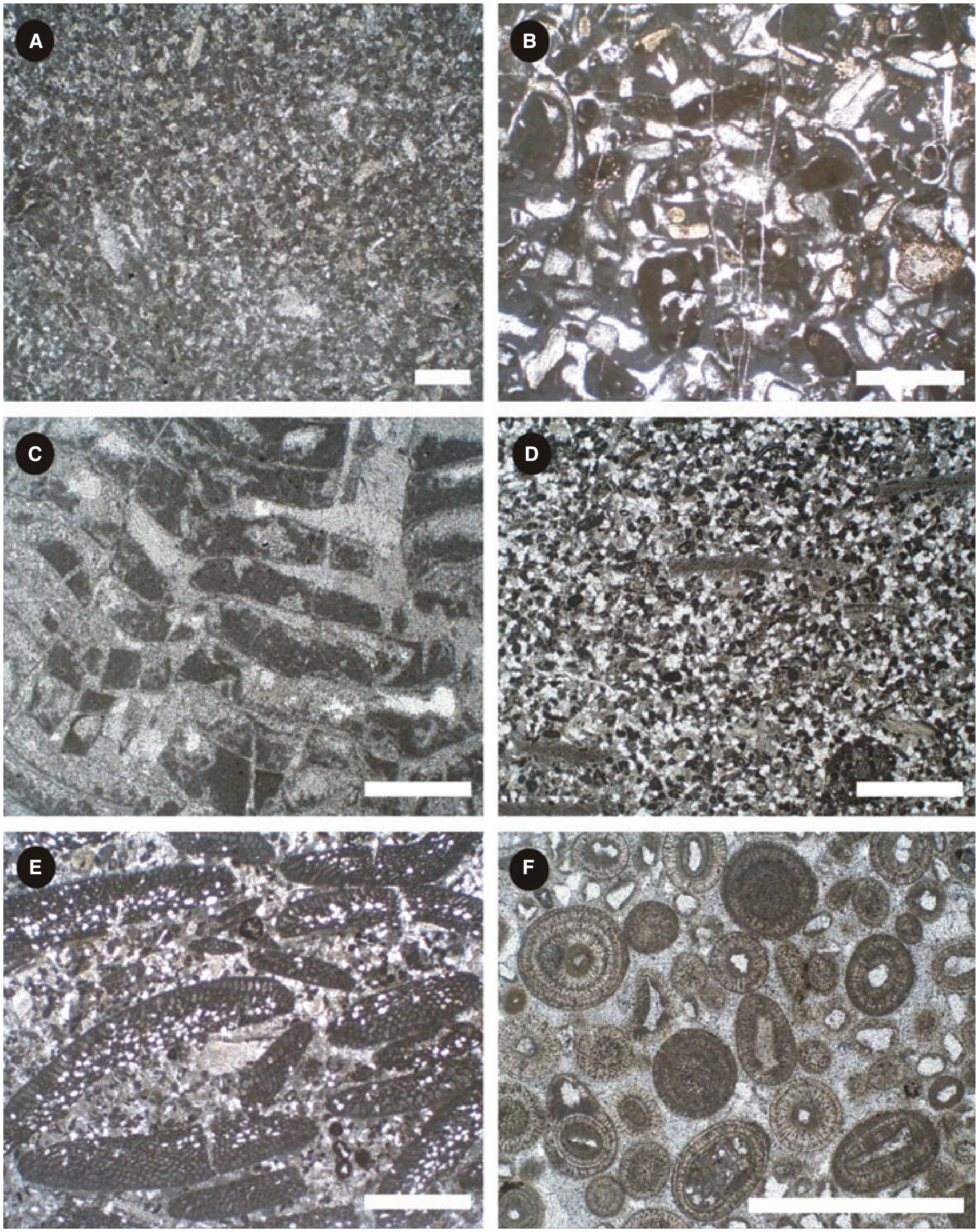

Fig. 7. Microfacies of the Serdj Formation (Facies Zones A to C). The scale is 1 mm for all images. (A) Facies Zone A, microfacies type 1. Bioclastic to peloidal wackestone and packstone. This thin section is dominated by mud peloids, fine-grained skeletal detritus and small shell fragments. (B) Facies Zone B, microfacies type 3. Bioclastic to peloidal wackestone and packstone. The thin section shows a high abundance of smaller shell fragments. (C) Facies Zone B, microfacies type 4. Coral framestone. (D) Facies Zone B, microfacies type 5. Siltstone. The sample is rich in quartz grains, mud peloids and shells. A larger agglutinating foraminifera is seen in the lower right. (E) Facies Zone B, microfacies type 6. Orbitoline floatstone. The thin section also contains quartz grains, mud and bahamite peloids, and small shells. (F) Facies Zone C, microfacies type 7. Bioclastic to oolitic grainstone. Nuclei of the ooids in this thin section are quartz grains and shells.

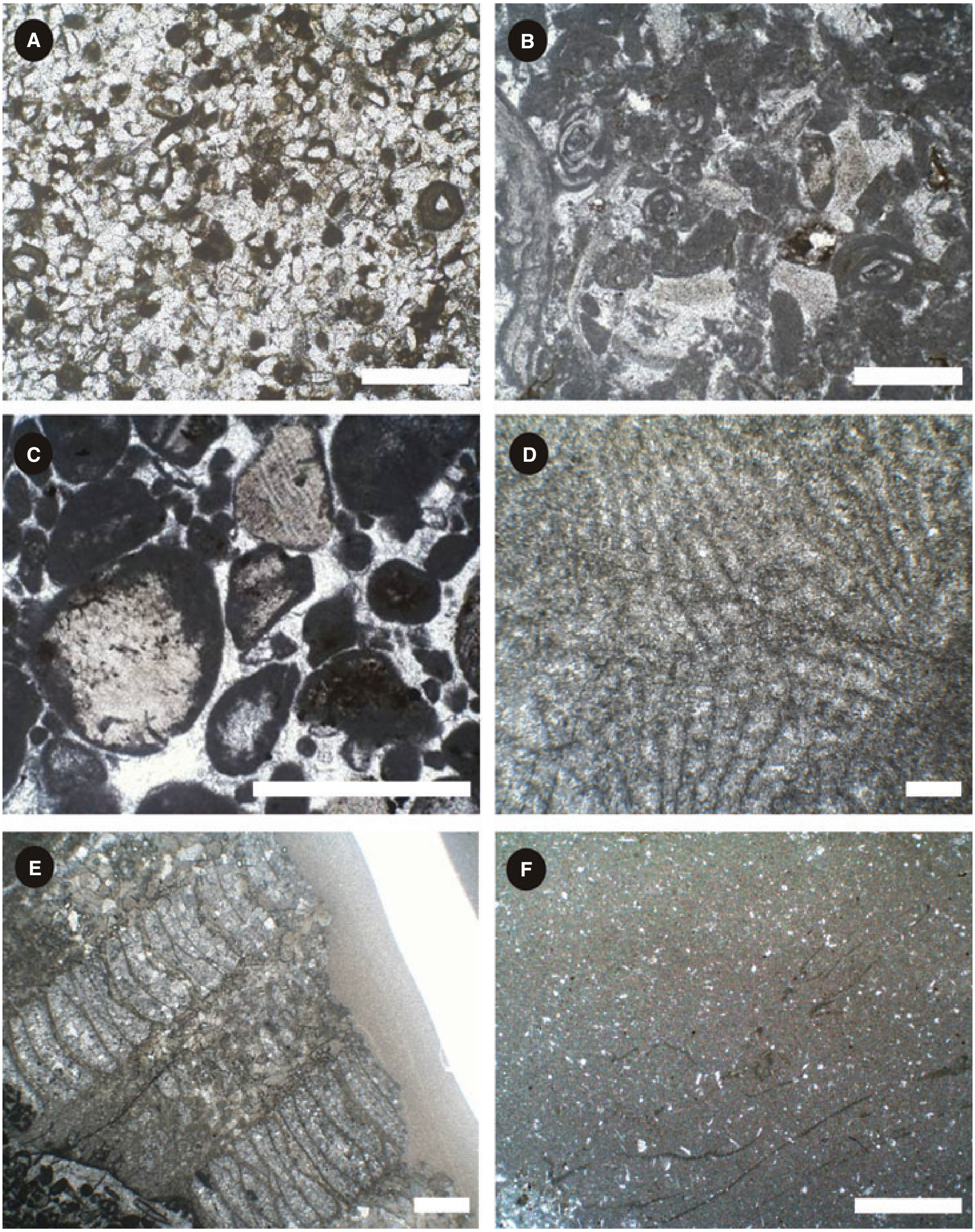

Fig. 8. Microfacies of the Serdj Formation (Facies Zones C and D). The scale is 1 mm for all images. (A) Facies Zone C, microfacies type 8. Siltstone. Additional components are ooids and mud peloids. (B) Facies Zone D, microfacies type 9. Bioclastic to peloidal wackestone and packstone. The thin section contains mud peloids, shell fragments and several miliolids. (C) Facies Zone D, microfacies type 10. Bioclastic grainstone. This sample is dominated by shells that are micritized almost completely (cortoids and bahamite peloids). (D) Facies Zone D, microfacies type 11. Coral framestone. The skeletons of the colonial corals show a loss of internal structures due to recrystallization. (E) Facies Zone D, microfacies type 12. Rudist bafflestone. (F) Facies Zone D, microfacies type 13. Mudstone. The thin section contains fine-grained skeletal detritus.

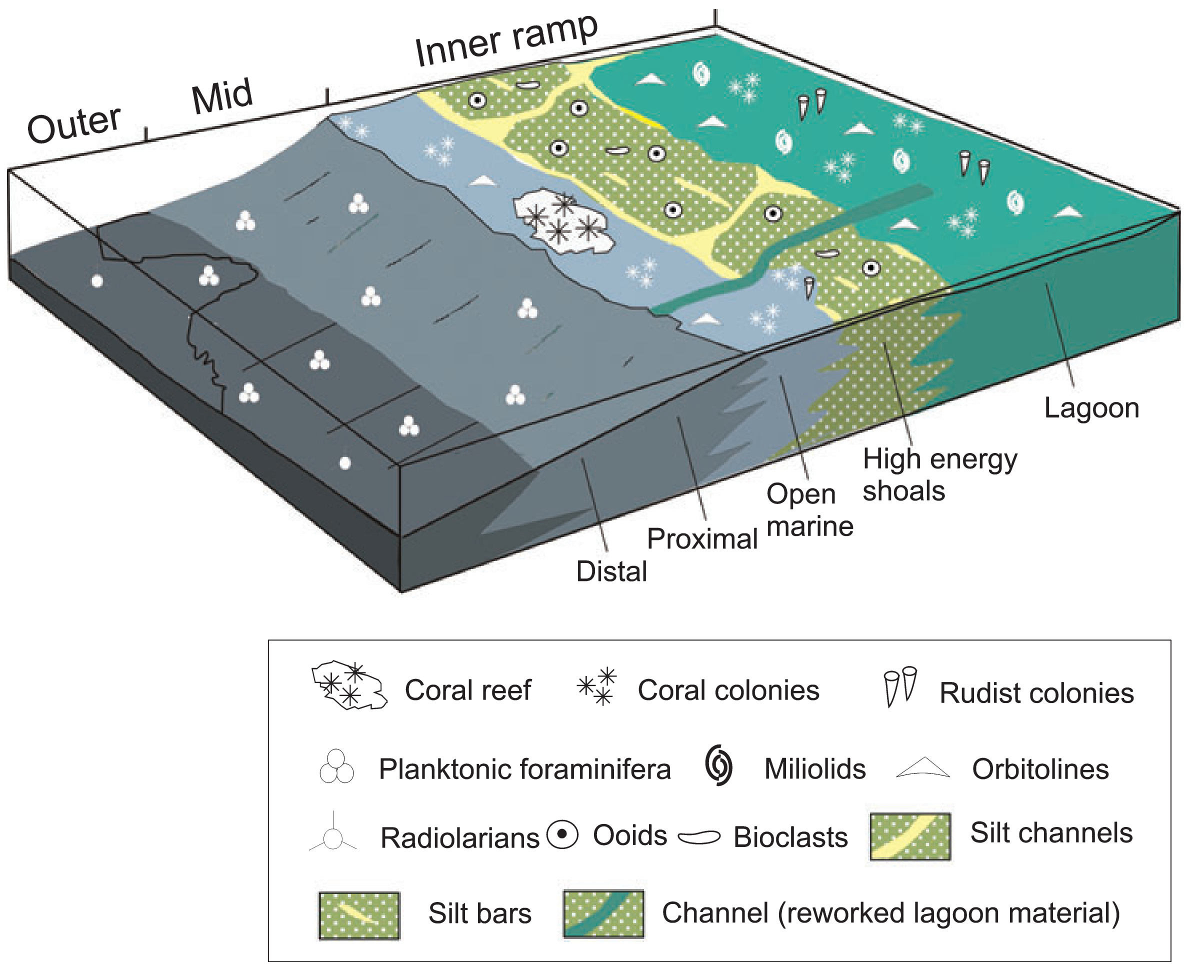

Fig. 9. Block diagram illustrating the Late Aptian palaeoenvironments in the Serdj region deduced from the microfacies data.

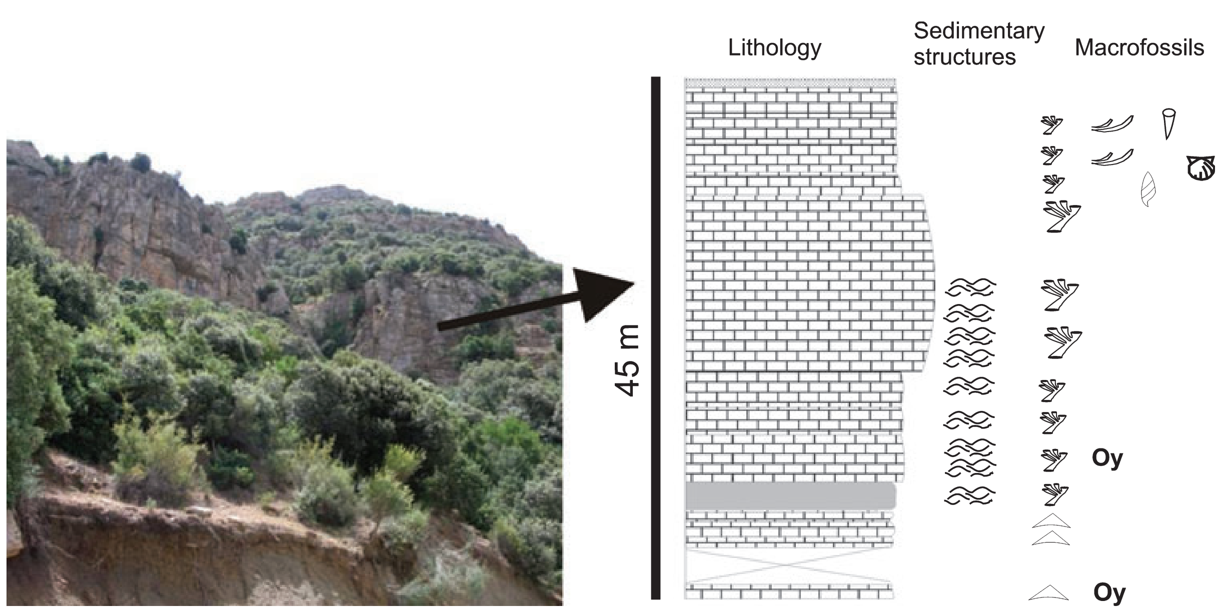

Fig. 10. Facies Zone B (inner ramp/open marine). In section SN, coral framestones form a massive, 25 to 30 m thick limestone cliff (compare Fig. 6, Section SH, 310 to 340 m). For legend see also Fig. 6.

position) are scarce within this facies zone. Four microfacies types that often merge into each other are distinguished: *MFT 3 Bioclastic to peloidal wackestone and packstone*, *MFT 4 Coral framestone*, *MFT 5 Siltstone* and *MFT 6 Orbitoline floatstone*. Common components in this facies zone are indistinct smaller sized fragmented shells (mainly <2 mm, often with thin micritic envelopes; cortoids), mud and bahamite peloids, quartz grains, remains of bivalves, gastropods, echinoderms and corals. Further skeletal grains include fragments of encrusting red algae, bryozoan colonies, worm tubes, rudists and green algae. Common completely preserved microfossils are small benthonic foraminifera (such as miliolids), orbitolines, large agglutinating foraminifera and ostracods. Planktonic micro-organisms (foraminifera, calcispheres of unknown origin) occur only sporadically. The components are poorly to moderately sorted. Shell fragments and quartz grains exhibit angular to sub-rounded shapes.

Palaeoenvironmental interpretation

The presence of shallow water platform biota/components (corals, miliolids, cortoids and peloids) and the scarceness of planktonic microfossils indicate a shallow marine environment. The present authors assume an open marine/inner-ramp palaeoenvironment with a strong detrital influx at times. The deposits were generated during low to intermediate water energy. The light-dependence of the corals allows a maximum water depth of a few tens of metres (Masse, 1992) for the distal portions of the palaeoenvironment. A similar platform community with *in situ* coral colonies, rudists, orbitolines and miliolids has been described by Vilas *et al.* (1995) from a comparable outer platform setting of the upper Barremian to Lower Aptian in SE Spain.

Facies Zone C: Inner ramp/high-energy shoals

Description

This facies zone consists of 35 to 115 m thick commonly cross-bedded greyish limestones and grey to brownish siltstones (bedded at decimetre to metre-scale; Table 1, Figs 7F and 8A). Ripple marks or channels (both microfacies types) are observed at a few horizons (Fig. 11). Few siltstones show nodular bedding. Macrofossils are represented by large bivalve shells (for example, oysters) only. Two microfacies types are distinguished: *MFT 7 Bioclastic to oolitic grainstone* and *MFT 8 Siltstone*. The microfacies types often merge into each other. The most common components observed in this facies zone are ooids, quartz grains and shell fragments with highly varying sizes (often with micritic envelopes and cortoids). Common skeletal grains are the remains of bivalves, gastropods, green algae (which become abundant in several beds), echinoderms and bryozoan colonies. Encrusting red algae, abraded orbitolines, parts of large agglutinating foraminifera, small benthonic foraminifera and ostracods are rare. Mud and bahamite peloids occur only sporadically. The nuclei of the ooids include skeletal grains, micritic carbonate grains and

Fig. 11. Facies Zone C (high-energy shoals). The measuring stick is subdivided into centimetres. This facies zone is characterized by the occurrence of cross-bedded grainstones (A) and siltstones, in which a few channels (B) filled by both microfacies types are intercalated. The facies and sedimentary structures point to a shallow marine, agitated environment which was influenced by wave action and/or tidal currents.

quartz grains. The bioclasts are moderately to well-sorted and rounded within both microfacies types. The quartz grains are angular to sub-angular in shape.

Palaeoenvironmental interpretation
The ooids, microfossils and textures in combination with the sedimentary structures suggest *in situ* deposition in an agitated, high-energy shallow marine environment. The channels may be related to tidal flows. Comparable deposits usually are associated with shallow, high-energy shoal/bank environments, strongly affected by wave and/or current action (Burchette & Wright, 1992; Flügel, 2004). Green algae suggest transport from the platform interior.

Facies Zone D: Inner ramp/lagoon

Description
Facies zone D is represented by 85 to 125 m thick, sometimes nodular bedded grey marly limestones and limestones (bedded at decimetre to metre-scale; Table 1, Fig. 8B to F). Common macrofossils are bivalves, colonial corals (often *in situ* colonies, maximum decimetre-scale; Fig. 12), rudists (decimetre-scale *in situ* colonies or single individuals), gastropods, echinoids and solitary corals (often in growth position). Ammonites and belemnites are rare (Lehmann *et al.*, 2009). Five microfacies types are distinguished: *MFT 9 Bioclastic to peloidal wackestone and packstone*, *MFT 10 Bioclastic grainstone*, *MFT 11 Coral framestone*, *MFT 12 Rudist bafflestone* and *MFT 13 Mudstone*. Common components within this facies zone are fine-grained skeletal detritus (silt to sand-size) and/or fragmented shells with highly varying sizes (mostly <3 mm). Cortoids and bahamite peloids are common. Other common skeletal fragments are the remains of echinoderms, bryozoan colonies, colonial corals, solitary corals, rudists, gastropods and worm tubes. Rare skeletal grains are fragments of red and green algae, large agglutinating foraminifera, planktonic foraminifera, and calcispheres of unknown origin and sponge spicules. The latter becomes abundant within the mudstones only. Common completely preserved microfossils within the facies zone are miliolids and other small benthonic foraminifera, orbitolines, ostracods and alveolinids. The components are poorly sorted and show angular to rounded shapes. Thin sections of the bioclastic grainstones only show high abundances of well-rounded components (reworked material of MFT 9).

Palaeoenvironmental interpretation
High abundance of shallow water platform components (cortoids, bahamite peloids and miliolids), common *in situ* coral and rudist colonies, and the scarceness of planktonic organisms, indicate a shallow marine environment. A lagoonal palaeoenvironment is suggested with maximum water depth of a few metres, which was occasionally influenced by tidal currents and/or wave action as indicated by the occurrence of grainstones with strongly reworked components. The mudstones might be related to a restricted depositional palaeoenvironment or to deposition in areas with calmer water.

Fig. 12. Facies Zone D. *In situ* rudist (A) and coral colonies (B) within FZ D (inner ramp/lagoon). The investigated carbonate platform was colonized repeatedly by corals and rudists (FZ B and D) which points to nutrient-depleted water conditions at times. The size of the loupe for scale in (A) is *ca* 6 cm, the visible part of the pencil in (B) is *ca* 9 cm.

DISCUSSION

Biostratigraphy and carbon isotope stratigraphy

Integrated biostratigraphy and chemostratigraphy confirm a Middle Gargasian to Latest Clansayesian age for the investigated deposits of the Serdj Formation at Djebel Serdj as proposed by Tlatli (1980). The planktonic foraminiferal zones (*G. ferrolensis*, *G. algerianus*, this study and Tlatli, 1980) in the lower parts of the investigated sections indicate the Middle Gargasian. Considering the Latest Clansayesian age indicated by the first occurrence of *Orbitolina* (*Mesorbitolina*) *subconcava* in the uppermost deposits investigated, it is assumed that the interval which is devoid of biostratigraphic markers comprises the Late Gargasian to Late Clansayesian (Fig. 4). This time interval corresponds to a prominent global warming event of *ca* 3 to 4 Myr, starting directly after the *G. algerianus* planktonic foraminiferal zone (Figs 4 and 5; Weissert & Lini, 1991; Weissert *et al.*, 1998; Herrle & Mutterlose, 2003; Takashima *et al.*, 2007).

This biostratigraphic framework is generally supported by the $\delta^{13}C$ stratigraphy. The overall trends in $\delta^{13}C$ values are consistent with other records worldwide, but the absolute values in the interval between 390 and 625 m (Fig. 5) show some irregular minima, which are up to 5‰ lower than the rather stable values of *ca* 2‰ to 3‰ registered in other global sections (Weissert *et al.*, 1998; Bralower *et al.*, 1999; Jenkyns & Wilson, 1999; Herrle *et al.*, 2004). Most of the irregular $\delta^{13}C$ minima correspond to levels enriched in siliciclastic material (Fig. 4), which might be explained by ^{12}C-enriched coastal freshwater runoff coupled with terrigenous sedimentation or a strong groundwater influence. Diagenetic alterations could also have caused the anomalies. Although carbon isotopes are fairly resistant to most diagenetic processes related to deep burial, subaerial or meteoric diagenesis can alter primary $\delta^{13}C$ isotope signals considerably (Brand & Veizer, 1981; Moss & Tucker, 1995; Jian *et al.*, 1997; Heydari *et al.*, 2001; Immenhauser *et al.*, 2003). Allan & Matthews (1982) demonstrated that limestones beneath exposure surfaces are often enriched in $\delta^{12}C$ by 2 to 4‰ due to early meteoric diagenesis above the water table, meteoric influx and soil zone CO_2. It is quite possible that some exposure surfaces were not recorded during the present fieldwork due to bad outcrop conditions, especially at horizons with softer material such as siltstones. Tlatli (1980) described karstic features and vadose silt from the Latest Gargasian (unit S3 of Tlatli, compare Fig. 4) of Djebel Bellouta, in close proximity south-west of Djebel Serdj.

Bathymetric changes

A third-order sea-level curve for the eastern Tunisian shelf (Fig. 4) is established by using changes in the depositional settings. The discussion is focused on section SN, which shows the most complete record and stands representatively for all sections. In the first 290 m of this section, the transition from a mid-ramp palaeoenvironment (FZ A) to an inner ramp open marine and high-energy shoal setting (FZ B and C) indicates a continuous shallowing of the sea. The reoccurrence of these facies zones suggests a short-lived deepening between 290 to 385 m and subsequent shallowing. Further shallowing of the sea is indicated by the occurrence of the lagoonal facies at 460 m (FZ D). The sea-level curve for the eastern Tunisian shelf correlates roughly with the global curve of Haq *et al.* (1988) (Fig. 4). Both curves reflect the prominent eustatic sea-level rise during the Late Aptian warming event. The onset of this sea-level rise is somewhat later in the Serdj curve. This eustatic sea-level rise, which is also reflected in some regional curves (for a compilation of Aptian regional sea-level curves, see Lehmann *et al.*, 2000), is thought to have caused the drowning of eutrophic mid-Late Aptian carbonate platforms in the sub-tropical realm (Föllmi *et al.*, 1994; Weissert *et al.*, 1998). However, the herein presented sea-level curve is not in agreement with the curve of Haq *et al.* (1988) in the Latest Clansayesian (385 to 535 m), when the investigated area was severely affected by tectonic uplift (see *Lithostratigraphy* and *Geological setting of the studied area* sections above). Shorter-term sea-level variations than those described above, which are reported from several other coeval carbonate platforms (Grötsch *et al.*, 1993; Rosales, 1999; Immenhauser *et al.*, 2001; Yilmaz *et al.*, 2004), are not reflected in the deposits investigated. These variations probably were outcompeted by the extraordinarily high subsidence rate in north/central Tunisia during the Late Aptian.

Palaeoecology and palaeoclimate of the Tunisian platform margin during the Late Aptian

The microfacies analyses in combination with field observations provide information on the

Late Aptian palaeoenvironmental evolution of the eastern Tunisian carbonate platform edge. Although Tlatli (1980) interpreted the deposits of the Serdj Formation as outer-ramp to inner-ramp deposits, these new data suggest deposition in mid-ramp to inner-ramp palaeoenvironments. The sedimentological analyses suggest a simultaneous evolution of the palaeoenvironments in the investigated area. Lateral differences within these palaeoenvironments are small and are reflected in varying abundances of the microfacies types (Fig. 6). This study subdivides the Late Aptian palaeoenvironmental evolution into three intervals (Fig. 4): a pre-warming interval, a warming interval and a post-warming interval. The warming interval corresponds to the prominent mid-Late Aptian warming event identified by several authors (Fig. 5; Weissert & Lini, 1991; Föllmi *et al.*, 1994; Herrle & Mutterlose, 2003; Takashima *et al.*, 2007). All three intervals are discussed below with respect to the local sedimentary expression of the prominent warming interval.

Pre-warming interval (Facies Zone A)

The lowermost parts of sections SN and SH, which are thought to represent the pre-warming interval (Early to Middle Gargasian), are characterized by limestones (bioclastic to peloidal wackestone and packstones) and marlstones of a mid-ramp palaeoenvironment (Fig. 6; FZ A). The biotic assemblage is dominated mainly by planktonic and small benthonic foraminifera. The occurrence of shallow water platform components in the upper part of FZ A probably indicates the transition from the mid-ramp settings to the shallow-marine, inner-ramp palaeoenvironments (FZ B to D). The biotic assemblage of FZ A does not provide detailed information on ecological conditions on the platform due to a general lack of significant fossils.

Warming interval (Facies Zones B and C)

The warming interval (Late Gargasian to Late Clansayesian) comprises FZ B and C and is characterized by limestones, siliciclastic-rich limestones and siltstones that are interpreted as inner ramp/open marine (FZ B) and inner ramp/high-energy shoal deposits (FZ C).

The deposits of FZ B (bioclastic to peloidal wackestones and packstones, coral framestones, orbitoline floatstones and siltstones) provided a diverse platform biota, including *in situ* colonial and solitary corals, bivalves, gastropods, benthonic foraminifera (such as miliolids and orbitolines) and the remains of several other organisms. Carbonate platforms extensively colonized by corals are generally referred to nutrient-depleted water conditions (Hallock & Schlager, 1986; Wood, 1993; Kiessling *et al.*, 2003). However, some horizons within this facies zone are dominated by siltstones or quartz-rich orbitoline floatstones. The mass occurrence of orbitolines has sometimes been related to elevated nutrient levels (Bachmann & Hirsch, 2006; Burla *et al.*, 2008), which often accompany increased terrigenous sedimentation.

The deposits of FZ C (quartz-rich oolitic to bioclastic grainstones and siltstones) are entirely devoid of oligotrophic indicators, such as corals and rudists, which could be also related to elevated nutrient levels. These deposits contain fragments of bivalves, gastropods, echinoderms and other organisms, as well as a high abundance of macro-green algal fragments in several beds. In recent mixed carbonate-siliciclastic settings or in environments under terrigenous influence, benthonic macro-green algae (such as *Halimeda*) play a significant role (Mutti & Hallock, 2003). These algae are less susceptible to environmental stresses, such as nutrients, turbidity and sedimentation rate, than most other platform organisms (Gussmann & Smith, 2002; Vecsei, 2003).

It is suggested here that the pronounced increase in siliciclastics during the warming interval, which might originate from weathering on the Saharan Platform and/or Kasserine Island (Fig. 1), could reflect a pluvial interval with increased coastal runoff on the Tunisian shelf. According to Weissert (1990) and Wortmann *et al.* (2004), intensified greenhouse conditions, accelerated water cycling and increased coastal runoff were the main trigger of widespread siliciclastic deposition on the shelves in the Tethyan-Atlantic seaway during the mid-Late Aptian. A facies change towards more terrestrial-influenced sedimentation and a decline in abundance of corals has also been reported from other parts of the Tunisian platform margin, which points to a platform-wide event (Tandia, 2001).

Post-warming interval (Facies Zone D)

The deposits of FZ D are thought to represent the post-warming interval (Latest Clansayesian). These sediments are characterized by limestones (bioclastic to peloidal wackestones, packstones and grainstones, coral framestones, rudist bafflestones and mudstones) which contain a diverse platform biota, including *in situ* colonial and solitary corals, *in situ* rudists, bivalves, gastropods, benthonic foraminifera (such as miliolids and orbitolines) and the remains of several other organisms. This assemblage points to favourable growth conditions on the eastern Tunisian carbonate platform edge under nutrient-depleted water conditions.

Palaeoecological changes on carbonate platforms during the mid-Late Aptian

Widespread carbonate platform drowning in the Tethyan and Atlantic realms?

The pronounced increase in terrigenous influx and decline in abundance of oligotrophic biota on the Tunisian shelf during the mid-Late Aptian are in accordance with an episode of intensified greenhouse conditions, increased coastal runoff and elevated nutrient transfer rates through rivers as suggested by several authors (Fries *et al.*, 1984; Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Wortmann *et al.*, 2004). However, in contrast to some sub-tropical carbonate platforms on the northern Tethys margin or in the Gulf of Mexico (locations 1 to 3 in Fig. 13; Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Lehmann *et al.*, 2000; Föllmi & Gainon, 2008), the Tunisian carbonate platform was not affected by drowning.

Following a hypothesis developed in the 1990s, it is argued that river-influenced sub-tropical/tropical platforms in the circum-Tethyan and Atlantic realms were synchronously affected by drowning during the mid-Late Aptian (Föllmi *et al.*, 1994; Weissert *et al.*, 1998). It has been further suggested that platforms beyond the reach of detrital sediments and nutrients (such as the isolated Apulia or Gavroro platforms of the southern Tethys realm; locations 10 to 12 in Fig. 13; Ferreri *et al.*, 1997; Grötsch *et al.*, 1998; Yilmaz *et al.*, 2004) were not affected by these drowning events. However, the hypothesis of widespread carbonate platform drowning along river-influenced coasts is confirmed for some areas of the sub-tropical northern Tethys realm and Gulf of Mexico only. The assumption that river-influenced carbonate platforms of lower latitudes also drowned during the mid-Late Aptian was based on the observation that several coeval tropical shelves were affected by increased siliciclastic influx, which should have been accompanied by heavy nutrient loads similar to some sub-tropical regions (Weissert, 1990; Föllmi *et al.*, 1994; Weissert *et al.*, 1998). In contrast, the results from the Tunisian carbonate platform (location 15 in Fig. 13) and comparison with

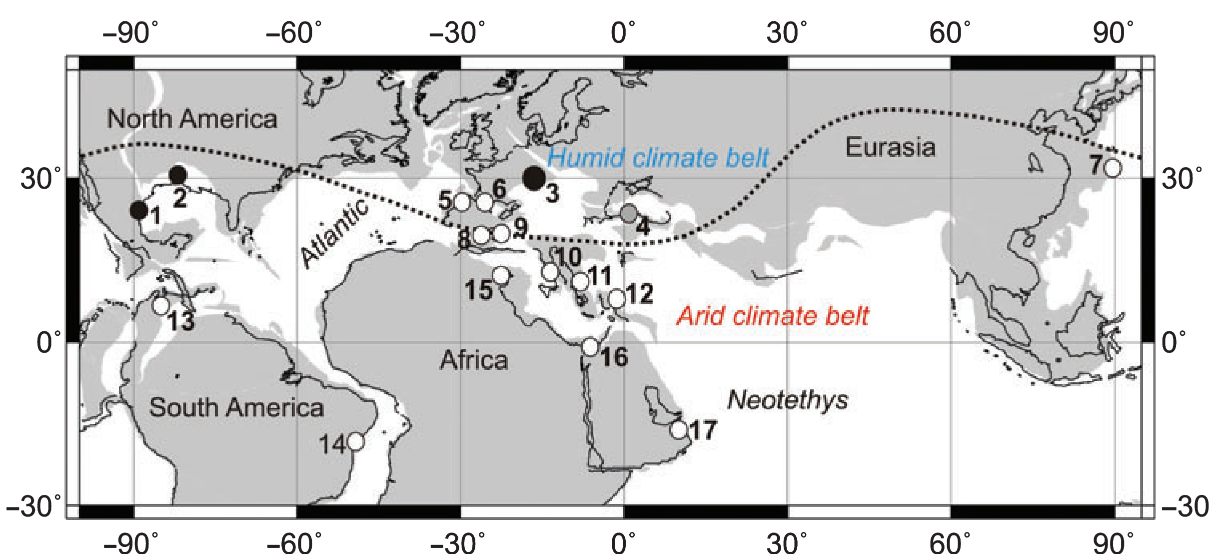

Fig. 13. The spatial distribution of drowned and not drowned carbonate platforms during the mid-Late Aptian. The stippled line marks the boundary between the sub-tropical humid and sub-tropical/tropical arid climate belts. Sub-tropical carbonate platforms (>23·5° N): 1 to 9, tropical platforms: 10 to 17. Black circles indicate carbonate platform drowning in the sub-tropical realm (1 – Northern rim Gulf of Mexico, 2 – Cupido Platform, 3 – Helvetic region). The grey circle indicates an uncertain age determination of drowning (4 – Pontide Platform). White circles mark platforms unaffected by drowning during the mid-Late Aptian (5 – Castro Uridales Platform, 6 – Aquitaine-Pyrénées region, 7 – Japanese Islands platforms, 8 – Jumilla region, 9 – Alicante Platform, 10 – Apulia Platform, 11 – Gavroro Platform, 12 – Tauride Platform, 13 – Maracaibo Platform, 14 – Sergipe region, 15 – Central Tunisian Platform, 16 – Levant Platform, 17 – Arabian Platform). For full references see text. Climate zones after Chumakov *et al.* (1995). Palaeogeographic map: http://www.odsn.de

publications on time-equivalent carbonate platforms of the tropical continental margins (locations 13 to 17 in Fig. 13; Masse & Thieuloy, 1979; Martinez & Hernandez, 1992; Koutsoukos *et al.*, 1993; Vahrenkamp *et al.*, 1993; Masse *et al.*, 1997; Bachmann & Hirsch, 2006) point to an absence of widespread platform drowning within lower latitudes during the mid-Late Aptian.

Non-drowning in the tropical realm

The absence of widespread platform drowning in the tropical realm during the mid-Late Aptian raises questions concerning the factors promoting platform growth during a time of strongly increased coastal runoff (Weissert, 1990; Weissert *et al.*, 1998; Wortmann *et al.*, 2004; present study). The tropical carbonate platforms were located within the broad arid climate belt of Chumakov *et al.* (1995) (Fig. 13) during that time, an observation documented by numerous investigations on terrestrial sediments and the widespread occurrences of evaporites on the African and American continental margins (Chumakov *et al.*, 1995; Ziegler *et al.*, 2003; Chaabani & Razgallah, 2006). A tropical, equatorial humid climate belt probably was absent (Russell & Paesler, 2003; Skelton, 2003). Studies on terrestrial sediments in North Africa suggest steppe-like landscapes and semi-arid climate conditions for the Aptian (Schrank, 1991; Abdel-Kireem *et al.*, 1996; Russell & Paesler, 2003; Ziegler *et al.*, 2003). Arid to semi-arid climates are the most favourable situation for carbonate platforms and reefs (Leinfelder, 1997; Voigt *et al.*, 1999; Tucker, 2003). Clastic sediments delivered by rivers under these climate conditions are almost barren of fine clay particles and poor in nutrients so that the parts of the carbonate platforms that are bypassed by coarser-grained terrigenous material are not, or are only moderately, affected by environmental changes and covered portions are able to rebuild rapidly (Leinfelder, 1997; Wilson & Lokier, 2002). Some elevated bioconstructions may even persist within areas of increased terrigenous sedimentation. A classic recent example is the Red Sea reefs which grow directly within a siliciclastic setting (Leinfelder, 1997). Furthermore, arid coastal systems are characterized by an anti-estuarine circulation pattern, which generally promotes favourable nutrient-depleted water conditions (Hay, 1995; Voigt *et al.*, 1999).

It is suggested that the observed increase in siliciclastics on the Tunisian shelf and in other parts of the tropical arid realm (Weissert, 1990) during the mid-Late Aptian might have been related to accelerated water cycling coupled with coarser-grained terrigenous coastal sedimentation possibly by semi-perennial or ephemeral rivers. The increased runoff was accompanied by low or moderate nutrient concentrations, which allowed the carbonate platforms to survive or rebuild rapidly and thus keep pace with the eustatic sea-level rise of the mid-Late Aptian.

Drowning and non-drowning in the sub-tropical realm

Carbonate platforms of the sub-tropical continental margins that were affected by drowning during the mid-Late Aptian (Gulf of Mexico and Helvetic region of the northern Tethys margin; locations 1 to 3 in Fig. 13) were located in the warm humid climate belt of Chumakov *et al.* (1995) or on the northern edge of the hot arid climate belt discussed before. The global warming proposed for the mid-Late Aptian might have resulted in a widening of areas of intense humidity in the sub-tropical realm, which then affected some carbonate platforms by riverine input. In contrast to arid regions, terrigenous influx in humid areas is rather persistent and generally is accompanied by fine clay particles, nutrient and freshwater influx (Hallock & Schlager, 1986; Wood, 1993; Wilson & Lokier, 2002). The accelerated water cycle and increased coastal runoff proposed for the mid-Late Aptian probably resulted in a strong deterioration of the environmental conditions for the above-mentioned carbonate platforms, especially due to elevated river nutrient loads as suggested by Föllmi *et al.* (1994) and Weissert *et al.* (1998). Most platforms that drowned during the mid-Late Aptian were located close to their northern latitudinal limit, where platforms are very sensitive and easy to destabilize.

However, several sub-tropical carbonate platforms around the boundary between the humid and arid climate belts did not drown during the mid-Late Aptian (locations 5 to 9 in Fig. 13; Arnaud-Vanneau *et al.*, 1979; Masse, 1995; Ruiz-Ortiz & Castro, 1998; Rosales, 1999; Fenerci-Masse *et al.*, 2006; Takashima *et al.*, 2007), although some of them were affected by increased coarser-grained terrigenous input during that time (Arnaud-Vanneau *et al.*, 1979; Fries *et al.*, 1984; Weissert, 1990; Wortmann *et al.*, 2004). These carbonate platforms probably were attached to areas of lower humidity or areas with some degree of aridity and thus less affected by riverine nutrient loads. Aridity in some areas of the northern Tethys margin could be indicated by the common occurrence of mixed carbonate and siliciclastic successions (Masse *et al.*, 2002; Fenerci-Masse *et al.*, 2006).

Comparison with the late Early Aptian Oceanic Anoxic Event 1a

Tropical carbonate platforms were probably generally less affected by ecological changes during the warming intervals of the Aptian. Another example is the late Early Aptian Oceanic Anoxic Event 1a (OAE 1a), which is also associated with intensified greenhouse conditions, increased terrigenous runoff and shallow marine eutrophication (Caldeira & Rampino, 1991; Bralower *et al.*, 1994; Jones & Jenkyns, 2001). Although several eutrophic platforms on the sub-tropical continental margins drowned during this event (Yilmaz *et al.*, 2004; Wilmsen, 2005; Castro *et al.*, 2006; Föllmi *et al.*, 2006), those on the tropical continental margins were characterized by intact carbonate production factories probably under mesotrophic water conditions (Vahrenkamp *et al.*, 1993; Pittet *et al.*, 2002; Immenhauser *et al.*, 2005; Thielemann, 2006; Heldt *et al.*, 2008). It is suggested here that aridity and thus comparably low nutrient runoff were also the most important reasons for more favourable growth conditions within lower latitudes during this event.

However, factors other than climate certainly also influenced the observed spatial distribution of drowned and undrowned platforms during the warming events of the Aptian. Platform drowning might have been supported regionally by strong tectonic subsidence (Schlager, 1981) or intensified coastal upwelling (Föllmi *et al.*, 2006), whereas tectonic uplift could have promoted platform growth in other places. Some platforms might have been sheltered from terrigenous input by structural and sedimentary traps or longshore currents (Leinfelder, 1997). Other platforms were not connected to river delta systems or situated far off the coast beyond the reach of riverine input. Increased terrigenous input on carbonate platforms could also have been regionally related to changing tectonic activities in the hinterlands. However, Weissert (1990) and Wortmann *et al.* (2004) provided good evidence that increased terrigenous influx on the shallow marine Tethyan and Atlantic shelves during the Aptian was triggered predominantly by climate (for example, indicated by the specific petrological composition of siliciclastic accumulations and their synchronous occurrence on shelves with different palaeotectonic settings).

CONCLUSIONS

The Upper Aptian (Middle Gargasian to Upper Clansayesian) deposits of the Serdj Formation at Djebel Serdj have provided an excellent opportunity to study the palaeoenvironmental evolution of a tropical southern Tethys carbonate platform margin and to investigate its response to temporarily intensified greenhouse conditions related to the mid-Late Aptian warming event. The successions consist of limestones, marlstones and siltstones, suggesting deposition within mid-ramp and inner-ramp palaeoenvironments. The deposits provided a diverse platform biota, consisting of colonial corals, rudists, gastropods, bivalves, benthonic foraminifera, green algae, red algae and other organisms typical for warm-water carbonate platforms of this time interval.

Integrated biostratigraphy and chemostratigraphy has allowed identification of a prominent Late Aptian warming event. This 3 to 4 Myr global warming episode is associated with increased terrigenous influx on the sub-tropical/tropical shelves and river-induced nutrification. This hypothesis is confirmed in the investigated area by a pronounced increase in siliciclastics during the event and changes in the biotic associations (for example, mass occurrences of orbitolines and green algae, a decrease in the abundance of oligotrophic biota). Some authors proposed a synchronous drowning of river-influenced sub-tropical/tropical carbonate platforms for this time interval, which has not been proven in the tropical realm. The results of this investigation and a comparison with other tropical river-influenced platforms suggest that none of them drowned during the mid-Late Aptian. Carbonate platforms in the tropics were also less affected by ecological changes during other warming events of the Aptian, for example, during the late Early Aptian Oceanic Anoxic Event 1a. It is suggested that the more favourable growth conditions for platforms in the tropical realm during the Aptian were related to the arid climate within lower latitudes during that time, which promoted platform growth due to comparably low nutrient runoff. In contrast, the sub-tropical platforms that were repeatedly affected by drowning during the Aptian were situated in or close to a sub-tropical humid climate zone, which promoted heavily eutrophic shallow marine waters. Additionally, these platforms were located close to the northern latitudinal limit for carbonate platforms and thus were easier to destabilize.

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REFERENCES

Abdel-Kireem, M.R., **Schrank, E.**, **Samir, A.M.** and **Ibrahim, M.I.A.** (1996) Cretaceous palaeoecology and palaeoclimatology of the northern Western Desert, Egypt. *J. Afr. Earth Sci.*, **22**, 3–112.

Allan, J.R. and **Matthews, R.K.** (1982) Isotope signatures associated with early meteoric diagenesis. *Sedimentology*, **29**, 797–817.

Arnaud-Vanneau, A., **Arnaud, H.**, **Charollais, J.**, **Conrad, M.A.**, **Cotillon, P.**, **Ferry, S.**, **Masse, J.P.** and **Peybernès, B.** (1979) Paleogeography of the Urgonian limestones of Southern France. *Géobios Mem. Spec.*, **3**, 363–383.

Bachmann, M. and **Hirsch, F.** (2006) Lower Cretaceous carbonate platform of the eastern Levant (Galilee and the Golan Heights): stratigraphy and second order sea-level change. *Cret. Res.*, **27**, 487–512.

Barron, E.J. (1983) A warm, equable Cretaceous: the nature of the problem. *Earth Sci. Rev.*, **29**, 305–338.

Ben Ferjani, A., **Burollet, P.F.** and **Mejri, F.** (1990) Petroleum Geology of Tunisia. *Mem. E. T. A. P.*, **1**, 194.

Boltenhagen, C. (1985) Paléogéographie du Crétacé moyen de la Tunisie centrale. In: *Actes du 1er Congrès national des sciences de la Terre*, Tunisia, Tunis, **1**, 97–114.

Bralower, T.J., **Arthur, M.A.**, **Leckie, R.M.**, **Sliter, W.V.**, **Allard, D.J.** and **Schlanger, S.O.** (1994) Timing and paleoceanography of oceanic dysoxia/anoxia in the Late Barremian to Early Aptian (Early Cretaceous). *Palaios*, **9**, 335–369.

Bralower, T.J., **Fullagar, P.D.**, **Paull, C.K.**, **Dwyer, G.S.** and **Leckie, R.M.** (1997) Mid-Cretaceous strontium-isotope stratigraphy of deep-sea sections. *Geol. Soc. Am. Bull.*, **109**, 1421–1442.

Bralower, T.J., **CoBabe, E.**, **Clement, B.**, **Sliter, W.V.**, **Osburn, C.L.** and **Longoria, J.** (1999) The record of global change in mid-Cretaceous (Barremian–Albian) sections from the Sierra Madre, northeastern Mexico. *J. Foraminif. Res.*, **29**, 418–437.

Brand, U. and **Veizer, J.** (1981) Chemical diagenesis of multicomponent carbonate system-2: stable isotopes. *J. Sed. Petrol.*, **51**, 987–997.

Burchette, T.P. and **Wright, V.P.** (1992) Carbonate ramp depositional systems. *Sed. Geol.*, **79**, 3–57.

Burla, S., **Heimhofer, U.**, **Hochuli, P.A.**, **Weissert, H.** and **Skelton, P.** (2008) Changes in sedimentary patterns of coastal and deep-sea successions from the North Atlantic (Portugal) linked to Early Cretaceous environmental change. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **257**, 38–57.

Burollet, P.F. (1956) Contribution à l'étude stratigraphique de la Tunisie centrale. *Ann. Mines Géol. Tunis*, **18**, 352 pp.

Burollet, P.F. (1990) Structures and tectonics of Tunisia. *Tectonophysics*, **195**, 359–369.

Caldeira, K. and **Rampino, M.R.** (1991) The mid-Cretaceous super plume, carbon dioxide, and global warming. *Geophys. Res. Lett.* **18**, 987–990.

Castro, J.M., **de Gea, G.A.** and **Quijano, M.L.** (2006) Registro del evento anóxico oceánico OAE 1a (Aptiense inferior) en un contexto de plataforma. Prebético (provincia de Allicante). *Geogaceta*, **40**, 251–254.

Chaabani, F. and **Razgallah, S.** (2006) Aptian sedimentation: an example of interaction between tectonics and eustatics in Central Tunisia. In: *Tectonics of the Western Mediterranean and North Africa* (Eds G. Moratti and A. Chalouan), *Geol. Soc. London Spec. Publ.*, **262**, 55–74.

Chumakov, N.M., **Zharkov, M.A.**, **Herman, A.B.**, **Doludenko, M.P.**, **Kalandadze, N.M.**, **Lebedev, E.L.**, **Ponomareko, A.G.** and **Rautian, A.S.** (1995) Climatic belts of mid-Cretaceous time. *Strat. Geol. Corr.*, **3**, 241–260.

Clarke, L.J. and **Jenkyns, H.C.** (1999) New oxygen isotope evidence for long-term Cretaceous climate change in the southern hemisphere. *Geology*, **27**, 699–702.

Coffin, M.F., **Pringle, M.S.**, **Duncan, R.A.**, **Gladczenko, T.P.**, **Storey, M.**, **Muller, R.D.** and **Gahagan, L.A.** (2002) Kerguelen hotspot magma output since 130 Ma. *J. Petrol.*, **43**, 1121–1139.

Fenerci-Masse, M., **Masse, J.P.**, **Arias, C.** and **Vilas, L.** (2006) *Archaeoradiolites*, a new genus from the Upper Aptian of the Mediterranean region and the origin of the rudist family Radiolitidae. *Palaeontology*, **49**, 769–794.

Ferreri, V., **Weissert, W.**, **D'Argenio, B.** and **Buonocunto, F.P.** (1997) Carbon isotope stratigraphy: a tool for basin to platform correlation. *Terra Nova*, **9**, 57–61.

Flügel, E. (2004) *Microfacies of Carbonate Rocks*. Springer Verlag, Berlin, Heidelberg, New York, 976 pp.

Föllmi, K.B. and **Gainon, F.** (2008) Demise of the northern Tethyan Urgonian carbonate platform and subsequent transition towards pelagic conditions: the sedimentary record of the Col de la Plaine Morte area, central Switzerland. *Sed. Geol.*, **205**, 142–159.

Föllmi, K.B., **Weissert, H.**, **Bisping, M.** and **Funk, H.** (1994) Phosphogenesis, carbon-isotope stratigraphy and carbonate platform evolution along the northern Tethyan margin. *Geol. Soc. Am. Bull.*, **106**, 729–746.

Föllmi, K.B., **Godet, A.**, **Bodin, S.** and **Linder, P.** (2006) Interactions between environmental change and shallow water carbonate buildup along the northern Tethyan margin and their impact on the Early Cretaceous carbon isotope record. *Paleoceanography*, **21**, 1–16.

Fries, G., **Beaudoin, B.**, **Joseph, P.** and **Paternoster, B.** (1984) Les grès de Rosans et les slumpings aptiens associés: restitution paléomorphologique. *Bull. Soc. Geol. France*, **7**, 693–702.

Funk, H., **Föllmi, K.B.** and **Mohr, H.** (1993) Evolution of the Tithonian–Aptian Carbonate Platform along the Northern Tethyan margin, Eastern Helvetic Alps. In: *Cretaceous Carbonate Platforms* (Eds J.A.T. Simo, R.W. Scott and J.P. Masse), *AAPG Mem.*, **56**, 111–126.

Grötsch, J., **Schroeder, R.**, **Noé, S.** and **Flügel, E.** (1993) Carbonate platforms as recorders of high amplitude sea-level fluctuations: the late Albian *appenninica*-event. *Bas. Res.*, **5**, 197–212.

Grötsch, J., **Billing, I.** and **Vahrenkamp, V.** (1998) Carbon-isotope stratigraphy in shallow water carbonates: implications for Cretaceous black shale deposition. *Sedimentology*, **45**, 623–634.

Gussmann, O.A. and **Smith, A.M.** (2002) Mixed Siliciclastic-Skeletal Carbonate Lagoon Sediments from a High Volcanic Island, Viti Levu, Fiji, Southwest Pacific. *Pacific Sci.*, **56,** 169–189.

Hallock, P. and **Schlager, W.** (1986) Nutrient Excess and the Demise of Coral reefs and Carbonate Platforms. *Palaios*, **1,** 389–398.

Haq, B.U., Hardenbol, J. and **Vail, P.R.** (1988) Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: *Sea-Level Changes: An Integrated Approach. Soc. Econ. Palaeontol. Mineral. Spec. Publ.*, **42,** 71–108.

Haworth, M., Hesselbo, S.P., McElwain, J.C., Robinson, S.A. and **Brunt, J.W.** (2005) Mid-Cretaceous $p\mathrm{CO_2}$ based on stomata of the extinct conifer *Pseudofrenelopsis* (Cheirolepidiaceae). *Geology*, **33,** 749–752.

Hay, W.W. (1995) A comparison of modern and Cretaceous paleoceanography. *Geol. Carpathica*, **46,** 257–266.

Heimhofer, U., Hochuli, P.A., Herrle, J.O., Andersen, N. and **Weissert, H.** (2004) Absence of major vegetation and palaeoatmospheric $p\mathrm{CO_2}$ changes associated with Oceanic Anoxic Event 1a (Early Aptian, SE France). *Earth Planet. Sci. Lett.*, **223,** 303–318.

Heldt, M., Bachmann, M. and **Lehmann, J.** (2008) Microfacies, biostratigraphy, and geochemistry of the hemipelagic Barremian–Aptian: influence of the OAE 1a on the southern Tethys margin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **261,** 246–260.

Herrle, J.O. and **Mutterlose, J.** (2003) Calcareous nannofossils from the Aptian–Lower Albian of southeast France: palaeoecological and biostratigraphic implications. *Cret. Res.*, **24,** 1–22.

Herrle, J.O., Kößler, P., Friedrich, O., Erlenkeuser, H. and **Hemleben, C.** (2004) High-resolution carbon isotope records of the Aptian to Lower Albian from SE France and the Mazgan Plateau (DSDP Site 545): a stratigraphic tool for paleoceanographic and paleobiologic reconstruction. *Earth Planet. Sci. Lett.*, **218,** 149–161.

Heydari, E., Wade, W.J. and **Hassanzadeh, J.** (2001) Diagenetic origin of carbon and oxygen isotope compositions of Permian–Triassic boundary strata. *Sed. Geol.*, **143,** 191–197.

Hudson, J.D. (1977) Stable isotopes and limestone lithification. *J. Geol. Soc. Lond.*, **133,** 637–660.

Immenhauser, A., Van Der Kooij, B., Van Vliet, A. and **Schlager, W.** (2001) An ocean-facing Aptian–Albian carbonate margin, Oman. *Sedimentology*, **48,** 1187–1207.

Immenhauser, A., Della Porta, G., Kenter, J.A.M. and **Bahamonde, J.R.** (2003) An alternative model for positive shifts in shallow-marine carbonate δ^{13}C and δ^{18}O. *Sedimentology*, **50,** 953–959.

Immenhauser, A., Hillgärtner, H. and **Van Bentum, E.** (2005) Microbial-foraminiferal episodes in the Early Aptian of the southern Tethyan margin: ecological significance and possible relation to Oceanic Anoxic Event 1a. *Sedimentology*, **52,** 77–99.

Jenkyns, H.C. and **Wilson, P.A.** (1999) Stratigraphy, paleoceanography and evolution of Cretaceous Pacific guyots: relics from a greenhouse earth. *Am. J. Sci.*, **299,** 341–392.

Jian, L., Zhizheng, Y., Chunrui, H., Xinbo, L. and **Gaosheng, Q.** (1997) Meteoric diagenesis in Pleistocene reef limestones of Xisha Islands, China. *J. SE Asian Earth Sci.*, **15,** 465–476.

Johnson, C.C., Barron, E.J., Kauffman, E.G., Arthur, M.A., Fawcett, P.J. and **Yasuda, M.K.** (1996) Middle Cretaceous reef collapse linked to ocean heat transport. *Geology*, **24,** 376–380.

Jones, C.E. and **Jenkyns, H.C.** (2001) Seawater strontium isotopes, oceanic anoxic events, and seafloor hydrothermal activity in the Jurassic and Cretaceous. *Am. J. Sci.*, **301,** 112–149.

Kiessling, W., Flügel, E. and **Golonka, J.** (2003) Patterns of Phanerozoic carbonate platform sedimentation. *Lethaia*, **36,** 195–226.

Koutsoukos, E.A.M., Destro, N., de Azambuja Filho, N.C. and **Spadini, A.R.** (1993) Upper Aptian–Lower Coniacian Carbonate Sequences in the Sergipe Basin, Northeastern Brazil. In: *Cretaceous Carbonate Platforms* (Eds J.A.T. Simo, R.W. Scott and J.P. Masse), *AAPG Mem.*, **56,** 111–126.

Kuhnt, W., Moullade, M., Masse, J.P. and **Erlenkeuser, H.** (1998) Carbon isotope stratigraphy of the lower Aptian historical stratotype at Cassis-La Bédoule (SE France). *Geol. Mediterr.*, **3/4,** 63–79.

Lefranc, J.Ph. and **Guiraud, R.** (1990) The Continental Intercalaire of northwestern Sahara and its equivalents in the neighbouring regions. *J. Afr. Earth Sci.*, **10,** 27–77.

Lehmann, C., Osleger, D.A. and **Montanez, I.P.** (2000) Sequence stratigraphy of Lower Cretaceous Barremian–Albian carbonate platforms of northeastern Mexico, regional and global correlations. *J. Sed. Res., B. Stratigr. Glob. Stud.*, **70,** 373–391.

Lehmann, J., Heldt, M., Bachmann, M. and **Negra, M.E.H.** (2009) Aptian (Lower Cretaceous) biostratigraphy and cephalopods from north central Tunisia. *Cret. Res.*, **30,** 895–910.

Leinfelder, R. (1997) Coral reef and carbonate platforms within a siliciclastic setting. General aspects and examples from the Late Jurassic of Portugal. *Proc. 8th Int. Coral Reef Sym.*, **2,** 1737–1742.

M'Rabet, A. (1981) *Stratigraphie, sédimentation et diagenèse carbonatée de séries du Crétace inférieur de Tunisie Centrale*. PhD thesis, University of Paris Sud Orsay, 54 pp.

M'Rabet, A. (1987) Stratigraphie, sédimentation et diagenèse carbonatée des series du Crétacé Inférieur de Tunisie Centrale. *Ann. Mines Géol. Répub.Tunisienne*, **30,** 410 pp.

M'Rabet, A., Mejri, F., Burollet, P.F., Memmi, L. and **Chandoul, H.** (1995) Recueil des coupes types de Tunisie. *ETAP Mem.*, **8B**, 123 pp.

Marie, J., Trouve, P., Desforges, G. and **Dufaure, P.** (1982) Nouveaux Elements de Paléogéographique du Crétacé de Tunisie. *Cret. Res.*, **3,** 167–170.

Martinez, J.I. and **Hernandez, R.** (1992) Evolution and drowning of the Late Cretaceous Venezuelan carbonate platform. *J. S. Am. Earth Sci.*, **5,** 197–210.

Masse, J.P. (1992) The Lower Cretaceous Mesogean benthonic ecosystems: palaeoecologic aspects and palaeobiogeographic implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **91,** 331–345.

Masse, J.P. (1995) Lower Cretaceous rudist biostratigraphy of southern France–A reference for Mesogean correlations. *Rev. Mex. Cienc. Geol.*, **12,** 236–256.

Masse, J.P. and **Chiki-Aouimeur, F.** (1982) La plate-forme carbonatée de l'Ouenza (Sud Constantinois-Algérie). Organisation et dynamique durant l'Aptien supérieur. *Géol. Méditerr.*, **3,** 259–267.

Masse, J.P. and **Thieuloy, J.P.** (1979) Précisions sur l'âge des calcaires et des formations associées de l'Aptien sud-constantinois (Algérie). Conséquences paléogéographiques. *Bull. Soc. Géol. France*, **7,** 65–71.

Masse, J.P., Borgomano, J. and **Al Maskiry, S.** (1997) Stratigraphy and tectonosedimentary evolution of a late Aptian–

Albian carbonate margin: the northeastern Jebel Akhdar (Sultanate of Oman). *Sed. Geol.*, **113,** 269–280.

Masse, J.P., Fenerci-Masse, M. and **Özer, S.** (2002) Late Aptian rudist faunas from the Zonguldak region, western Black Sea, Turkey (taxonomy, biostratigraphy, palaeoenvironment and palaeobiogeography). *Cret. Res.*, **23,** 523–536.

Moss, S. and **Tucker, M.E.** (1995) Diagenesis of Barremian–Aptian platform carbonates (the Urgonian Limestone Formation of SE France): near-surface and shallow-burial diagenesis. *Sedimentology*, **42,** 853–874.

Mutterlose, J. (1992) Migration and evolution patterns of floras and faunas in marine Early Cretaceous sediments of NW Europe. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **94,** 261–282.

Mutterlose, J. (1998) The Barremian–Aptian turnover of biota in northwestern Europe: evidence from belemnites. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **144,** 161–173.

Mutti, M. and **Hallock, P.** (2003) Carbonate systems along nutrient and temperature gradients: some sedimentological and geochemical constraint. *Int. J. Earth Sci.*, **92,** 465–475.

Pervinquiére, L. (1903) Etude géologique de la Tunisie centrale, Thése, Faculté des Sciences de Paris, *F.R. de Rudeval. Paris*, **359** pp.

Pittet, B., van Buchem, F.S.P., Hillgärtner, H., Razin, P., Grötsch, J. and **Droste, H.** (2002) Ecological succession, palaeoenvironmental change, and depositional sequences of Barremian–Aptian shallow-water carbonates in northern Oman. *Sedimentology*, **49,** 555–581.

Premoli Silva, I. and **Sliter, W.V.** (1999) Cretaceous paleoceanography: evidence from planktonic foraminiferal evolution. *Geol. Soc. Am. Spec. Pap.*, **332,** 301–328.

Premoli Silva, I. and **Sliter, W.V.** (2002) Practical manual of cretaceous planktonic foraminifera. In: *International School on Planktonic Foraminifera, 1st Course* (Eds I. Premoli Silva and R. Rettori), 462 pp. Dipartimento di Scienze della Terra, University of Perugia, Italy.

Price, G.D. (2003) New constraints upon isotope variation during the early Cretaceous (Barremian–Cenomanian) from the Pacific ocean. *Geol. Mag.*, **140,** 513–522.

Pucéat, E., Lécuyer, C., Sheppard, S.M.F., Dromart, G., Reboulet, S. and **Grandjean, P.** (2003) Thermal evolution of Cretaceous Tethyan marine waters inferred from oxygen isotope composition of fish tooth enamels. *Paleoceanography*, **18,** 1–12.

Rosales, I. (1999) Controls on carbonate-platform evolution on active fault blocks: the Lower Cretaceous Castro Urdiales Platform (Aptian–Albian, Northern Spain). *J. Sed. Res.*, **69,** 447–465.

Ruiz-Ortiz, P.A. and **Castro, J.M.** (1998) Carbonate depositional sequences in shallow to hemipelagic platform deposits; Aptian, Prebetic of Alicante (SE Spain). *Bull. Soc. Géol. France*, **169,** 21–33.

Russell, D.A. and **Paesler, M.A.** (2003) Environments of Mid-Cretaceous Saharan dinosaurs. *Cret. Res.*, **24,** 569–588.

Schlager, W. (1981) The paradox of drowned reefs and carbonate platforms. *Geol. Soc. Am. Bull.*, **92,** 197–211.

Schrank, E. (1991) Mesozoic palynology and continental sediments in NE Africa (Egypt and Sudan) – a review. *J. Afr. Earth Sci.*, **12,** 363–373.

Schroeder, R. (1975) General evolutionary trends in orbitolinas. *Rev. Esp. Micropaleontol., Núm especial*, 117–128.

Skelton, P.W. (2003) *The Cretaceous World.* The Open University, Cambridge University Press, Cambridge, 360 pp.

Steuber, T., Rauch, M., Masse, J.P. and **Malkoc, M.** (2005) Low-latitude seasonality of Cretaceous temperatures in warm and cold episodes. *Nature*, **437,** 1341–1344.

Takashima, R., Sano, S.I., Iba, Y. and **Nishi, H.** (2007) The first Pacific record of the Late Aptian warming event. *J. Geol. Soc. Lond.*, **164,** 333–339.

Tandia, I.S. (2001) *Etude Lithostratigraphique et Sédimentologique des Séries du Crétacé inférieur (Barrémian–Albian) de la Tunisie centro-septentrionale (régions du Krib et de Tajerouine).* PhD thesis, University of Tunis El Manar, 288 pp.

Thielemann, J. (2006) *Veränderungen der Levantischen Karbonatplattform in der Mittleren Kreide unter besonderer Berücksichtigung des OAE-1a am Beispiel des Gebel Raghawi, Nordsinai, Ägypten.* Diploma thesis, University of Bremen, 91 pp.

Tlatli, M. (1980) *Étude des calcaires de l'Albo–Aptien des Djebel Serdj et Bellouta (Tunisie Centrale).* PhD thesis, University of Marseille, 187 pp.

Tucker, M.E. (2003) Mixed Clastic-Carbonate Cycles and Sequences: quarternary of Egypt and Carboniferous of England. *Geol. Croatia*, **56,** 19–37.

Turki, M.M. (1975) *Etude géologique du Massif Serd-Bargou (Atlas tunisien central).* Thèse 3ème cycle, Univ. P. Et M. Curie Paris 5, 85 pp.

Turki, M.M. (1977) Structure et évolution du massif Serdj Bargou. *Notes Serv. Géol. Tunisie*, **43,** 23–36.

Vahrenkamp, V.C., Franssen, R.C.W.M., Grötsch, J. and **Munoz, P.J.** (1993) Maracaibo platform (Aptian–Albian), Northwestern Venezuela. In: *Cretaceous Carbonate Platforms.* (Eds J.A.T. Simo, R.W. Scott and J.P. Masse), *AAPG Mem.*, **56,** 81–96.

Vecsei, A. (2003) Nutrient control of the global occurrence of isolated carbonate banks. *Int. J. Earth Sci.*, **92,** 476–481.

Vilas, L., Masse, J.P. and **Arias, C.** (1995) *Orbitolina* episodes in carbonate platform evolution : the early Aptian model from SE Spain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **119,** 35–45.

Voigt, S., Hay, W.W., Höfling, R. and **DeConto, R.M.** (1999) Biogeographic distribution of late Early to Late Cretaceous rudist-reefs in the Mediterranean as climate indicators. In: *Evolution of the Cretaceous ocean-climate system* (Eds E. Barrera and C.C. Johnson), *GSA Spec. Pap.*, **332,** 91–104.

Weissert, H. (1990) Siliciclastics in the early Cretaceous Tethys and north Atlantic oceans – documents of periodic greenhouse climate conditions. *Mem. Soc. Geol. Ital.*, **44,** 59–69.

Weissert, H. and **Erba, E.** (2004) Volcanism, CO_2 and palaeoclimate: a late Jurassic–Early Cretaceous carbon and oxygen isotope record. *J. Geol. Soc. Lond.*, **161,** 695–702.

Weissert, H. and **Lini, A.** (1991) Ice Age Interludes during the time of Cretaceous Greenhouse climate? In: *Controversies in Modern Geology* (Eds D.W. Müller, J.A. McKenzie and H. Weissert), pp. 173–191. Academic Press, London.

Weissert, H., Lini, A., Föllmi, K.B. and **Kuhn, O.** (1998) Correlation of Early Cretaceous carbon isotope stratigraphy and platform drowning events: a possible link?. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **137,** 189–203.

Wilmsen, M. (2005) Stratigraphy and biofacies of the Lower Aptian of Cuchía (Cantabria, northern Spain). *J. Iber. Geol.*, **31,** 253–275.

Wilson, M.E.J. and **Lokier, S.W.** (2002) Siliciclastic and volcaniclastic influences on equatorial carbonates: insights from the Neogene of Indonesia. *Sedimentology*, **49,** 583–601.

Wissler, L., Funk, H. and **Weissert, H.** (2003) Response of early Cretaceous carbonate platforms to changes in atmospheric

carbon dioxide levels. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **161,** 1–8.
Wood, R.A. (1993) Nutrients, predation and the history of reef building. *Palaios*, **8,** 526–543.
Wortmann, U.G., Herrle, J.O. and **Weissert, H.** (2004) Altered carbon cycling and coupled changes in Early Cretaceous weathering patterns: evidence from integrated carbon isotopes and sandstone records of the western Tethys. *Earth Planet. Sci. Lett.*, **220,** 69–82.
Yilmaz, I.Ö., Vennemann, T., Altiner, D. and **Satir, M.** (2004) Stable Isotope Evidence for meter-scale sea level changes in Lower Cretaceous inner platform and pelagic carbonate successions of Turkey. *Geol. Carp.*, **55,** 19–36.
Ziegler, A.M., Eshel, G., McAllister Rees, P., Rothfus, D.B., Rowley, D.B. and **Sunderlin, D.** (2003) Tracing the tropics across land and sea: permian to present. *Lethaia*, **36,** 227–254.

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