High-frequency sea-level changes recorded in deep-water carbonates of the Upper Cretaceous Dol Formation (island of Brač, Croatia)

DAMIR BUCKOVIĆ, MAJA MARTINUŠ, DUJE KUKOČ, BLANKA CVETKO TEŠOVIĆ and IVAN GUŠIĆ

Department of Geology, Faculty of Science, University of Zagreb, Horvatovac 102a, 10000 Zagreb, Croatia; buckovic@geol.pmf.hr

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Abstract: The upper part of the Middle Coniacian/Santonian–Middle Campanian deep-water Dol Formation of the island of Brač is composed of countless fine-grained allodapic intercalations deposited in an intraplatform trough. Within the studied section 13 beds can be distinguished, each defined by its lower part built up of dark grey limestone with abundance of branched, horizontally to subhorizontally oriented burrows, and the upper part, in which the light grey to white limestone contains larger burrows, rarely branched, showing no preferential orientation. The lower, dark grey, intensively bioturbated levels are interpreted as intervals formed during high-frequency sea-level highstands, while the upper, light grey-to-white levels are interpreted as intervals formed during the high-frequency sea-level lowstands. Cyclic alternation of these two intervals within the fine-grained allodapic beds is interpreted as the interaction between the amount of carbonate production on the platform margin and the periodicity and intensity of shedding and deposition in the distal part of toe-of-slope environment, which is governed by Milankovitch-band high frequency sea-level changes.

Key words: Campanian, Croatia, Adriatic-Dinaric carbonate platform, Dol Formation, carbonate sedimentology, high-frequency sea-level changes, intraplatform trough.

Introduction

Lithostratigraphically, the six formations composing the Upper Cretaceous succession on island of Brač include carbonate deposits ranging in age from Middle Cenomanian to Maastrichtian (Fig. 1). Their dating is based on rudists and larger benthic foraminiferal assemblages, which were correlated with corresponding rudist cenozones established by Polšak (1967) and Slišković (1968), and benthic foraminiferal zones established by Fleury (1980) (Cvetko Tešović et al. 2001). Recently, the chronostratigraphy of the Coniacian-Maastrichtian formations has been revised, based on numerical ages derived from strontium-isotope stratigraphy (SIS) measured in the low-Mg calcite of rudist shells (Steuber et al. 2005).

The Middle Coniacian/Santonian–Middle Campanian Dol Formation, previously introduced by Pejović & Radoičić (1987), is represented by intraplatform trough carbonates, which are relatively uniform in lithological character. Consequently, the diagnostic sedimentological criteria commonly used in shallow-water settings for the identification of high-frequency sea-level changes are completely lacking here. However, in other deep-water sediments, the presence of high-frequency sea-level changes responsible for a cyclic sedimentary signature with periodicities consistent with orbital (so-called Milankovitch) forcing has been demonstrated in many studies (e.g. Savrda & Bottjer 1986, 1989, 1994; Masetti et al. 1991; Erba & Silva 1994; Damholt & Surlyk 2004; Heard et al. 2008). In many shallow-water carbonate platform settings, the cyclically stacked building blocks of 3rd-order sequences can equally be attributed to orbital forcing of sea-level changes. Each cycle has a predictable upward facies succession containing repetitive patterns of lithologic, biotic, ichnologic, and/or taphonomic change (Lukasik & James 2003). Such building blocks represent the 4th- to 6th-order parasequences (sensu Van Wagoner et al. 1988).

The Cenomanian to Maastrichtian 3rd-order sequences of the island of Brač represent a complete succession of mixed shallow- and deep-water carbonate sediments deposited within the Adriatic-Dinaric carbonate platform realm (ADCP) (Vlahović et al. 2005). The 4th- to 6th-order parasequences, exhibiting sedimentological evidence of high-frequency (Milankovitch band) sea-level changes, are well exposed in this shallow-water platform setting (Moro 1997; Cvetko Tešović et al. 2001; Moro et al. 2002). However, cyclicity in contemporaneous deep-water platform environments has not been observed and described so far. Therefore, the intention of this paper is to contribute to the understanding of the role of orbital forcing on cyclic sedimentation in deep-marine environments, that is to show how high frequency sea-level changes can produce a cyclic sedimentary signature in an intraplatform trough that is synchronous to that on the platform. For this purpose, one selected deep-water section from the upper part of the Lower Campanian Dol Formation has been studied in detail.

Geological setting

The island of Brač is situated along the central part of the eastern Adriatic coast, showing a rather complete, relatively undisturbed and well exposed Upper Cretaceous succession

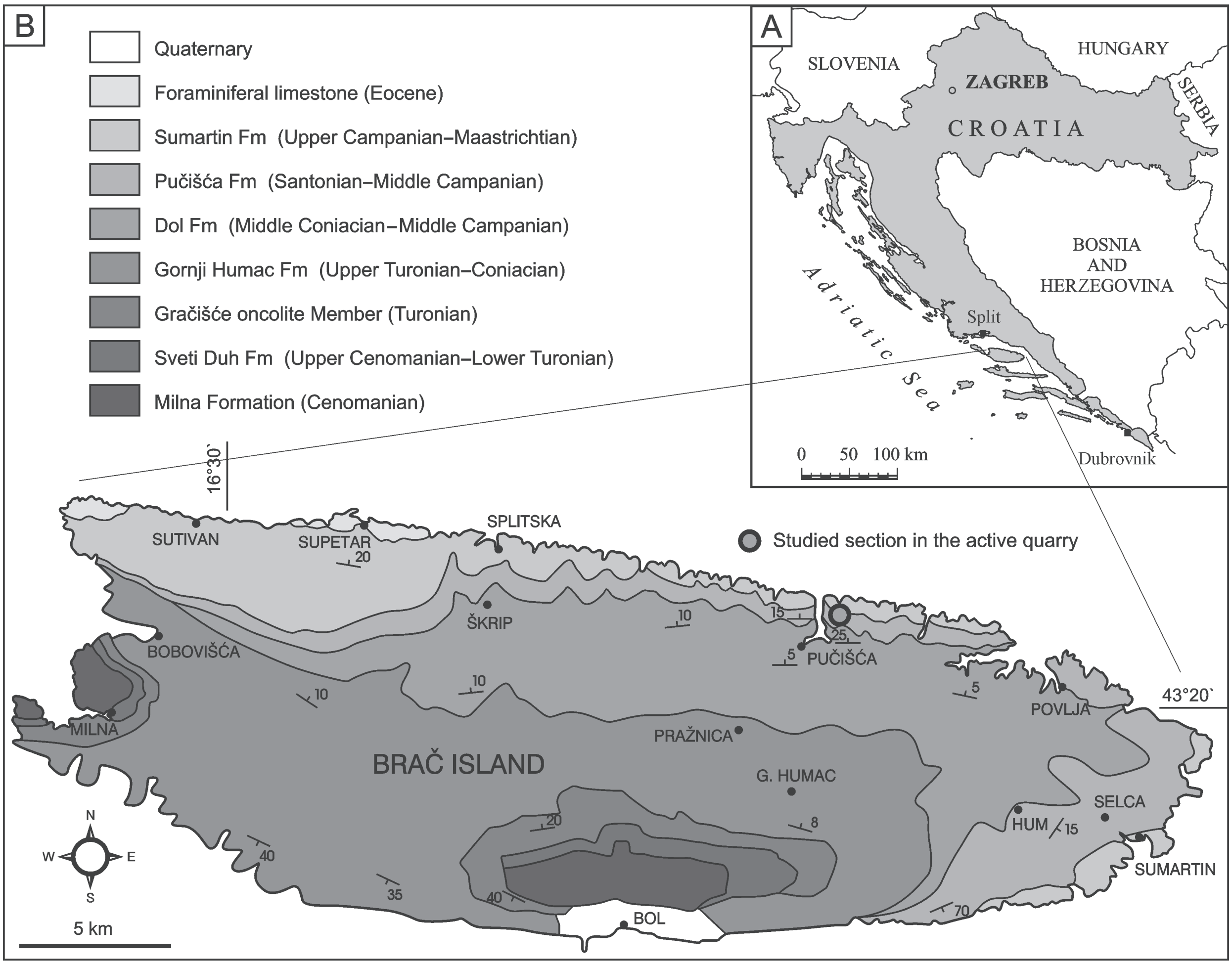

Fig. 1. A — Map showing location of the island of Brač in the eastern Adriatic region. **B** — Simplified lithostratigraphic map of the island of Brač (modified after Gušić & Jelaska 1990; Steuber et al. 2005) showing the position of the studied section near Pučišća.

(Fig. 1). This succession is a representative example of Upper Cretaceous carbonates of that part of the Adriatic-Dinaric carbonate platform (Gušić & Jelaska 1990). The Adriatic-Dinaric carbonate platform succession evolved as an isolated carbonate realm from the Late Triassic to the middle Eocene (Gušić & Jelaska 1993; Pamić et al. 1998; Jelaska et al. 2000; Jelaska et al. 2003). The inception of the isolated depositional environment was accompanied by extensive deposition of shallow-water carbonates overlying platform siliciclastics and carbonates of an epeiric realm that was attached to Gondwana. This isolated platform evolution was punctuated by many periods of subaerial exposure as well as by pelagic drowning episodes. One of these pelagic episodes occurred during the Campanian (e.g. Hancock & Kauffman 1979; Hallam 1984; Haq et al. 1987) and partly coincides with the deposition of the Dol Formation of the island of Brač, described in detail by Gušić & Jelaska (1990).

Description of the studied section

The deep-water Dol Formation crops out along the north-northeastern limb of the Brač anticline, normally and conform-

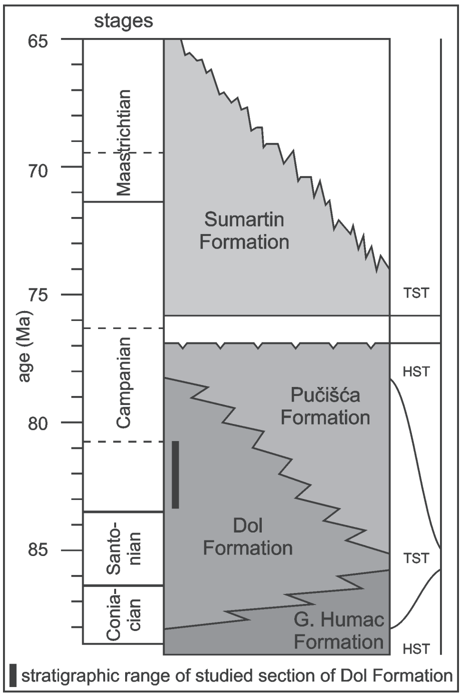

Fig. 2. Chronostratigraphy of the island of Brač with sequence stratigraphic interpretation (adapted from Cvetko Tešović et al. 2001, and Steuber et al. 2005).

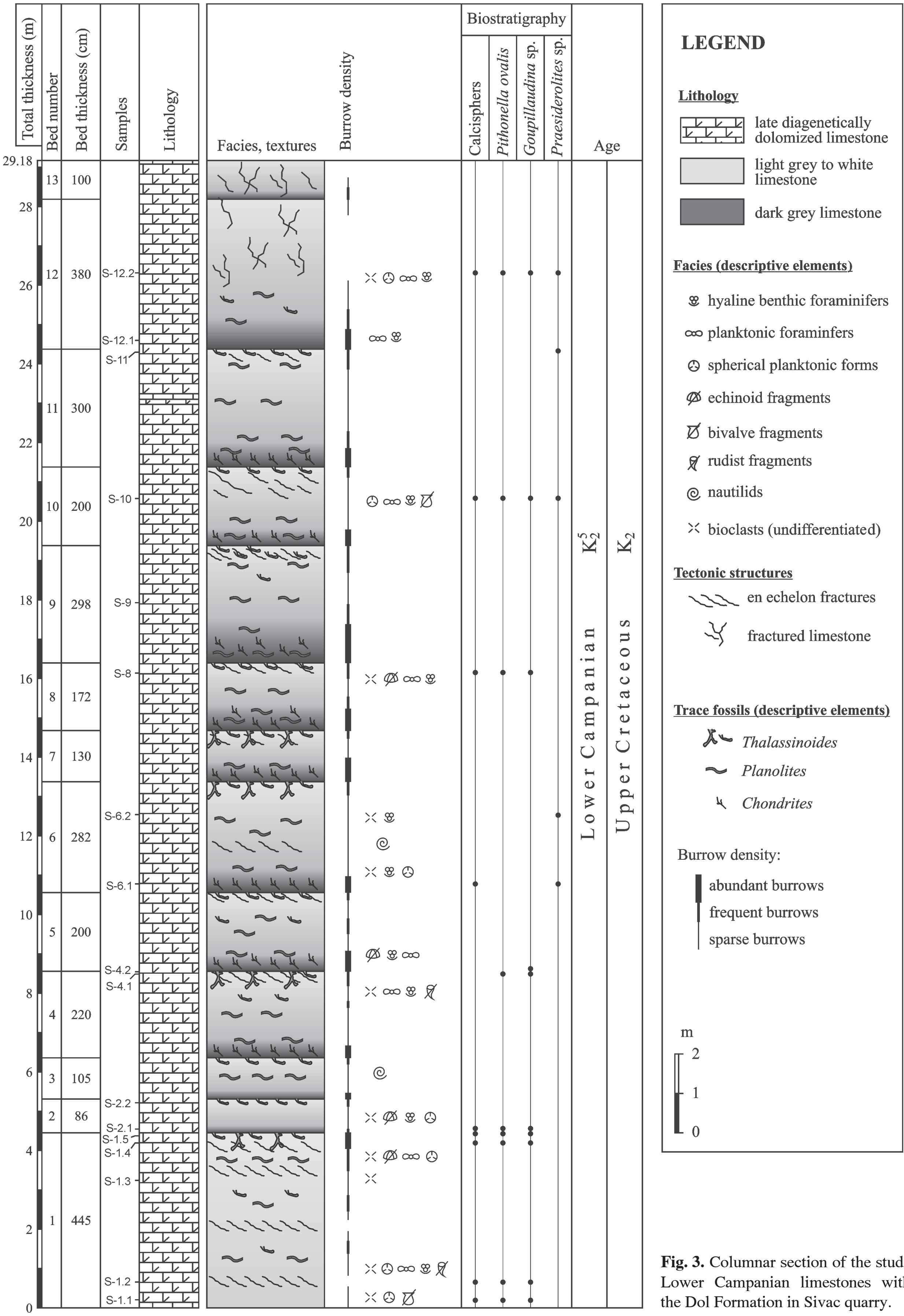

Fig. 3. Columnar section of the studied Lower Campanian limestones within the Dol Formation in Sivac quarry.

ably overlying the shallow platform Gornji Humac Formation (Figs. 1 and 2). The Dol Formation is typically 80–200 m thick (Moro et al. 2002). The thickness of the Dol Formation is greatest in the northeastern part of the limb and decreases towards the western part, while in the southern part the Dol Formation is thin and occurs only sporadically as intercalations within the Gornji Humac Formation. The Dol Formation represents the transgressive systems tract deposits that are overlain by a heterogeneous late transgressive-highstand systems tract unit comprised of various limestone types, known as the Pučišća Formation, which represent shallow-water deposits of the prograding platform (Gušić & Jelaska 1990; Cvetko Tešović et al. 2001).

The studied section of the Dol Formation is located on the north part of the island of Brač in the area near Pučišća, but only one location in the Sivac quarry pit was investigated and described in detail, owing to excellent exposure due to active quarrying. The section of a total thickness of 29.18 m comprises 13 identifiable beds (Figs. 3 and 4). Each bed is entirely composed of bioclastic wackestone-packstone/grainstones. This facies is commonly present within the Dol Formation. According to Gušić & Jelaska (1990), the bioclastic wackestone-packstone/grainstones of the Dol Formation represent bioclastic intercalations within the pelagic mudstones–bioclastic wackestones. Pelagic mudstones–bioclastic wackestones usually contain "oligosteginids" (calcispheres, pithonellas) and variously oriented sections of globotruncanid foraminifers. However, this facies is not observed in the studied section. The intercalations of bioclastic wackestone-packstone/grainstones within the Dol Formation usually represent several decimeters to several meters thick lens-shaped bodies, hundreds of meters in lateral extension, with sharp and uneven lower bedding planes (Gušić & Jelaska 1990). However, due to its fine-grained texture throughout the studied section, the recognition of a single bioclastic intercalation is difficult. The only certain visual feature is represented by the cyclic alternation of burrow density and colour of beds. Each bed is defined by a lower part, built up of dark grey limestone with abundance of branched, horizontally to subhorizontally oriented burrows, and an upper part in which the light grey-to-white limestone contains larger burrows, rarely branched, showing no preferential orientation. Bed limits are recognized as sharp, although occasionally gradual change in colour is observed (Fig. 5). The classification of burrows focuses on their macroscopic features such as orientation, shape, length and diameter of individual burrows, and the intensity of bioturbation in various parts of each bed. Observations were made on vertical sections, since bedding surfaces are not exposed. Therefore, an evaluation of the horizontal extension of individual feature was not possible. Burrow structures are well preserved and show very little or no diversity throughout the studied section. They are mostly present as more or less unlined, rarely branched ("y" shape), horizontal to subvertical cylindrical tunnels. Burrows occur throughout each of the 13 distinguished bioclastic beds. Burrows found in the lower, darker part of each bed are smaller, more branched, lighter in colour than the host rock and show prevailing horizontal to subhorizontal orientation (Fig. 5). In the light grey-to-white part of each bed, that is in its upper part, the burrows are larger, rarely branched, darker than the host rock and show no preferential orientation (Fig. 7). In addition to the differences in size, the bioturbation is most intense in the lower, darker part of each bed. Some darker parts are completely bioturbated, making individual burrow structures invisible (differences in burrow density are presented in Fig. 3). The length and diameter of burrows have been measured: maximum diameter of individual tunnels is 3 cm and maximum length is 30 cm

Fig. 4. The vertical surface of the Sivac quarry pit showing the investigated profile with individual beds marked.

Fig. 5. An individual bed (bed 5) showing dark, completely bioturbated lower part and sparse burrows in the middle and upper parts (scale bar is 1 meter long).

in the upper part, while burrow diameter in the dark parts is mostly up to 1 cm and their length up to 12 cm. Measured specimens commonly comprise burrow segments that probably represent part of a larger structure. Therefore, the measurements correspond to minimum length. Burrow fills are structureless and of the same facies as the host rock. However, polished and thin-sections reveal that burrow fills are slightly more dolomitized than the host rock due to their greater initial permeability during the influence of rising waters rich in Mg. Identification of the trace fossils is restricted to the ichnogeneric level for the reason mentioned above. The smaller and branched burrow structures occurring in lower parts of beds are assigned to *Chondrites* (Fig. 6). The unlined, horizontal to subhorizontal cylindrical burrows are attributed to *Planolites* (Fig. 7), whereas the largest, vertical to subvertical cylindrical burrows, showing "y" shaped branching, are identified as *Thalassinoides* (Fig. 7). The facies of the whole studied section consists of a variety of fine-grained particles, such as calcispheres, pithonellas, sponge spicules, echinoderm debris and undefined calcitic grains (probably also of skeletal origin) (Fig. 8). Sporadically, coarser rudist, other mollusk, and/or echinoderm fragments

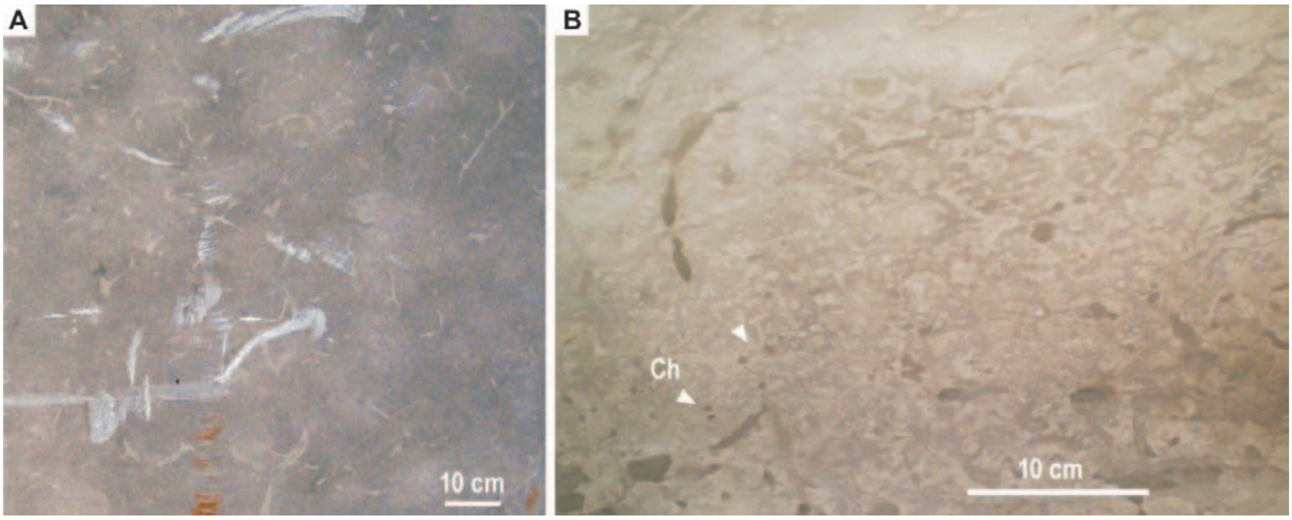

Fig. 6. Trace fossils on vertical surface of the quarry pit: distribution of trace fossils within the lower part of an individual bed built up of dark grey limestone: **A** — *Chondrites*; **B** — almost completely burrowed part with *Chondrites* (Ch).

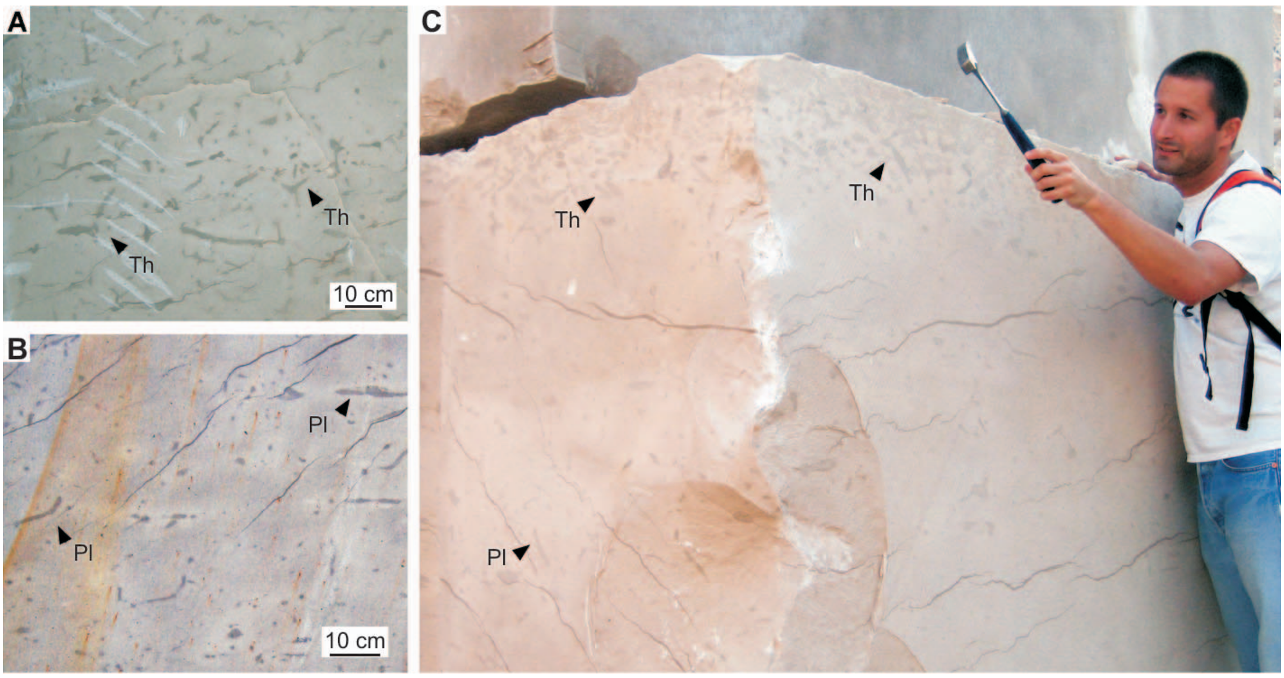

Fig. 7. Trace fossils on vertical surface of the quarry pit: **A** — *Thalassinoides* (Th); **B** — *Planolites* (Pl); **C** — distribution of trace fossils within the upper part of an individual bed built up of light grey to white limestone: sparse *Planolites* (Pl) in the lower part and abundant *Thalassinoides* (Th) in the upper part.

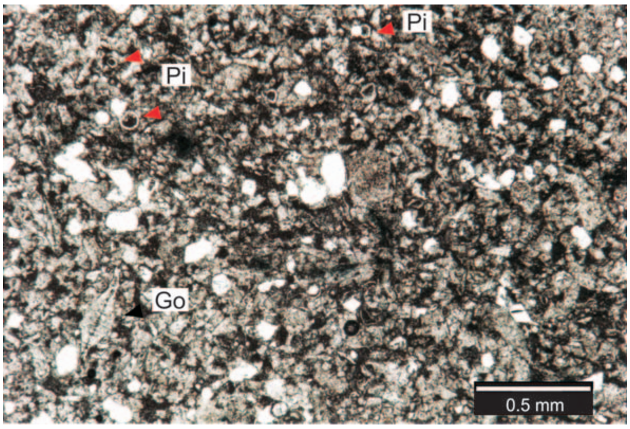

Fig. 8. Microphotograph of bioclastic packstone microfacies with pithonellas (Pi), *Goupillaudina* sp. (Go) and undefined calcitic debris. Subhedral and euhedral dolomite crystals are frequent (Sample S-4.1).

Fig. 9. Unbroken nautiloid shell within fine-grained limestone found in bed 6.

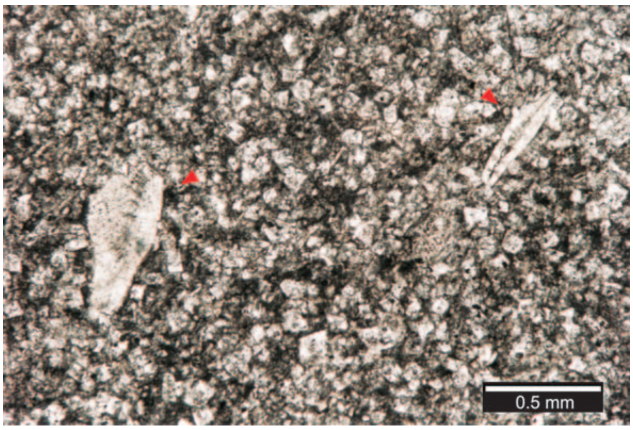

Fig. 10. Microphotograph of intensively dolomitized limestone containing hyaline foraminifer *Goupillaudina* sp., with frequent subhedral and euhedral dolomite crystals (Sample S-12.2).

occur in the fine-grained groundmass. Large nautiloid (Fig. 9) and unbroken rudist remains are rare. Elongated particles are mostly oriented parallel to bedding. Among the pithonellas, *Pithonella ovalis* (Kaufmann) and *Pithonella perlonga* (Andri) are the most common (Fig. 8). Oval to suboval tiny faecal pellets and peloids (micritized bioclasts and/or rounded intraclasts?) are also present, as well as sporadic sections of the foraminifer *Goupillaudina* sp. (Fig. 10). Subhedral and euhedral dolomite crystals, ranging in size from 0.1–0.2 mm, frequently occur (Fig. 10) and, in places, the dolomitization is so pervasive that the primary bioclastic structure is not recognizable. According to the biofacies association this section was assigned to the Early Campanian (Gušić & Jelaska 1990). The age of upper part of Dol Formation near Pučišća was also determined as Early Campanian based on strontium-isotope stratigraphy (Steuber et al. 2005).

Sedimentary environment

The facies characteristics of the Dol Formation imply countless fine-grained intercalations deposited in an intraplatform trough (Gušić & Jelaska 1990), that is in the distal parts of the toe-of-slope environments as has been described by many authors (e.g. Reijmer & Everaars 1991; Reijmer et al. 1991; Herbig & Bender 1992; Harris 1994; Herbig & Mamet 1994).

The platform-derived bioclasts, such as sporadic coarser rudist fragments in the fine-grained bioclastic groundmass, clearly indicate re-deposition from a shallow-water platform into the adjacent deep-water intraplatform trough environment. A connection with the open Tethys Ocean is assumed on the basis of a variety of pelagic biota (calcispheres, pithonellas and sporadic nautilid skeletons).

The intraplatform trough was formed during the Middle Coniacian–Early Santonian (Steuber et al. 2005), when some parts of the hitherto uniform ADCP area were sunk due to the synsedimentary block-faulting, forming depositional environments at least a few hundred meters deep (Gušić & Jelaska 1990). Therefore, in the unaffected platform parts, the deposition of shallow-water carbonates continued, while in the sunken platform parts the deposition of deep-water carbonates took place. Within the intraplatform trough environment, the monotonous deep-water pelagic deposition was periodically disturbed by bioclastic flows, carrying shallow-water material along the inclined trough slope, inserting and mixing various shallow-water platform debris with pelagic particles. Such sections, consisting of derived turbiditic bioclastic intercalations, are usually referred as the allodapic limestones (Meischner 1964). In our section, the occurrence of countless, exclusively fine-grained, allodapic intercalations clearly indicates a distal depositional setting within the toe-of-slope environment. In a more proximal setting coarse-grained intercalations would be expected (e.g. Reijmer & Everaars 1991; Reijmer et al. 1991; Herbig & Bender 1992; Harris 1994; Herbig & Mamet 1994). This shedding of platform-derived material onto the inclined trough slope led to gradual infilling of the intraplatform trough and to progradation of the shallow-water Pučišća Formation (Gušić & Jelaska 1990).

Discussion

The facies and environmental framework outlined above indicates a mutual relationship between depositional processes on the platform margin and its toe-of-slope area. It can be assumed that both sedimentary systems were controlled by one or more common mechanisms. High-frequency sea-level changes and progradation of the platform are considered to be the most important parameters. Although high-frequency sea-level changes have been widely considered to reflect Milankovitch cycles, the exact mechanism for the development of parasequences is not always easy to explain unequivocally. Orbital cycles modulate insolation and thus induce fluctuations of climate. Waxing and waning of ice caps, especially during icehouse times, act as amplifiers of the inherently weak insolation signal. Orbitally controlled waxing and waning of the ice caps but also thermal expansion and retraction of the ocean surface waters, translate into high-frequency sea-level changes that, on the platform, may lead to meter-scale shallowing-upward cycles (e.g. Strasser 1991; Goldhammer et al. 1993; Strasser 1994; D'Argenio et al. 1997; Buonocunto et al. 1999; Strasser et al. 1999; Yang & Lehrmann 2003; Zühlke et al. 2003; Strasser et al. 2006).

Miller et al. (2003) have shown that the Late Cretaceous ice sheets had large and rapid influence on sea-level changes. Consequently, orbitally-controlled high-frequency sea-level changes are to expected. On the shallow platform, these sea-level changes significantly controlled the phases of productivity and exporting of carbonate towards the intraplatform trough.

During high-frequency sea-level highstands, when the sea-floor on the platform margin reached depths below the fair-weather wave-base (Fig. 11a), the amount of carbonate production and wave energy was low (e.g. Bucković et al. 2001; Bucković et al. 2005). In such circumstances, shedding of carbonate detritus along the trough slope was minor, triggered more intensively only by sporadic seismic activity and/or heavy storms. As the majority of the bioclasts from the proximal allodapic intercalations within the Dol Formation consist of coarse-grained rudist debris (Gušić & Jelaska 1990), it is obvious that the platform margin must have been inhabited by rudist buildups (Fig. 11a). These buildups constituted massive biostromes instead of true reefs. Such rudist biostromes would have acted as a sort of barrier separating the back reef area from the slope area (Gušić & Jelaska 1990). During high frequency sea-level highstands, when the sea-bottom on the platform margin was drowned below the fair-weather wave-base, the deposition on the margin was constant but slow, accumulating in-situ bioclastic shallow-water debris; benthic foraminifers occasionally associated with tiny rudist bioclasts and peloids inserted in carbonate mud, producing the lower member of the 4th- to 6th-order parasequence (Fig. 11a.1). On the other hand, during this phase the distal part of the toe-of-slope represented a quiet depositional environment with high nutrient content previously derived from the platform flat. Many bottom dwellers burrowed through this fine-grained bioclastic debris to obtain food, eating either other organisms or organic detritus. The remains of planktonic organisms sank to the sea-bottom, providing an additional food source. The lack of light precluded carbonate production by phototrophic organisms. Consequently, the benthic communities were dominated by such detritus feeders.

During these high-frequency sea-level highstands, distal, deep-water toe-of-slope environment experienced conditions very similar to condensation, representing here "short" geological time spans without major bioclastic inputs (Fig. 11a). However, these conditions do not represent true condensation because authigenic minerals such as glauconite, typical of condensed sections, do not occur in the studied outcrop. Hardgrounds with iron, manganese or phosphorite crusts have not been found either. However, slow rates of sediment accumulation in this distal environment allowed more time for burrowing organisms to rework a given package of sediment, so burrowed intervals are common (Fig. 11a.2). These are especially intensive within the dark grey levels of our section. So really, dark grey, intensively bioturbated levels from our section can be interpreted as the levels very similar to condensation.

The dark grey colour that regularly characterizes these deep-water, intensively bioturbated levels (Fig. 11a.2), certainly points to presence of organic matter. Such organic-rich beds are commonly assumed to represent conditions of low to very low dissolved oxygen content at the sea-bottom. Cyclical alternation of organic-rich and organic-poor intervals has been reported in many studies and is commonly attributed to orbital forcing (e.g. Bellanca et al. 1999; Turgeon & Brumsack 2006; Uchman et al. 2008; Mitchell et al. 2008). Therefore, we reasonably assume that vertical alternation of organic-rich and organic-poor beds observed in our section, clearly points to alternating oxic-dysoxic and anoxic marine conditions governed by Milankovitch-band cyclicity.

Oxic-dysoxic conditions in the distal, deep-water toe-of-slope environment occurred during high-frequency sea-level lowstands. During these periods, when the sea-bottom on the platform margin became positioned closer and/or above the fair-weather wave-base (Fig. 11b), the carbonate production and wave energy increased (e.g. Bucković et al. 2001, 2005). Under such shallower-water and higher energy conditions, various coarser-grained rudist particles were formed, producing the upper member of the 4th- to 6th-order parasequence (Fig. 11b.1). With continuing carbonate production, accommodation space further decreased and the sea-bottom continued to aggrade. The accommodation space decreased and was no longer available for in-situ rudist debris accumulation. Therefore, currents winnowed the coarser-grained rudist bioclasts, initiating a more or less intensive shedding of the bioclastic debris along the inclined trough slope, producing numerous fine-grained allodapic intercalations at the distal part of toe-of-slope environment (Fig. 11b). These countless bioclastic shedding events during phases of higher energy conditions on the platform resulted in gradual infilling of the trough (gradual progradation of the Pučišća Formation). The light grey-to-white colour of these bioclastic levels (Fig. 11b.2) clearly suggest their formation under conditions of higher dissolved oxygen content on the deep-water toe-of-slope environment. Additionally, higher oxygen levels are confirmed by the appearance of the larger ichnogenera such as *Planolites* and *Thalassinoides* (Fig. 11b.2) that commonly point to increased oxygenation levels on the sea-floor (e.g. Bromley & Ekdale 1984).

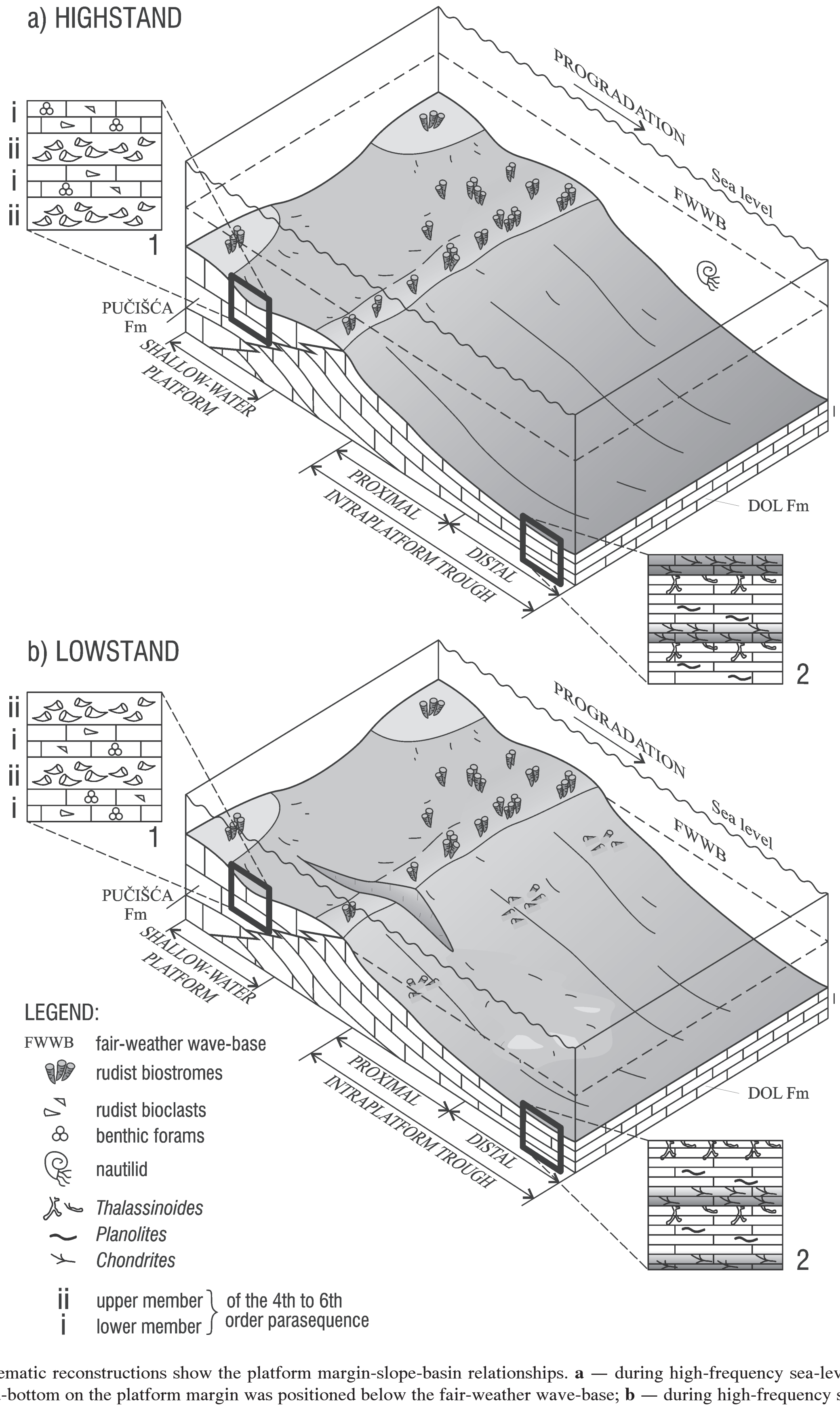

Fig. 11. Schematic reconstructions show the platform margin-slope-basin relationships. **a** — during high-frequency sea-level highstands when the sea-bottom on the platform margin was positioned below the fair-weather wave-base; **b** — during high-frequency sea-level lowstands, when the sea-bottom on the platform margin was positioned closer and/or above the fair-weather wave-base (11a.1 and 11b.1 parasequences modified after Moro et al. 2002) (not to scale).

Conclusion

We hypothesize that the sedimentary signature of the studied carbonate section from the upper part of the Dol Formation may have resulted from processes that were influenced by Milankovitch-band high-frequency sea-level changes. During periodical high-frequency sea-level highstands, when the sea-floor on the platform margin became drowned below the fair-weather wave-base, significant deficiency of dissolved oxygen at the distal part of the intraplatform trough occurred, but never so extreme that burrowing organisms would disappear. Without major bioclastic input from the platform margin, they burrowed through the fine-grained bioclastic debris in order to obtain food, producing intensively and densely bioturbated intervals that contain more organic matter.

In contrast to this, during high-frequency sea-level lowstands, when the sea-bottom on the platform margin reached depths closer and/or above the fair-weather wave-base, the quantity of dissolved oxygen in the deep-water environment increased, but now the intraplatform trough bottom was constantly filled up with derived allodapic fine-grained intercalations. Thus, although the oxygen conditions were very favourable, burrowing organisms suffered heavily from the constant infilling of the trough. So burrows are rarer, or more widely dispersed in the oxygenated light grey-to-white levels than in the darker, oxygen deficient levels. This indicates that these organisms had enough time to bioturbate the sediment to a certain extent, that is they were capable of keeping pace with the addition of newly derived sediment.

Therefore, the results of this research provide congruous recognition of Milankovitch-band high-frequency sea-level changes that governed platform-intraplatform trough interaction through the periodicity and intensity of intraplatform trough infilling. Moreover, for the first time on the ADCP area, alternating periods of oxic-dysoxic and anoxic marine conditions within the intraplatform trough environments are attributed to this Milankovitch-band cyclicity.

However, due to the unpredictable variations in the re-depositional flows, more or less controlled by autocyclic "noise" on the platform flat (e.g. seismic activity and/or heavy storms could trigger intensive shedding of detritus even during high-frequency sea-level highstands), the studied sedimentary signature cannot reliably reveal periodicities consistent with certain Milankovitch perturbation (precession, obliquity or eccentricity). Therefore, we do not speculate about the type of orbital forcing that triggered high-frequency sea-level changes. We only demonstrated that the allocyclic model offers a reasonably plausible explanation for the observed changes in deep-water carbonates of the Dol Formation.

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