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The origin of coarsening-upward cycle architecture; an example from Middle Liassic platform carbonates of mountain Velika Kapela (Croatia)

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Abstract: The Middle Liassic carbonate succession of Mt Velika Kapela is composed of coarsening-upward cycles. Analysis of facies alternation and stacking pattern reveals a sporadic appearance of oolitic facies indicating oolitic shoal progradation from neighbouring topographic highs. These progradations interrupted the constant "in situ" carbonate sediment aggradation, which produced typical coarsening-upward architecture. Two types of coarsening-upward cycles were distinguished: **1** — cycles with peloidal-bioclastic upper cycle members, and **2** — cycles with oolitic upper cycle members. These coarsening-upward cycles are regarded as a record of the sea-bottom oscillations below and above the fair-weather wave-base and model for evolution and cyclic response of carbonate facies to these oscillations is presented.

Key words: Croatia, Adriatic-Dinaric carbonate platform, autocyclicity, carbonate sedimentology, Middle Liassic limestones, facies analysis.

Introduction

This paper is the result of our frequent encounters with Middle Liassic cyclic sedimentary signatures throughout the Karst Dinarides platform area. Numerous studies of the effects of high-frequency relative sea-level changes in carbonates show that cycles are excellent indicators of sea-level fluctuations because their formation is highly dependent on many variable parameters (Hays et al. 1976; Goodwin & Anderson 1985; Grotzinger 1986; Goldhammer et al. 1990; Gonzales 1996; Strasser et al. 1999; Egenhoff et al. 1999). Thus, the cycle architecture depends on environmental factors that change periodically causing rapid facies changes through time. These facies changes occur when a physical, chemical, and/or biological treshold is passed, and when the sediment acquires a new composition and texture (Strasser et al. 1999). This study represents an attempt to interpret Middle Liassic coarsening-upward cycles. We have chosen a Middle Liassic interval from Mt Velika Kapela (Croatia) because it represents a depositional sequence revealing typical facies alternations with successive and repeated coarsening-upward trends, typical for the Middle Liassic succession of the Karst Dinarides.

Geological setting

The studied profile of Middle Liassic limestones is well exposed along the road between Jasenak and Novi Vinodolski at Mt Velika Kapela (Fig. 1). This area represents the western part of the Karst Dinaridic platform area. Due to its complex geological history, there are different opinions among Croatian geologists concerning two important issues: (a) the name of the Karst Dinaridic platform area and, (b) its stratigraphic range. Gušić & Jelaska (1993), Jelaska et al. (1994, 2000), and Jelaska (2003) consider that the depositional area of the Karst Dinarides belongs to the Adriatic-Dinaric carbonate platform area (ADCP), with its lower boundary marked by a regional unconformity between the Hauptdolomit and various pre-Norian units. On the other hand, Tišljar et al. (1991) and Velić (2000) regard the depositional area of the Karst Dinarides as belonging to the Adriatic carbonate platform (ACP), where the Hauptdolomit would represent only the lower boundary of the second ACP megasequence and the entire ACP sequence would extend from the Upper Paleozoic to Paleogene (Tišljar et al. 1991; Velić 2000). However, we prefer to use the name "Adriatic-Dinaric carbonate platform (ADCP)" in the sense proposed and elaborated by Jelaska (2003). A more detailed explanation of our choice is beyond the scope of this paper (see Velić et al. 2003; Jelaska 2003).

Until the Middle Triassic, the area of what is to become the Adriatic-Dinaric carbonate platform, represented a part of the northern Gondwana shelf area, characterized by deposition of siliciclastics and carbonates. During the Middle Triassic, disintegration of the shelf foundation and separation of a huge shallow-water shelf fragment named the Adria Microplate took place within the Tethyan realm (Bernoulli & Jenkyns 1974). During the late Early Jurassic, the Adria Microplate disintegrated, resulting in the formation of three shallow-water areas mutually separated by deep-water basins. These were the Adriatic-Dinaric, Apenninic, and Apulian

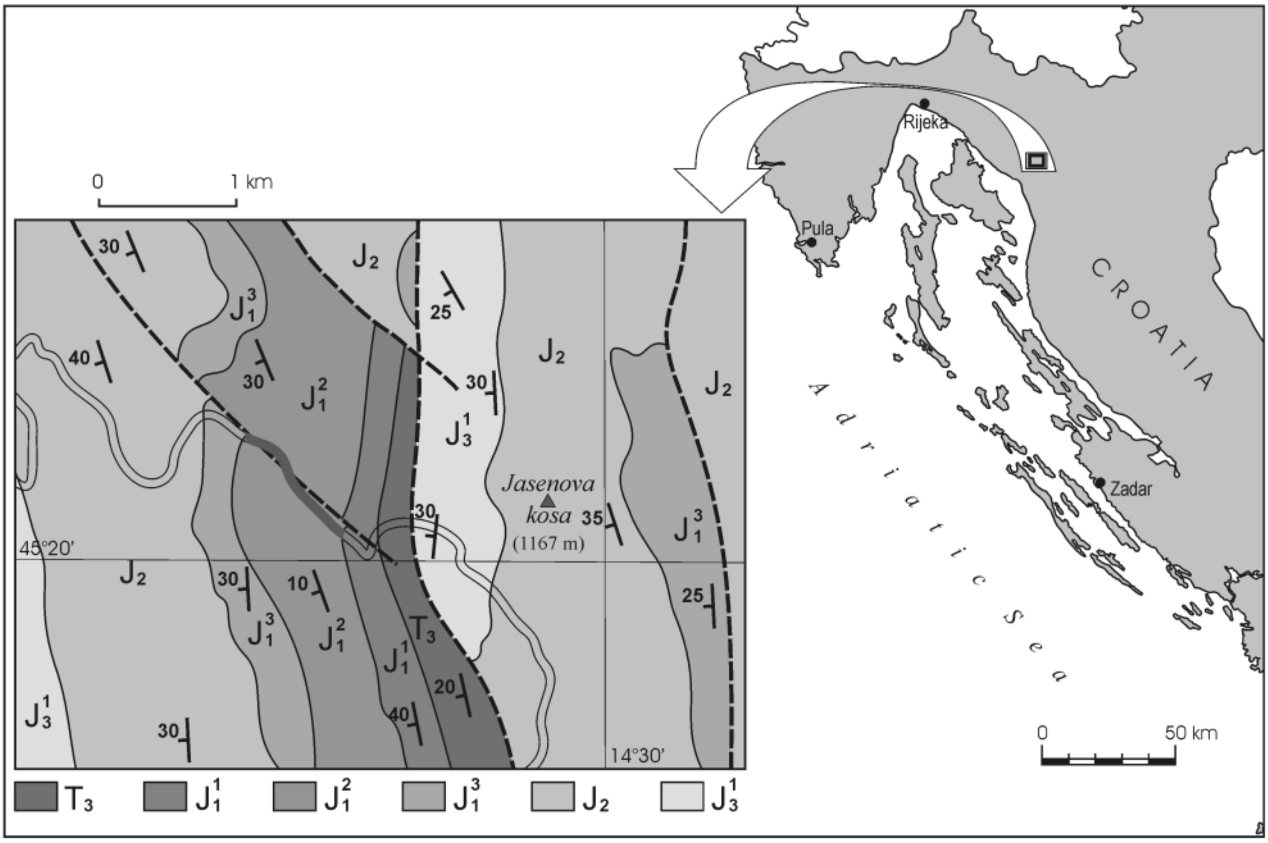

Fig. 1. Geographical location of the studied succession (studied profile is exposed along the shaded part of the road). Geological sketch according to Basic Geological Map 1:100,000, sheet Crikvenica (Šušnjar et al. 1970) (modified). $\mathbf{T_3}$ — Upper Triassic, $\mathbf{J_1}^1$ — Lower Lias, $\mathbf{J_1}^2$ — Middle Lias, $\mathbf{J_1}^3$ — Upper Lias, $\mathbf{J_2}$ — Dogger, $\mathbf{J_3}^1$ — Lower Malm.

carbonate platforms separated by the Adriatic and Molise-Lagonero Basins (Velić et al. 2003). From the late Early Jurassic until the end of the Cretaceous, successive series of shallow-water limestones were deposited predominantly on the Adriatic-Dinaric platform area.

General characteristics of the Karst Dinaridic Liassic limestones

The Karst Dinaridic Liassic limestones reveal an informal tripartite division (Fig. 2a) (Velić 1977): 1 — The Lower Liassic succession is characterized by the stacking of autocyclic parasequences, that is successive series of coarsening- and shallowing-upward cycles with cycle members of variable thickness and abundant emersion surfaces (Bucković et al. 2001). The thickness of the lower cycle members ranges from 0.9 to 1.8, whereas the upper cycle members vary from 0.3 to 0.5 m in thickness. Sporadically, the upper members may be dolomitized. 2 — Similar textural features also characterize the onset of the Middle Liassic complex. Additionally, the upper part of the Middle Liassic succession is usually marked with more or less common biostromes containing large "*Lithiotis*" bivalve shells. These biostromes vary in thickness from 10–70 cm and are present in many Karst Dinaridic Middle Liassic localities, but in some places, they are lacking. However, the Middle Liassic succession described in this paper contains no "*Lithiotis*" biostromes, so their more detailed description will be given elsewhere. 3 — The Upper Liassic "Spotted Limestones" are mud-rich and mostly intensely bioturbated with small, indeterminable bioclasts. In places, some thicker packages of the "spotty" successions are build up of coarsening-upward cycles, with upper cycle members dolomitized or showing emersion features. Throughout the Karst Dinarides, Lower Jurassic limestone successions are sporadically interrupted with thinner or thicker dolomitic lenses and intervals.

Description of studied Middle Liassic coarsening-upward cycles

The Middle Liassic successions are predominantly composed of series of coarsening-upward cycles. The cyclic stacking pattern always reveals very similar characteristics. Two coarsening-upward cycle types can be recognized: 1 — cycles with peloidal-bioclastic upper cycle members, and 2 — cycles with oolitic upper cycle members. As this cycle architecture is commonly present within the entire Middle Liassic Karst Dinaridic area, we considered in detail only one interval from Mt Velika Kapela (Croatia) that amounts to ca. 325 m (Figs. 1 and 2a).

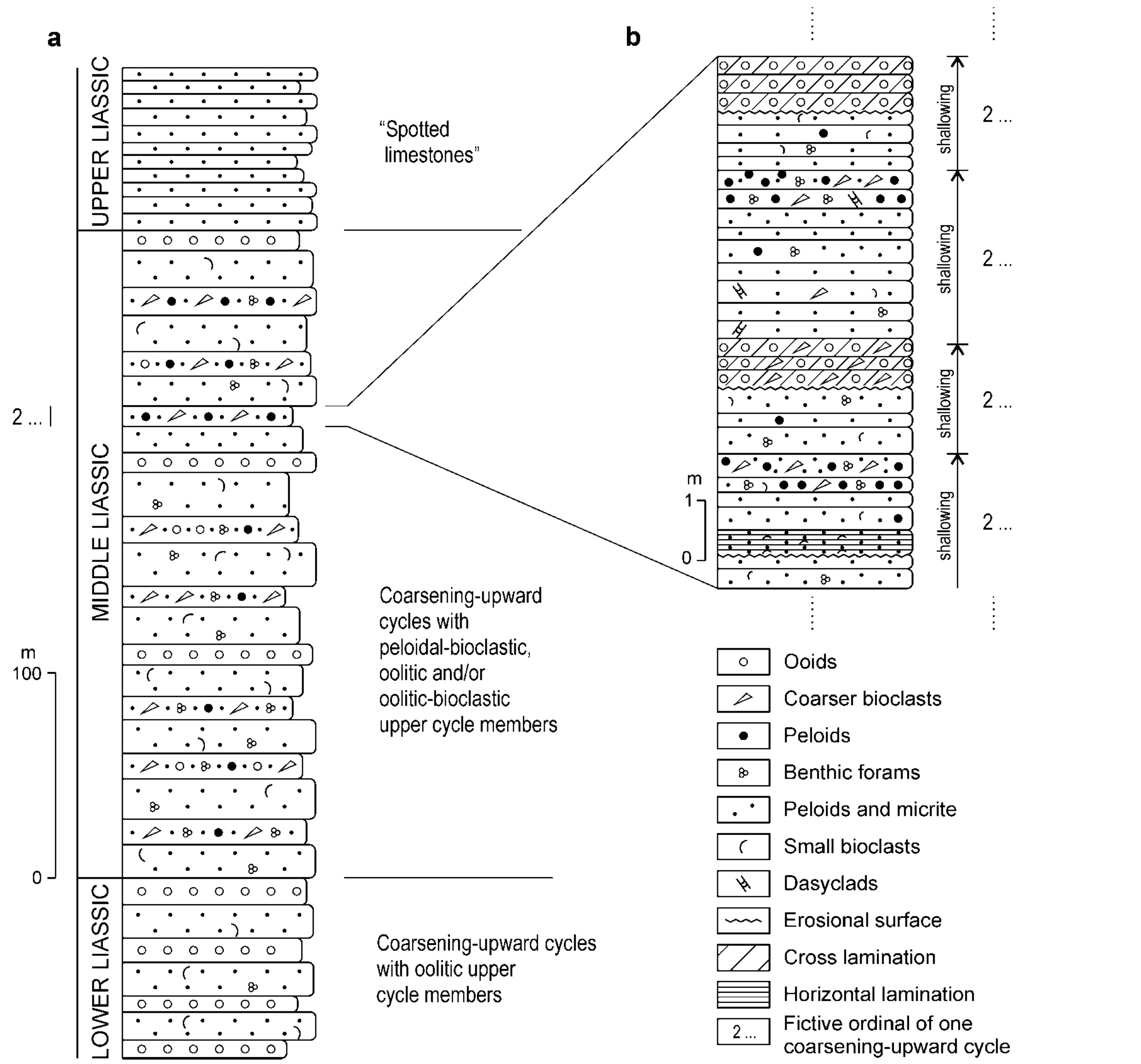

Fig. 2. a — Lithofacies column of Mt Velika Kapela Liassic limestones. **b** — Lithofacies column with typical series of few Middle Liassic coarsening-upward cycles (in scale from the field).

Cycles with peloidal-bioclastic upper cycle members

These coarsening-upward cycles contain mudstone or peloidal-bioclastic wackestone as the lower cycle members (Fig. 2b). The thickness of the lower cycle members varies from 0.7–2 m, whereas the upper cycle members range from 0.1–0.6 m. Mudstones and peloidal-bioclastic wackestones are composed of micrite with variable amounts of peloids, molluscan and ostracode fragments and individual benthic foraminifers (Fig. 3). Separate LLH (Laterally Linked Hemispheroids) stromatolitic laminae and laminoid fenestrae are sporadically present. Bioturbation occurs locally. Within these mud-rich limestone types, intercalations of horizontally laminated peloidal-bioclastic packstone-grainstone, 0.1–0.3 m thick, can occasionally be found (Fig. 4). Single horizontal 1–3 mm thick laminae are graded. These intercalations are always separated at their bottom by sharp, erosional surfaces. They have gradational upper boundaries into overlying mudstones or wackestones. Peloids, foraminifers, small echinoid and ostracode fragments embedded in micrite and/or drusy cement dominate. Elongated bioclasts are always oriented parallel to bedding.

Coarse-grained particles are present within upper cycle members (Fig. 2b). These wackestone/packstones to grainstones are abundant in peloids, coarser molluscan and sporadic echinoderm bioclasts (Fig. 5). More rarely, they contain subrounded micritic intraclasts and concentric oncoids with bioclastic nuclei surrounded by few cryptocrystalline envelopes. Coarser-grained bioclasts are always more or less recrystallized and randomly oriented. Some beds contain rich foraminiferal debris. They are best dated by the occurrence of the foraminifers *Orbitopsella praecursor* (Gümbel) (Figs. 5a and 6a) and *Lituosepta compressa* Hottinger (Fig. 6b), important biostratigraphic markers in the Tethyan realm. Other foraminifers, including *Amijella amiji* Henson, *Mayncina termieri* Hottinger, *Haurania deserta* Henson, "Siphovalvulina" (Fig. 5d) as well as algae *Palaeodasycladus* ex gr. *mediterraneus* (Pia) (Fig. 6c), *Thaumatoporella parvovesiculifera* (Raineri)

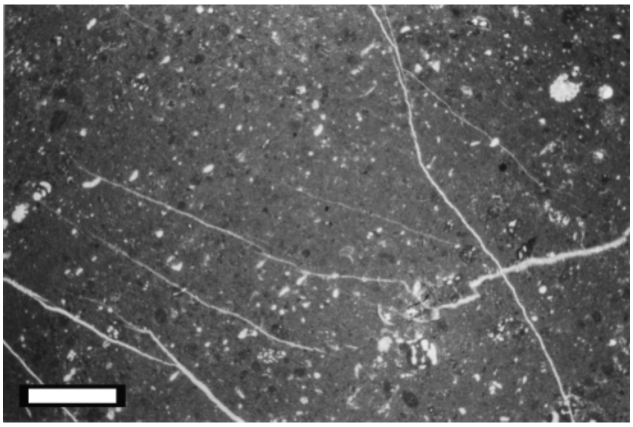

Fig. 3. Peloidal-bioclastic wackestone. Scale bar 1.6 mm.

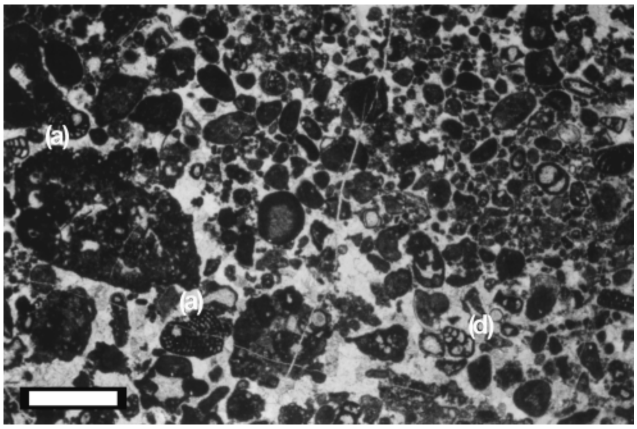

Fig. 5. Peloidal-bioclastic grainstone with *Orbitopsella praecursor* (Gümbel), (a), and "Siphovalvulina", (d). Scale bar 1.6 mm.

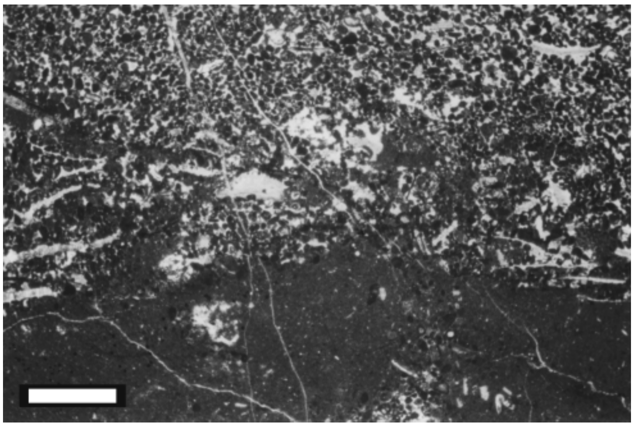

Fig. 4. Contact between peloidal-bioclastic wackestone and peloidal-bioclastic grainstone. Scale bar 1.6 mm.

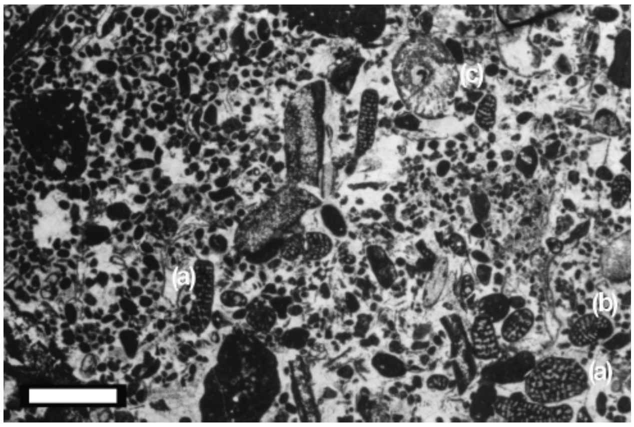

Fig. 6. Peloidal-bioclastic grainstone with *Orbitopsella praecursor* (Gümbel), (a), *Lituosepta compressa* Hottinger, (b), and *Palaeodasycladus* ex. gr. *mediterraneus* (Pia), (c). Scale bar 1.6 mm.

and *Cayeuxia* sp., can also be sporadically found. Various textulariids and verneuilinids are commonly present but have no biostratigraphic significance. In places, horizontal lamination is present, when sharp and uneven erosional contacts with underlying unlaminated beds are visible.

By periodically changing conditions, from low-energy shallow subtidal to higher-energy subtidal above the fair-weather wave-base, a series of coarsening-upward cycles have been produced. During low-energy shallow subtidal conditions with slow and constant rate of sediment accumulation, a large amount of carbonate mud with rare bioclasts was deposited. A much more intensive production of various coarser-grained particles occurred during periodical subtidal shallowing above the fair-weather wave-base (see Discussion). Sporadic horizontal lamination observed within the packstone-grainstone intercalations and even wackestone/packstone to grainstone beds was formed during periods of intensive unidirectional tidal and/or storm currents. These currents eroded the subtidal bottom, winnowed the muddy peloidal-bioclastic material, removed the carbonate mud, oriented elongated bioclasts parallel to bedding, and formed the horizontal, graded laminae.

Cycles with oolitic and oolitic-bioclastic upper cycle members

The same features as were described in the previous chapter characterize mudstones or peloidal-bioclastic wackestones as the lower members of these cycles. However, their thicknesses are generally smaller, amounting to 0.4–1.1 m. The upper cycle member is represented by ooid grainstones and/or ooid-bioclastic packstones to grainstones (Fig. 2b). Ooid grainstones consist of well-sorted ooids with peloidal or bioclastic nuclei, surrounded by an envelope of radial fibrous fabric (Fig. 7). The ooids are white to cream in colour, have a pearly lustre, and usually range in size from 0.2 mm to 1.0 mm. They have frequently recrystallized envelopes and even nuclei. The diagenesis of these grainstones includes fibrous calcite on the surface of the ooids and drusy calcite spar in the intergranular pores. Sporadically, pore spaces are filled up by crystal silt. Among the ooids there are sporadic small molluscan fragments and foraminiferal tests. Distinct cross- and/or horizontal lamination can be sporadically observed. However, these structures are mostly hard to recognize because of the well-sorted nature of the

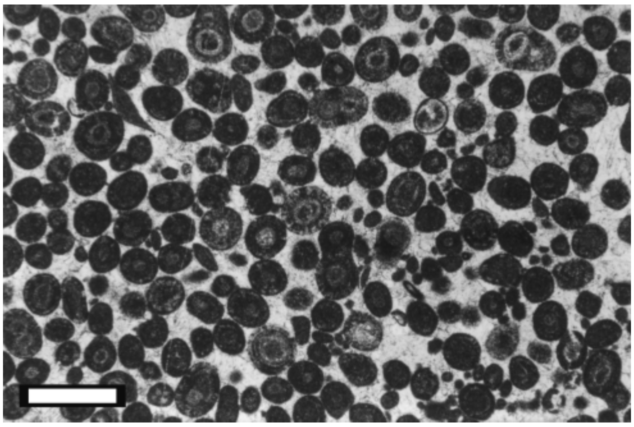

Fig. 7. Ooid grainstone. Scale bar 0.8 mm.

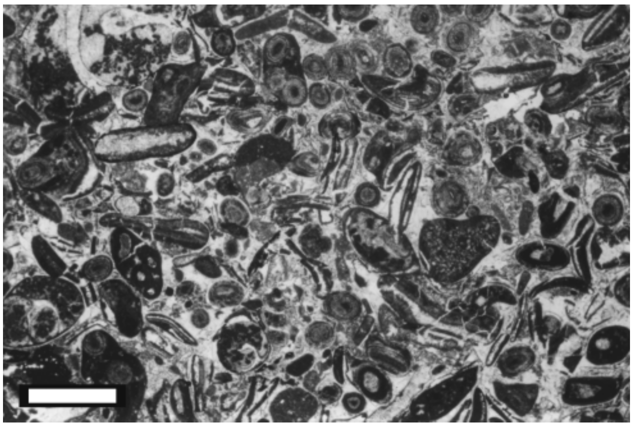

Fig. 8. Ooid-bioclastic grainstone. Scale bar 1.6 mm.

grainstones. The bases of oolitic members are commonly erosional surfaces. In drusy calcite spar or micritic matrix the ooid-bioclastic packstones to grainstones contain ooids and variety of poorly sorted, abraded and broken molluscan, echinoderm and hydrozoan fragments, as well as variously sized intraclasts (Fig. 8). Elongated coarser-grained particles are mostly randomly oriented.

These cycles also represent a sedimentary response to cyclic environmental changes from low-energy shallow subtidal to higher-energy subtidal above the fair-weather wave-base. However, environmental conditions during the formation of the oolitic upper cycle members were different compared with the conditions in which peloidal-bioclastic upper cycle members were deposited (see Discussion). At first glance it is recognized by the frequent erosional surfaces underlying the oolites and by absence of micrite and peloids. That implies shallower and higher energy subtidal conditions of oolitic shoals, which migrated laterally over the relatively deeper subtidal environments. Their migration by tidal and/or storm currents of different energy led to formation of sporadic cross- and/or horizontal lamination. Rare findings of crystal silt in pore spaces of oolites indicate the neighbouring presence of the vadose zone from which calcite crystals were washed and transported in suspension to the oolitic shoals.

Discussion

The high-frequency cycles described in this study are usually referred to as parasequences (Goldhammer et al. 1990). They are often interpreted to be of allocyclic origin and to be caused by climatic fluctuations associated with Milankovitch cycles (Vail et al. 1991). Milankovitch cycles are orbital cycles, which modulate insolation and are commonly related to fluctuations of climate, whereby the waxing and waning of ice caps, especially during glaciations (such as nowadays), act as amplifier of the inherently weak insolation signal. Orbitally controlled waxing and waning of ice caps translate into high-frequency sea-level fluctuations, which may lead to metre-scale shallowing- and coarsening upward cycles (e.g. Strasser 1991; Goldhammer et al. 1993; Strasser et al. 1999). However, it is difficult to correlate here studied cycles with Milankovitch cycles because during the Jurassic, ice in high latitudes was probably present, but ice-volumes were not sufficient to induce important glacio-eustatic fluctuations (Frakes et al. 1992; Eyles 1993; Valdes et al. 1995), although volume changes of alpine glaciers could make a small contribution (Fairbridge 1976; Valdes et al. 1995). Additionally, the Early Jurassic was a time of climatic warming (Hallam & Wignall 1999), because of rapid rise in CO_2 levels caused by the outpouring of the Central Atlantic Magmatic Province as a result of the rifting of Pangea (Nance & Murphy 1994; Marzoli et al. 1999). In such circumstances, there was probably no pronounced seasonality during the Early Jurassic. However, we assume that high-frequency sea-level fluctuations of allocyclic origin were present during the Early Jurassic, but were small and thus hardly perceptible in the sedimentary record. Therefore, predominantly based on the sedimentary mechanisms active in platform shallow-water environments, we interpret the ADCP Middle Liassic coarsening-upward cycles as being the result of autocyclic processes, but having in mind that some allocyclic signal was also present, but for the time being hard to recognize.

Large carbonate platforms, without prominent elevation differences, are characterized by small water depths (mainly less than 10 m), and the fair-weather wave-base at less than 5 m (Tucker & Wright 1990). Judging from this, one can presume that successive series of coarsening-upward cycles may be a record of changes in water depth through varying sediment accumulation, when the sea-bottom seemingly oscillates around the fair-weather wave-base (the fair-weather wave-base — FWWB amounts to half of the wavelength — WL/2). This assumption is based on two well-known facts: 1 — under optimum conditions carbonate sediments can accumulate rapidly, resulting in a high and mostly constant carbonate production rate (Smith 1973; Hallock 1981) and 2 — carbonate production in modern depositional environments, as a rule, exceeds the average amount of platform subsidence and

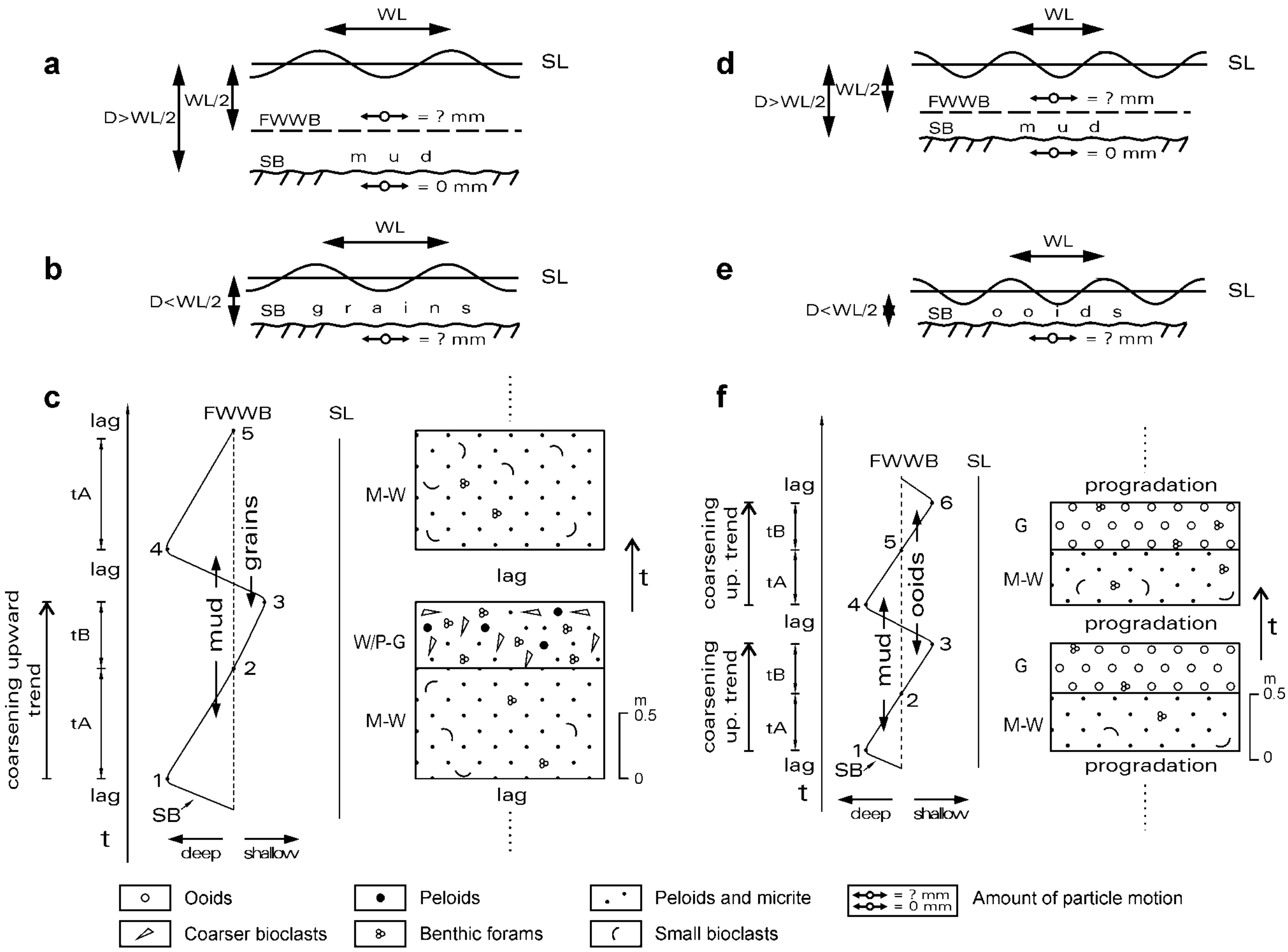

Fig. 9. A model for the origin of coarsening-upward cycle architecture (Bucković 2001, modified). **tA (1–2, 4–5)** — "catch-up" phase, **tB (2–3, 5–6)** — "keep-up" phase, **3–4** — lag phase, progradation, **4** — "start-up" phase, **FWWB** — fair-weather wave-base, **SL** — sea-level, **SB** — sea-bottom, **D** — water depth, **WL** — wavelength, **t** — time, **M** — mudstone, **W** — wackestone, **P** — packstone, **G** — grainstone.

moderate eustatic sea-level rise (Tucker & Wright 1990). The typical sedimentation rate of modern carbonate deposits is 1 m per 1000 yr, typical subsidence rates of passive continental margins, where many ancient carbonate platforms developed, are 0.01–0.1 m per 1000 yr, and typical eustaic sea-level changes are 0.01 m per 1000 yr (Tucker & Wright 1990). Rapid subsidence, generally fault-induced and major sea-level rises through glacial melting, are not included. From these, it can be presumed that the facies differences, that is the cycle architecture, observed in the examined Middle Liassic strata, are mainly the result of processes operating within the ADCP. Among these processes, aggradation of subtidal carbonate deposits and progradation of small ooid shoals appear to be most important.

During periods when the water depth (i.e. accommodation space) (D) on many ADCP parts was greater than one-half of the wavelength (D > WL/2), there was no movement of sediment particles at the sea-bottom (SB) (Fig. 9a). Therefore, in quiet subtidal environments below the fair-weather wave-base, peloids and calcareous mud, as well as benthic foraminifers occasionally associated with various bioclasts, were predominantly accumulated, producing muddy carbonate deposits (Fig. 9c; points 1–2 and 4–5 — tA) ("catch-up" phase sensu Kendall & Schlager 1981).

It is presumed that the carbonate production rate exceeded both the rate of subsidence and the rate of eustatic sea-level rise (i.e. relative sea-level rise). Such a high carbonate accumulation rate caused gradual reduction of accommodation space, that is a decrease of water depth. When the water depth became less than one-half of the wavelength (D < WL/2) (Fig. 9b), there were occasional motions of sediment particles by waves on the sea-bottom. Under such shallower-water and higher energy conditions, various coarser-grained calcareous particles were formed, producing grain supported deposits (Fig. 9c; point 2). With continuing carbonate production, accommodation space further decreased and the sea-bottom continues to aggrade (Fig. 9c; points 2–3 — tB) ("keep-up" phase sensu Kendall & Schlager 1981). Yet, such environment with agitated water, supersaturated with $CaCO_3$, became unfavourable for the majority of carbonate-producing benthic organisms (e.g. foraminifers, mollusks). Highly oxygenated pore waters and high water exchange rates also enhanced the process of cementation. Under such conditions, the rate of new carbonate sediment production slowed down, so that the carbonate accumulation was easily outpaced by continued relative sea-level rise, and the sea-bottom was lowered below the fair-weather wave-base (Fig. 9c; points 3–4 — lag). After this "lag phase" (Read et al. 1986; Schlager 1992), carbonate-producing organisms (mostly mass faecal pellets producers, e.g. worms, ostracodes, gastropods) colonized the sea-bottom drowned below the fair-weather wave-base, and carbonate production was re-established (Fig. 9c; point 4) ("start-up" phase sensu Kendall & Schlager 1981; or "log phase" sensu Schlager 1992); a new cycle with a muddy lower member started to accumulate (Fig. 9c; points 4–5) ("catch-up" phase sensu Kendall & Schlager 1981). Such autocyclic mechanism would explain the origin of the coarsening-upward cycles with peloidal-bioclastic upper cycle members.

In contrast to that, environmental conditions within sporadically presented subtidal topographic highs were rather different (Fig. 9d–f). In these places, the water depth was smaller and the wavelength was consequently shortened, so the sea-bottom (SB) was positioned closer to the fair-weather wave-base (FWWB) (Fig. 9d). Thus, when the water depth became less than one-half of the wavelength ($D<WL/2$), water temperature and pH as well as the carbonate saturation level and water energy increased, favouring the formation of ooids (e.g. Gonzales 1996) (Fig. 9e). In such conditions, the ooids were in constant motion allowing them to grow around a nucleus forming an oolitic shoal. With continuing production of ooids the accommodation space decreased (Fig. 9f; points 2–3 — tB). When oolitic shoals aggraded close to the sea level, they began to prograde laterally (Fig. 9f; points 3–4) under influence of tidal and/or storm currents (when distinct cross- and/or horizontal lamination was formed), covering the adjacent deposits below and/or above the fair-weather wave-base and forming the coarsening-upward cycles with distinct upper oolitic and/or oolitic-bioclastic cycle members. Therefore, the occurrence of cycles with ooids reflects the oolitic shoal progradations. These oolitic shoal progradations were random, episodic processes depending on physical factors working in the sedimentary environment. Among those, the most important was the formation of subtidal topographic highs on which the water depth was reduced (see above for explanation). The topographic highs in the shallow Middle Liassic ADCP realm would develop through sediment trapping by organisms (e.g. fleshy algae), or through slight tectonic uplifts. However, as evidence for the formation of barriers through sediment trapping in the investigated Middle Liassic succession was not noticed, we assume that small-scale synsedimentary uplifts were a more likely scenario. These small-scale uplifts were random events, with no predictable periodicity and place of occurrence. Thus, in periods when oolitic shoals prograded over the subtidal below the fair-weather wave-base, one coarsening-upward cycle with ooid grainstone as the upper cycle member was formed. Analogously, in periods when oolitic shoals prograded over the subtidal above the fair-weather wave-base, one coarsening-upward cycle with ooid-bioclastic packstones to grainstones as the upper cycle member was formed. In periods when high energy storm events triggered progradation, that is rapid migration of oolites, these currents succeeded in eroding subtidal bottom when erosive bases of the oolites were formed.

During periods without oolitic shoal progradations, only vertical aggradation of subtidal carbonate deposits occurred, producing successive series of coarsening-upward cycles with peloidal-bioclastic upper cycle members.

Conclusion

The studied Middle Liassic sedimentary succession has been formed within the interior of the isolated Adriatic-Dinaric carbonate platform area. It reveals successive coarsening-upward trend from the subtidal below the fair-weather wave-base to the subtidal above the fair-weather wave-base as the predominant response to the autocyclicity in the sedimentary environment. Gradual aggradation of the muddy carbonate material, deposited below the fair-weather wave-base reduced the accommodation space, causing the sea-bottom to rise above the fair-weather wave-base. Here, more grainy carbonates were deposited, creating one coarsening upward cycle with mudstones or peloidal-bioclastic wackestones as the lower cycle member and peloidal-bioclastic wackestone/packstones to grainstones as the upper cycle member. During the "lag phase", the sea-bottom has sunk below the fair-weather wave-base, which enabled the formation of the next coarsening-upward cycle. The progradations of neighbouring oolitic shoals periodically and randomly interrupted this process. Oolitic shoals, sporadically formed on topographic highs within the subtidal area, prograded over the surrounding environment below or above the fair-weather wave-base, producing sporadic coarsening-upward cycles with ooid grainstones and/or ooid-bioclastic packstones to grainstones as the upper cycle member.

Therefore, the Middle Liassic coarsening-upward architecture of Mt Velika Kapela resulted from interplay of repeated sediment aggradations, interrupted by periodical and random oolitic shoal progradations.

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