Early Jurassic foraminiferal assemblages in platform carbonates of Mt. Krim, central Slovenia

Spodnjejurske foraminiferne združbe v plitvomorskih karbonatih na območju Krima, osrednja Slovenija

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Abstract

During the Early Jurassic, the subtropical carbonate platforms of the peri-Tethys Ocean experienced significant changes in their architectures, as well as in their biota compositions. Shallow-water carbonates from the northern part of the ancient Adriatic Carbonate Platform (External Dinarides) were investigated in six sections, which taken together cover the development of the platform from deposition of the uppermost Triassic Main Dolomite to the middle Lower Jurassic, lithiotid limestone. Our aim was to establish a detailed foraminiferal biostratigraphy and to observe the changes in size, abundance and diversity of foraminifera in different types of facies. As a result, the succession was successfully divided into stage or substage levels. Foraminiferal assemblages were shown to experience a gradual change in taxonomic composition (including an increase in the proportion of complex agglutinated forms), a general increase in abundance of specimens, and greater diversity in each facies type, except in bindstone and mudstone. Notable is the difference between Hettangian assemblages, which display fairly uniform compositions in all facies types and the predominance of opportunists, and the post-Hettangian assemblages, which become progressively more species-rich and where the differences in facies are perhaps more pronounced. Changes in the size of the species *Meandrovoluta asiagoensis* Fugagnoli & Rettori, and of the largest specimen in the assemblages, however, are less clear, but are arguably present. Faunal changes roughly correspond to the gradual change from the flat-top platform of the upper Triassic – Hettangian, where biota would be repeatedly subjected to stressed peritidal conditions, to a platform differentiated into lagoon, sand bars and ephemeral emergent areas, offering numerous habitats and perhaps more stable living conditions for organisms.

Izvleček

Karbonatne platforme območja Tetide so v času starejše jure doživljale znatne spremembe v morfologiji in sestavi biote. Plitvomorske karbonate Jadranske karbonatne platforme (Zunanji Dinaridi) smo raziskali v šestih profilih na širšem območju Krima. Profili skupaj zajemajo interval od vrhnjega dela, glavnega dolomita do litiotidnega apnenca. Naš cilj je bil identifikacija foraminifernih biocon. Poleg same taksonomske sestave smo beležili še raznolikost foraminifernih združb, pogostnost (ali gostoto) foraminifer ter spremembo v velikosti vrste *Meandrovoluta asiagoensis* Fugagnoli & Rettori ter v velikosti največjih primerkov v združbah. Po pričakovanjih rezultati kažejo postopne spremembe v taksonomski sestavi foraminifernih združb, vključno z naraščanjem deleža kompleksnih aglutiniranih vrst ter splošen porast gostote primerkov in raznolikosti v vseh faciesih razen v bindstone in mudstone faciesih. Zanimivo je, da hettangijske združbe izkazujejo precejšnjo podobnost v sestavi in prevlado oportunističnih vrst, medtem ko so razlike med združbami glede na facies v mlajših plasteh bolj izrazite. Sprememba v velikosti vrste *M. asiagoensis* je znotraj posamičnega faciesa težko dokazljiva, celokupno gledano pa največji osebki te vrste dosegajo večjo velikost v mlajših plasteh. Podobno velja za velikost največjih osebkov v združbi. Favnistične spremembe približno sovpadajo s postopno spremembo v morfologiji platforme, ki se postopno diferencira v laguno, delno omejeno s peščenimi sipinami.

Introduction

The end-Triassic biocalcification crisis is generally thought to have had a significant influence on carbonate platforms (GALLI et al., 2005; GREENE et al., 2012). The acidification of oceanic water greatly influenced carbonate-secreting organisms like corals and calcareous sponges, and many of the marine groups experienced elevated extinction rates (HAUTMANN, 2004; KIESSLING et al., 2007, 2009). Among the strongly affected organisms were also foraminifera, microscopically small, mostly marine, unicellular eukaryotes, which by the end of the Triassic formed diverse shallow-water communities composed of Involutinoidea, Duostominidae, Lagenida, Miliolida and Textulariida (GALLI et al., 2005; MANCINELLI et al., 2005; GALE, 2012; GALE et al., 2012). The change to Early Jurassic assemblages, almost completely dominated by agglutinated forms, is a striking example of community replacement.

The Adriatic (Dinaric sensu BUSER, 1989) Carbonate Platform, the remnants of which are presently incorporated into the structurally deformed margin of the Adriatic tectonic microplate (PLACER, 1999; TARI, 2002; CSONTOS & VÖRÖS, 2004), was a platform with a seemingly less dramatic lithological change at the Triassic-Jurassic boundary, as peritidal deposition continues from the Upper Triassic to the lowermost Jurassic (e.g., MILER & PAVŠIČ, 2008; OGORELEC, 2009). Afterwards, the succession records a gradual transition from tidal-flat to restricted lagoon setting, where the present "lithiotid limestone" deposited. This change of the platform topography, however, remains poorly researched, especially due to the lack of biostratigraphically well-defined sections.

This paper has two main aims. First, we show the stratigraphic distribution of foraminifera in six sections from the broader area of Mt. Krim, south of Ljubljana, from the base of the Hettangian Krka Limestone Member to the lower part of the Pliensbachian Lithiotid Limestone Member. Five of the sections were investigated in detail. On the basis of foraminifera, we determine the age of the sections to the stage or substage level. Secondly, we follow changes in terms of taxonomic composition, abundance of foraminifera, diversity, the size of *Meandrovoluta*, and the change in the largest specimen among foraminifera for each of the stages/substages, in order to gain more detailed insight into the origin of the post-extinction community. We do this for each facies type in order to avoid lithologically-induced bias.

Geological Setting and General Stratigraphy

The studied exposures are located in the northern External Dinarides (Fig. 1; PLACER, 1999, 2008). The Lower Jurassic succession consists of shallow-marine carbonates deposited on the Adriatic Carbonate Platform (AdCP; VLAHOVIĆ et al., 2002, 2005), locally also known as the
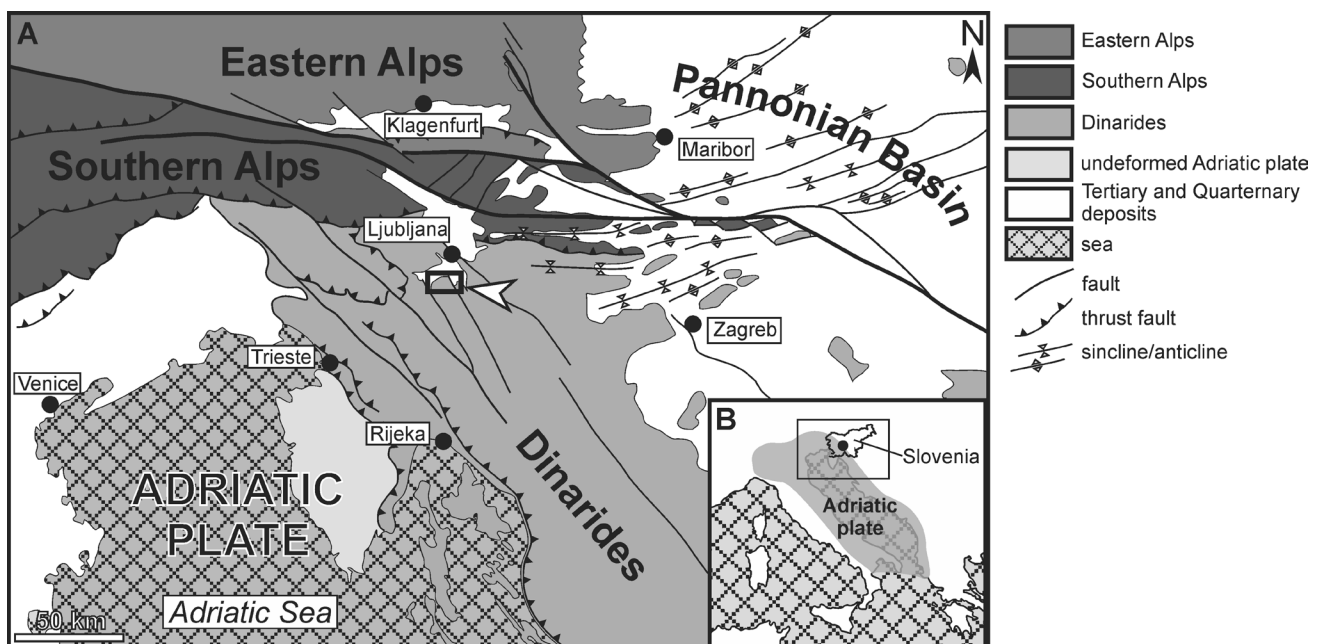

Fig. 1. Regional schematic structural map. The position of the studied area is marked by the white arrowhead. A: Structural map of the north-eastern corner of the present Adriatic tectonic plate. B: Present position of the Adriatic tectonic plate and position of Slovenia. The studied area is marked with a black dot. Modified after VRABEC and FODOR (2006).

Dinaric Carbonate Platform (BUSER, 1989; OGORELEC & ROTHE, 1993), which was during the Early Jurassic situated at a paleolatitude of approximately 25°N (STAMPFLI & MOSAR, 1999; STAMPFLI & KOZUR, 2006; BOSENCE et al., 2009; BERRA & ANGIOLINI, 2014). The thick sequence of carbonates, which continued to be deposited up until the uppermost Cretaceous (BUSER, 1989), was later tilted and broken into several tectonic blocks, and separated by faults that in the studied area run in approximately N-S and WNW-ESE to NW-SE directions, separating tectonic blocks comprising Upper Triassic to Middle Jurassic carbonates (Fig. 2; BUSER et al., 1967; PLENIČAR, 1970; BUSER, 1968, 1974).
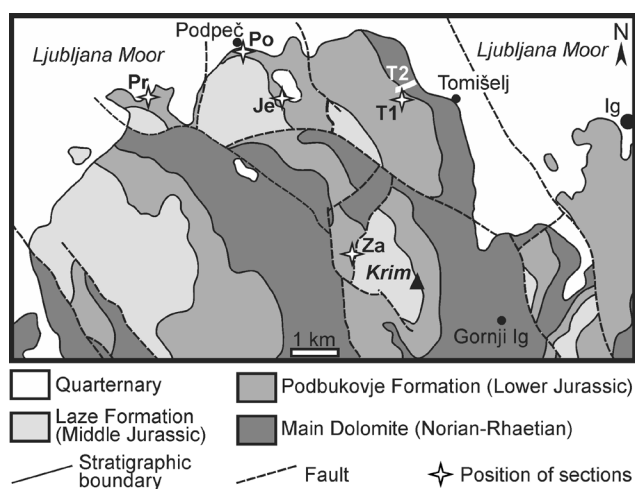

Fig. 2. Simplified geologic map of the studied area and location of studied sections. Modified after BUSER et al. (1967) and BUSER (1968). Je: Jezero (45°57´30´´ N, 14°26´00´´ E); Po: Podpeč (45°58´22´´ N, 14°25´16´´ E); Pr: Preserje (45°57´56´´ N, 14°23´47´´ E); T1: Tomišelj 1 (45°57´51´´ N, 14°28´06´´ E); T2: Tomišelj 2 (45°58´00´´ N, 14°28´16´´ E); Za: Zalopate (45°56´09´´ N, 14°27´21´´ E).

The lithostratigraphic subdivision of Lower Jurassic carbonates in the External Dinarides was recently revised by DOZET and STROHMENGER (2000), MILER and PAVŠIČ (2008), and DOZET (2009) (Fig. 3). The Norian-Rhaetian Main Dolomite is typified by medium- to thick-bedded crystalline dolomite, stromatolitic dolomite, and intraclastic breccia, indicating cyclically interchanging shallow subtidal, intertidal, and supratidal conditions (i.e., Lofer facies in FISCHER, 1964) on a flat-topped carbonate platform (OGORELEC & ROTHE, 1993). Peritidal sedimentation continued into the earliest Jurassic (OGORELEC, 2009), though the position of the Triassic-Jurassic boundary is merely arbitrary (MILER et al., 2007). The Lower Jurassic Podbukovje Formation (DOZET & STROHMENGER, 2000; Predole Beds in DOZET, 2009) consists of five members. The Hettangian-Sinemuri-
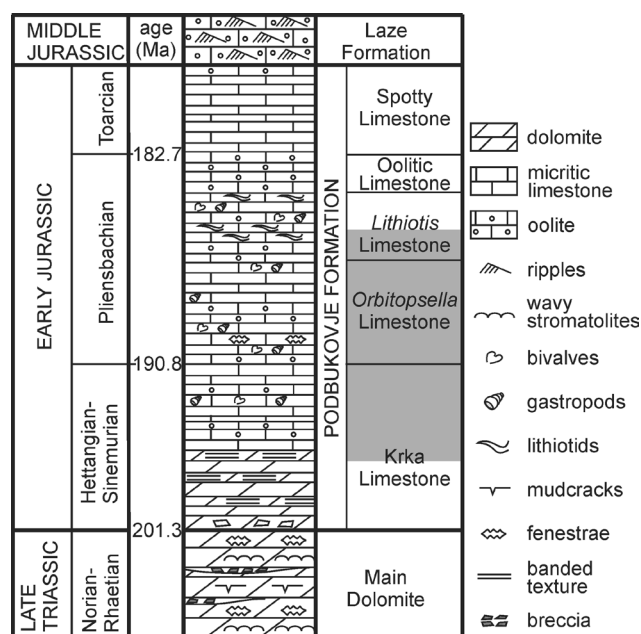

Fig. 3. Schematic lithostratigraphic column of the studied area. Shading indicates the interval covered by the detailed sections (the schematic Tomišelj 2 sections ranges further down to the Main Dolomite). Adopted after MILER and PAVŠIČ (2008), DOZET (2009). Vertical scale is reconciled to thicknesses given in DOZET (2009). Ages for are taken after OGG et al. (2012).

an Krka Limestone (i) is composed of crystalline dolomite, laminated (rarely stromatolitic) dolomite, mudstone, wackestone, rarely pellet or ooid grainstone, and intraclastic breccia (DOZET, 1993; DOZET & STROHMENGER, 2000; DOZET, 2009; OGORELEC, 2009). MILER and PAVŠIČ (2008) also note thick bodies of mud-supported breccia, which could be indicative of Early Jurassic tectonic activity. The following Upper Sinemurian-Pliensbachian *Orbitopsella* Limestone (ii), Lithiotid Limestone (iii) and Ooidal Limestone (iv) members mark the establishment of lagoons restricted by oolitic bars (MILER & PAVŠIČ, 2008; DOZET, 2009; GALE, 2014). The Podbukovje Formation ends with the Toarcian Spotty Limestone Member (v) with nodular mudstone-wackestone and black ooid packstone (DOZET & STROHMENGER, 2000; DOZET, 2009; KRESNIK, 2016).

Material and methods

The Lower Jurassic succession was investigated in five detailed sedimentological sections (Preserje, Tomišelj 2, Jezero, Zalopate, Podpeč sections), which structurally belong to the External Dinarides. Together the sections span the interval from the Krka Limestone to the Lithiotid Limestone Member sensu DOZET and STROHMENGER (2000). The Preserje section was measured previ-

ously by OGORELEC (2009) and is reproduced herein. Although the succession of this section was originally placed near or at the Triassic-Jurassic boundary, we suggest a slightly younger age for these rocks on the basis of lithostratigraphic correlation and foraminiferal biozonation. The sixth, Tomišelj 1 section was measured schematically and reaches to the underlying Main Dolomite.
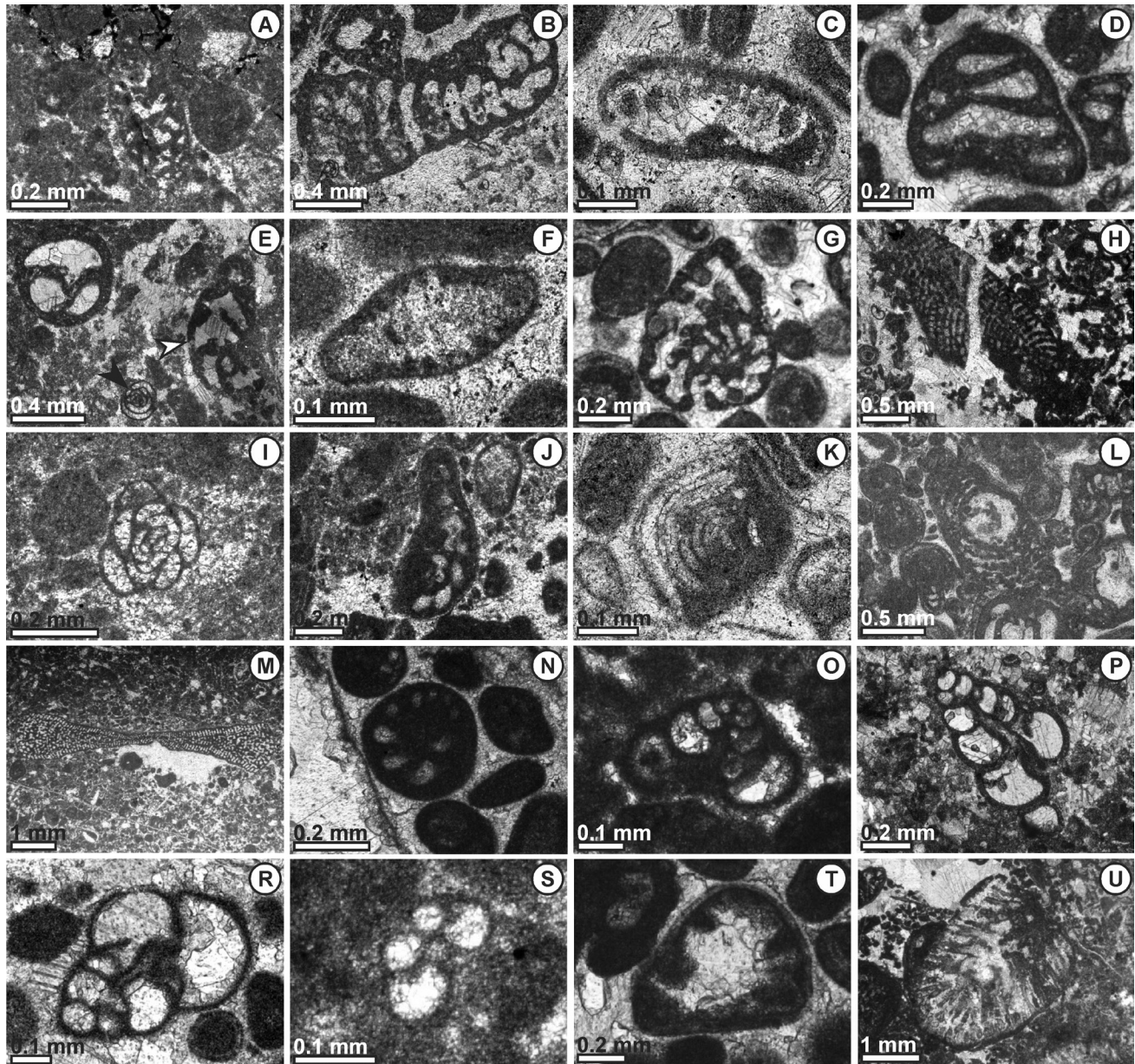

Fig. 4. Early Jurassic foraminifera and algae from the investigated sections.

A*: Amijiella amiji* (Henson). Thin section 535. Section Podpeč. Early Pliensbachian. B: *Bosniella oenensis* Gušić. Thin section 510. Section Podpeč. Early Pliensbachian. C: ?*Coronipora* sp. Thin section 528. Section Podpeč. Early Pliensbachian. D: *Duotaxis metula* Kristan. Thin section 418. Section Zalopate. Late Sinemurian-earliest Pliensbachian. E: *Everticyclammina praevirguliana* Fugagnoli (white arrowhead). Black arrowhead points at *Meandrovoluta asiagoensis*, whereas the section in the upper left corner belongs to *Duotaxis metula*. Thin section 328. Section Zalopate. Late Sinemurian-earliest Pliensbachian. F: *Involutina* sp. Thin section 528. Section Podpeč. Early Pliensbachian. G: *Lituolipora termieri* (Hottinger). Thin section 536. Section Podpeč. Early Pliensbachian. H: *Lituosepta recoarensis* Cati. Thin section 329. Section Zalopate. Late Sinemurian-earliest Pliensbachian. I: *Meandrovoluta asiagoensis* Fugagnoli & Rettori. Thin section 535b. Section Podpeč. Early Pliensbachian. J: *Mesoendothyra*? sp. Thin section 515. Section Podpeč. Early Pliensbachian. K: *Ophthalmidium* sp. Thin section 522. Section Podpeč. Early Pliensbachian. L: *Orbitopsella praecursor* (Gümbel). Thin section 529. Section Podpeč. Early Pliensbachian. M: *Orbitopsella primaeva* Henson. Thin section 535b. Section Podpeč. Early Pliensbachian. N: *Pseudopfenderina butterlini* (Brun). Thin section 510. Section Podpeč. Early Pliensbachian. O: *Siphovalvulina gibraltarensis* BouDagher-Fadel, Rose, Bosence & Lord. Thin section 328. Section Zalopate. Late Sinemurian-earliest Pliensbachian. P: *Siphovalvulina variabilis* Septfontaine. Thin section 412. Section Zalopate. Late Sinemurian-earliest Pliensbachian. R: *Siphovalvulina variabilis* Septfontaine. Thin section 329b. Section Zalopate. Late Sinemurian-earliest Pliensbachian. S: *"Trochammina" almtalensis* Koehn-Zaninetti. Thin section Jezero. Early - Middle Sinemurian. T: *Trocholina* sp. Thin section 325. Section Zalopate. Late Sinemurian-earliest Pliensbachian. U: *Palaeodasycladus mediterraneus* (Pia). Thin section 34. Section Preserje. Early - Middle Sinemurian.

Approximately 200 thin sections 47×28 mm and 75×49 mm in size from 184 beds were investigated for foraminifera (Fig. 4), and assemblages from different facies types were distinguished. Sparse and dense wackestones were distinguished by a borderline value of 30 % of grains. The number of foraminifera in thin sections varies from 0 to 60 per cm^2, with up to 434 specimens counted in a single thin section. Changes in abundance (number of specimens per cm^2), species richness and diversity for each facies type were investigated on the basis of approximately 150 thin sections. When generic or species determination was not possible, open nomenclature was used instead (e.g. Foraminifera indet. sp. A). *Aeolissacus/Earlandia* specimens were not counted due to their indistinct character. Some Nodosariidae were likewise difficult to separate into distinct species. As a result, biodiversity indices do not represent absolute values that could be directly compared to present-day values. The total number of foraminifera in each thin section was divided by the surface area of the investigated area in order to normalize the resulting values. The biodiversity of each sample was estimated on the basis of the Shannon-Wiener diversity index H´ (Hammer & Harper, 2006). In addition to calculating diversity, the maximum specimen size from each biozone was measured (see Payne et al., 2011). We also measured the largest specimen of the most common and widespread species, *Meandrovoluta asiagoensis*, in different facies types.

Description of sections and biostratigraphy

Tomišelj 2

This section serves as a reference section for the easier lithostratigraphic positioning of other sections. Due to the patchy exposure of beds (up the forested slope), no detailed sampling was possible. The section comprises the upper 18 m of the Rhaetian Main Dolomite and almost 300 m of the Lower Jurassic Krka Limestone Member (Fig. 5).

The Main Dolomite consists of medium thick beds of dolomitized bindstone with stromatolites and crystalline dolomite. Birds' eyes, tee-pee structures, desiccation cracks, black pebbles, and irregular bedding surfaces filled with lithified clasts in a clayey matrix are common. Only rare, small agglutinated forms and small Nodosariidae (Lagenida) were found in the uppermost part of the Main Dolomite.

The lower part of the Krka Limestone Member is to a large extent dolomitized. Medium- to very thick-bedded dolomite is coarsely crystalline, or exhibits planar laminae measuring a few millimetres in thickness. Fine-scale wrinkles, typical of stromatolites of the underlying Main Dolomite, are extremely rare. Tee-pee structures, black pebbles, and birds' eyes, however, are still common, as well as occasional irregular and clayey bedding planes. After approximately 70 m, medium- to thick-bedded micritic limestone with mudstone to wackestone texture dominates for 15 m, followed again by crystalline dolomite. Upwards, limestone (mudstone, and rarely wackestone) starts to gradually predominate over dolomite. Laminae, desiccation cracks, and birds' eyes structures are occasionally present. Approximately 100 m from the base of the Krka Limestone Member, the foraminiferal assemblage with *Duotaxis metula*, small Nodosariidae, *Reophax* sp., ?*Siphovalvulina colomi*, *Siphovalvulina variabilis*, ?"*Trochammina*" *almtalensis* and *Textularia* sp. were found. According to Velić (2007), *S. variabilis* first appears in the latest Hettangian.

Approximately 130 m from the base of the Krka Limestone, packstone and grainstone with bioclasts, intraclasts, and peloids are encountered. Leached-out clasts may be abundant. Packstone and grainstone are more common as we move to the uppermost part of the section, although mudstone still predominates. Red and/or irregular clayey bedding-planes and bird's eye vugs are occasionally present. The foraminiferal assemblage is notably more diversified and includes: *Amijiella amiji*, *D. metula*, *Everticyclammina praevirguliana*, Nodosariidae, *Meandrovoluta asiagoensis*, ?*Pseudopfenderina butterlini*, *Reophax* sp., *Siphovalvulina gibraltarensis*, *Siphovalvulina* sp., *Textularia* sp., *Trocholina* sp., and *Valvulina* sp. According to Boudagher-Fadel and Bosence (2007), *E. praevirguliana* first appears in the Middle Sinemurian, but Velić (2007) sets its first appearance already in the Late Hettangian. Furthermore, Velić (2007) sets the first appearance of *S. gibraltarensis* at the beginning of the Sinemurian. This part of the section is thus dated as Early Sinemurian. In the uppermost part of the Tomišelj 2 section, *M. asiagoensis* and ?*Lituosepta recoarensis* were also recorded. *Lituosepta recoarensis* first appears in the Late Sinemurian (Boudagher-Fadel & Bosence, 2007; Velić, 2007).
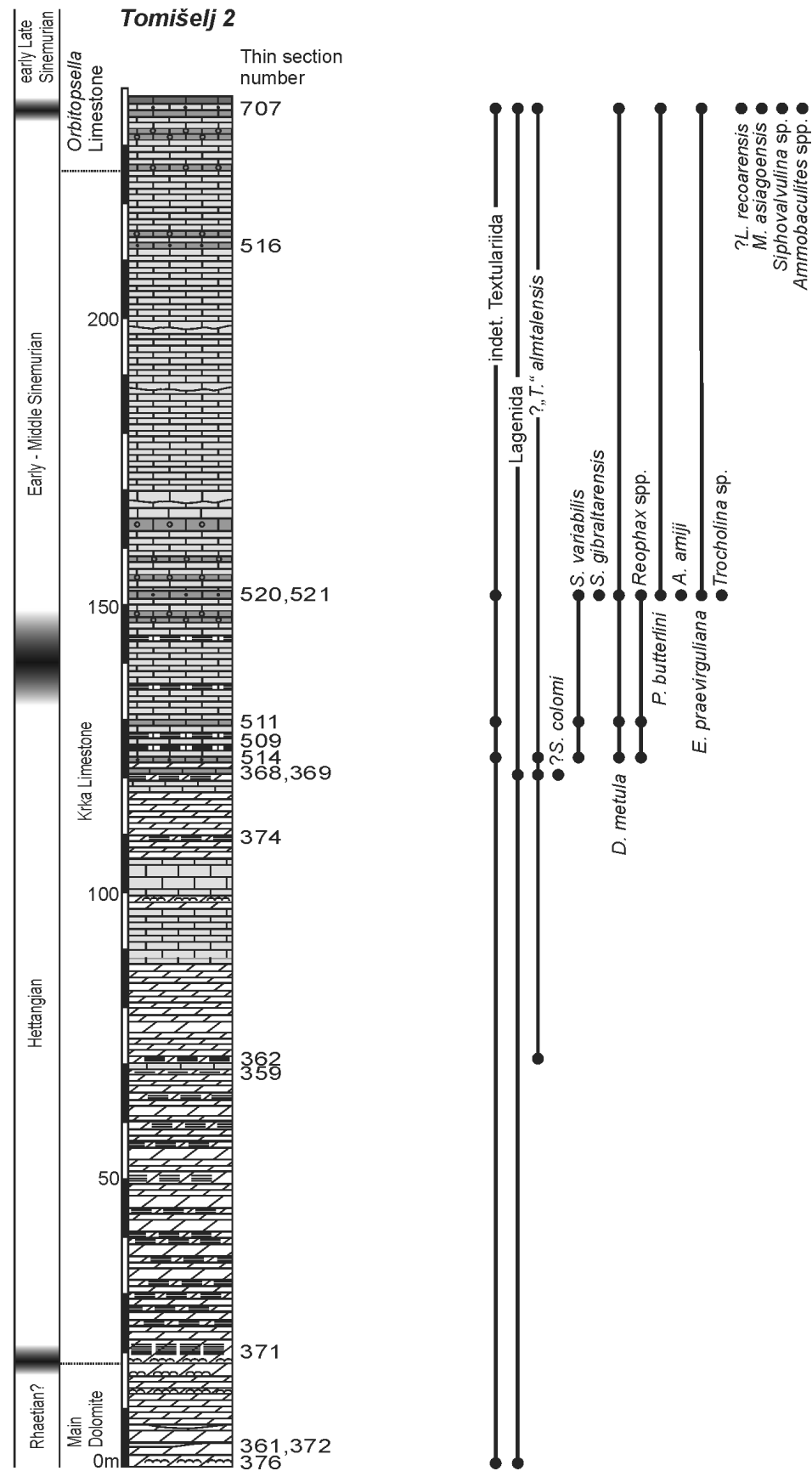
Fig. 5. Schematic stratigraphic log of the Tomišelj 2 section. The section is exposed along the slope from Tomišelj towards Mt. Krim and is partly covered.

Preserje

Medium to thick beds predominate. The lowermost part of the section is strongly dolomitized. Mudstone, bioclast and peloid wackestone predominate throughout the section (Fig. 6). Fragmented thin-shelled bivalves, foraminifera, ostracods, gastropods, echinoderms, green algae (*Palaeodasycladus mediterraneus*), and microproblematica *Thaumatoporella parvovesiculifera* are present among bioclasts. Horizons and beds of laminated dolomite, very rarely stromatolites, and intraclastic breccias are subordinate, as well as oolite with micritized grain-centres. Desiccation cracks and pores are present (Ogorelec, 2009).
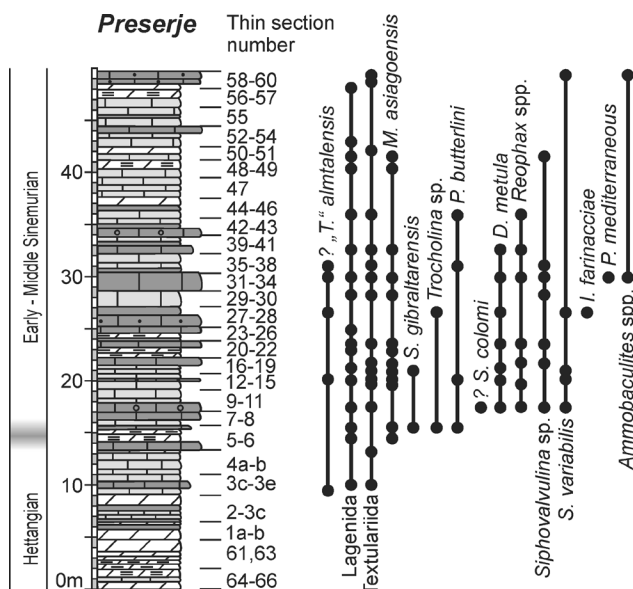

Fig. 6. The Preserje section. Redrawn and simplified after Ogorelec (2009). For the legend see Fig. 5.

The lowermost part of the section contains few foraminifera. Only Nodosariidae, small *Textularia* and ?"*T.*"*almtalensis* were determined. The rest of the section contains *Ammobaculites* sp., *D. metula*, *Involutina* sp., Nodosariidae, *M. asiagoensis*, *P. butterlini*, *Reophax* sp., ?*S. colomi*, *S. gibraltarensis*, *S. variabilis*, *Siphovalvulina* sp., *Textularia* sp., ?"*T.*" *almtalensis*, and *Trocholina* sp. Whereas the previous assemblage could possibly belong to the Hettangian, this assemblage is placed in the Early to Middle Sinemurian according to the stratigraphic chart for the Dinarides in Velić (2007). Additionally, according to Boudagher-Fadel and Bosence (2007), *P. butterlini* first appears in the Early to Middle Sinemurian *Siphovalvulina colomi* zone.
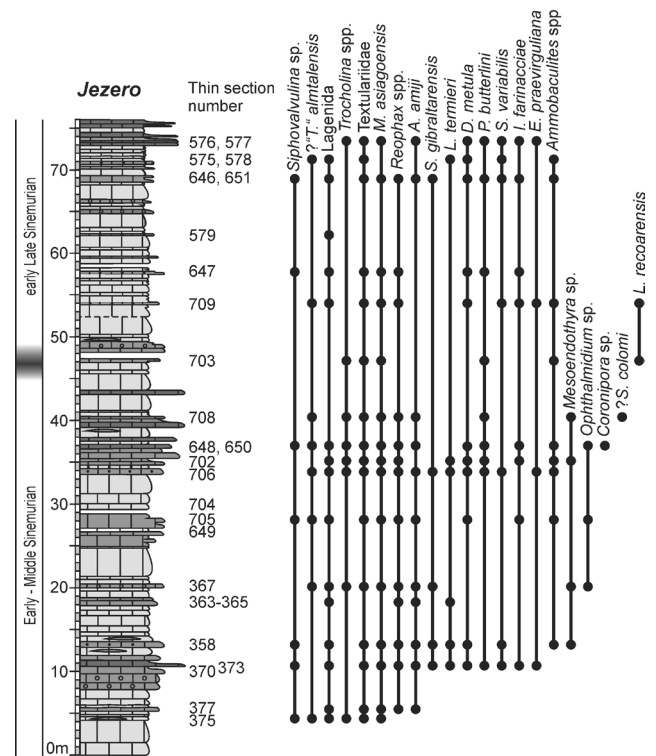

Fig. 7. Jezero section. For the legend see Fig. 5.

Jezero

Beds vary in thickness from thin, rarely even platy, to very thick. Grey and black mudstone and wackestone predominate (Fig. 7). Ooidal limestone is subordinate, sometimes presenting only horizons or lenses. Floatstone with bivalve and gastropod shells is likewise rare, whereas bioclast rudstone is slightly more abundant in the uppermost part of the section. Peloids predominate among clasts. Horizontal lamination in mudstone and gently dipping cross lamination are rare. Small-scale erosion relief, reworked mud chips, shell lags, red clayey bed surfaces, boring and burrowing structures are present.

The foraminiferal assemblage is identical to the one in the Tomišelj 1 section. *Mesoendothyra* sp. first occurs 13 m from the base of the section, and *L. recoarensis* 47 m from its base. Thus, it is possible that the section spans the successive *Mesoendothyra* sp. partial-range zone between the Early and Late Sinemurian, and the *L. recoarensis* partial-range zone of the early Late Sinemurian (Velić, 2007).

Tomišelj 1

Beds are medium- and occasionally very thick (Fig. 8). Mudstone and wackestone with rare intraclasts, peloids, ooids, thin-shelled bi-
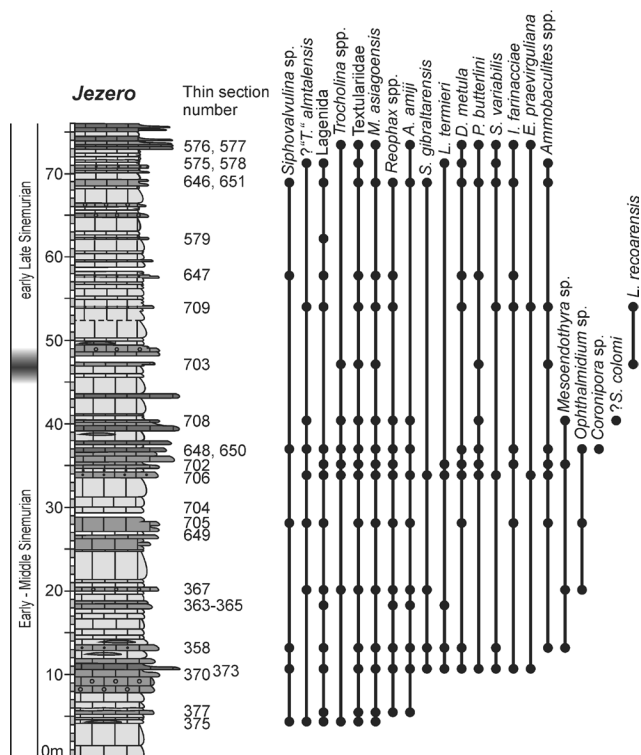
Fig. 8. Tomišelj 1 section. For the legend see Fig. 5.

valves, and small gastropods predominate. Ooid and bioclast-ooid packstone and grainstone are also common. Intraclast rudstone is rare and bivalve floatstone is present only in single horizons. Bioturbation is common in mudstone and wackestone, whereas normal and inverse gradings were rarely noted in ooid grainstone.

The foraminiferal assemblage consists of *A. amiji*, *Ammobaculites* spp., ?*Bosniella oenensis*, *Coronipora* sp., *D. metula*, *E. praevirguliana*, *Involutina* sp., Nodosariidae, ?*Lituolipora termieri*, ?*L. recoarensis*, *M. asiagoensis*, *Mesoendothyra* sp., *Ophthalmidium* sp., *P. butterlini*, *Reophax* spp., ? *S. colomi*, *S. gibraltarensis*, *S. variabilis*, *Siphovalvulina* sp., Textulariidae, ?*"T."* *almtalensis*, *Trocholina* spp., and *Valvulina* sp..

According to the presence of ?*L. recoarensis* and the absence of *Orbitopsella* sp., this section belongs to the *L. recoarensis* partial-range zone of the early Late Sinemurian. Alternatively, because determination of *Lituosepta* is here questionable, it could belong to the older, *Mesoendothyra* sp. partial-range zone, spanning the transition from the Early to Late Sinemurian (VELIĆ, 2007). According to BASSOULLET (1997), this assemblage would be of Late Sinemurian age. Due to the early occurrence of *A. amiji*, the stratigraphic scheme of BOUDAGHER-FADEL and BOSENCE (2007) seems less appropriate for this assemblage.

Zalopate

The predominant lithology in the Zalopate section is ooid grainstone in mostly medium thick beds (Fig. 9). Bivalve fragments, brachiopods, intraclasts, and oncoids are sometimes accumulated at the base of the oolite, and may be common enough to constitute a bioclast-ooid grainstone. Mudstone, lithiotid rudstone, peloid wackestone with *T. parvovesiculifera*, bivalve floatstone to rudstone with a bioclast-peloid wackestone-packstone matrix, and peloid grainstone are subordinate to grainstone. Normal and inverse grading, red clay partings, scour structures and flow-ripples are occasionally present.
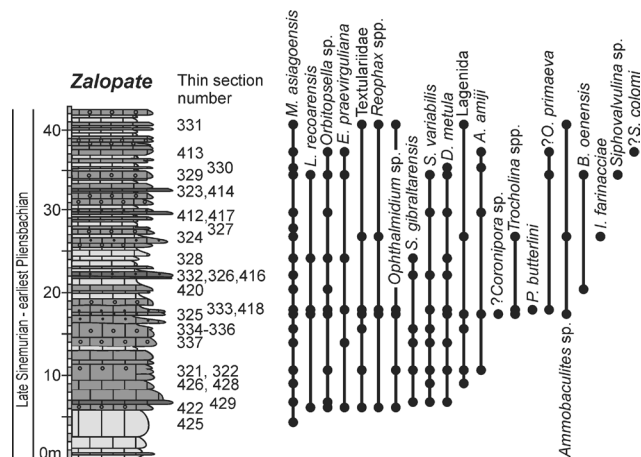

Fig. 9. Zalopate section. For the legend see Fig. 5.

The foraminiferal assemblage comprises *A. amiji*, *Ammobaculites* spp, *B. oenensis*, *Coronipora* sp., *D. metula*, *E. praevirguliana*, *Involutina* sp., Nodosariidae, *L. recoarensis*, *M. asiagoensis*, *Ophthalmidium* sp., *Orbitopsella primaeva*, *Orbitopsella* sp., *P. butterlini*, *Reophax* spp., ?*S. colomi*, *S. gibraltarensis*, *S. variabilis*, *Siphovalvulina* sp., *Textularia* spp., *Trocholina* spp., and *Valvulina* sp. According to the presence of *Orbitopsella* sp. and *O. primaeva*, this section represents the *O. primaeva* partial-range zone of Late Sinemurian to earliest Pliensbachian age (VELIĆ, 2007).

Podpeč

The dominant lithology of the Podpeč section (Fig. 10) is medium to massive bedded grey ooid grainstone and bioclast-ooid grainstone. Also common are peloid wackestone to packstone, and oncoid and bioclast floatstone. Fragments of bivalves are the most frequent bioclasts; terebratulid brachiopods, foraminifera, gastropods and

green algae are other common bioclasts. Lithiotid bivalves are mostly accumulated inside red claystone beds, rarely at the bases of limestone beds. Thin to medium thick beds of wackestone and mudstone are subordinate. Irregular bedding planes, red clayey surfaces, parallel lamination and grading are common. Cross-lamination in ooid grainstone was found outside the quarry.
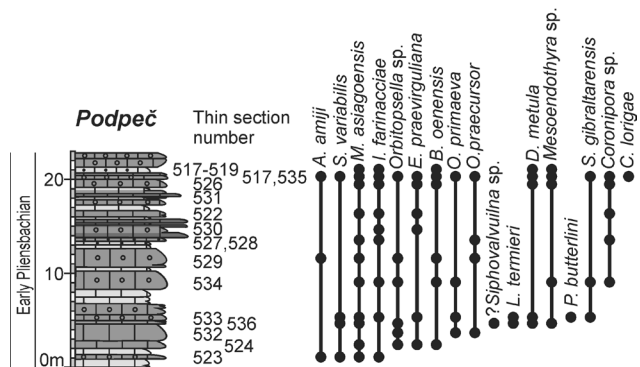

Fig. 10. Podpeč section. For the legend see Fig. 5.

The foraminiferal assemblage consists of *A. amiji*, *Ammobaculites* spp., *B. oenensis*, *Coronipora* sp., *D. metula*, *E. praeviruliana*, *Involutina* sp., Lagenida, *L. termieri*, *M. asiagoensis*, *Mesoendothyra* sp., *Ophthalmidium* sp., *Orbitopsella praecursor*, *O. primaeva*, *Orbitopsella* sp., *P. butterlini*, *Reophax* spp., ?*S. colomi*, *S. gibraltarensis*, *S. variabilis*, *Siphovalvulina* sp., Textularidae, *Trocholina* spp., and *Valvulina* sp. This assemblage belongs to the *O. praecursor* taxon-range zone of Early Pliensbachian age (Velić, 2007).

Trends in foraminiferal assemblages

Stratigraphic distribution of foraminifera is shown in Figures 5-10. Table 1 summarizes the composition of assemblages of successive time intervals and is divided according to facies. The highest abundance of specimens per cm² of thin section, the highest number of species and the highest calculated diversity are also given. These parameters, together with corresponding proportions of complex agglutinated foraminifera, are graphically shown in Figure 11. Figure 12 shows the change in size of *M. asiagoensis* and of the absolute largest specimen for each time interval.

Discussion

Facies changes

Lithological succession in the measured sections is summarized as follows:

i) Lofer cycles are typical for the Hettangian part of the succession (Dozet, 1993; Ogorelec, 2009). Irregular surfaces, clay infillings, and black pebbles point to occasional subaerial exposure (Haas et al., 2007), which together with birds' eyes, tee-pee structures, and desiccation cracks indicate intertidal sedimentation on a platform with a flat top.

ii) Mudstone, bioclast and peloid wackestone gradually start to become more common during the Late Hettangian, indicating longer-lasting subtidal conditions and/or the gradual recovery of invertebrates after the end-Triassic mass extinction, while stromatolites and subaerial exposures become less frequent. Transgression may be partly related to the global rise in sea level (Haq et al., 1988; Hallam, 2001) and/or the tectonic subsidence of the AdCP northern margin (Bucković et al., 2001).

iii) During the Early - Middle Sinemurian and in the early Late Sinemurian, bioclastic limestone gradually becomes more common. Red clayey bed surfaces indicate short periods of exposure (Martinuš et al., 2012).

iv) Ooid and bioclast-ooid packstone and well-sorted ooid grainstone with mature ooids become common during the early Late Sinemurian, and predominate in the Late Sinemurian and the Early Pliensbachian. Accumulations of bioclasts and scour structures indicate the influence of occasional storms (see Flügel, 2004: 714). Well-preserved and paired shells of lithiotid bivalves suggest the presence of bivalve bioherms in the vicinity (Fraser et al., 2004; Posenato & Avanzini, 2006; Posenato & Masetti, 2012). Short-lasting emersions are still evident as occasional red and clayey bedding planes. This type of platform was no longer dominated by peritidal conditions, but probably resembled internally differentiated lagoon with accumulations and/or buildups of lithiotid bivalves and oolitic sand shoals (Gale, 2015).

Table 1. The largest values for diversity (H), abundance and number of species per thin section and the list of determined foraminifera.

Microfacies	Age	Max H'	Max abundance per cm²	*Max No. species	Assemblage (determined taxa only, without species held in open nomenclature)
Bindstone	Rhaetian – Middle Hettangian	1.00	0.42	3	Nodosariidae, Textulariida
	Late Hettangian	0.56	1.06	2	*Meandrovoluta asiagoensis*, Nodosariidae
	Early – middle Sinemurian	0.75	5.87	6	*Meandrovoluta asiagoensis*, Nodosariidae, *Pseudopfenderina butterlini*, Textulariida, *"Trochammina" almtalensis*, *Trocholina* sp.
	early Late Sinemurian	0	0	0	/
Mudstone	Late Hettangian	0	0.29	1	*»Trochammina« almtalensis*
	Early - Middle Sinemurian	1.31	2.26	5	*Meandrovoluta asiagoensis*, Nodosariidae, *Pseudopfenderina butterlini*, *Reophax* sp., *Siphovalvulina* sp., Textulariida
	early Late Sinemurian	0.8	0.97	3	*Ammobaculites* sp., Nodosariidae, *Pseudopfenderina butterlini*
	Late Sinemurian – earliest Pliensbachian	/	0	0	/
Sparse wackestone	Late Hettangian	/	0	0	/
	Early - Middle Sinemurian	2.48	10.77	9	*Amijiella amiji*, *Ammobaculites* sp., ?*Coronipora* sp., *Duotaxis metula*, *Involutina* sp., *Meandrovoluta asiagoensis*, Nodosariidae, *Ophthalmidium* sp., *Pseudopfenderina butterlini*, *Reophax* sp., *Siphovalvulina* sp., Textulariida, *"Trochammina" almtalensis*, ?*Trocholina* sp.
	early Late Sinemurian	1.98	8.55	11	*Amijiella amiji*, *Everticyclammina praevirguliana*, *Meandrovoluta asiagoensis*, Nodosariidae, *Reophax* sp., *Siphovalvulina* sp., Textulariida
Dense wackestone	Late Hettangian	0.72	10.12	4	*Duotaxis metula*, *Meandrovoluta asiagoensis*, Nodosariidae, Textulariida
	Early - Middle Sinemurian	1.56	36.13	16	*Amijiella amiji*, *Ammobaculites* sp., *Duotaxis metula*, *Lituolipora termieri*, *Meandrovoluta asiagoensis*, Nodosariidae, *Pseudopfenderina butterlini*, *Reophax* sp., *Siphovalvulina gibraltarensis*, *Siphovalvulina variabilis*, Textulariida, *"Trochammina" almtalensis*, *Trocholina* sp.
	early Late Sinemurian	2.06	11.58	13	*Ammobaculites* sp., *Duotaxis metula*, *Everticyclammina praevirguliana*, *Meandrovoluta asiagoensis*, Nodosariidae, *Pseudopfenderina butterlini*, *Reophax* sp., *Siphovalvulina* sp., Textulariida, *"Trochammina" almtalensis*
	Late Sinemurian – earliest Pliensbachian	1.83	1.69	7	*Siphovalvulina gibraltarensis*
	Early Pliensbachian	1.94	28.67	20	*Ammobaculites* sp., *Involutina farinnaciae*, *Meandrovoluta asiagoensis*, *Mesoendothyra* sp., Nodosariidae, *Ophthalmidium* sp., *Reophax* sp., Textulariida, *Trocholina* sp.

				Age	Taxa
Packstone	1.64	2.94	6	Late Hettangian	Duotaxis metula, Reophax sp., Siphovalvulina variabilis, Textulariida
	3.18	14.62	24	Early – Middle Sinemurian	Amijiella amiji, Ammobaculites sp., ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituolipora termieri, Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Pseudopfenderina butterlini, Reophax sp., ?Siphovalvulina colomi, Siphovalvulina gibraltarensis, Siphovalvulina sp., Textulariida, "Trochammina" almtalensis, Trocholina sp.
	2.38	24.28	15	early Late Sinemurian	Amijiella amiji, Ammobaculites sp., ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Meandrovoluta asiagoensis, Nodosariidae, Ophthalmidium sp., Pseudopfenderina butterlini, Reophax sp., Siphovalvulina gibraltarensis, Siphovalvulina sp., Textulariida, "Trochammina" almtalensis, Trocholina sp.
	2.38	29.82	30	Late Sinemurian – earliest Pliensbachian	Amijiella amiji, Ammobaculites sp., ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituosepta recoarensis, Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Orbitopsella primaeva, Orbitopsella sp., Pseudopfenderina butterlini, Reophax sp., Siphovalvulina gibraltarensis, Siphovalvulina variabilis, ?Siphovalvulina colomi, Textulariida, Trocholina sp.
	2.21	59.86	18	Early Pliensbachian	Amijiella amiji, Bosniella oenensis, ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Orbitopsella praecursor, Orbitopsella primaeva, Orbitopsella sp., Siphovalvulina gibraltarensis, Siphovalvulina variabilis, Textulariida, Trocholina sp.
Grainstone	1.63	4.83	6	Late Hettangian	Duotaxis metula, Nodosariidae, Reophax sp., Siphovalvulina variabilis, Textulariida
	2.31	18.89	16	Early – Middle Sinemurian	Amijiella amiji, Ammobaculites sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituolipora termieri, Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Planiinvoluta sp., Pseudopfenderina butterlini, Reophax sp., Siphovalvulina gibraltarensis, Siphovalvulina variabilis, Siphovalvulina sp., Textulariida, "Trochammina" almtalensis, Trocholina sp.
	2.62	26.62	17	early Late Sinemurian	Amijiella amiji, Ammobaculites sp., Bosniella oenensis, ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituolipora termieri, Lituosepta recoarensis, Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Pseudopfenderina butterlini, Reophax sp., ?Siphovalvulina colomi, Siphovalvulina variabilis, Textulariida, "Trochammina" almtalensis, Trocholina sp.
	2.64	29.48	25	Late Sinemurian – earliest Pliensbachian	Amijiella amiji, Ammobaculites sp., ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituosepta recoarensis, Meandrovoluta asiagoensis, Nodosariidae, Ophthalmidium sp., Orbitopsella primaeva, Orbitopsella sp., Pseudopfenderina butterlini, Reophax sp., Siphovalvulina gibraltarensis, Siphovalvulina variabilis, Textulariida, Trocholina sp.
	2.02	29.94	24	Early Pliensbachian	Amijiella amiji, Ammobaculites sp., ?Coronipora sp., Duotaxis metula, Involutina sp., Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Orbitopsella sp., Reophax sp., Siphovalvulina sp., Textulariida, Trocholina sp.
Ooidal grainstone	2.38	3.35	12	Early – Middle Sinemurian	Amijiella amiji, Ammobaculites sp., Duotaxis metula, Involutina sp., Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Reophax sp., Siphovalvulina gibraltarensis, Siphovalvulina variabilis, Textulariida, "Trochammina" almtalensis, Trocholina sp.
	2.53	11.03	17	early Late Sinemurian	Amijiella amiji, Ammobaculites sp., Bosniella oenensis, Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituolipora termieri, Lituosepta recoarensis, Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Pseudopfenderina butterlini, Reophax sp., ?Siphovalvulina colomi, Siphovalvulina gibraltarensis, Siphovalvulina variabilis, Textulariida, Trocholina sp.
	2.21	18.08	18	Late Sinemurian – earliest Pliensbachian	Amijiella amiji, Bosniella oenensis, ?Coronipora sp., Involutina sp., Lituosepta recoarensis, Meandrovoluta asiagoensis, Nodosariidae, Ophthalmidium sp., Planiinvoluta sp., Pseudopfenderina butterlini, Reophax sp., ?Siphovalvulina colomi, Siphovalvulina variabilis, Textulariida, Trocholina sp.
	2.92	43.39	29	Early Pliensbachian	Amijiella amiji, Ammobaculites sp., Bosniella oenensis, ?Coronipora sp., Duotaxis metula, Everticyclammina praeviriguliana, Involutina sp., Lituolipora termieri, Meandrovoluta asiagoensis, Mesoendothyra sp., Nodosariidae, Ophthalmidium sp., Orbitopsella primaeva, Orbitopsella praecursor, Orbitopsella sp., Pseudopfenderina butterlini, Reophax sp., Siphovalvulina gibraltarensis, Siphovalvulina variabilis, ?Siphovalvulina colomi, Textulariida, Trocholina sp.

* species held in open nomenclature included

A

B

C
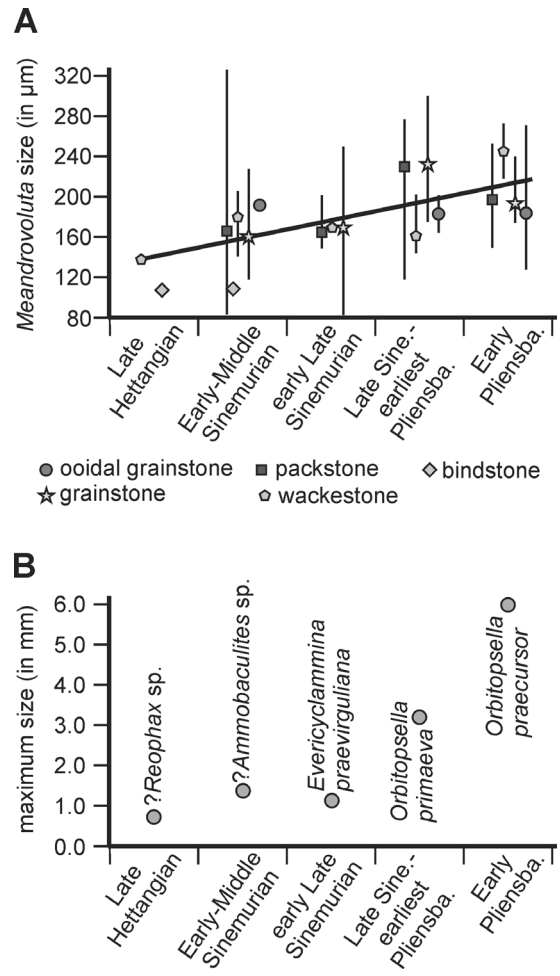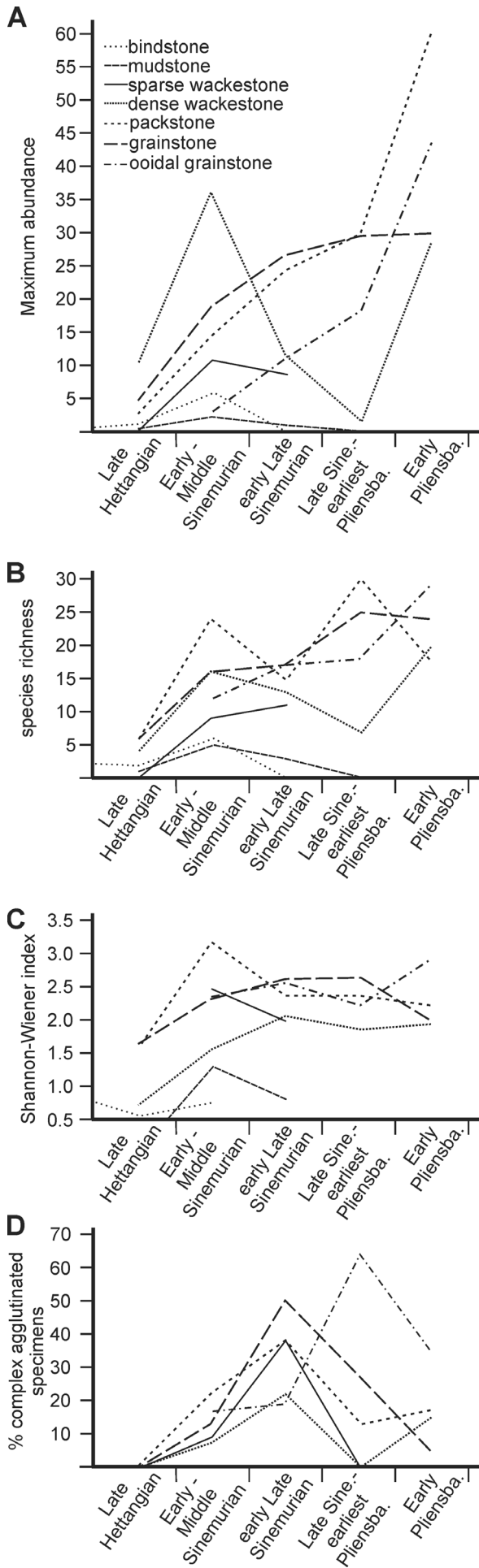

D

A

B

Fig. 12. Trends in sizes of foraminifera. A: A within-genus change of size for *Meandrovoluta* per facies type. Vertical bars indicate variability within distinct facies types, and the symbol the mean size. The oblique solid line represents a general increase in size. B: The among-genus change in size. The largest specimens encountered in different time-slices were measured, regardless of facies type.

Fig. 11. Changes in foraminiferal assemblages according to different facies. A: Maximum abundance (number of specimens per cm^2 of thin section). B: Maximum number of species (species richness) per facies type. C: Maximum diversity for different facies types. D: Percent of relatively complex agglutinated foraminifera. Specimens with an advanced endoskeleton (e.g., axial infill, pillars) and/or with exoskeletal structures (complex outer wall, possibly for hosting endosymbionts) were counted, and include the genera: *Bosniella, Lituolipora, Pseudopfenderina, Amijiella, Mesoendothyra, Lituosepta, Orbitopsella, Everticyclammina, Cymbriaella*.

Diversification in foraminifera

Foraminiferal assemblages from Hettangian to Pliensbachian undergo significant changes in composition, diversity and abundance, which take place cotemporaneous with a facies change from restricted tidal-flat to predominantly subtidal and normal marine conditions:

i) Until the Late Hettangian, the taxonomic composition is virtually the same in all facies types of the peritidal environment. The assemblage consists of species, that may be considered opportunists (see Fugagnoli, 2004; BouDagher-Fadel, 2008), e.g. *M. asiagoensis*, *Siphovalvulina* spp., and Triassic survivors, e.g. *D. metula*, *"T." almtalensis.*

ii) A strong increase in abundance, species richness, diversity of foraminifera and number of complex agglutinated forms is common to all facies types, except mudstone and bindstone in the Early - Middle Sinemurian. There is a strong possibility of a continued increase in the abundance of foraminifera until the Early Pliensbachian, which is the youngest sampled interval. As such increase occurs in all facies types (except in bindstone and mudstone), we can rule out the possibility of simply sampling a more suitable facies type (i.e., more "grainy" limestone opposed to micritic limestone).

iii) *Bosniella oenensis*, *L. recoarensis*, and *Orbitopsella* spp. are restricted to packstone, grainstone and ooid grainstone since the early Late Sinemurian. These may be more strongly agitated facies types.

iv) Although the size of *M. asiagoensis* varies, there may be a general trend in increase in size; and the size of the largest species in the assemblage also increases.

The recorded succession of faunas parallels the studies of benthic foraminifera elsewhere in the present peri-Mediterranean area (Chiocchini et al., 1994; Zambetakis-Lekkas et al., 1996; BouDagher-Fadel et al., 2001; Eren et al., 2002; Kabal & Tasli, 2003; Barattolo & Romano, 2005; Mancinelli et al., 2005; Pomoni-Papaioannou & Kostopoulou, 2008; Bosence et al., 2009; Tunaboylu et al., 2014). The contrasting Hettangian - Early Sinemurian and Late Sinemurian - Pliensbachian communities are mostly interpreted as survival and recovery communities of

the post-extinction period (Barattolo & Romano, 2005; Mancinelli et al., 2005; BouDagher-Fadel & Bosence, 2007; BouDagher-Fadel, 2008; Tunaboylu et al., 2014), and could be interpreted as part of the global community maturation process (Hottinger, 1996, 2014). However, Fugagnoli (2004; see also Septfontaine, 1986) related a low-diversity assemblage dominated by *Glomospira/Planiinvoluta* spp. (i.e., *Meandrovoluta* sp.), together with *Duotaxis*, simple textulariids and valvulinids, to eutrophic conditions (bioturbated mudstone-wackestone alternating with black shale), while the diversity and proportion of complex lituolids increase as conditions changed towards meso- and oligotrophic. The change in nutrient supply and oxygen availability from Hettangian to Pliensbachian is not as strongly supported in the present study, as there is no transition from organic-rich facies (although algal mats contained plenty of organic matter, while well-washed sands in the younger part of the succession were well oxygenated). Rather, environmental stability itself might be more important in establishing more complex associations of foraminifera. Such stability might have been related to stabilization of the physical environment (e.g., ocean chemistry, sea temperature) after the end-Triassic extinction, or to the increasing interactions among organisms, but it might also have come with the transition from highly fluctuating peritidal conditions where there are drastic changes in light intensity, salinity and temperature, to predominantly subtidal and thus more physically stable conditions (see Hallock, 1988). Furthermore, although a steady increase in the size of foraminifera has been recorded after the Permian-Triassic boundary extinction and used as an argument for a true (i.e., not facies-change related) recovery of foraminifera (Payne et al., 2011; Rego et al., 2012), it is not known whether such an increase in size is possible also during the time of rising sea level (Wilmsen & Neuweiler, 2008). In other words, the increased complexity of foraminiferal assemblages in transgression-affected succession should not be attributed solely to post-extinction biotic recovery and diversification, but may instead reflect a rather local re-establishment of suitable habitat.

Conclusions

The precise age of Lower Jurassic carbonates from the Mt. Krim area (External Dinarides) was determined on the basis of foraminifera. Such biostratigraphic framework is obligatory for poten-

tial future studies of the northern Adriatic Carbonate Platform. During the Late Hettangian, sedimentation took place on a relatively flat platform with quickly interchanging subtidal and intertidal conditions, as can be concluded from the exchange of micritic limestone/dolomite with laminated (stromatolitic) limestone/dolomite and emersion surfaces. Foraminiferal assemblage, consisting of small opportunists, is identical in all microfacies types, even in rare packstone and grainstone. The low diversity of the assemblage may be attributed to the early stages of recovery after the end-Triassic extinction, or to unstable environmental conditions. Towards the Early – Middle Sinemurian, foraminiferal assemblages of various facies types show an increase in abundance, species richness, and diversity. Larger agglutinated species appear for the first time. This change in the assemblage corresponds to a shift towards predominantly subtidal and more stable conditions. The younger strata show a continuing increase in abundance until the Early Pliensbachian, but the trend is not so clear as regards species richness and diversity. The facies association suggests the contemporaneous development of an internally differentiated lagoon, which hinders distinguishing between the true speciation and the mere colonisation of suitable habitats.

Acknowledgements

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