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ORIGINAL ARTICLE

Facies development and paleoecology of rudists and corals: an example of Campanian transgressive sediments from northern Croatia, northeastern Slovenia, and northwestern Bosnia

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Abstract At six localities in northern Croatia (Donje Orešje, Gornje Orešje), Slovenia (Stranice, Slovenj Gradec), and Bosnia (Bešpelj and Kober), successions of shallow-water Campanian deposits transgressively covered a tectonically uplifted and eroded paleorelief. They constitute different lateral parts of a transgressive subtidal environment, where rudists and corals are typical macrofossils. At the investigated localities, two types of succession were distinguished: (a) clastic and (b) carbonate. Most localities are within the extended chronostratigraphic range of *Calveziconus* cf. *lecalvezae* (80.5–79.03 Ma), which comprises the upper part of the *Vaccinites alpinus* interval zone (for Stranice and Slovenj Gradec localities) and beginning of the *Pironaea polystyla* interval zone (for Bešpelj and Kober localities). In clastic successions, corals are the most abundant macrofossils, whereas rudists predominate within carbonate sections. The depositional setting of the investigated localities results from rapid relative sea-level rise with a tectonic overprint, which covered different types of paleorelief. In cases when the paleorelief is gentle, a transgressive succession starts with clastic coral-rich sediments or carbonates with radiolitids. In areas of steeper paleorelief carbonate sediments were deposited with a mixed radiolitid-hippuritid community, and the rudists, as the major macrofossils, indicate higher sedimentation rates in comparison with the clastic situations.

Keywords Upper Cretaceous · Corals · Rudists · Transgressive sediments · Facies · Chronostratigraphy · Clastics · Carbonates · Paleoecology

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Introduction

Rudists are the most common macrofossils in Upper Cretaceous deposits of the Tethyan Realm. They lived as epibenthic suspension feeders (Skelton 1978) and sediment dwellers (Skelton et al. 1995) and could locally form vast biostromal congregations within subtidal environments (Moro et al. 2002, 2008), with or without associated corals (Moro et al. 2010). The former were termed coral-rudist formations (Masse and Philip 1981; Ross and Skelton 1993; Gili et al. 1995) and they commonly formed biostromes (Götz 2003). Mixed rudist-coral facies are characteristic of the Internal Dinarides (Herak 1986, 1991), as well as Austro-Alpine shallow-water sediments (Turnšek 1997).

Late Jurassic to Early Cretaceous tectonism and nappe stacking as a result of convergence between the SW Apulia and NW Tisza plates (Tari 2002) were followed by subaerial exposure of large parts of the orogenic belt (Ratschbacher et al. 1989; Herak 1991; Schlagintweit et al. 2013) (Fig. 1). The NW exposed parts of the paleoland were transgressively overlain during the Upper Cretaceous (Herak 1991; Lužar Oberiter et al. 2012). Subaerial erosion produced truncation surfaces with differentiated relief cut locally into Triassic (Basch 1983) and Cretaceous carbonates (Marinković and Ahac 1979) or Permo-Triassic clastic rocks (Mioč and Žnidarčič 1976). From the Turonian to

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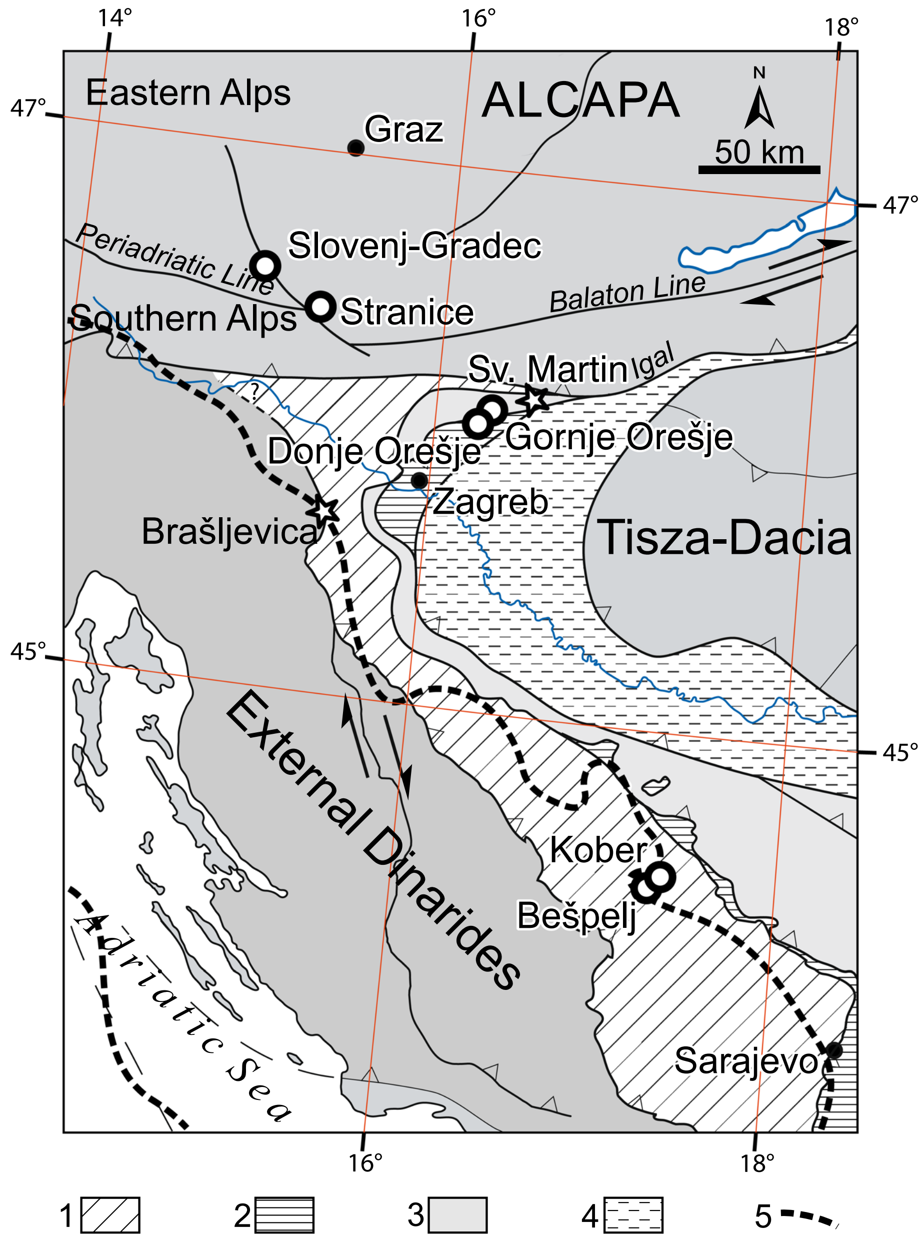


Fig. 1 Paleopositions of investigated localities (*circles*) in the Mediterranean Tethys, plotted on a map of the Dinaride-Alpine-Pannonian region (after Lužar Oberiter et al. 2012). Internal Dinarides units: *1* Pre-Karst and Bosnian Flysch Unit, *2* The West Vardar Ophiolitic Unit, *3* Thrusted sheets composed of partly metamorphosed post-Variscan basement units of the distal margin of Adria, *4* The Sava Zone, *5* Position of the Adriatic carbonate platform (AdCP) after Vlahovic et al. (2005). ALCAPA–tectonic mega unit which includes the Austroalpine nappes and the Central and Inner West Carpathians. Investigated localities in *dotted circles*, localities after Moro et al. (2010) in *stars*

Senonian times, in formerly exposed areas, a major marine transgression led to deposition of a thick Upper Cretaceous to Eocene succession. This began in depocenters that probably originated by extension and strike-slip fault movement (Sanders and Höfling 2000).

In this paper, data are presented from the transgressive sequences exposed at localities in northwestern Slovenia, Croatia, and Bosnia (Fig. 2): Stranice, Slovenj Gradec (Slovenia), Donje Orešje, Gornje Orešje (Croatia), and Kober and Bešpelj (Bosnia). These outcrops are distributed over an area of approximately 20,000 km^2. The distances between the Croatian and Slovenian localities are 78 km (Stranice) and 104 km (Slovenj Gradec), and between Croatian and Bosnian sites, 186 km. Outcrops of the Upper Cretaceous Austro-Alpine, Internal Dinarides, and the marginal area of the Adriatic carbonate platform are mostly represented by deepwater sedimentation (Lužar Oberiter et al. 2012) whereas shallow-water successions are rare, occurring in random roadcuts (Slovenj Gradec), stone (Donje Orešje, Gornje Orešje and Stranice) and bauxite (Bešpelj and Kober) quarries.

These six outcrops were chosen because they represent the only available remnants of the transgressive successions of different tectonic plates and units within the Late Cretaceous tectonically active orogenic system (Tari 2002; Schmid et al. 2008; Lužar Oberiter et al. 2012). Most of these transgressive successions are known for their richness and good preservation of macrofossils, which range from

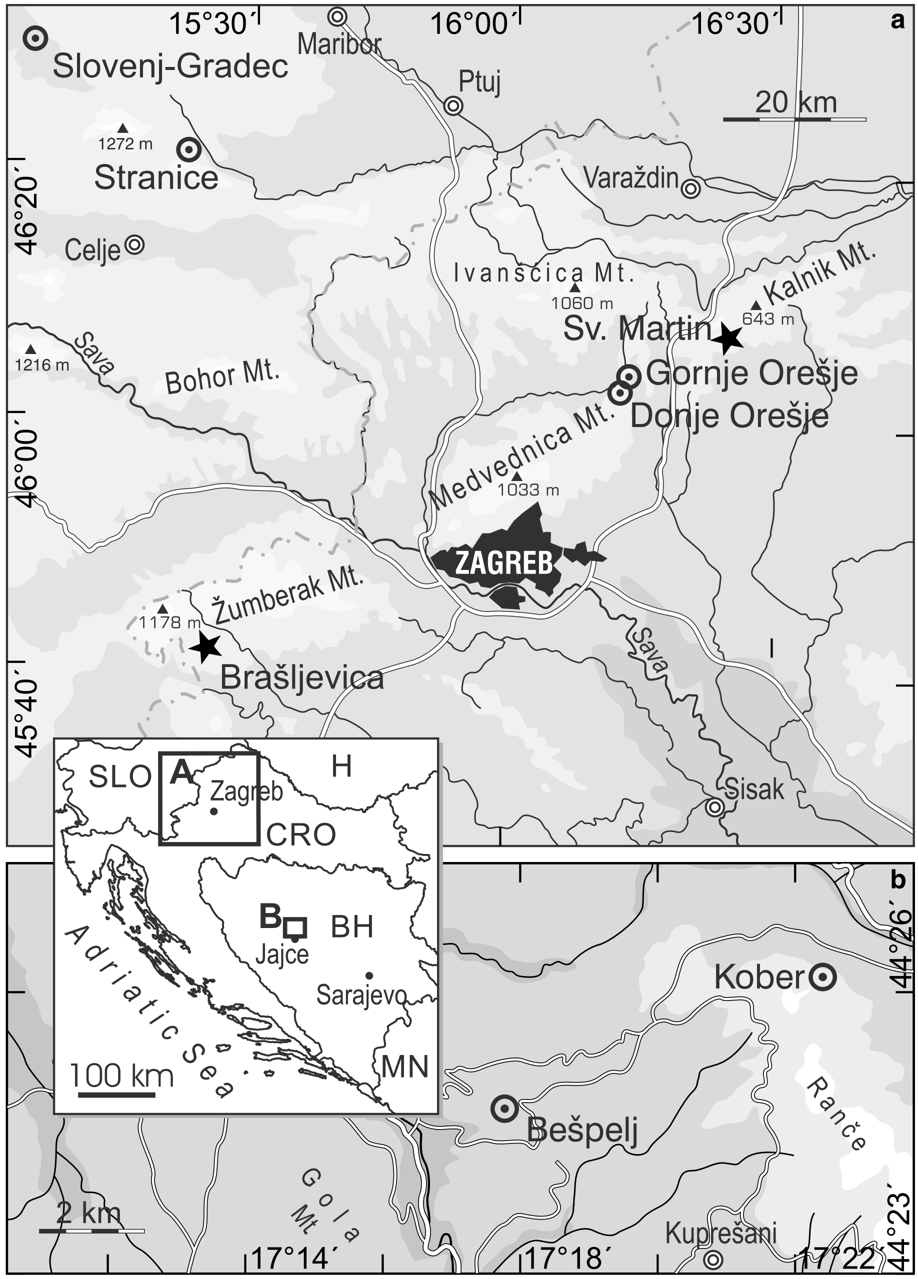


Fig. 2 Location map with the positions of the investigated profiles. **a** Northwestern Croatia and Slovenia, **b** area north of Jajce, northwestern Bosnia. Localities marked with *stars* after Moro et al. (2010)

pure coral through mixed coral-rudist towards complete rudist assemblages. These macrofossil communities occur within different lithologies (clastic and carbonate) and the interaction between community development and sediment type is explored in this study. In addition, these outcrops present a chronostratigraphic challenge since the biostratigraphy based on benthic foraminifera and rudists indicates a wide range (Santonian-Campanian). A subareal exposure surface of Campanian age can be correlated regionally with mid-Campanian emergence on the Adriatic Carbonate Platform (Gušić and Jelaska 1990; Moro et al. 2002; Vlahovic et al. 2005; Steuber et al. 2005), and globally as a sequence boundary in the Boreal Realm of Europe (Niebuhr 1995), the southern Tethyan margin in Egypt (Lüning et al. 1998) and in North America (Miller et al. 2003).

The rudist-coral facies at the localities in northeastern Slovenia are of the Gosau-type and they transgressively overlie different levels of the Mesozoic, and locally Permo-Triassic basement (Fig. 1). North Croatian localities show facies that belong to the Internal Dinarides (Herak 1991; Schmid et al. 2008; Korbar 2009; Lužar Oberiter et al. 2012; Márton et al. 2014). The localities in northwestern Bosnia show facies that represent the marginal area of the Adriatic carbonate platform (ADCP) (Vlahovic et al. 2005; Korbar 2009) or Pre-karst and Bosnian Flysch Unit of the Internal Dinarides (Schmid et al. 2008; Lužar Oberiter et al. 2012) (Fig. 1). As a result of the location of the depositional area for the aforementioned Bosnian localities, shallow-water carbonate successions predominate at the beginning of transgressive successions. They were the result of the interaction of eustatic sea-level changes and increasing tectonic compression, which resulted in the final disintegration of the ADCP during the Late Cretaceous (Vlahovic et al. 2005).

The aims of this work are (1) to determine the microfossil assemblage associated with the different rudist biozones (Steuber and Schüter 2012) which, with the strontium isotope stratigraphy (SIS) provide a chronostratigraphic framework for the investigated localities, (2) to correlate the chronostratigraphic data with sea-level changes deduced from the lithofacies succession, with a view to unraveling the nature of the transgression with regard to eustatic versus tectonic influences, and (3) to determine the paleoenvironmental and paleoecological characteristics of the rudist-coral communities and their interaction with sediment type, particularly relative to carbonate production/clastic sediment influx rate.

Geological background of the studied sites

All localities with transgressive Upper Cretaceous deposits, except Slovenj Gradec and Gornje Orešje, have been previously investigated by several authors, chiefly in view of the abundance of macrofossils. At the Stranice locality, Pleničar (1971, 1993, 1994, 2005), Pleničar and Šribar (1992) and Chaffau (2002) determined rudists, and Turnšek (1978, 1994, 1997) identified corals in deposits which are now scarce or unavailable due to extensive quarrying. According to the microfossil assemblage, Pleničar and Šribar (1992) determined the biostratigraphic age as Santonian–Campanian.

Rudists and corals from Santonian to Lower Campanian strata at Donje Orešje were described by Turnšek and Polšak (1978) and Polšak (1979). According to the microfossils from the overlying pelagic limestones, and nannofossils from marly sediments (Polšak et al. 1978), Korolija et al. (1995) distinguished an Early to Late Campanian age for the transgressive succession. They also reported a lateral transition between clastic and carbonate sediments. According to the strontium isotope stratigraphy of the rudist association, Moro et al. (2010) determined the chronostratigraphic age as the upper part of the Early Campanian.

In NW Bosnia at the localities of Bešpelj and Kober, Devidé-Neděla and Polšak (1961) and Polšak (1964) identified rudists and a microfossil assemblage of benthic and pelagic foraminifers from overlying turbidites as being Maastrichtian in age. Tomić (1985) recognized a peri-reefal lithofacies of Santonian-Lower Maastrichtian age, while Polšak et al. (1982) and Dragičević (1987) defined the paleogeography of Bešpelj and the surrounding area as the marginal zone of the ADCP. It is worth mentioning here that the listed rudist species (Table 1) determined by Polšak (1979) and Pleničar (1971, 1993, 1994) are correct according to Steuber (1999, 2002), Moro et al. (2010) and Steuber and Schüter (2012) for synonyms, notably *Vaccinites braciensis* and *Pironaea praeslavonica*.

Methods

For biostromes composed predominately of corals, the descriptive classification according to Insalaco (1998) was utilized. Determination of chronostratigraphic age is based on SIS data obtained from rudist shells and correlated with the rudist biozones of Steuber and Schüter (2012). Also, for biostratigraphic purposes, the subdivision of the Upper Cretaceous of the Adriatic-Dinaric carbonate platform is based on the ranges of benthic foraminifers (Velić 2007) and larger foraminifera from southern Italy (Frijia et al. 2015), following the classification of foraminifera by Loeblich and Tappan (1988).

Strontium isotope ratios of samples are adjusted to a ratio of 0.710247 of standard NBS 987 to derive numeric ages from the "Look-Up" table (Version 4: 08/03) provided by Horwath and McArthur (1997) and McArthur et al. (2001). The other sample splits were analyzed by AAS for elemental composition using the procedure suggested by Steuber and Rauch (2005), using a Perkin-Elmer Analyst 700, at the Croatian Geological Survey, Zagreb.

Granulometric analysis of clastic sediments from the Strance locality were undertaken at the Faculty for Biotechnology, University of Ljubljana, and adjusted to Trefethen (1950). XRD analysis of clastic sediments from Gornje Orešje were completed at the Mineralogical and Petrological Laboratory, Faculty of Science, University of Zagreb.

Lithology and biostratigraphy of the transgressive successions

At all the studied localities, Upper Cretaceous successions represent transgressive deposits over highly eroded Permo-Triassic (Stranice) and Triassic (Donje Orešje) or Upper Cretaceous (Bešpelj and Kober) sedimentary rocks. The basal surface of the sections at Slovenj Gradec and Gornje Orešje successions are tectonic contacts (Fig. 3).

The Slovenj Gradec locality, Slovenia

The Slovenj Gradec succession is 24 m thick and composed entirely of carbonates with bed thicknesses from 30

Table 1 List of determined rudists from the investigated localities

Species	Locality
Hippuritidae	
Hippuritella castroi (Vidal, 1874)	S, Ko
Ha. lapeirousei (Goldfuss 1840)	S, Ko
Ha. sulcatissima (Douvillé 1894)	DO
Ha. toucasi (d'Orbigny 1847)	DO
Ha. variabilis (Munier-Chalmas, in Gaudry 1867)	S, DO, GO, Ko
Hippurites colliciatus (Woodward, 1855)	S
H. canaliculatus (Rolan du Roquan 1841)	DO
H. cornucopiae Defrance 1821	Ko
H. heritschi Pejović and Kühn 1960	S
H. lamarcki (Douviillé 1893)	Ko
H. matheroni (Douvillé 1893)	DO
H. nabrasiensis Futterer 1893	DO, Ko
H. radiosus Des Moulins, 1826	S
H. socialis irregularis (Toucas 1903)	DO
H. striatus (Defrance 1821)	DO
H. sulcatoides Douvillé 1892	DO
H. vidali Matheron 1878–81	DO
Pironaea polystyla Pirona 1868	Ko
V. archiaci (Douvillé 1892)	S, DO, GO
Vaccinites chaperi (Douvillé 1879)	S, DO
V. oppeli (Douvillé 1892)	S, DO, GO
V. oppeli santoniensis (Kühn 1948)	DO
V. plenicari Polšak and Sliskovic 1989	DO
V. robustus (Toucas 1904)	S
V. sulcatus (Defrance 1821)	S, DO
V. ultimus (Milovanović, 1935)	S, DO
V. vesiculosus (Woodward, 1855)	S, DO, GO, Ko
V. vredenburgi (Kühn 1933)	DO
Radiolitidae	
Biradiolites bipriminter Astre 1954	S
B. leychertensis Toucas 1908	S
Bystrickya sp.	S
Bournonia excavata (d'Orbigny 1842)	S
B. retrolata (Astre, 1929)	Be
Durania martelli Parona 1911	DO
Gorjanovicia endrissi (Boehm 1927)	Be
Joufia reticulata Boehm 1879	Ko
Lapeirouseia jouanneti (Des Moulins 1826)	S
L. laskarevi Milovanović 1938	S
L. pervinquièrei (Toucas 1908)	S
L. plana Milovanović 1937	S
L. zitteli Douvillé 1913	S
Praelapeirouseia bjelusensis Slišković 1984	S
P. kossmati Wiontzek, 1934	S
P. pajtleri Pleničar 1993	S
P. wiontzeki Slišković 1975	S
Praeradiolites sinuatus (d'Orbigny 1850)	Be
Pseudosabinia sp.	GO
Radiolites sp.	Ko
R. angeoides (Lapeirouse 1781)	S
R. aurigerensis Toucas 1908	S
R. galloprovincialis Mathron 1842	Be
R. mammillaris Matheron 1842	DO
Sauvagesia meneghiniana (Pirona 1869)	S, DO
S. slovenica Pleničar 1973	S
Sauvagesia sp.	S
Sphaerulites sp.	Ko
Pseudopolyconites sp.	GO, Ko
Plagioptychidae	
Mitrocaprina bayani (Douvillé 1888)	Be
Plagioptychus sp.	DO, GO
P. paradoxus Matheron 1842	DO
Trechmannellidae	
Dictyoptycus morgani (Douvillé 1904)	S

GO-Gornje Orešje, DO-Donje Orešje, S-Stranice, Ko-Kober, Be–Bešpelj. After Pleničar (1971, 1993, 1994, 2005), Chaffau (2002), Turnšek and Polšak (1978), Polšak (1979) and Polšak et al. (1982) except for Gornje Orešje. Corrected for higher taxa after Skelton (2011) and for synonyms according to Bilotte (1985), Laviano and Gallo Maresca (1992), Vicens (1992) (after Steuber 2002)

to 120 cm. Beds show similar textures and an absence of structures throughout the outcrop, which laterally ranges from 1 to 5 m. The lower boundary of the succession is marked by a fault with Miocene marly sediments (Mioč and Žnidarčič 1976). The carbonate facies are packstone–grainstone and floatstone-rudstone, with both lithotypes distributed randomly throughout the succession. Completely preserved macrofossils are rare and consist of small radiolitid individuals up to 4 cm high and 0.8 cm in diameter in the lower part of the succession (Fig. 4a). Thin-sections of packstone–grainstone (Fig. 4b) reveal shallow-water non-skeletal and skeletal particles including peloids, benthic foraminifers and rare, small fragments of macrofossils.

The fossil assemblage comprises the following agglutinated and porcellaneous foraminiferal species (Fig. 5a–e): *Accordiella conica* Farinacci, *Calveziconus* cf. *lecalvezae* Caus & Cornella, *Scandonea samnitica* De Castro, *Dicyclina schlumbergeri* Munier-Chalmas, *Dictyopsella kiliani* Munier-Chalmas, *Cuneolina pavonia* D'orbigny and *Peudocyclammina sphaeroidea* Gendrot. The benthic foraminifers determined in the Slovenj Gradec succession indicate the *Calveziconus* cf. *lecalvezae* subzone (Frijia et al. 2015) in the upper part of the Lower Campanian to lowermost Middle Campanian. According to the benthic fossil community and textures, the depositional environment can be interpreted as shallow subtidal with moderate water energy.

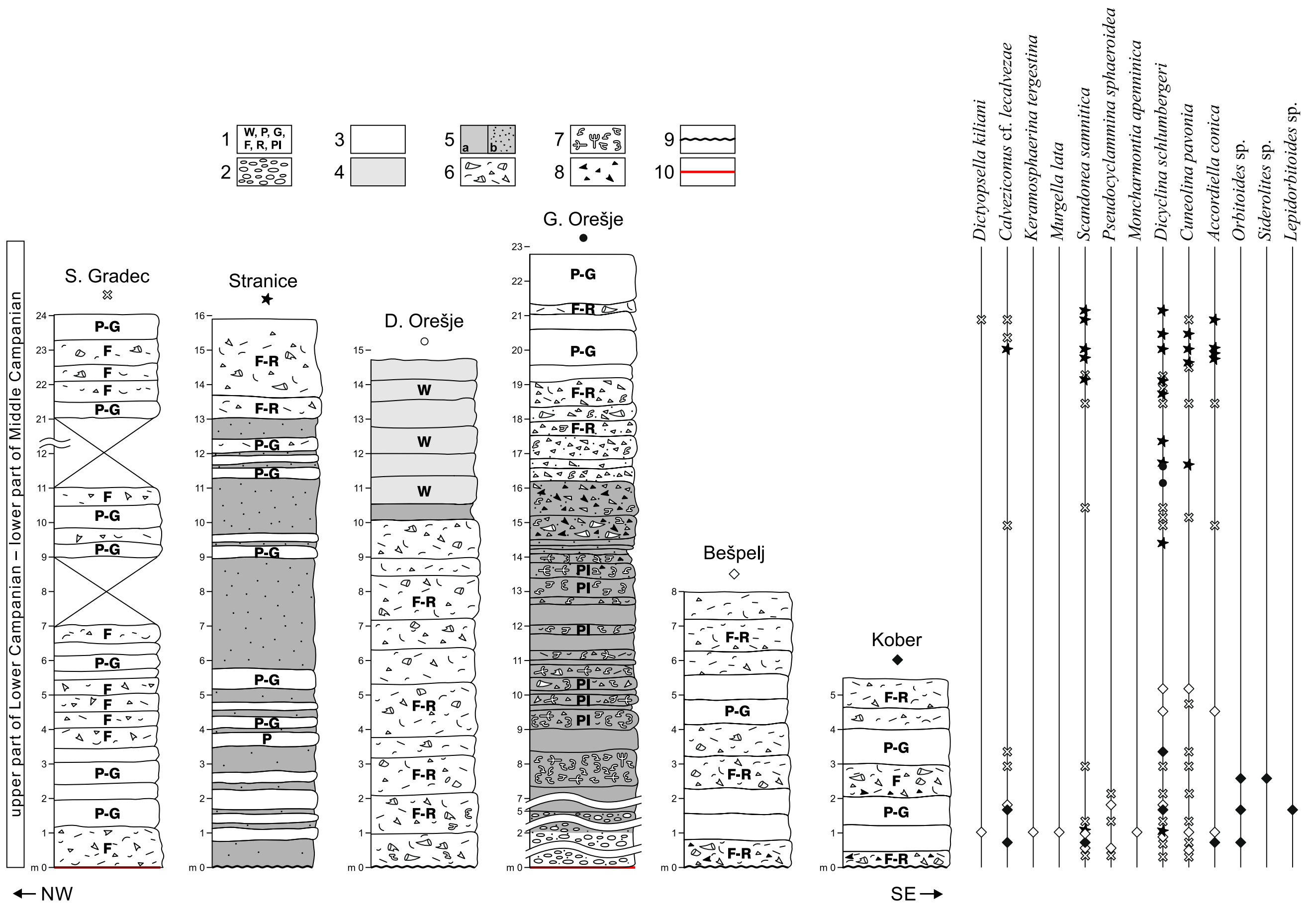


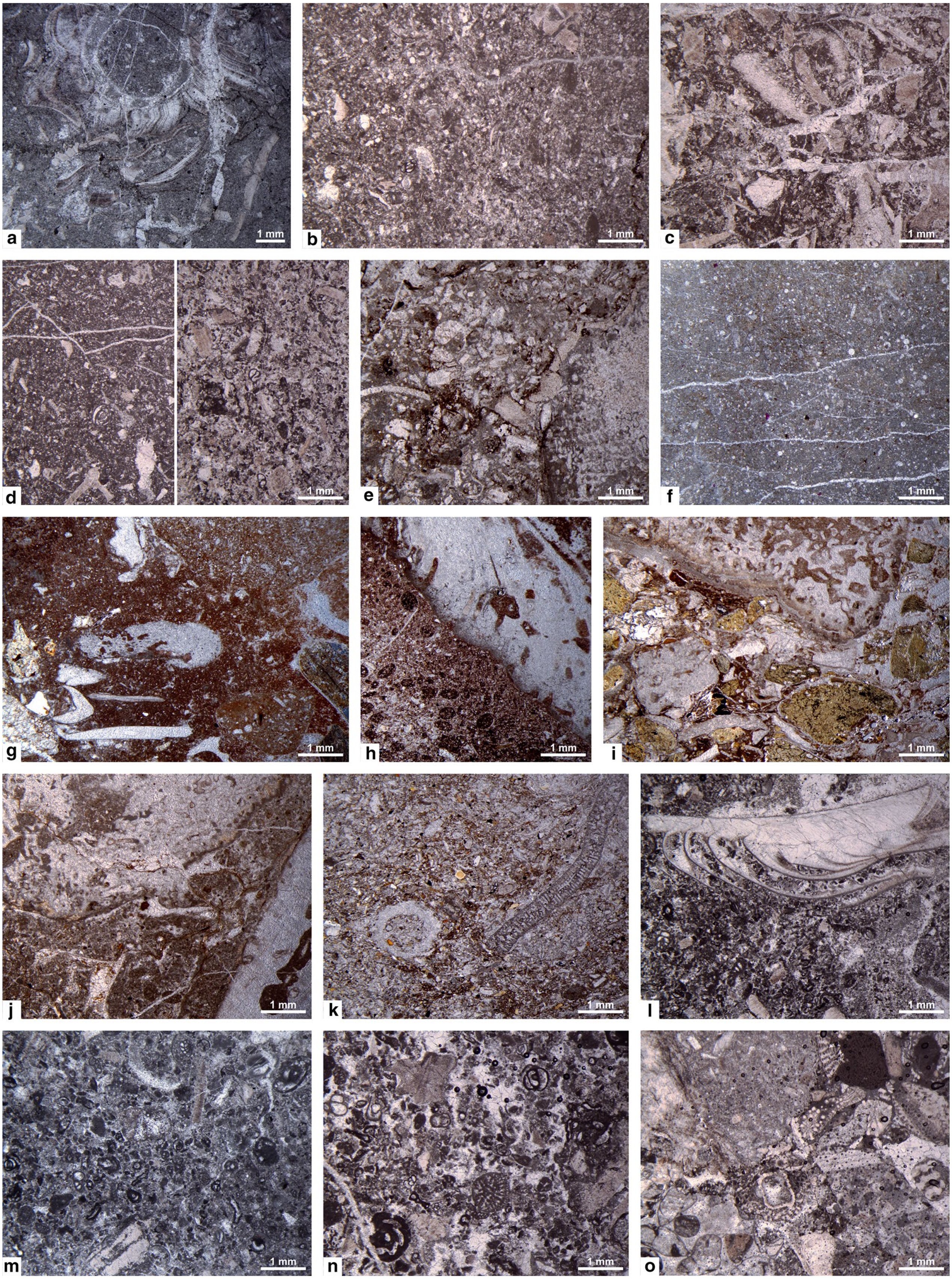
Fig. 3 Biostratigraphy and lithology with microfossil communities of the investigated sections. *1* Classification according to depositional texture and Insalaco (1998) coral description: *W* wackestone, *P* packstone, *G* grainstone, *F* floatstone, *R* rudstone, *Pl* pillarstone, *2* Conglomerates, *3* Shallow-water carbonates, *4* Pelagic carbonates, *5* Clastic (**a**) mud and (**b**) sandy mud, *6* Rudist shells and fragments, *7* Corals, whole and fragments, *8* Lithoclasts, *9* Transgression, *10* Tectonic contact (fault)

The Stranice locality, Slovenia

The maximum total thickness of the studied profile at Stranice is 15.80 m (Figs. 3, 6). Bed thickness ranges from 10 to 220 cm. The succession can be divided into a lower 13.60-m-thick clastic section with intercalations of carbonate sediment, and an upper 2.20 m of carbonate. Beds have similar textural features throughout the outcrop with an absence of sedimentary structures. Clastic sediments are clayely silt in the lower part and sandy/clayely silt to sandy silt towards the top. Laterally within the clastic sediments, a rich coral community is present (Turnšek 1994; Pleničar and Šribar 1992), forming a mixstone (Turnšek 1994, 1997; sensu Insalaco 1998), where encrusting-bulbous *Columactinastraea* and cylindrical *Dimorphastraea* prevail (Turnšek 1994) (Table 2). Coral growth forms are 2–9 cm high and 3.5–6 cm wide (Turnšek 1994, 1997) (Fig. 7). The carbonates are bioclastic floatstone-rudstone (Fig. 4c) to packstone-grainstone (Fig. 4d), depending on the proportion of macrofossil fragments. Grains include peloids, benthic

Fig. 4 Photographs of thin-sections from carbonate (**a**–**f**, **j**–**o**) and ▶ clastic (**g**–**i**) sediments. Localities **a**, **b** Slovenj Gradec, **c**, **d** Stranice, **e**, **f** Donje Orešje, **g**–**k** Gornje Orešje, **l**, **m** Bešpelj, **n**, **o** Kober. **a** Small radiolitid within floatstone, **b** Packstone–grainstone with small fragments of macrofossils, **c** Floatstone-rudstone with fragments of macrofossils, **d** Packstone (*left*) and packstone-grainstone (*right*), **e** Bioclastic floatstone, **f** Wackestone with pelagic particles **g** Clay with bioeroded fragments of coral, **h** Clay with peloids and bioeroded coral fragments, **i** Lithoclastic-bioclastic sandy mud with a bioeroded fragment of coral, **j** floatstone with fragment of coral and rudist, **k** Packstone-grainstone with *Dicyclina schlumbergeri* Munier-Chalmas, **l** floatstone-rudstone with fragments of macrofossils and radiolitids, m. Packstone-grainstone with small fragments of macrofossils, peloids and benthic foraminifers, **n** Packstone-grainstone with *Calveziconus* cf. *lecalvezae* Caus & Cornella, **o** Bioclastic-lithoclastic floatstone-rudstone with *Orbitoides* sp. and *Siderolites* sp.

foraminifers and small bioclasts. Above the described limestones, Pleničar (1971, 1994) recorded a rich rudist community with *Vaccinites, Hippurites*, and *Hippuritella*, and above the clastic sediments radiolitids and rare *Dictyoptycus* individuals (Table 1), but these deposits have since been removed as a result of quarrying. Dimensions of *Vaccinites*



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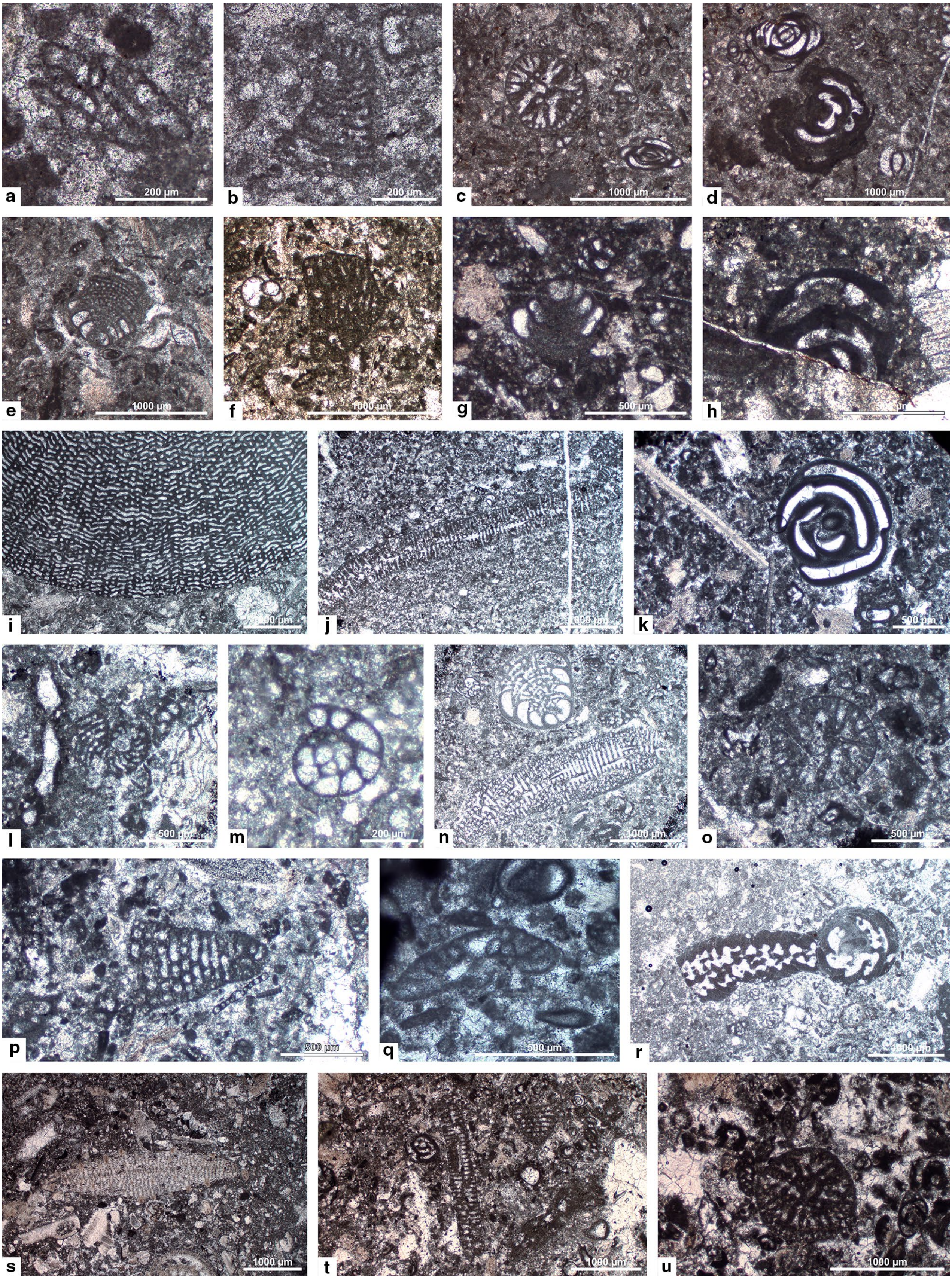
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◂**Fig. 5** Microfossils from the investigated localities used in biostratigraphic analysis Localities **a–e** Slovenj Gradec, **f–h** Stranice, **i–r** Bešpelj, **s–u** Kober. **a** *Dictyopsella kiliani* Munier-Chalmas, **b** *Pseudocyclammina sphaeroidea* Gendrot, **c** *Calveziconus* cf. *lecalvezae* Caus & Cornella, **d** *Scandonea samnitica* De Castro, **e** *Accordiella conica* Farinacci, **f** *Calveziconus* cf. *lecalvezae* Caus & Cornella, **g** *Accordiella conica* Farinacci, **h** *Scandonea samnitica* De Castro, **i** *Keramosphaerina tergestina* Stache, **j** *Dicyclina schlumbergeri* Munier-Chalmas, **k** *Scandonea samnitica* De Castro, **l** *Peudocyclammina sphaeroidea* Gendrot, **m** *Moncharmontia appeninica* (De Castro), **n** *Accordiella conica* Farinacci and *Dicyclina schlumbergeri* Munier-Chalmas, **o**, **p** *Calveziconus* cf. *lecalvezae* Caus & Cornella, **q** *Dictyopsella kiliani* Munier-Chalmas, **r** *Murgella lata* (Luperto Sini), **s** *Lepidorbitides* sp. **t** *Calveziconus* cf. *lecalvezae* Caus & Cornella and *Dicyclina schlumbergeri* Munier-Chalmas, **u** *Calveziconus* cf. *lecalvezae* Caus & Cornella

individuals range in diameter from 8 to 9 cm, rarely 16 cm, and in height from 16 to 30 cm. *Hippurites* specimens are 2–8 cm wide and 12 cm high, and those of *Hippuritella* are from 1 to 4.5 cm in diameter. Radiolitids are 2–6 cm long and 1–6 cm in diameter, and dictyoptichids are 12 cm long and 13 cm in diameter (Pleničar 1971, 2005). Vaccinitids occurring within carbonates are the tallest (Fig. 7), which is similar to their appearance at Donje Orešje and Gornje Orešje localities where they also outpace in height the branched corals.

The microfossil assemblage comprises both agglutinated and porcellaneous foraminiferal species (Fig. 5f–h): *Accordiella conica* Farinacci, *Calveziconus* cf. *lecalvezae* Caus & Cornella, *Scandonea samnitica* De Castro, *Dicyclina schlumbergeri* Munier-Chalmas, *Cuneolina pavonia* d'Orbigny. Macrofossils within floatstone-rudstone form a rich community of elevator radiolitids and rare hippuritids in toppled positions. The identified benthic foraminifers (Pleničar and Šribar 1992; Velić 2007; Frijia et al. 2015), rudists (Pleničar 2005; Steuber and Schüter 2012) and corals (Turnšek 1997) indicate the upper part of the Lower Campanian to the lowermost Middle Campanian. The facies indicate a shallow-marine, moderate-energy environment.

The Donje Orešje locality, Croatia

The Donje Orešje section is 14.75 m thick with bed thickness ranging from 55 to 155 cm. There are two types of carbonate: floatstone–rudstone in the lower 10 m of the succession, and mudstone-wackestone in the upper 4 m. A single marly bed can be observed at about 10 m above the base. Beds have similar textural features throughout the outcrop. Sedimentary structures are absent. In the floatstone-rudstone, the most common grains are densely packed bioclasts in a muddy matrix (Fig. 4e). Microfossils include miliolids and calcispheres in the upper pelagic mudstone-wackestone (Fig. 4f). Within the marly bed, nannofossils are common (Polšak et al. 1978).

There is no biostratigraphically significant microfossil assemblage present as it consists of miliolids. Hippuritid and vaccinitid rudists (Polšak 1979; Moro et al. 2010) occur in floatstone–rudstone with rare fragments of coral (Table 1; Fig. 4e) in the lower part. Determined dimensions of rudist individuals are mostly their diameters due to sampling from the hard rock. Rare specimens of *Hippurites* are up to 7.5 cm high, and those of *Vaccinites* range from 16 to 23 cm. Specimen diameter ranges are 3.7–8.8 cm for *Vaccinites*, 1.9–4.6 for *Hippurites*, and 1.3–4.5 for *Hippuritellas*. In laterally equivalent clastic sediments close by, Polšak (1979) and Turnšek and Polšak (1978) described a coral community (Table 2) in a mixstone with bulbous coral growth forms of different coral taxa (Turnšek and Polšak 1978). Bulbous and cylindrical coral growth forms are 3–9 cm high and 2.5–6 cm wide. An exception is a branching *Actinastraea ramosa* with 16 cm height and 12 cm width (Turnšek and Polšak 1978), which is still lower in comparison with vaccinitids from carbonates (Fig. 7). The corals (Turnšek 1997), rudists, and SIS data (Moro et al. 2010; Steuber and Schüter 2012), nannofossils (Polšak 1979) and pelagic foraminifers (Korolija et al. 1995), indicate the upper part of the Lower Campanian. The facies suggest a moderate-energy shallow-marine environment in the lower part of the succession and a deeper-water setting for the upper part (Fig. 3).

The Gornje Orešje locality, Croatia

The maximum thickness exposed at Gornje Orešje is 22.80 m (Figs. 3, 8) with bed thickness ranging from 10 to 500 cm and similar textural characteristics throughout the outcrop. The succession consists of a lower part with clastic sediment and an upper part of carbonate. The beginning of the clastic succession is characterized by an up to 5-m-thick bed of pebble conglomerate. Matrix in the first 2 m is a carbonate lithoclastic floatstone and in the upper 3 m, a clastic sandy mud (Fig. 9). There is no sharp transition that could be taken as a bedding plane. The well-rounded clasts, up to 9 cm long and 4 cm wide, are of serpentine. They are derived from the peridotite basement and show various degrees of alteration. The clasts show a generally preferred orientation parallel to the bedding. Conglomerates are followed by a 9.5-m-thick succession of mudstone (Fig. 4g, h) rich in corals (Fig. 10), with rare rudists, both mostly toppled. Corals form a muddy pillarstone (Insalaco 1998) with predominantly toppled branched *Columactinastraea*, *Astraraea*, *Actinastraea*, and *Actinacis* (Fig. 10c, h–k, m) and subordinate cylindrical, bulbous and solitary growth forms (Fig. 10a, b, d–g, n–o), represented by six specimens. Dimensions of coral growth forms range from 5 to 11.5 cm in height and 4–7 cm in width. Branched growth forms, mostly toppled and

Fig. 6 Field photograph of the Stranice locality. Beginning of transgressive succession marked with *arrows*

fragmented due to bioerosion, are from 7.5 (Fig. 10c) to 22 cm high and up to 16 cm wide. The density of branched corals is from 4000 to 5400 branches/m^2. Macroborings present in branched corals are the result of annelids and lithophagids (Fig. 10g, h). Thickness of pillarstones ranges from 35 to 55 cm. Rudists are rare with a few individuals of hippuritid 2.5 cm in diameter and plagioptychids (10.5 cm high and 6.5 cm in diameter, Figs. 10c1, 11b, f), which thrived within branches of coral (Fig. 10c1, c2). From 14.5 to 16.30 m, the clastic succession is lithoclastic-bioclastic sandy mudstone (Fig. 4i) with toppled and fragmented, mostly branched rarely bulbous and cylindrical corals, common low domal individuals of *Pseudopolyconites* (up to 21 cm high and 22 cm in diameter, Figs. 11a, c, 12d), rare vaccinitids represented by two specimens (up to 28 cm high and 9.5 in diameter, Figs. 11e, 12a, c) and one individual of *Pseudosabinia* (7 cm in diameter, Fig. 12b). Rare vaccinitid shells could be macrobored by lithophagid and clinoid sponge. Similar to Donje Orešje, vaccinitids here towards the top of the clastic part, are higher in comparison with branched corals (Fig. 7).

The carbonates are shallow-water floatstone-rudstone (Fig. 4j) and packstone-grainstone (Fig. 4k), with benthic foraminifers, bioclasts, peloids, as well as rare small lithoclasts (Fig. 4k). Fragments of coral occur in the lower part of the section and rudists are present throughout, with rare individuals of vaccinitids (Fig. 11d). In both clastic and carbonate parts, there is an absence of sedimentary structures.

The microfossil assemblage is sparse with the rare occurrence of miliolids and *Dicyclina schlumbergeri* Munier-Chalmas (Fig. 4k). The Gornje Orešje succession belongs to the upper part of the Lower Campanian according to the microfossil assemblage (Velić 2007) and the rudist community (Steuber and Schüter 2012). The above-described facies characteristics correspond to a low-energy shallow-marine environment in the lower clastic part of succession, and a shallow-water, moderate energy subtidal setting for the upper carbonate part.

The Bešpelj profile, Bosnia

The total thickness of the studied profile at Bešpelj is 8 m (Fig. 3) with bed thickness ranging from 70 to 100 cm. The succession consists of shallow-marine packstone-grainstone and floatstone–rudstone. Radiolitids are mostly toppled or form rare congregations up to 2–3 m wide and 60 cm high in the upper part of thicker beds (90–100 cm). Sedimentary structures are absent. The floatstone–rudstone (Fig. 4l) consists mostly of bioclasts, lithoclasts and peloids, and shallow-water microfossils. Packstone–grainstone (Fig. 4m) contains peloids, bioclasts and benthic foraminifers. The rich microfossil assemblage is composed of agglutinated-porcellaneous benthic foraminifers (Fig. 5i–r): *Accordiella conica* Farinacci, *Calveziconus* cf. *lecalvezae* Caus & Cornella, *Scandonea samnitica* De Castro, *Moncharmontia appeninica* (De Castro), *Dicyclina schlumbergeri* Munier-Chalmas, *Dictyopsella kiliani* Munier-Chalmas, *Cuneolina pavonia* d'Orbigny, *Peudocyclammina sphaeroidea* Gendrot, *Murgella lata* (Luperto Sini) and *Keramosphaerina tergestina* Stache. The alga *Thaumatoporella parvovesiculifera* (Raineri) is also present. Macrofossils include Radiolitidae (Table 1), mostly toppled, within the floatstone-rudstone. Radiolitid individuals are 4–7 cm high and 1–2 cm in diameter. From the benthic foraminiferal assemblage the Bešpelj succession corresponds to the *Calveziconus* cf. *lecalvezae* subzone (Frijia et al. 2015) of the upper part of the Lower Campanian to the lowermost Middle Campanian. The textural features and fossil community indicate a shallow-water, moderate-energy environment.

Table 2 List of coral species, their growth form and polyparia arrangement from Stranice (S), Donje Orešje (DO) [after Tunšek (1978, 1994, 1997)] and Turnšek and Polšak (1978) and Gornje Orešje (GO)

Species, solitary or colonial	Form	Polyparia arrangement	Locality
Actinacis martiniana d'Orbigny, 1850	Encrusting	Plocoid	S, DO, GO
A. reussi Oppenheim, 1930	Encrusting, branching	Plocoid	S, GO
Actinastraea elongata Alloiteau, 1954	Bulbous	Cerioid	GO
A. octolamellosa (Michelin, 1846)	Branching, bulbous	Cerioid	S, DO
A. ramosa (Michelin, 1847)	Branching	Cerioid, ramose	S, DO, GO
Acrosmilia conica d'Orbigny, 1850	Solitary	Flabellate	S
Acrosmilia sp.	Solitary	Flabellate	GO
Astraraea media (Sowerby, 1832)	Massive, bulbous	Thamnasteroid	DO
Astraraea sp.	Branching	Thamnasteroid	GO
Aulosmilia aspera (Sowerby, 1831)	Solitary	Flabellate	S
A. cuneiformis (Milne Edwards and Haime, 1849)	Solitary	Flabellate, compressed	S
Columactinastraea pygmaea (Felix, 1903)	Bulbous, branching, encrusting	Cerioid	S, DO, GO
Columnastrarea formosa (Goldfuss, 1826)	Bulbous, cylindrical	Plocoid	DO
C. striata (Goldfuss, 1826)	Bulbous, encrusting	Plocoid	DO
Conicosmilotrochus dentatus Turnšek, 1978	Solitary	Ceroid	S
C. stranicesis Turnšek, 1978	Solitary	Ceroid	S
C. strictus Turnšek, 1978	Solitary	Ceroid, compressed	S
Cunnolites (Cunnolites) reussi (Fromentel, 1870)	Solitary	Discoidal	S
C. (Cunnolites) stellata (Quenstedt, 1880)	Solitary	Discoidal	S
C. (Paracunnolites) scutellum (Reuss, 1854)	Solitary	Discoidal	S
C. (Pleisocunnolites) cycloides (Felix, 1903)	Solitary	Discoidal	S
C. (Pleisocunnolites) depresa (Reuss, 1854)	Solitary	Discoidal	S
C. Pleisocunnolites) dispar (Quenstdt, 1880)	Solitary	Discoidal	S
C. (Pleisocunnolites) faecata (Stoliczka, 1873)	Solitary	Discoidal	S
C. (Pleisocunnolites) gosavicus (Oppenheim, 1930)	Solitary	Discoidal	S
C. (Plesiocunnolites) orbigny (Fromentel, 1864)	Solitary	Discoidal	S
C. (Pleisocunnolites) undulata (Goldfuss, 1826)	Solitary	Discoidal	S
C. (Plesiocunnolitopsis) robusta (Quenstedt, 1880)	Solitary	Discoidal	S
Cunnolites sp.	Solitary	Discoidal	GO
Dasmiopsis lamellicostatus (Reuss, 1854)	Solitary	Trochoid	S
Dermosmiliopsis orbigny Alloiteau, 1957	Rounded	Phaceloid	DO
D. tenuicosta (Reuss, 1854)	Rounded	Phaceloid	DO, GO
Dimorphastraea composite (Sowerby, 1835)	Cylindrical, bulbous, fungiform	Thamnasteroid	S
D. leptophyllia (Felix, 1903)	Fungiform to cylindrical	Thamnasteroid	S, GO
Elasmophyllia deformis (Reuss, 1854)	Rounded	Phaceloid	S, DO
Ellipsosmilia sp.	Solitary	Trochoid	DO
Enallocoenia salisburgensis Beauvis, 1982	Bulbous	Subcerioid	S
Hydnopora ataciana d'Orbigny, 1850	Cylindrical	Hydnoporoid	S
H. multilamellosa Reuss, 1854	Cylindrical	Hydnoporoid	S, GO
Mycetophylliopsos antiqua (Reuss, 1854)	Massive	Meandroid	DO
Neocaeniopsis corollaris (Reuss, 1854)	Bulbous	Plocoid	S
N. excelsa (Fromentel, 1867)	Massive, digitate	Plocoid	S, GO
Neocoenia lepida (Reuss, 1854)	Massive	Plocoid	DO
Orbignygyra daedalea (Reuss, 1854)	Massive	Meandroid	S
Phragmosmilia sp.	Solitary	Trochoid	S
Phyllocoeniopsis pediculate (Deshayes, 1831)	Massive	Plocoid	DO
Phyllocoeniopsis sp.	Massive	Plocoid	DO
Phyllosmilia sp.	Solitary	Trochoid, compressed	S

Table 2 continued

Species, solitary or colonial	Form	Polyparia arrangement	Locality
Placosmilia gracilis (Felix, 1903)	Uniserial	Meandroid	S
Pleurocora crassa (Reuss, 1854)	Branched	Dendroid	DO
P. haueri Milne-Edwards and Haime, 1848	Branched	Dendroid	DO
Polytremacis sp.	Encrusting	Plocoid	S
Procadocora simonyi (Reuss, 1854)	Branched round	Phaceloid-dendroid	S, DO
P. tenuis (Reuss, 1854)	Branched round	Phaceloid-dendroid	S, DO
Rennensismilia chondrophora (Felix, 1903)	Solitary	Flabellate	S, DO
R. complanata (Goldfuss, 1826)	Solitary	Flabellate, compressed	S, DO
R. subinduta (Reuss, 1854)	Solitary	Urbinate	S, DO
Stephanosmilia polydectes Kolosváry, 1954	Solitary	Urbinate	S
Synastraea procera (Reuss, 1854)	Encrusting	Thamnasteroid	S, DO
Thamnoseris hoernesi (Reuss, 1854)	Bulbous, massive, encrusting	Cerioid	DO

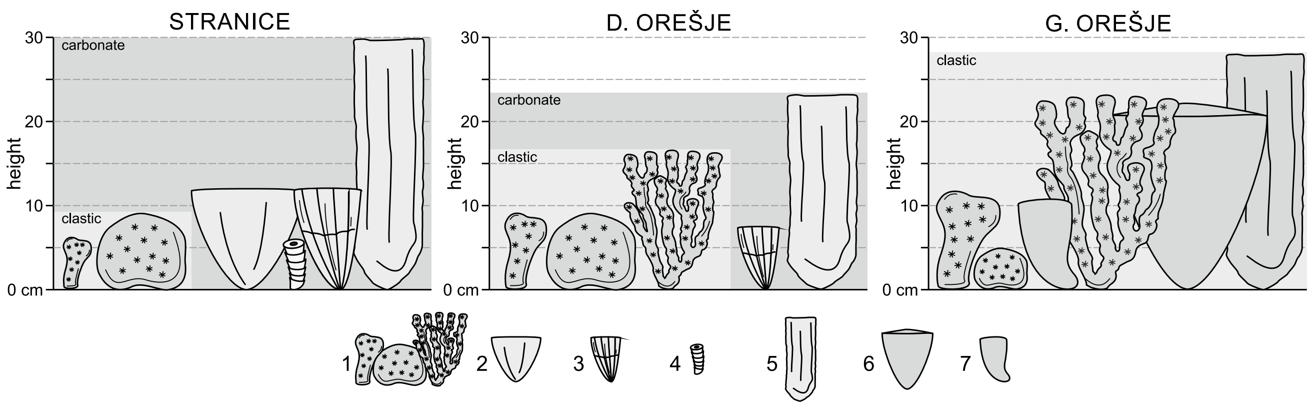


Fig. 7 Distribution of measured heights for corals and rudists. *1* Corals (cylindrical, bulbous, branching), *2* Dictyoptychids, *3* Hippuritids, *4* Radiolitids, *5* Vaccinitids, *6* Pseudopolyconitids, *7* Plagoiptychids. Only rudist and coral specimens with measurable heights of preserved shells and coral growth forms are presented. *Horizontal axis* generalized vertical succession from *left to right*

Fig. 8 Panoramic field photograph of Gornje Orešje locality. Tectonic beginning of succession marked with *arrows*

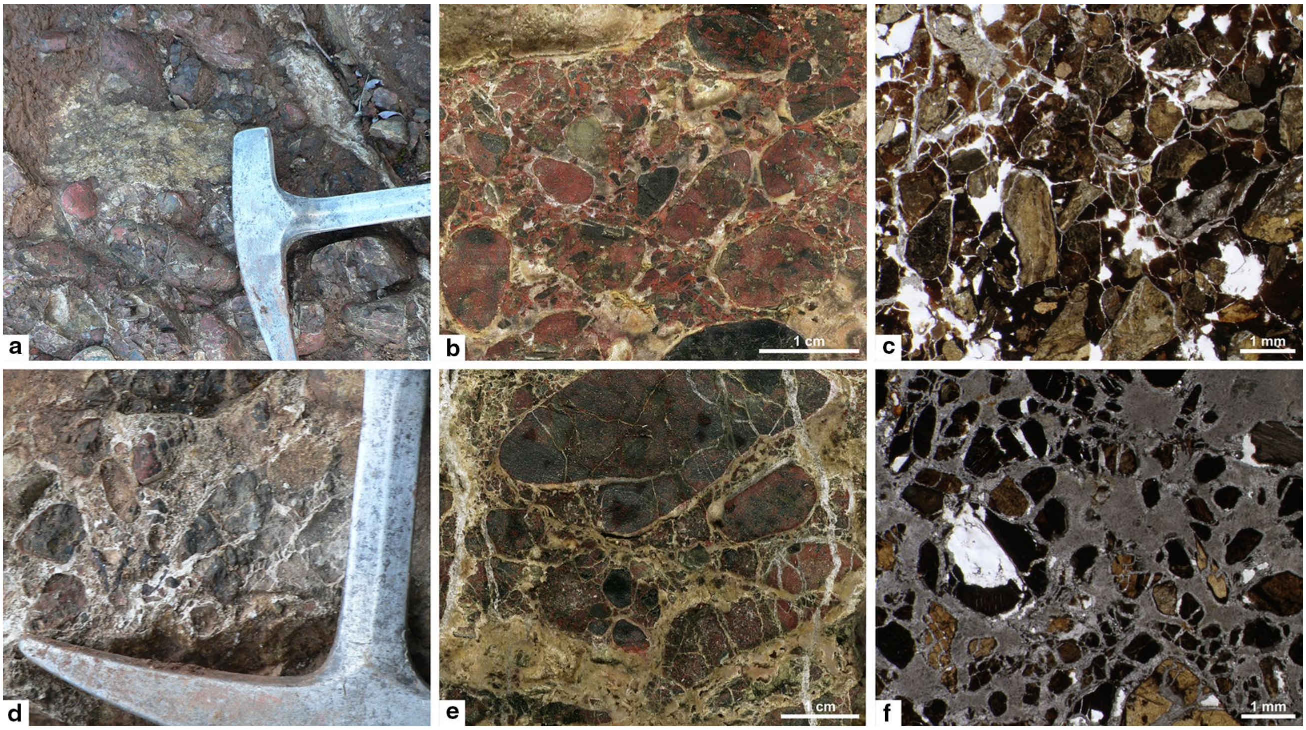


Fig. 9 Basal conglomerates from Gornje Orešje locality. Lower carbonate (**c**–**e**) and upper clastic (**a**–**c**) part. From *left to right* field photo (**a**, **d**), polished slabs (**b**, **e**) and thin-sections (**c**, **f**)

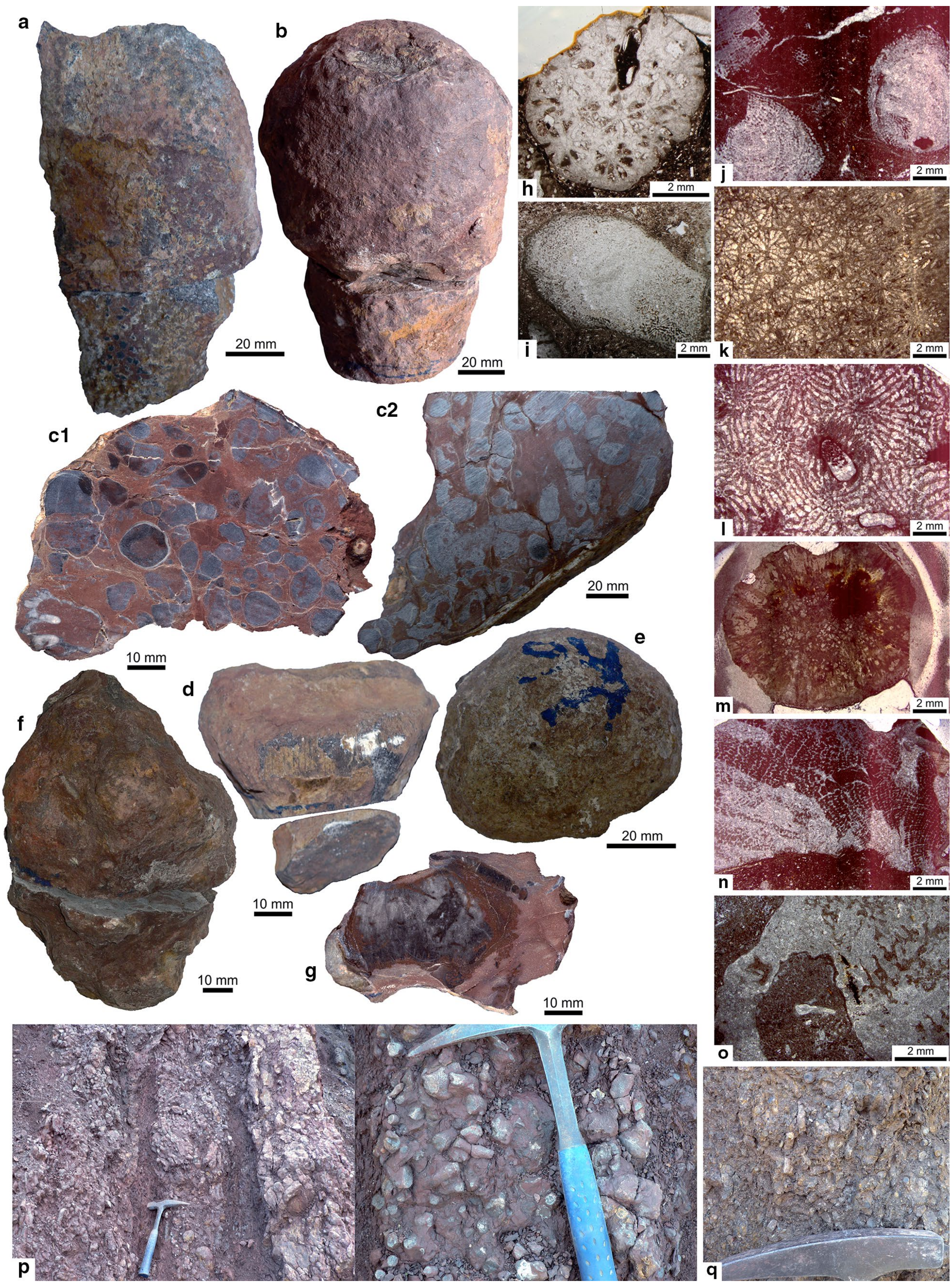
The Kober profile, Bosnia

The Kober succession is 5.5 m thick and consists of floatstone-rudstone and packstone-grainstone, with a bed thickness ranging from 50 to 100 cm (Fig. 3). Beds show similar textural characteristics and an absence of sedimentary structures throughout the outcrop. The packstone–grainstone (Fig. 4n) consists of peloids, benthic foraminifers and rare small bioclasts. Floatstone–rudstone (Fig. 4o) is similar but with larger macrofossils and lithoclasts. The fossil assemblage comprises agglutinated-hyaline foraminiferal species (Figs. 4n, o, 5s–u): *Calveziconus* cf. *lecalvezae* Caus & Cornella, *Accordiella conica* Farinacci, *Scandonea samnitica* De Castro, *Dicyclina schlumbergeri* Munier-Chalmas, *Orbitoides* sp., *Siderolites* sp., *Lepidorbitoides* sp. as well as fragments of red algae. Within the packstone-grainstone are rare toppled individuals of Radiolitidae and Hippuritidae (Fig. 12e–g). One specimen of *Vaccinites vesiculosus* is 7.6 cm in diameter (Fig. 12e). *Hippurites* specimens are 3–4.5 cm in diameter, and those of *Hippuritella* 2.5–4 cm (Devidé-Nedĕla and Polšak 1961). Chronostratigraphically, the benthic foraminiferal assemblage of the *Calveziconus* cf. *lecalvezae* subzone (Frijia et al. 2015) and rudists of the *Pironaea polystyla* rudist biozone (Steuber and Schüter 2012) indicate the lower part of the Middle Campanian. With the presence of hyaline benthic foraminifers, the environment may well have been relatively deeper-water, moderate energy, subtidal.

Chronostratigraphy

Two splits of samples of the outer shell layer of the hippuritid rudists were taken for geochemical and strontium isotope analysis. At each locality, three to four samples, (depending on the available number of hippuritid shells), were submitted for elemental composition and strontium isotope analysis. Almost all analyzed specimens show relatively poor preservation potential for calculation of mean $^{87}Sr/^{86}Sr$ (Steuber 2003a) because the Fe and Mn concentrations are too high.

Only sample 2 from Stranice with a numerical age of 80.50–80.55 Ma, has an acceptable elemental composition with concentrations of Sr 1320, Mg 2835, Fe 77 and Mn 13 mg/kg and mean $^{87}Sr/^{86}Sr$ value of 0.707518. These data fit well with the microfossil chronostratigraphic range from the upper part of the Lower Campanian to the lowermost part of the Middle Campanian age. According to the rudist biozone determinations (Steuber and Schüter 2012), this locality corresponds to the upper part of the Lower Campanian *Vaccinites alpinus* interval zone with a chronostratigraphic range of 84.12–79.03 Ma. Most probably the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◀**Fig. 10** Corals from Gornje Orešje: cylindrical (**a**, **b**), solitary (**d**), branching (**c**, **h**–**j**, **m**), rounded (**e**), bulbous (**f**, **g**, **o**) and encrusting (**n**) growth forms with plocoid (**i**, **n**, **o**), thamnasteroid (**l**) and cerioid (**h**, **j**, **k**, **m**) polyparia arrangement. **a** *Hydnophora multilamellosa* Reuss, **b** *Dimorphastraea leptophyllia* (Felix), c1,2. *Astraraea* sp. with hippuritid (*lower left*), transversal (*1*) and longitudinal (*2*) section, **d** *Acrosmilia* sp., **e** *Actinastraea elongate* Alloiteau, **f** *Dermosmiliopsis tenuicosta* (Reuss), **g** *Neocoeniopsis excelsa* (Fromentel), **h** *Actinastraea ramosa* Michelin, **i** *Actinacis reussi* Oppenheim, **j** *Astraraea* sp., **k** *Actinastraea elongate* Alloiteau, **l** *Dimorphastraea leptophyllia* (Felix), **m** *Columactinastraea pygmaea* (Felix), **n** *Actinacis martiniana* d'Orbigny, **o** *Neocoeniopsis excelsa* (Fromentel), **p** Subvertical beds of pillarstone with toppled predominately branched corals within mud matrix. On left, detail from middle bed. Succession from *left to right*, **q** A detail from pillarstone with toppled branched corals within sandy mud. Succession from *left to right*

nearby Slovenj Gradec section has the same chronostratigraphic age since rudist taxa typical of the *V. alpinus* interval zone are present (Pleničar 2005).

For the Gornje Orešje, there are Sr-isotope data from nearby Donje Orešje (Moro et al. 2010; Steuber and Schüter 2012). The numerical age (81.19 Ma, Fig. 13) corresponds to the upper part of the Lower Campanian *Vaccinites alpinus* interval zone with a chronostratigraphic range of 84.12–79.03 Ma. These data fit well with the determined rudist community. Both Bosnian localities, Kober and Bešpelj, according to the *Calveziconus* cf. *lecalvezae* biostratigraphical range, correspond to the upper part of the Lower Campanian to the lowermost part of the Middle Campanian (Steuber et al. 2005; Frijia et al. 2015). Also, the Kober rudist community corresponds chronostratigraphically to the *P. polystyla* rudist biozone with a chronostratigraphic age range of 79.03–75.27 Ma (Steuber and Schüter 2012). *Calveziconus* cf. *lecalvezae* appears on the Adriatic carbonate platform within a slightly deeper subtidal facies, which lacks shallowing-upward cycles, with a mixed radiolitid-hippuritid community (Gušić and Jelaska 1990; Moro et al. 2002; Steuber et al. 2005). This facies is quite rare and is restricted to a short interval of the Campanian after a renewed flooding of the Adriatic platform (Gušić and Jelaska 1990; Moro et al. 2002; Steuber et al. 2005), or, as in the Bosnian localities, a time of relatively rapid deepening with deposition of carbonate to carbonate-clastic turbidites (Tomić 1985; Dragičević 1987; Polšak et al. 1982); the latter is not typical during a phase of deepening (Haq 2014). Thus, most probably the sections in the two Bosnian outcrops were deposited at the beginning of the *P. polystyla* biozone. This implies that the biostratigraphical range of *Calveziconus* cf. *lecalvezae* could be extended to the beginning of the *P. polystyla* rudist biozone (79.03 Ma). As for the biostratigraphic range of *M. lata*, recent investigations in the Central Apennines (Frijia et al. 2015) reported the occurrence of *M. lata* up to the uppermost part of the Lower Campanian. Here, *M. lata* appears together with *C.* cf. *lecalvezae*, indicating a wider range which extended into the lower part of the Middle Campanian.

Hippurites nabrasiensis is of dubious taxonomic status (Steuber and Schüter 2012), and has often been confused or considered as a synonym of either *Hippuritella lapeirousei* (Pleničar 1994, 2005; Polšak et al. 1982; Moro et al. 2010) or *Hippurites heritschi* (Chaffau and Pleničar 1995; Steuber 2001, 2003a, b; Pons and Vicens 2002). The taxonomic concept used here refers to morphological and chronostratigraphic features as described by Steuber and Schüter (2012), that thick-shelled individuals with broad pillars, occurring throughout the *Vaccinites chaperi, V. alpinus* and *Pironaea polystyla* rudist zones, could be considered as *Hippurites nabrasiensis* or *H. heritschi* (Table 1).

Sea-level change and depositional environments

The deposits described above from the various localities constitute the different lateral parts of a shallow-marine, subtidal transgressive system where rudists and corals were the dominant macrofossils. For the investigated profiles, two successions can be distinguished: (a) clastic mudstone to sandy mudstone and (b) carbonate. The characteristics of the investigated successions are described below within a framework of sea-level change, and an ideal transgressive vertical succession.

Generally, the successions of the *V. alpinus* biozone occur during the regressive (Donje Orešje and Gornje Orešje localities), lowstand (Brašljevica and Sv. Martin localities) and transgressive (Stranice locality) parts of a short-term sea-level curve (see Fig. 13 after Haq 2014). The apparent broad stratigraphic range of the beginning of the transgression within the *V. alpinus* biozone (81.19–79.8 Ma), which occurs around the major cycle boundary at 80 Ma could be related to the poor biostratigraphic control of the Late Cretaceous successions, as well as the effect of local tectonics in this active continental margin setting (Steuber and Schüter 2012) resulting in a more or less pronounced paleorelief. At Donje Orešje a short period of shallow-water deposition is sharply replaced by pelagic limestone (Polšak 1979) or, as is the case at other localities in the Internal Dinarides, with marly sediment (Moro et al. 2010; Lužar Oberiter et al. 2012). Although regionally there is a continuous distribution of rudist communities (Steuber and Schüter 2012), deepening of the depositional environment during the upper part of the *V. alpinus* biozone represents a tectonic overprint of sea-level change. The transgression at the Kober and Bešpelj localities occurs at the beginning of the *Pironaea polystyla* biozone. It coincides with the highstand of a short-term

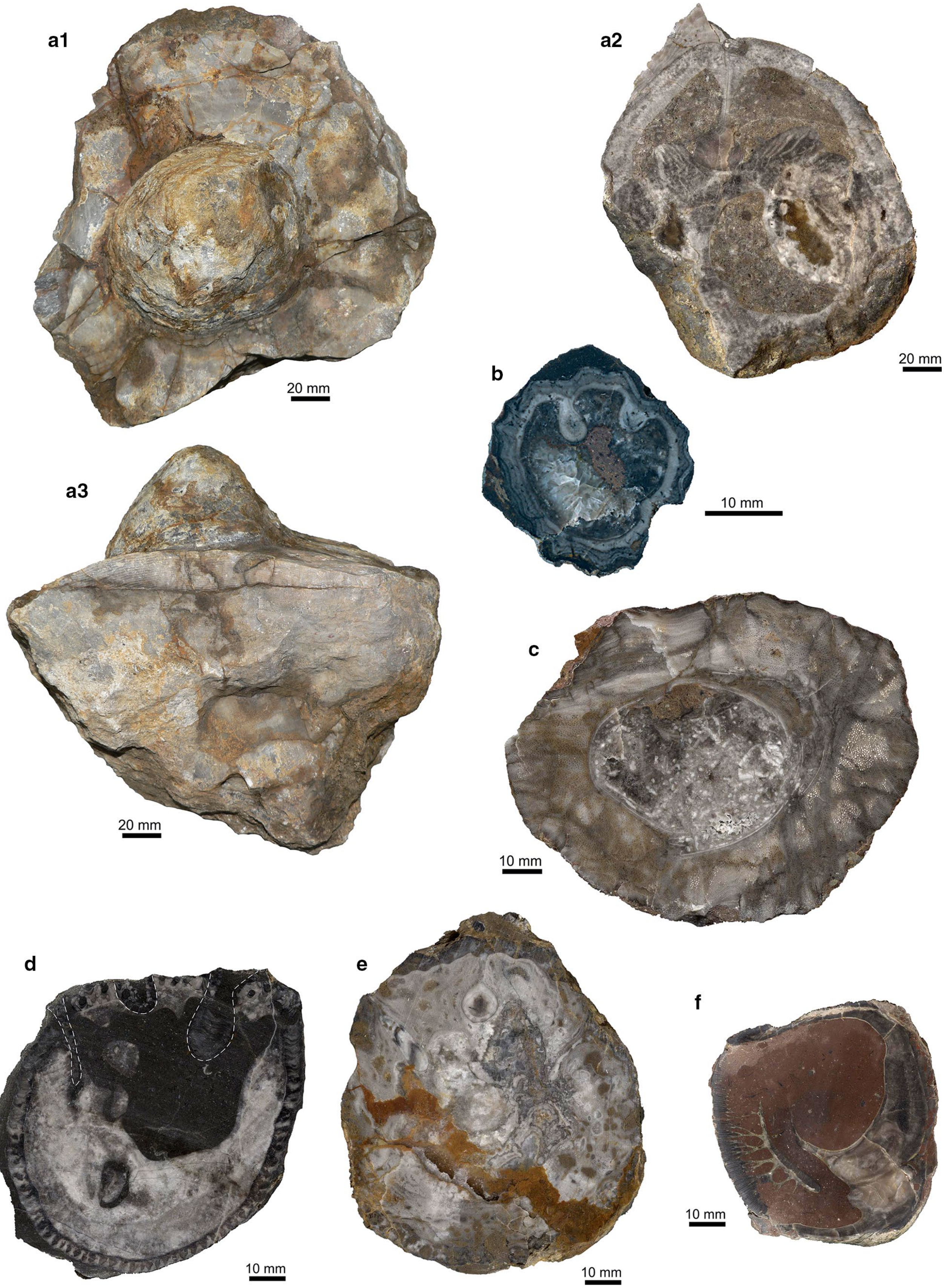


Fig. 11 Rudist species form Gornje Orešje locality. **a1–a3** *Pseudopolyconites* sp., **b** *Hippuritella variabilis* (Munier-Chalmas, in Gaudry 1867), **c** *Pseudopolyconites* sp, **d** *Vaccinites archiaci* (Douvillé), **e** *Vaccinites vesiculosus* (Woodward), **f** *Plagioptychus* sp.

sea-level curve of Haq (2014) (Fig. 13). The result was a rapid deepening of the environment with a short period of subtidal sedimentation with a radiolitid or mixed radiolitid-hippuritid rudist community. Although a gap in the regional distribution of rudist communities at the beginning of the *P. polystyla* biozone (Steuber and Schüter 2012) coincides with a third-order sequence boundary (at 78.4 Ma), the absence of rudists as a result of the deposition of turbidites at the Bosnian localities (Tomić 1985) suggests a tectonic overprint of sea-level change. Tectonic influence, together with sea-level change (Moro et al. 2002; Steuber et al. 2005) resulted in regional development of an palaeogeographically extensive subtidal environment, without shallowing-upward cycles, which preceded emergence (Gušić and Jelaska 1990; Moro et al. 2002; Steuber et al. 2005) or developed at the beginning of transgression, as is case with the investigated localities. This resulted in the presence of rudist species and genera of *V. alpinus* and *P. polystyla* biozones within this part of the central-eastern Mediterranean.

During the Campanian there was a constant sea-level rise (Haq 2014) although there were also short-term falls (Fig. 13). All the transgressive successions of investigated localities were deposited relatively rapid (Fig. 13) without the repetition of lithofacies or cyclicity, similar to the transgressive successions of the Lower Gosau supergroup in Austria (Sanders and Pons 1999).

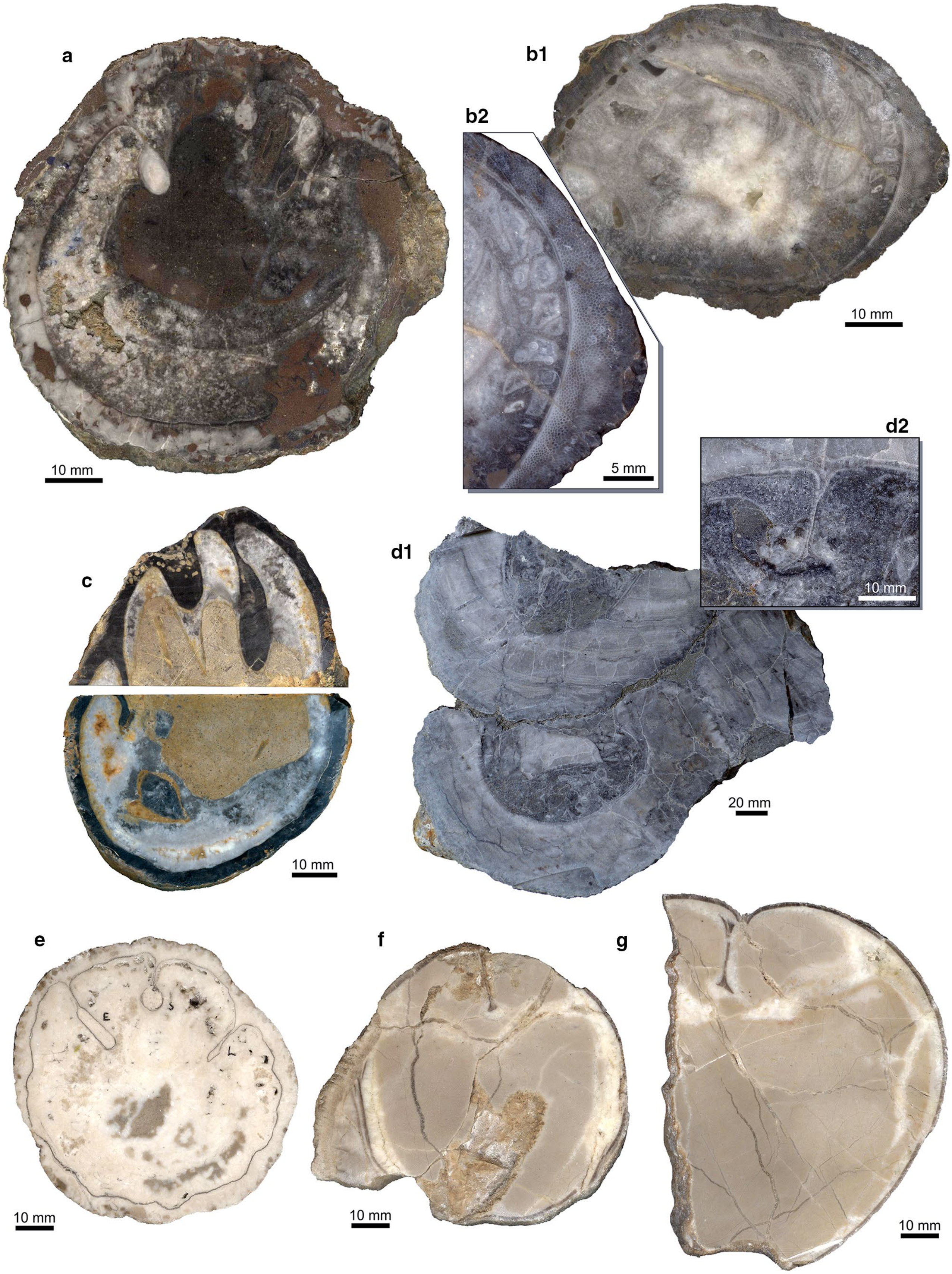
The depositional environment of the clastic-dominated transgressive facies consists of beach conglomerates which pass up into shallow subtidal mudstone with corals and rare rudists and mudstone/sandy mudstone facies with corals (Fig. 14). Towards the top of the succession, the depositional environment became gradually deeper and more open-marine with lithoclastic-bioclastic sandy mudstone and carbonate interbeds. At the top of the clastic succession there are limestones with a vertical alternation of packstone-grainstone and floatstone-rudstone. The foraminiferal community within the limestones, with agglutinated and porcellaneous tests, together with hippuritids and radiolitids, indicates that the paleoenvironment was still relatively shallow, with the absence of shallowing-upward cycles (Moro et al. 2002) probably due to the relatively rapid sea-level rise over a gently inclined paleorelief. Also, the clastic succession could equate laterally with the carbonates at Donje Orešje-Gornje Orešje, presumably as a result of the more inclined part of palaeorelief with carbonate sedimentation. A similar facies architecture is observed in the Lower Gosau Subgroup in Austria where transgressive successions depended on the combined effect of differentiated relief of a narrow shelf with an overall high siliciclastic input (Sanders and Höfling 2000).

Within the transgressive carbonate successions, as well as carbonates overlying clastic sediments (Figs. 3, 14) with similar packstone-grainstone to floatstone-rudstone lithofacies, it is possible to distinguish (1) a shallow subtidal facies with agglutinated-porcellaneous foraminifers and a rudist community which ranges from radiolitid (Bešpelj, Slovenj Gradec) to mixed radiolitid-hippuritid (Stranice, Donje Orešje, Gornje Orešje), and (2) a relatively deeper and more open subtidal facies, with agglutinated-porcellaneous-hyaline foraminifers and hippuritids with rare radiolitids at Kober in Bosnia. Corals are either absent or only present as rare fragments in the early part of the section, when clastic sediment was being deposited, as is case at Donje Orešje (Polšak 1979; Korolija et al. 1995) or the lower part of the Gornje Orešje succession. The absence of shallowing-upward cycles within the carbonate successions, together with the above-mentioned features of the fossil communities, particularly for localities which were likely the result of the same transgression (Bešpelj and Kober sections, Fig. 3) are probably a result of a relatively rapid sea-level rise (Fig. 13) over a laterally more (Kober) or less (Slovenj Gradec and Bešpelj) pronounced paleorelief (Fig. 14).

These carbonate successions could pass laterally into pelagic deposits basinwards (Polšak 1979, 1981; Tomić 1985) with no evidence of the movement of a barrier-shoal, with or without rudists or corals; this situation is similar to those in the External Dinarides where gradual deepening of the subtidal zone ended with foundered platform deposits (Gušić and Jelaska 1990; Moro 1997; Moro and Ćosović 2000; Moro et al. 2002, 2008; Vlahovic et al. 2005; Korbar et al. 2010).

Although the presence or absence of clastic sedimentation at the studied localities is generally dependent upon the nature of the basement being transgressed and the surrounding area (Mioč and Žnidarčič 1976; Marinković and Ahac 1979; Šimunić et al. 1983; Basch 1983) (Figs. 1, 3), especially for Bosnian localities, carbonate sedimentation always followed clastics which wedge out and gradually pass up into carbonates. The clastic sediments would have been derived through erosion, and then deposition within the flatter parts of an irregular transgressive surface. They represent the shallowest facies, similar to that of the shallow embayments of the transgressive sequence in the Oman Mountains of the Maastrichtian age (Skelton et al. 1990) and siliciclastic successions of the Northern Calcareous Alps, Austria (Sanders and Pons 1999), with the carbonates deposited in somewhat deeper subtidal areas during the Turonian-Lower Campanian.

The differentiation of the depositional setting for the investigated localities with respect to sea-level change may be considered to result from the relatively rapid transgression which covered the paleorelief. In cases where the clastic or carbonate paleorelief was gentle, the transgressive succession starts with clastic coral-rich sediments or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◀**Fig. 12** Rudist species from Gornje Orešje (**a–d**) and Kober (**e–g**) localities. **a** *Vaccinites oppeli* (Douvillé), **b** *Pseudosabinia* sp. with detail of outer and inner shell layer (**b2**), **c** *Vaccinires archaici* (Douvillé). Oblique (**c1**) and transverse (**c2**) section of the same specimen. **d** *Pseudopolyconites* sp. with enlarged ligamental ridge (**d2**), **e** *Vaccinites vesiculosus* (Woodward), **f**, **g** *Pseudopolyconites* sp.

carbonates with radiolitids, and where the paleorelief was steeper, carbonate sediments were deposited with a mixed radiolitid-hippuritid community (Fig. 14).

Paleoecology of the rudist-coral transgressive successions

From the features of the studied successions, a general model can be constructed for the paleoenvironmental overlap of rudists and corals within the Campanian transgression. Relative changes in rates of carbonate production/sediment influx are analyzed through changes in the rudist communities and predominance of different coral growth forms. In the carbonate facies, corals are completely absent, and rudists are represented by a mixed radiolitid-hippuritid community. For rudists, with a constratal colonization strategy (Gili et al. 1995; Götz 2003) of elevator morphotypes, which could thrive as sediment dwellers in densely packed congregations (Gili et al. 1995), carbonate production rates were probably more favorable. By way of contrast, in clastic sediments, conditions were less favorable for both corals and rudists with respect to sediment influx rate of mud and sandy mud. Although the predominance of clay-silt sized sediment may have raised water turbidity (Roy and Smith 1971), the presence of sand-sized grains at the Strance locality with smaller branched corals in comparison with the mud-dominated sediment of Gornje Orešje where branched corals are higher (Fig. 7) excludes the possible influence of grain-size to coral growth.

Corals as reef-builders (Gili et al. 1995), with their superstratal growth, are dependent on higher water energy (Götz 2003) and a low sediment influx rate. At Strance, the sandy mud succession is dominated by bulbous, low cylindrical growth forms, and subordinate *Actinacis* and *Actinastraea* which have highly adaptive skeletons, with high sediment tolerances (Sanders and Baron-Szabo 2005), and a complete absence of rudists. In cases when the muddy succession is dominated by branching growth forms, where corals kept up with sedimentation (Sanders and Baron-Szabo 2005), as in the case of Gornje Orešje,

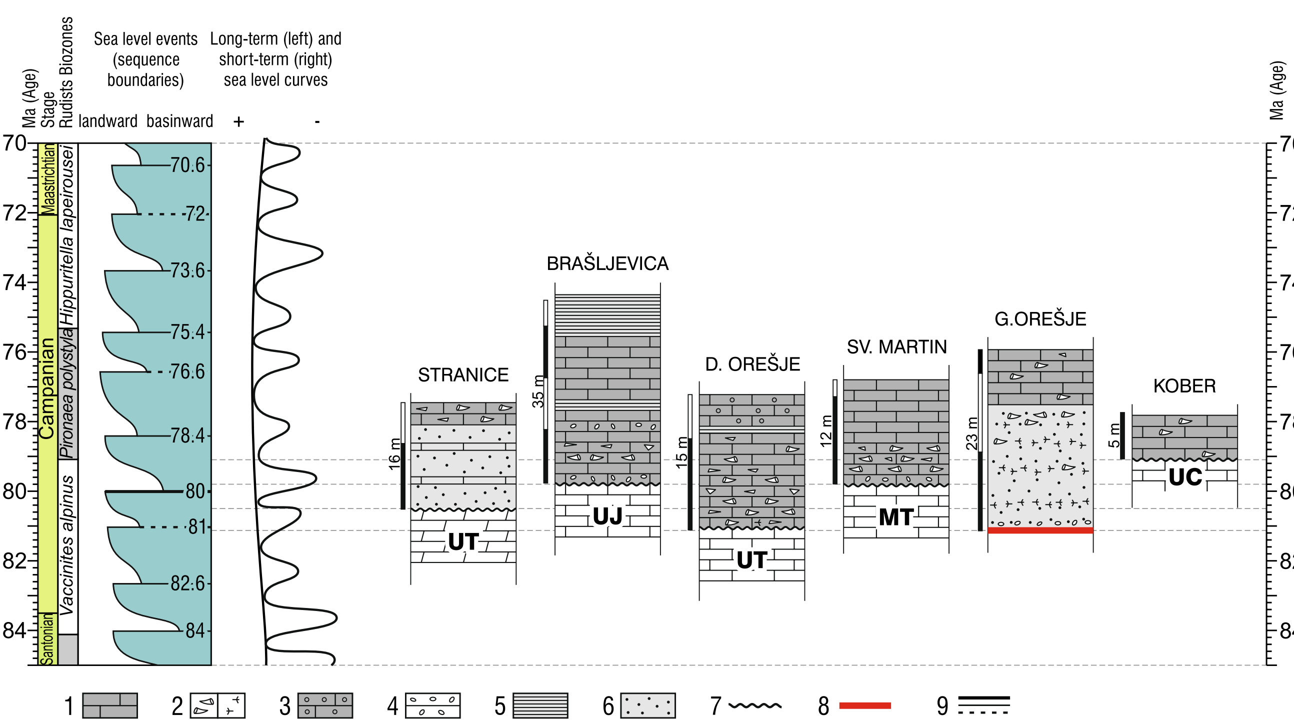

Fig. 13 Stratigraphic distribution of localities in northwestern Croatia, Slovenia, and Bosnia. Brašljevica and Sv. Martin locality after Moro et al. (2010). Sea-level events (sequence boundaries), long-term and short-term sea-level curves after Haq (2014) tied to the geological time-scale after Gradstein et al. (2012). Rudist zones after Steuber and Schüter (2012). *1* Carbonate, *2* Rudists and corals, *3* Pelagic limestone, *4* Pebbles, *5* Marly sediment with nannofossils, *6* Clastic sediment, *7* Transgression, *8* Fault. *9* Downwards: Major cycle boundary, medium or minor cycle boundary, potential global cycle boundary, *UJ* Upper Jurassic, *UT* Upper Triassic, *MT* Middle Triassic, *UC* Upper Cretaceous

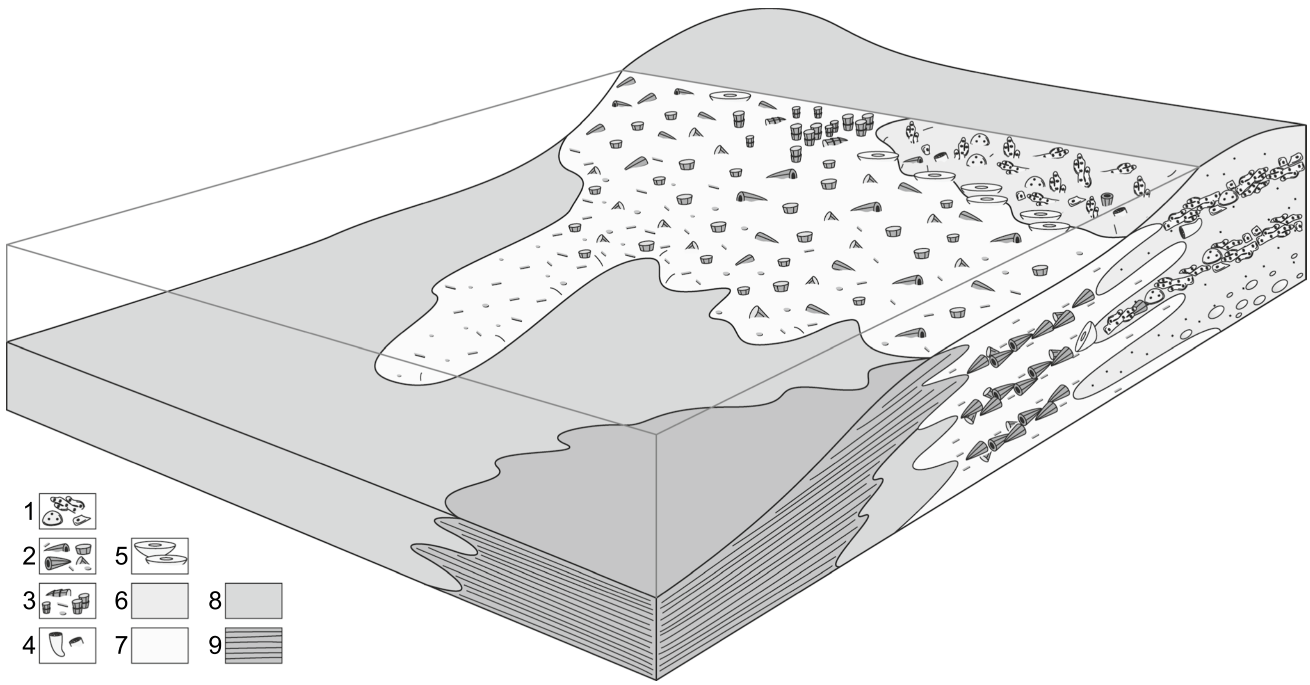

Fig. 14 Reconstruction of an idealized depositional palaeoenvironment for the investigated localities. *1* Corals, *2* Hippuritids, *3* Radiolitids, *4* Plagioptychids, *5* Pseudopolyconitids, *6* Clastic sediment, *7* Carbonate, *8* Pelagic carbonate, *9* Deep water marly sediment

sediment influx rates were relatively high, in comparison with the bulbous, low cylindrical growth form dominated succession of Stranice. The absence of encrusters and relatively rare lithophagid and annelid borings within dendroid corals at Gornje Orešje also indicates relatively higher sediment influx rates (Sanders and Baron-Szabo 2005). Macroborings are absent on the rare small and low cylindrical and bulbous growth forms of Gornje Orešje, which were rapidly buried through (for them) the relatively higher sediment influx rate. Rudists are present as rare individuals of hippuritids (Fig. 10c) and plagyoptichids which occur within coral branches surrounded by sediment as constratal sediment dwellers keeping pace with deposition (Gili et al. 1995). Corals were dominated by thamnasteroid-cerioid-hydnophoroid polyp integration and this is generally indicative of biostromes formed in conditions of low to moderate turbidity and sedimentation rate (Sanders and Baron-Szabo 2005). While relatively low sediment influx rates promote a bulbous-cylindrical coral community but completely exclude rudists, a relatively higher sediment influx gives rise to a more branching coral growth form and the possibility for rare constratal, sediment-dwelling rudists to thrive together with corals.

Besides sediment influx, salinity, turbidity, and nutrient supply are possible controlling factors for organisms. For investigated localities, deposited during subtropical conditions (Camoin et al. 1993; Wilson and Lokier 2002), there is a complete absence of macrofossils at the beginning of clastic sedimentation (Gornje Orešje). One possible explanation is a decrease in salinity which is often associated with clastic influx (Woolfe and Larcombe 1999; Wilson and Lokier 2002). Transgression within pure carbonate sediments on the Adriatic carbonate platform (Moro et al. 2002; Vlahovic et al. 2005; Steuber et al. 2005), as well as at investigated localities (Donje Orešje, Bešpelj, Kober), is characterized by the presence of stenohaline macrofossils from the beginning of deposition. Therefore, reduced salinity because of more or less persistent freshwater input appears improbable. Clastic shallow-water environments with ramose-colonial and branched low integrated (dendroid, phaceloid) coral taxa (Sanders and Baron-Szabo 2005), as is the case for the Gornje Orešje succession, are characterized by low turbidity waters of shallow depths (Tudhope and Scoffin 1994; Sanders and Baron-Szabo 2005). Also the presence of rudists, which mostly thrive in more muddy matrices on carbonate platforms and are adapted to more turbid waters than corals (Gili et al. 1995) makes turbidity improbable as a controlling factor for them in clastic sediment. Although turbidity within carbonate successions could be a limiting factor for corals, the moderate energy of the packstone-grainstone environment, makes turbidity less likely as a controlling factor for them in carbonates. Carbonate producers, such are rudist and corals, are generally associated with oligotrophic or nutrient-poor conditions (Hallock and Schlager 1986; Wilson and Lokier 2002). The presence of both in the investigated localities,

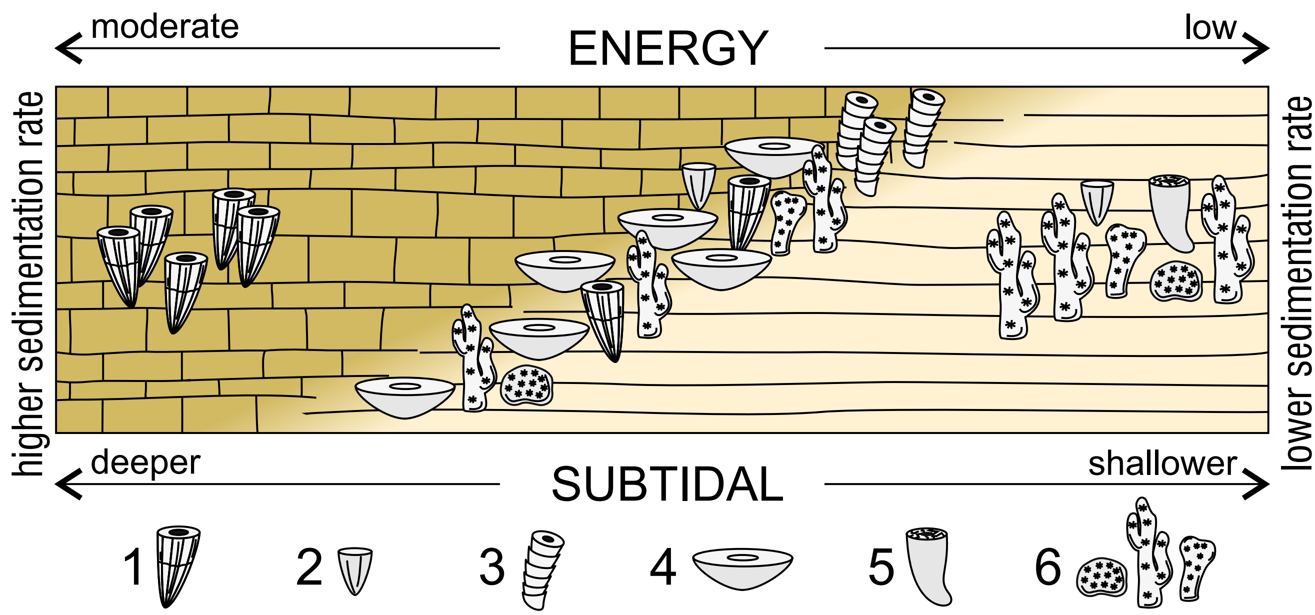

Fig. 15 Environmental overlap of Campanian rudists and corals for the investigated deposits according to relative depth, sediment type, rate of sedimentation and water energy (modified after Götz 2003) *1* vaccinitids, *2* hippuritids, *3* radiolitids, *4* pseudopolyconitids, *5* plagioptychids, *6* corals. As clastic sedimentation with corals declined, the transition line between clastics and carbonates will move right and at the end became horizontal, exclusively with rudists

although corals predominate in clastics and rudist in carbonates, excludes nutrition as a controlling factor in their distribution.

Rudists predominate, together with mostly branching corals, towards the end of clastic sedimentation, giving rise to a rich community of loosely packed thick-shelled, wide conically shaped *Pseudopolyconites* individuals (Fig. 7). This presumably indicates that sediment influx rates were close to those of carbonate production, but still not sufficient for the prevalence of cylindrical rudist growth forms which dominate in marine environments with positive sedimentation rates and an absence of corals (Gili et al. 1995). This is also indicated by macroborings of rare vaccinitid shells and their absence in pseudopolyconitid shells. Cylindrical vaccinitids probably protruded above the sediment surface in comparison with wide conical, completely emergent pseudopolyconitids.

The co-occurrence of non-competitive corals and rudists within a relatively low-energy clastic environment for both, most probably close to their ecological limits (Götz 2003) with respect to the sediment influx rate (Fig. 15), resulted in most of them being toppled over. Corals were likely toppled due to slower growth and their inability to make a superstratal framework, which forced them to attain maximum horizontal coverage within biostromes (Götz 2003). Constratal elevator rudists, which thrive mostly within muddy matrices (Ross and Skelton 1993; Gili et al. 1995; Moro et al. 2002), grew relatively faster than corals; they were frequently toppled as a result of their inability to attain vertical growth in a situation of insufficient sediment influx. Also, the toppled position of closed hippuritid shells within relatively low-energy clastic environments in the Guinea Corn Formation of Jamaica (Mitchell 2002), could indicate that rudists were forced into partial superstratal growth due to an unfavorable sediment influx rate. The toppled position of both rudists and corals indicates that the sediment influx rate was too high for corals and too low for rudists within the low energy clastic environment of the investigated localities.

Laterally within outcrops of the Stranice and Gornje Orešje localities, there is a complete absence of corals and rudists within the clastic sediments. For rudists, it is known that their patchy distribution is dependent upon suitable attachment surfaces, and their larvae having settling preferences within the subtidal environment (Skelton 1979; Skelton et al. 1995; Skelton and Gili 2002; Moro et al. 2002). Here, in addition to the aforementioned factors, the clastic sediment influx rate was most probably too low for their sediment-dwelling mode of life (Gili et al. 1995; Skelton 1979; Steuber et al. 1998; Moro et al. 2002) and therefore they were completely excluded from the bulbous-cylindrical coral community or their presence is subordinate in comparison with the corals, as is also the case for branching coral growth forms. Corals, on the other hand, could be absent as a result of the increased clastic sediment influx rates being close to those for carbonates. One of the possible reasons for the absence of both corals and rudists could be a too high sediment influx as result of a paleoland flood.

This possibility is observable in both clastic successions, at Stranice, where relatively positive clastic influx rates could resulted in the lateral absence of corals (Turnšek 1978, 1994, 1997), and at Gornje Orešje with the vertical alternation of clastic mud beds with and without corals and rare rudists (Figs. 3, 14). Similar textural features throughout both clastic successions and the above mentioned characteristic of lateral patchy distribution of rudists make that process less likely. Therefore, the presence or absence of corals within the same type of clastic sediment could be considered as a result of lateral variations of more or less favorable (for them) sediment influx rates. This is similar to the observations for mixed coral-rudist associations from the Northern Alpine Gosau in Austria, where co-existing corals and rudists are either present or absent, where there is adequate sediment input, because they provide hard substrates for settlement for each other (Sanders and Baron-Szabo 1997).

The co-occurrence of corals and rudists within the Late Cretaceous deposits and the same bioconstructions as a result of environmental overlap is described and confirmed by several authors (Scott 1988, 1995; Baron Szabo 1997; Sanders and Baron-Szabo 1997, 2005; Skelton et al. 1997; Sanders and Pons 1999; Götz 2003). At investigated localities clastic successions characterize gently inclined subtidal environments. Bulbous-cylindrical corals without rudists occur in environments of relatively lower sediment influx in comparison with dendroid assemblages which co-occur with rare rudists within relatively higher sediment influx rate environments. Relatively higher sedimentation rates are more adequate for 2–4 cm/year fast-growing vaccinitid rudists (Steuber 1996, Steuber et al. 1998, Götz 2003), in comparison with 0.3–0.6 cm/year slow growing branched phaceloid corals (Kružic and Požar-Domac 2002; Kružić and Benković 2008).

Both pass vertically into relatively shallow-water carbonates with a mixed radiolitid-hippuritid community. In cases when transgressive successions are carbonate corals are completely absent; in areas of gently inclined paleorelief radiolitids are present, and more inclined paleorelief characterize a mixed radiolitid-hippuritid community (Figs. 14, 15). The rate of carbonate mud production is presumably relatively high, and therefore more suitable for sediment-dwelling, relatively fast-growing (Steuber 1996; Steuber et al. 1998; Götz 2003) elevator rudists, whereas the probably lower input of clastic sediments is generally more adequate for corals (Fig. 15). Also, with incoming carbonate sedimentation there is an increase in water energy. Rudists, more tolerant to settings with restricted water circulation (Gili et al. 1995), at investigated localities also thrive in moderate energy, more open packstone-grainstone environments. Despite the relatively higher energy of carbonate environments, corals with superstratal organic growth fabric and functional resistance to wave/current action (Gili et al. 1995), are completely absent. Therefore, difference in sediment influx/carbonate production rate could be one of the main reasons why corals are mainly absent in areas of pure carbonate sedimentation, as it is case on the ADCP (Moro et al. 2002).

Conclusions

It is possible to draw the following conclusions from the sedimentological, paleontological, and paleoenvironmental analysis of the Upper Cretaceous transgressive deposits of Slovenj Gradec, Stranice, Donje Orešje, Gornje Orešje, Bešpelj and Kober:

1. On the basis of the chronostratigraphy of benthic fossil remains, rudist communities and the SIS dating of rudist shells, deposition of the transgressive succession started during the upper part of the *Vaccinites alpinus* interval zone at Donje Orešje, Gornje Orešje, Slovenj Gradec and the Stranice locality, and beginning of the *Pironaea polystyla* Interval zone at Bešpelj and Kober locality. Most localities are within the extended chronostratigraphic range of *Calveziconus* cf. *lecalvezae* (80.5–79.03 Ma).
2. Shallow-water, transgressive sediments are stacked in two different successions: clastics with a coral/coral-rudist fossil assemblage, and a pure carbonate succession with rudists. Corals and rudists thrived together within the low-energy clastic succession, both close to the limits of their ecological tolerance with respect to clastic sediment influx. Coral biostromes range from mixstone with prevailing bulbous-cylindrical forms where rudists are completely absent, to pillarstone with a prevailing dendroid coral growth form. Rare rudists thrive in the latter due to a relatively higher sediment influx rate in comparison with the former. Elevator rudists thrived in the moderate-energy carbonate facies in a relatively shallow-water radiolitid to mixed radiolitid-hippuritid community and in a relatively deeper-water environment with rare hippuritid individuals. Higher carbonate production rates were more suitable for them as sediment dwellers. Despite a relatively higher energy in the carbonate environment, corals were completely absent. Therefore, differences in sediment influx and carbonate production rate could be one of the main reasons why corals are mainly absent in areas of pure carbonate sedimentation.
3. The depositional setting of the investigated localities may be considered as a result of a relatively rapid sea-level rise and a tectonic influence. The result was short periods of shallow-water sedimentation during a time

of rapid deepening. Transgression generally extended towards the southeast and covered different types of technically uplifted and eroded paleorelief, ranging from predominantly carbonate to clastic. In cases where the paleorelief was gentle, the transgressive succession starts with clastic coral-rich sediments or carbonates with radiolitids. Where the paleorelief was steeper, the transgressive succession is characterized by carbonate sedimentation with a mixed radiolitid-hippuritid community.

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References

Baron Szabo RC (1997) Die Korallenfazies der ostalpinen Kreide (Helvetikum: Allgäuer Schrattenkalk; Nördliche Kalkalpen. Brandenburger Gosau) Taxonomie. Palökologie. Zitteliana 21:3–97

Basch O (1983) Basic geological map of SFRY, Sheet Ivanić-Grad L 33–81, Federal Geological Survey Beograd

Bilotte M (1985) Le Crétacé supérieur des plates-formes est-pyrénéenes. Strata 1–438, Toulouse

Camoin G, Bellion Y, Dercourt J, Guiraud R, Lucas J, Poisson A, Ricou LE, Vrielynck B (1993) Late Maastrictian (69.5–65 Ma). In: Dercourt J, Ricou LE, Vrielynck B (eds) Atlas Tethys Palaeoenvironmental Maps, explanatory notes. Gauthier-Villars, Paris, pp 179–196

Chaffau M (2002) *Bournonia excavate* (D'Orbigny) from the Campanian–Maastrichtian of Stranice (north-east Slovenia). Geologija 45:91–96

Chaffau M, Pleničar M (1995) Preliminary biometrical analysis on three similar hippuritid species. Geologija 37–38:123–140

Devidé-Neděla D, Polšak A (1961) Mastriht kod Bešpelja sjeverno od Jajca (Maastrichtian of Bešpelj area, northern from Jajce) (In Croatian with French summary). Geološki vjesnik 14:355–381

Dragičević I (1987) Paleogeographic evolution of Dinaridic platform marginal part between rivers Vrbas and Bosna (In Croatian), Dissertation, University of Zagreb, pp 1–90

Frijia G, Parente M, Di Lucia M, Mutti M (2015) Carbon and strontium isotope stratigraphy of the Upper Cretaceous (Cenomanian–Campanian) shallow-water carbonates of southern Italy: Chronostratigraphic calibration of larger foraminifera biostratigraphy. Cret Res 53:110–139. doi:10.1016/j.cretres.2014.11.002

Gili E, Masse JP, Skelton PW (1995) Rudists as gregarious sediment dwellers, not reef-builders, on Cretaceous carbonate platforms. Palaeogeogr Palaeoclim Palaeoecol 118:245–267. doi:10.1016/0031-0182(95)00064-X

Gradstein FM, Ogg JG, Schmitz MD, Ogg GM (2012) The geologic time scale 2012. Elsevier, Amsterdam

Gušić I, Jelaska V (1990) Stratigrafija gornjokrednih naslaga otoka Brača u okviru geodinamske evolucije Jadranske karbonatne platforme [Upper Cretaceous stratigraphy of the Island of Brač within the geodynamic evolution of the Adriatic carbonate platform (in Croatian and English). Djela Jugoslavenske akademije znanosti i umjetnosti 69, JAZU-IGI, Zagreb

Götz S (2003) Biotic interaction and synecology in a Late Cretaceous coral-rudist biostrome of southeastern Spain. Palaeogeogr Palaeoclim Palaeoecol 193:125–138. doi:10.1016/S031-0182(02)00719-8

Hallock P, Schlager W (1986) Nutrient excess and the demise of coral reef and carbonate platforms. Palaios 1:389–398

Haq BU (2014) Cretaceous eustasy revisited. Glob Planet Change 113:44–58. doi:10.1016/j.gloplacha.2013.12.007

Herak M (1986) A new concept of geotectonics of the Dinarides (Nova koncepcija geotektonike Dinarida). Acta Geol 16:1–42

Herak M (1991) Dinaridi-mobilistički osvrt na genezu i strukturu (Dinarides-mobilistic view of the genesis and structure) (In Croatian). Acta Geol 21:35–117

Horwath RJ, McArthur JM (1997) Statistics for strontium isotope stratigraphy: a robust LOWESS fit to the marine Sr-isotope curve for 0–206 Ma, with look-up table for derivation of numerical age. J Geol 105:441–456

Insalaco E (1998) Descriptive nomenclature and classification of growth fabrics in fossil scleractinian corals. Sediment Geol 118:159–186. doi:10.1016/S0037-0738(98)00011-6

Korbar T (2009) Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates. Earth-Sci Rev 96:296–312. doi:10.1016/j.earscirev.2009.07.004

Korbar T, Cvetko Tešović B, Radovanović I, Krizmanić K, Steuber T, Skelton PW (2010) Campanian *Pseudosabinia* from the Pučišća Formation on the island of Hvar (Adriatic Sea, Croatia). Turk J Earth Sci 19(6):721–731. doi:10.3906/yer-0901-9

Korolija B, Fuček L, Oštrić N, Velić I (1995) Upper Triassic and Senonian sediments at Donje Orešje. In: Šikić K (ed) Geološki vodić Medvednice (Geological Guidebook of Medvednica Mt. (In Croatian). Croatian Geological Institute, INA, Zagreb, pp 173–179

Kružić P, Benković L (2008) Bioconstructional features of the coral *Cladocora caespitosa* (Anthozoa, Scleractinia) in the Adriatic Sea (Croatia). Mar Ecol 29:125–139. doi:10.1111/j.1439-0485.2008.00220.x

Kružić P, Požar-Domac A (2002) Skeleton growth rates of coral bank of *Cladocora caespitosa* (Anthozoa, Scleractinia) in lake Veliko jezero (Mljet National Park). Period Biol 104:123–129

Laviano A, Gallo Maresca M (1992) Paleontological characters of the species *Vaccinites vesiculosus* (Woodward). Geol Romana 28:49–59

Loeblich AR, Tappan H (1988) Foraminiferal genera and their classification. Van Nostrand Reinhold, New York

Lüning S, Marzouk AM, Morsi AM, Kuss J (1998) Sequence stratigraphy of the Upper Cretaceous of central-east Sinai. Cret Res, Egypt. doi:10.1006/cres.1997.0104

Lužar Oberiter B, Mikes T, Dunkl I, Lj Babić, von Eynatten H (2012) Provenance of Cretaceous synorogenic sediments from the NW Dinarides (Croatia). Swiss J Geosci 105:377–399. doi:10.1007/s00015-012-0107-3

Marinković R, Ahac A (1979) Basic geological map of SFRY, Sheet Jajce L33-131, Federal Geological Survey Beograd

Márton E, Ćosović V, Moro A (2014) New stepping stones, Dugi otok and Vis islands, in the systematic paleomagnetic study of the Adriatic region and their significance in evaluations of existing

tectonic models. Tectonophysics 611:141–154. doi:10.1016/j.tecto.2013.11.016
Masse JP, Philip J (1981) Cretaceous coral-rudist buildups of France. In: Toomey DF (ed) European fossil reef models. Soc Econ Spec Pub, Tulsa, pp 399–426
McArthur JM, Horwath RJ, Bailey TR (2001) Strontium isotope stratigraphy: LOWESS version 3. Best-fit line to the marine Sr-isotope curve for 0 to 509 Ma and accompanying look-up table for deriving numerical age. J Geol 109:155–169. doi:10.1086/319243
Miller KG, Sugarman PJ, Browning JV, Kominz MA, Hernandez JC, Olsson RK, Wright JD, Feigenson MD, Van Sickel W (2003) A chronology of Late Cretaceous sequences and sea-level history: glacioeustasy during the greenhouse world. Geology 31:585–588. doi:10.1130/0091-7613(2003)031<0585:LCCOLR>2.0.CO;2
Mioč P, Žnidarčič M (1976) Basic geological map of SFRY, Sheet Slovenj Gradec L 33–55, Federal Geological Survey Beograd
Mitchell SF (2002) Palaeoecology of corals and rudists in mixed volcaniclastic-carbonate small-scale rhythms (Upper Cretaceous, Jamaica). Palaeogeogr Palaeoclim Palaeoecol 186:237–259. doi:10.1016/S0031-0182(02)00505-9
Moro A (1997) Stratigraphy and paleoenvironments of rudist biostromes in the Upper Cretaceous (Turonian–upper Santonian) limestones of southern Istria, Croatia. Palaeogeogr Palaeoclim Palaeoecol 131:113–131. doi:10.1016/S0031-0182(96)00144-7
Moro A, Ćosović V (2000) The rudists of southern Istria—an example of environmentally induced succession within Santonian limestones. Riv Ital Paleontol S 106(1):59–71
Moro A, Skelton PW, Ćosović V (2002) Palaeoenvironmental setting of rudists in the Upper Cretaceous (Turonian–Maastrichtian) Adriatic carbonate platform (Croatia), based on sequence stratigraphy. Cret Res 23:489–508. doi:10.1006/cres.2002.1017
Moro A, Mezga A, Ćosović V, Tunis G, Tarlao A (2008) Rudists and dinosaur footprints—mutual relationship within mud-supported Upper Cenomanian peritidal limestones of Istria, Croatia. Boll Soc Geol Italy 127(2):423–428
Moro A, Ćosović V, Benić J, Dokmanović J (2010) Taxonomy of rudists from the Campanian transgressive sediments of Brašljevica, Donje Orešje and Sv. Martin, Northern Croatia. Turk J Earth Sci 19:613–633. doi:10.3906/yer-0901-12
Niebuhr B (1995) Fazies-Differenzierungen und ihre Steuerungsfaktoren in der höheren Oberkreide von Niedersachsen/Sachsen-Anhalt (N-Deutschland): Berliner Geowissenschaftliche Abhandlungen A 174:1–131
Pleničar M (1971) The hippurites fauna of Stranice near Konjice. Acadmia Scientiarum et Artium Slovenica, Dissertationes, Classis IV, vol 18/4, pp 241–264
Pleničar M (1993) Radiolites from the Cretaceous beds of Stranice near Slovnske Konjic (Slovenia). Academia Scientarum et Artium Slovenica. Dissertationes. Classis IV, vol 34/3, pp 45–103
Pleničar M (1994) Hippuritids from the Upper Cretaceous rudistid reefs near Stranic and Lipa (NE Slovenia). Academia Scientarum et Artium Slovenica, Dissertationes, Classis IV, vol 35/2, pp 43–63
Pleničar M (2005) Upper Cretaceous rudists in Slovenia. Academia Scientiarium et Artium Slovenica, Dissertationes, Classis IV, vol 39, pp 1–255
Pleničar M, Lj Šribar (1992) Le récif de rudistes prés de Stranice (N.O. de la Yougoslavie). Geol Romana 28:305–317
Polšak A (1964) *Joufia reticulate* Boem iz mastrihta Bešplja, sjeverno od Jajaca (*Joufia reticulate* Boehm from Maastrichtian at Bešpelj area, northern from Jajce) (In Croatian). Geološki vjesnik 18(2):337–345
Polšak A (1979) Stratigraphy and paleogeography of the Senonian Biolititihic complex at Donje Orešje, Mt. Medvednica, North Croatia. Acta Geol IX/6 42:195–231
Polšak A (1981) Upper Cretaceous biolithitic complexes in a subduction zone: examples from the Inner Dinarides, Yugoslavia. Soc Econ Spec Pub 30:447–472
Polšak A, Devidé-Nedêla D, Turnšek D, Gušić I, Benić J (1978) Biostratigraphy of Upper Cretaceous reef, subreef and basin deposits of Donje Orešje (Mt. Medvednica, northern Croatia). Geološki vjesnik 30:189–197
Polšak A, Dragičević I, Tomić V, Devidé-Nedĕla D, Benić J (1982) Tektonska I paleogeografska dinamika u rubnoj zoni Jadranske ploče; primjer kredno-palogenskog kompleksa Jajce (Tectonics and paleogeographic dynamic in marginal part of Adriatic plate; an example of Cretaceous–Paleogene bauxite-bearing area of Jajce (In Croatian with English summary). (In Croatian with English abstract). Proceedings of 10th Congress of Yugoslavian geologists Budva, vol 1, pp 605–623
Pons JM, Vicens E (2002) Campanian and Maastrichtian rudists from southern Valencia province, southeast Spain. In: Sladić-Trifunović M (ed) Rudists, Proceedings, First International Conference on Rudists. Beograd, 1988, Union of Geological Societies of Yugoslavia, Memorial Publication, Beograd, pp 233–263
Ratschbacher L, Frisch W, Neubauer F, Schmid SM, Neugebauer J (1989) Extension in compressional orogenic belts: the eastern Alps. Geology 17:404–407. doi:10.1130/0091-7613
Ross DJ, Skelton PW (1993) Rudist formations of the Cretaceous: a palaeoecological, sedimentological and stratigraphical review. Sedimentol Rev 1:73–91
Roy KJ, Smith SV (1971) Sedimentation and coral reef development in turbid water: fanning Lagoon. Pac Sci 25:234–248
Sanders D, Baron-Szabo RC (1997) Coral-rudist bioconstructions in the Upper Cretaceous Haidach Section (Gosau Group; Northern Calcareous Alps, Austria). Facies 36:69–90. doi:10.1007/BF02536878
Sanders D, Baron-Szabo RC (2005) Scleractinian assemblages under sediment input: their characteristics and relation to the nutrient input concept. Palaogeogr Paleoclim Palaeocol 216:139–181. doi:10.1016/j.palaeo.2004.10.008
Sanders D, Höfling R (2000) Carbonate deposition in mixed siliciclastic-carbonate environments on top of an orogenic wedge (Late Cretaceous, North Calcareous Alps, Austria). Sediment Geol 137:127–146. doi:10.1016/S0037-0738(00)00084-1
Sanders D, Pons JM (1999) Rudist formations in mixed siliciclastic-carbonate depositional environments, Upper Cretaceous, Austria: stratigraphy, sedimentology, and models of development. Palaeogeogr Palaeoclim Palaeoecol 148:249–284. doi:10.1016/S0031-0182(98)00186-2
Schlagintweit F, Sanders D, Studny M (2013) Dasycladaleans from the Upper Turonian to Santonian of Austria (Gosau Group pro parte) and paleobiogeographic considerations. Facies 59:247–266. doi:10.1007/s10347-012-0316-2
Schmid SM, Bernoulli D, Fügenschum B, Matenco L, Schefer S, Schuster R, Tischler M, Ustaszewski K (2008) The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss J Geosci 101:139–183. doi:10.1007/s00015-008-1247-3
Scott RW (1988) Evolution of Late Jurassic and Early Cretaceous reef biotas. Palaios 3:184–193
Scott RW (1995) Global environmental controls on Cretaceous reefal ecosystems. Palaeogeogr Palaeoclimatol Palaeoecol 119:187–199. doi:10.1016/0031-0182(94)00068-9
Šimunić A, Pikija M, Hećimović I (1983): Basic geological map of SFRY, Sheet Varaždin L 33–69, Federal Geological Survey Beograd

Skelton PW (1978) The evolution of functional design in rudists (Hippuritacea) and its taxonomic implications. Philos T R Soc B 284:305–318. doi:10.1098/rstb.1978.0069

Skelton PW (1979) Gregariousness and proto-cooperation in rudists (Bivalvia). In: Larwood G and Rosen BR (eds) Biology and systematics of colonial organisms, Systematics Association, Special Volume 11, pp 257–279

Skelton PW (2011) Rudist higher taxa for the revised Bivalvia volumes of the Treatise on invertebrate paleontology. In: Mitchell SF (ed) The Ninth International Congress on Rudist Bivalves, 18th to 25th June 2011, Kingston, Jamaica, Abstracts, Articles and Field Guides: UWI Mona Contribution to Geology 6, pp 7–8

Skelton PW, Gili E (2002) Paleoecological classification of rudist morphotypes. In: Sladić-Trifunović M (ed) Rudists, Proceedings, first international conference on Rudists. Beograd, 1988, Union of Geological Societies of Yugoslavia, Memorial Publication, Beograd, pp 71–86

Skelton PW, Nolan SC, Scott RW (1990) The Maastrichtian transgression onto the northwestern flank of the Proto-Oman Mountains: sequences of rudist-bearing beach to open shelf facies. In: Robertson MP, Ries AC (eds) The geology and tectonics of the Oman region, Geol Soc Spec Publ, vol 49, pp 521–547

Skelton PW, Gili E, Vicens E, Obrador A (1995) The growth fabric of gregarious rudist elevators (hippuritids) in a Santonian carbonate platform in southern Central Pyrenees. Palaeogeogr, Palaeoclim Palaeoecol 119:107–126. doi:10.1016/0031-0182(95)00063-1

Skelton PW, Gili E, Rosen BR, Valldeperas X (1997) Corals and rudists in the late Cretaceous: a critique of the hypothesis of competitive displacement. Boletin de la Real Sociedad Espanola de Historia Natural. Seccion Geologica vol 92, pp 1–4, 225–239

Steuber T (1996) Stable isotope sclerochronology of rudist bivalves: growth rates and Late Cretaceous seasonality. Geology 24:315–318. doi:10.1130/0091-7613

Steuber T (1999) Cretaceous rudists of Beotia, central Greece. Spec Pap Paleontol, vol 61. Blackwell, London

Steuber T (2001) Strontium isotope stratigraphy of Turonian–Campanian Gosau-type rudist formations in the Northern Calcareous and Central Alps (Austria and Germany). Cret Res 22:429–441. doi:10.1006/cres.2001.0268

Steuber T (2002) A palaeontological database of rudist bivalves (Mollusca: Hippuritoidea, Gray 1848). http://www.paleotax.de/rudists/intro.htm

Steuber T (2003a) Strontium isotope stratigraphy of Cretaceous hippuritid rudist bivalves: rates of morphological and heterochronic evolution. Palaeogeogr Palaeoclim Palaeoecol 200:221–243. doi:10.1016/S0031-0182(03)00452-8

Steuber T (2003b) Strontium isotope chemostratigraphy of rudist bivalves and Cretaceous carbonate platforms. In: Gili E, Negra MEH, Skelton PW (eds) North African Cretaceous carbonate platform systems. NATO Science Series, IV. Earth and environmental Sciences, vol 28, pp 229–238

Steuber T, Rauch M (2005) Evolution of the Mg/Ca ratio of Cretaceous seawater: implications from the composition of biological low-Mg calcite. Mar Geol 217(3–4):199–213. doi:10.1016/j.margeo.2005.02.012

Steuber T, Schüter M (2012) Strontium-isotope stratigraphy of Upper Cretaceous rudist bivalves: biozones, evolutionary patterns and sea-level change calibrated to numerical ages. Earth-Sci Rev 114:42–60. doi:10.1016/j.earscirev.2012.04.004

Steuber T, Yilmaz C, Loser H (1998) Growth rates of early Campanian rudists in a siliciclastic-calcareous setting (Pontid Mts., North-central Turkey). Geobios Mem Spec 22:385–401

Steuber T, Korbar T, Jelaska V, Gušić I (2005) Strontium-isotope stratigraphy of Upper Cretaceous platform carbonates of the island of Brač (Adriatic Sea, Croatia): implications for global correlation of platform evolution and biostratigraphy. Cret Res 26(5):741–756. doi:10.1016/j.cretres.2005.04.004

Tari V (2002) Evolution of the northern and western Dinarides. A tectonostratigraphic approach. EGU Stephan Mueller Spec Publ Ser 1:223–236

Tomić V (1985) Prigrebenskei bazenske naslage senona u području Donjeg Bešpelja, sjeverno od Jajca (Peri-refal and basin deposits of the Senonian in the area of Donji Bešpelj, in the north of Jajce) (In Croatian with English summary). Geološki Vjesnik 38:81–86

Trefethen JM (1950) Classification of sediments. Am J Sci 248:55–62

Tudhope AW, Scoffin TP (1994) Growth and structure of fringing reefs in a muddy environment, South Thailand. J Sediment Res A 64:752–764

Turnšek D (1978) Solitary Senonian Corals from Stranice and Mt. Medvednica (NW Yugoslavia). Academia Scientarum et Artium Slovenica, Dissertationes, Classis IV, vol 21/4, pp 61–128

Turnšek D (1994) Upper Cretaceous reef building colonial corals of Gosau facies from Stranice near Slovenjske Konjice (NE Slovenia). Academia Scientarum et Artium Slovenica, Dissertationes, Classis IV, vol 35, pp 3–41

Turnšek D (1997) Mesozoic corals of Slovenia. ZRC SAZU, Ljubljana

Turnšek D, Polšak A (1978) Senonian colonial corals from the biolithite complex of Orešje on Mt. Medvednica (NW Yugoslavia). Academia Scientarum et Artium Slovenica, Dissertationes, Classis IV, vol 20, pp 129–179

Velić I (2007) Stratigraphy and palaeobiology of Mesozoic benthic foraminifera of the Karst Dinarides (SE Europe). Geol Croat 60(1):1–113. doi:10.4154/GC.2007.01

Vicens E (1992) Estudio de la fauna de rudistas (Hippuritidae y Radiolitidae) de los materiales cretácicos del Pirineo oriental: implicaciones bioestratigráficas. Publicaciones de Geología, Dissertation, Universidad Autónoma de Barcelona

Vlahović I, Tišljar J, Velić I, Matičec D (2005) Evolution of the Adriatic Carbonate platform: palaeogeography, main events and depositional dynamics. Palaeogeogr Palaeoclim Palaeoecol 220:333–360. doi:10.1016/j.palaeo.2005.01.001

Wilson MEJ, Lokier SW (2002) Siliciclastic and volcaniclastic influences on equatorial carbonates: insights from the Neogene of Indonesia. Sedimentology 49:583–601. doi:10.1046/j.1365-3091.2002.00463.x

Woolfe KJ, Larcombe P (1999) Terrigenous sedimentation and coral reef growth: a conceptual framework. Mar Geol 155:331–345. doi:10.1016/S0025-3227(98)00131-5