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Lithostratigraphy and biostratigraphy of the Upper Cretaceous limestones of Bjelopavlići (Montenegro): contribution to evolution and paleogeography of the Adriatic Carbonate Platform

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Abstract

The Upper Cretaceous limestones of Bjelopavlići (Montenegro) represent a megasequence of facies reflecting a transition from shallow- to deep-water depositional environments, succeeded by re-establishing shallow-water conditions again. The studied carbonate sequences are exposed on the south-eastern edge of the Adriatic Carbonate Platform (AdCP) in central Montenegro. Based on coupled sedimentological and biostratigraphical studies, the associations of eight spatially and temporally related facies were identified. The lower part of the megasequence comprises shallow-water carbonates originating in the inner-platform area, while the middle part is composed of pelagic and allodapic limestones. Shallow-water platform limestones occupy the upper part of the megasequence. The shallow-water carbonates of Bjelopavlići show a good correlation with the shallow-water Upper Cretaceous sediments in the AdCP. Deep-water limestones of Bjelopavlići are regarded as facies correlative to the spatially distinct deep-water limestones of Brač and as temporary and spatially correlative with slope-to-basin facies derived along the north-eastern margin of the AdCP. The drowning of the platform periphery and the evolution of a deep-water basin where the pelagic and allodapic carbonates of Bjelopavlići were deposited, as well as the subsequent exhumation of the platform are predominantly attributed to tectonics. The uppermost Cretaceous dynamics of the basin were controlled by tectonic mobilization of the foreland in front of regional fold-thrust belts that developed north-eastern from the AdCP.

1. Introduction

The evolution of the Adriatic Carbonate Platform (AdCP) can be tracked from the Middle Permian to the Eocene (Vlahović et al., 2002; Dragičević and Velić, 2002), but as a distinctive paleogeographic entity, it lasted from the Early Jurassic to the end of Cretaceous (Vlahović et al., 2005). Thick carbonate deposits of kilometre scale have been formed within the long-lasting platform, mostly under shallow marine conditions. The deposition of heterogenous limestones in the platform, regarding facies pattern, was controlled by local paleogeography. The most significant influence on local depositional conditions and platform evolution had the sea-level regime and syn-depositional tectonic mobility (Jelaska et al., 1994; Vlahović et al., 1994; Prtoljan et al., 2007; Brčić et al., 2017). The latter has been particularly expressed by the end of the Cretaceous when the final disintegration of AdCP took place (Otoničar, 2007; Korbar, 2009). The AdCP occupied the passive Adriatic margin of Neotethys during the Cretaceous (Schmid et al., 2020 and refer-

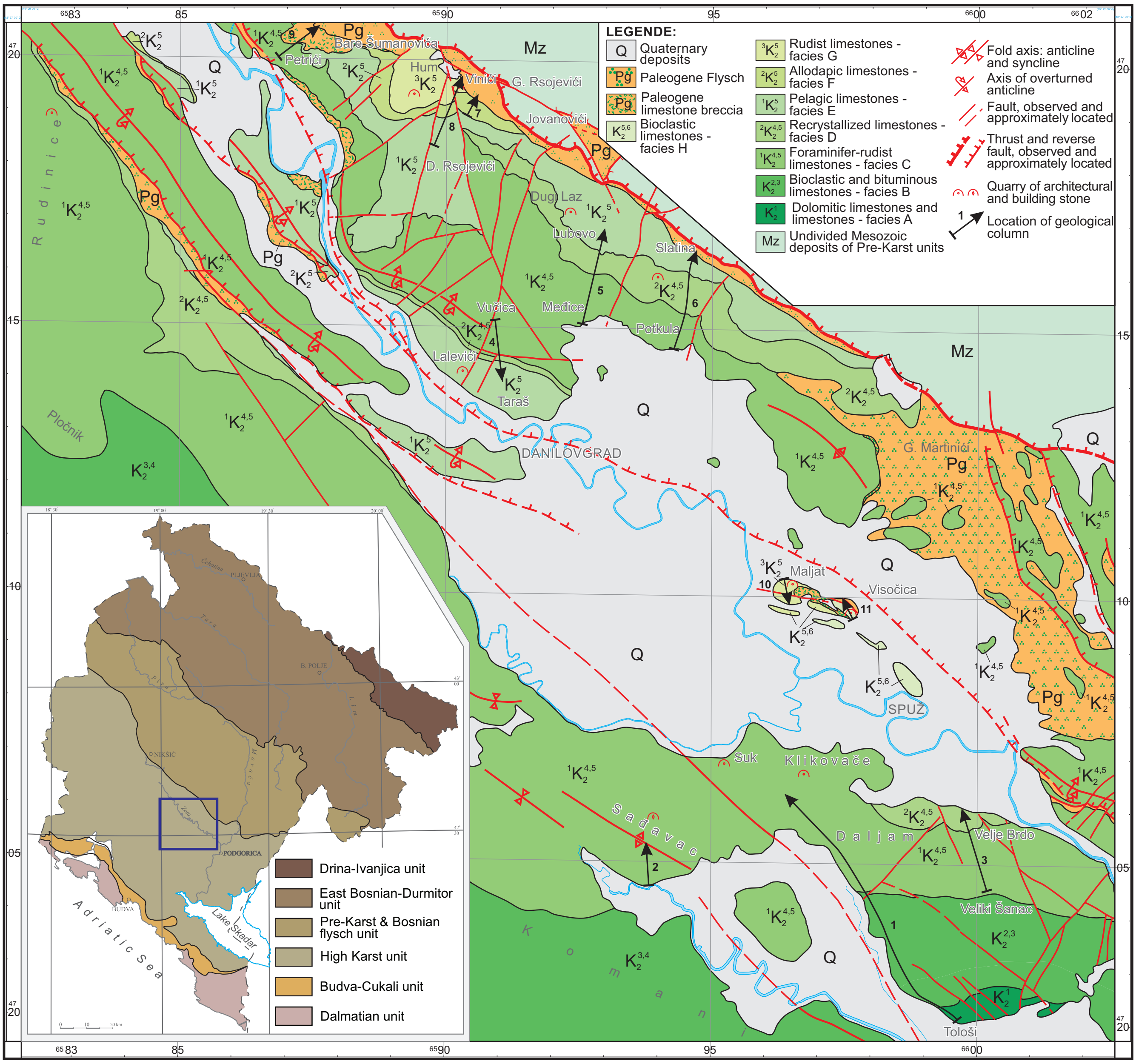

Figure 1: Geological map of Bjelopavlići with positions of studied profiles and major quarries. The insert represents the tectonic units of Montenegro (after Schmid et al., 2020, modified). The area presented by the geological map is marked with a dark blue rectangle.

ences therein). As the combined consequence of global sea-level changes and syn-depositional tectonic activity, the platform was exposed either to subsidence or to local uplifting, as well as to periodical emersions of platform carbonates. These events were either synchronous or alternated and repeated over time (Korbar et al., 2001; Dragičević and Velić, 2002; Vlahović et al., 2005; Špelić et al., 2021).

The remnants of the former AdCP are incorporated into the tectonic structures of the External Dinarides (Vlahović et al., 2005). In recent discussions on the tectonic framework of SE Europe Schmid et al. (2020) distinguished the Dalmatian, Budva-Cukali, High Karst and Pre-Karst and Bosnian flysch, East Bosnian-Durmitor and Drina-Ivanjica units as the Adria-derived allochthons in the Dinarides (insert in Fig. 1). The South Alpine unit forms complex, south-vergent Adria-derived unit thrust over the High Karst unit. A part of the South Alpine unit is the Tolmin nappe, derived from the Slovenian Basin, which is a part of the deep-water basins developed at the periphery of the AdCP (Goričan et al., 2022).

The AdCP is built by sediments that include different facies of platform carbonates, subordinated slope and deep-water carbonates (Tišljar et al., 2002). According to paleogeographic reconstructions, the largest part of the AdCP was throughout the Jurassic and most of the Cretaceous, the domain of active deposition of carbonates, just periodically exposed to short-lasting emersions. At the end of the Upper Cretaceous, the paleogeographic pattern of the platform became more complex (Dragičević and Velić, 2002; Vlahović et al., 2005; Korbar, 2009). A short stratigraphic hiatus has been recorded in sediments deposited at the K/Pg boundary on the island of Brač (Ćosović et al., 2004; Steuber et al., 2005; Vlahović et al., 2005; Cvetko Tešović et al., 2020). Maastrichtian limestones in Dalmatia are conformably overlain by Paleogene shallow-water muddy limestones. In the north-eastern part of the Dinarides, Maastrichtian carbonates are, due to synorogenic platform drowning, followed by a conformable succession of Paleogene calciclastic turbidites (for details, see Korbar, 2009). A large central part of the platform was subjected to emersion, while the exposed land was surrounded by regions of shallow-water platform carbonate deposition. The latter propagated further to SW and NE, gradually transiting into deep-water carbonate facies (Vlahović et al., 2005). The lithologic character of transitional and deep-water carbonates facies, paleogeographic conditions during their deposition within the central and northwestern parts of the AdCP, and the existence of intra-Upper Cretaceous emersions were often a subject of discussion (Buser, 1986; Jelaska et al., 1994; Korbar et al., 2001; Dragičević and Velić, 2002; Korbar, 2009; Moro and Ćosović, 2013; Brčić et al., 2017). In the Upper Cretaceous AdCP succession, deep-water carbonates were deposited in two spatially separated narrow depressions. Both sub-basins were oriented NW-SE (Velić et al., 2002; Vlahović et al., 2005). Limestones with pelagic foraminifera, fine rudist debris and chert nodules, and allodapic limestones were formed during the temporary drowning of the platform driven by the influence of eustatic sea-level rise and syndepositional tectonics (Tišljar et al., 2002).

Contrary to these well-known profiles of deep-water facies for the Croatian part of the platform, data related to pelagic and allodapic limestones of the AdCP in Montenegro are missing. One such facies sequence was developed in central Montenegro in the area of Bjelopavlići. The association of the Upper Cretaceous sediments that display a transition between shallow-platform carbonates and deep-water carbonates were studied in the south-eastern continuation of one depression (see Fig. 12, in Vlahović et al., 2005). Special attention was paid to intra-Cretaceous emersions and on the K/Pg boundary. The study results provide insights into the missing data regarding Upper Cretaceous facies, environments, age, spatial distribution, and transitions from shallow- to deep-water carbonates at the north-eastern margin of the AdCP. Furthermore, these data are important for the correlation of the Upper Cretaceous sediments across the Dinarides, including their northwesternmost part situated within the foreland of the Alpine thrusts.

2. Regional Geological setting

In the tectonic framework of Montenegro (insert in Fig. 1), situated in the External Dinarides and proximal parts of the AdCP, the following composite tectonic units can be recognized: Dalmatian, Budva-Cukali and High Karst. Part of the Internal Dinarides and distal parts of AdCP are the Pre-Karst and Bosnia flysch units, East Bosnian-Durmitor and Drina-Ivanjica units (Schmid et al., 2020).

The study area at Bjelopavlići is situated in the High Karst unit (Schmid et al., 2020), represented by Upper Cretaceous carbonates and the Paleocene-Eocene flysch. The Jurassic-Cretaceous carbonates (Živaljević et al., 1967; Božović, 2016) of the Pre-Karst unit are thrust over the High Karst unit (Aubouin et al., 1970; Schmid et al., 2020). Two different paleogeographic realms are recognized along the north-eastern periphery of the High-Karst Unit: a carbonate platform with prevailing shallow-water carbonate sedimentation during the Upper Cretaceous and a basin with turbiditic sedimentation in the Eocene (Božović, 2016). Thick-bedded and massive dolomites, dolomitic limestones and thick-bedded and massive limestones are of Cenomanian and Turonian age (Fig. 2). Thinly layered limestones with cherts occur intermittently in the lower parts of the Turonian unit, while bituminous limestones were noted in its middle parts. The earlier published data suggested particularly complex and insufficiently clarified conditions of both the origin and mutual relationships of the Upper Cretaceous, mainly Campanian sediments (Čađenović et al., 1996). Limestones, dolomitic limestones, and dolomites, with rich rudist assemblages, are of Coniacian-Campanian age (Živaljević et al., 1967). Pelagic carbonates and allodapic limestones are included in the Campanian Slap Formation (Čađenović et al., 1996). The late Campanian age of the shallow-water limestones in the Klikovača Formation has been determined, whereas a late Campanian-early Maastrichtian age is suggested for the lagoonal carbonates of the Visočica Formation (Čađenović et al., 1996). Biogenic crystalline limestones, dolomitic limestones, and marly limestones are of Maastrichtian age (Živaljević et al., 1967). In the topmost part of the Maastrichtian sequence, an intraformational breccia occurs and a less frequent conglomerate (Božović, 2016). During the Middle Eocene, a basin with flysch sediments developed at the north-eastern periphery of the carbonate platform (Živaljević et al., 1967). As a result of post-Eocene shortening, Mesozoic carbonates of the Pre-Karst unit were thrust southwestward over flysch (Mirković, 1997; Schmid et al., 2020).

3. Methods

The survey of carbonate rocks of Bjelopavlići included field and laboratory examinations of lithologic characteristics of the Upper Cretaceous carbonates and sedimentological, biostratigraphical and facies pattern analyses. Carbonate facies and their vertical distribution were studied at selected geological profiles and in quarries (Fig. 1). The interpretation was based on petrological and biostratigraphical analysis of many thin sections. Classifications of Folk (1959) were used for the petrographic de-

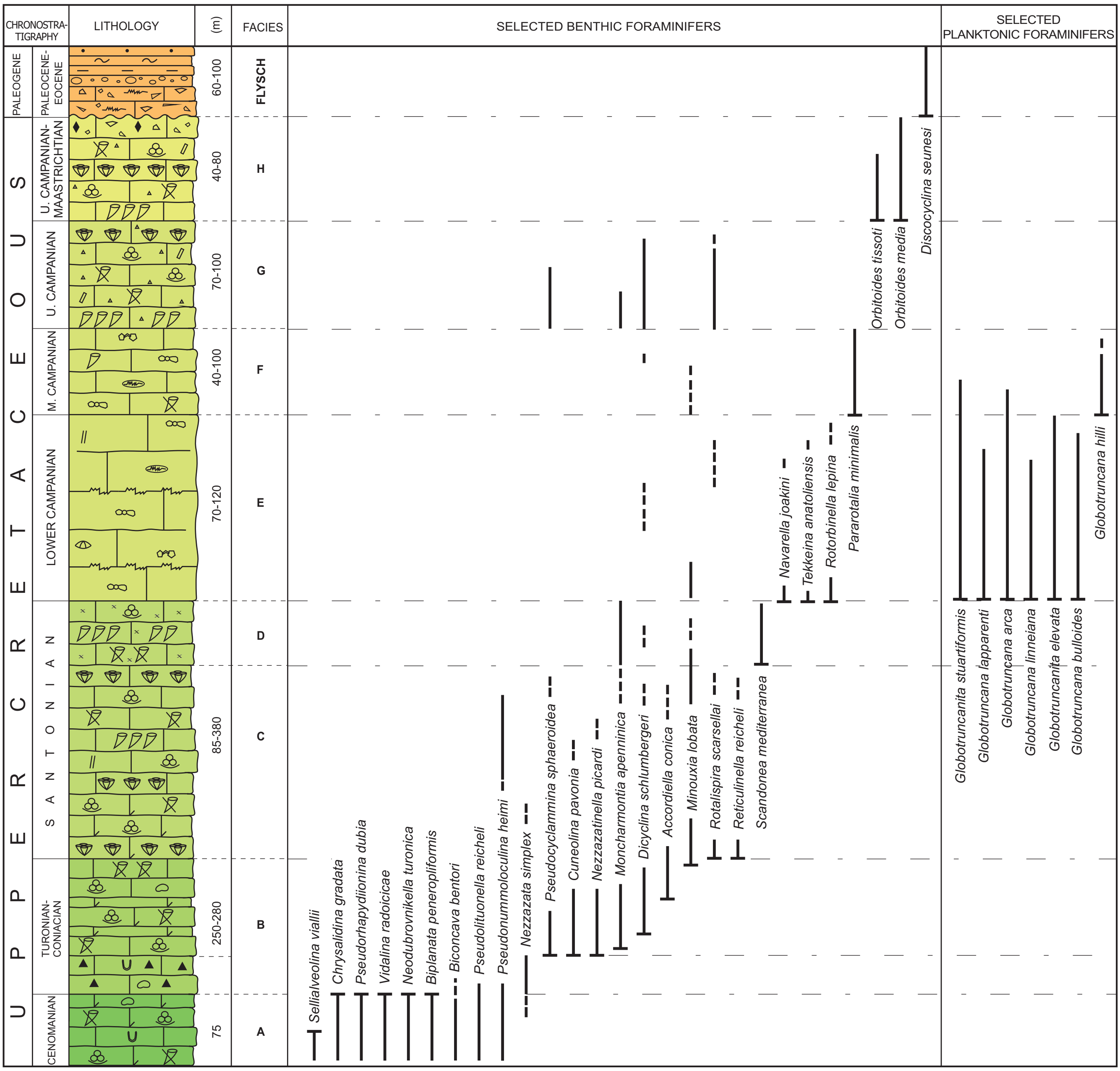

Figure 2: General lithostratigraphic column of the Upper Cretaceous to Eocene sediments in the area of Bjelopavlići, with distribution of selected benthic and planktonic foraminifera.

scriptions of carbonate rocks, as well as Dunham (1962), modified by Embry and Klovan (1971). Limestone facies were distinguished according to the dominant constituents of limestone, following the principles of facies analysis of carbonate rocks (Flügel, 2010). The interpretation of depositional environments is based on standard microfacies types and facies zones of carbonate sediments (Wilson, 1975; Flügel, 2010) and published data regarding the genesis of similar carbonate facies in the Dinarides (Velić et al., 2002; Vlahović et al., 2005; Velić, 2007). Benthic and planktonic foraminifera and algae were studied and analyzed in thin sections. Available data from exploration drill holes were additionally used for local correlation of units. The investigated samples and thin sections are housed in the repository of the Geological Survey of Montenegro.

4. Facies of the Upper Cretaceous carbonates of Bjelopavlići

The Upper Cretaceous deposits of Bjelopavlići display facies pattern variation due to changes in depositional conditions within the platform. In the study area, eight limestone facies associations were identified. Based on the field and laboratory studies of the carbonates of Bjelopavlići, three paleogeographic domains of the Upper Cretaceous were recognized. While the majority of carbonate rocks represent shallow-marine products of the carbonate platform, one facies is related to the pelagic environment, and one is related to the platform slope environment.

4.1. Facies A: dolomitized limestones

Dolomitized limestones of the facies A were analyzed along the profile Tološi-Klikovače (profile 1 in Fig. 1, and the lower part of geological column 1 in Fig. 6). They are underlain by dolomitic limestones of early Cenomanian age and overlain by Turonian-Coniacian bioclastic carbonates (Figs. 1 and 2). Carbonate rocks include the alternation of grey, thick-bedded, and massive limestones of mudstone, wackestone, packstone and subordinated grainstone lithofacies (Figs. 3a and 3b). Frequent peloids and bioclasts of bivalves (including rare rudists), echinoids, crinoids, and benthic foraminifers are embedded within the micrite matrix. Irregularly oriented fenestrae, as well as wavy microbial laminites in the form of LLH-stromatolites (Flügel, 2010), are also observed. These sediments are locally penetrated by macroscopic desiccation cracks. Partial dolomitization of limestones took place during late diagenesis.

The identified microfossil assemblage of benthic foraminifers includes: *Sellialveolina viallii* Colalongo, *Chrysalidina gradata* d'Orbigny, *Pseudolituonella reicheli* Mariae, *Biconcava bentori* Hamaoui, *Vidalina radoicicae* Cherci and Schroeder, *Pseudonummoloculina heimi* Bonet, *Neodubrovnikella turonica* Said and Kenawy, *Biplanata peneropliformis* Hamaoui and Saint-Marc and *Pseudorhapydionina dubia* De Castro, indicating a middle and late Cenomanian age (Figs. 2a and 2b).

Limestones of the facies A were deposited within the carbonate platform in a generally low energy, shallow subtidal-intertidal environment within the restricted shelf area (Wilson, 1975; Flügel, 2010). The environments are indicated by carbonate lithofacies, as well as the presence of fenestrae, laminated stromatolites, and desiccation shrinkages.

4.2. Facies B: bituminous and bioclastic limestones

Bituminous and bioclastic limestone of facies B are conformably overlying limestones of facies A. Sedimentological and biostratigraphical properties of these carbonate rocks were observed along the profile Tološi-Klikovače (Fig. 1, profiles 1 and Fig. 6, geological column 1). The lower part of the package is built of bioclastic and bioclastic-peloidal limestones of wackestone-packstone type, foraminiferal packstone and grainstone, sporadically with mud pebble plasticlasts. Among the benthic foraminifers *Biconcava bentori* Hamaoui, *Pseudonummoloculina heimi* Bonet and *Nezzazata simplex* Omara are observed.

Further upward, limestones are occasionally laminated, with finely dispersed bituminous matter in the laminae. Organic-rich horizons indicate a stratified water body and an anoxic environment during the latest Cenomanian – earliest Turonian. The age is inferred according to the superposition and the correlation of this strata with similar developments throughout the AdCP (e.g. Gušić and Jelaska, 1990, 1993).

The upper part of the section is built of alternations of bioclastic (fragments of rudists shells, echinoderms and gastropods) to foraminifer-bearing mudstone and wackestone and bioclastic-peloidal packstone and grainstone (Fig. 3c). Rare micritic intraclasts and pellets could also be found in sparry calcite matrix and less common in microsparite matrix. Mud pebbles and irregular lenses of siltstone that point to short emersions occur locally within the carbonate deposits. The first occurrence of hippurite and radiolitid coquinas is also noticed. Limestones of the facies B are affected by late diagenetic dolomitization with alteration to dolomicrites and dolomitic limestones.

Benthic foraminifers *Pseudocyclammina sphaeroidea* Gendrot, *Cuneolina pavonia* d'Orbigny, *Nezzazatinella picardi* Henson, *Moncharmontia apenninica* De Castro, *Dicyclina schlumbergeri* Munier-Chalmas and *Accordiella conica* Farinacci, suggest a Turonian and Coniacian age for the upper part of carbonates of the facies B (Fig. 3c).

These carbonates were deposited in the inner shelf area. Limestones in the lower part of the analyzed section are related to quiet environment with restricted circulation. A significant amount of peloidal wackestone-packstone lithofacies was produced in this environment. The upper part of the section includes sediments derived in the more open platform part with sporadic shallows, displaying water circulation and permanent communication with the open sea. The environment includes shallow subtidal where rudists thrived, subtidal to tidal flats with rudist lumachelles and tidal channels with transported material including benthic foraminifers. Diversification of the depositional area supported the accumulation of different textural types of limestone with plenty and diverse fossil fauna. Late-diagenetic dolomites and dolomitic limestones are common.

4.3. Facies C: foraminifer – rudist limestones

Limestones of this facies were studied at several profiles: Tološi – Klikovače, Sađavac, Veliki Šanac-Velje Brdo, Vučica – Taraš, Međice – Lubovo, Potkula – Slatina and Petrići, as well as in the quarries Klikovače and Suk (Figs. 1 and 6, profiles and geological columns 1, 2, 3, 4, 5, 6 and 9).

The lower part of the column is represented by alternating bedded and thick-bedded limestones of bioclastic and bioclastic-peloidal wackestone-packstone, foraminiferal packstone and subordinate bioclastic-foraminiferal grainstone. The middle part of the column occupies bioclastic wackestone-packstone and bioclastic-peloidal packstone in alternation. The upper part is of thick-bedded and massive bioclastic and bioclastic-peloidal wackestone and packstone, less abundant foramin-

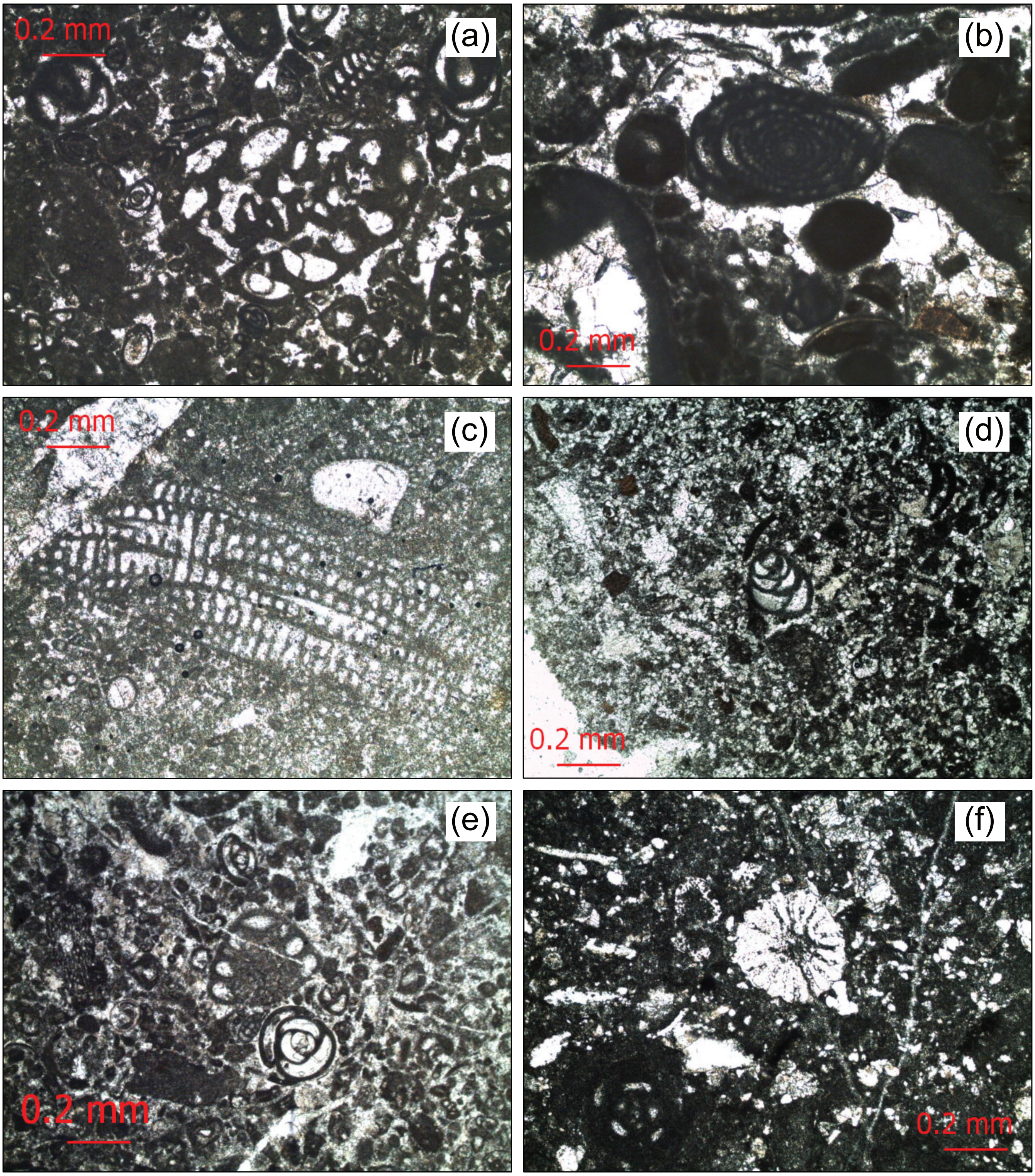

Figure 3: Microphotographs of the Upper Cretaceous limestones of Bjelopavlići: **(a)** Biopelsparite with *Chrysalidina gradata* d`Orbigny, facies A. **(b)** Bioclastic biointrasparite with *Sellialveolina viallii* Colalongo, facies A. **(c)** Algal-foraminifer biomicrosparite with *Dicyclina schlumbergeri* Munier-Chalmas and *Thaumatoporella parvovesiculifera* Raineri, facies B. **(d)** Biointrasparite with *Minouxia lobata* Gendrot, facies C. **(e)** Bioclastic-foraminiferal biomicrosparite with *Accordiella conica* Farinacci, facies C. **(f)** Biocalcrudite with *Salpingoporella donatae* Sokač and *Scandonea mediterranea* De Castro, facies D.

iferal-peloidal grainstone, rudist floatstone and rudstone and rudist biostrome (Fig. 3d and e).

The main constituents of these limestones are rudist and echinoderm bioclasts ranging in size from submillimeters to centimeters; large and well-preserved rudist shells of *Gorjanovicia endrissi* Boehm and *Vaccinites giganteus* d`Hombres-Firmas are frequent in the upper levels of the succession, sporadically forming biostromes (Čađenović et al., 1996). Common microfossils are benthic foraminifers such as: *Pseudonummoloculina heimi* Bonet, *Moncharmontia apenninica* De Castro, *Dicyclina schlumbergeri* Nunier-Chalmas, *Accordiella conica* Farinacci, *Pseudocyclammina sphaeroidea* Gendrot, *Minouxia lobata* Gendrot, *Rotalispira scarsellai* Torre, *Reticulinella reicheli* Cuvillier et al. Cyanobacteria *Decastronema kotori* Radoičić and microproblematicum *Thaumatoporella parvovesiculifera* Raineri are also frequent. The assemblage of rudists and microfossils indicates a Santonian age (Figs. 2d and 2e).

Variable textural types of limestones contain bioclasts and rudist particles, along with preserved either larger or small foraminifera, common peloids and intraclasts. Algal oncoids are rare. Thick rudist coquinas are typically seen as lateral facies of biostromes, composed of poorly sorted rudist bioclasts embedded in a micrite matrix, occasionally containing a small amount of organic matter. Re-deposition of fragments together with fine-grained matrix mud took part in a generally calm environment, whereas a fast decrease in water depth allowed rudists to flourish and form new buildups.

Limestones of the facies C are deposited in a restricted shelf area that gradually passes into an open marine environment with the development of rudist buildups at the outer shelf, as indicated by the rudist genera *Gorjanovicia* and *Vaccinites*.

4.4. Facies D: recrystallized limestones

This carbonate facies conformably overly limestones of the facies C. The investigation was carried out along the profiles Veliki Šanac – Velje Brdo, Vučica – Taraš, Međice – Lubovo and Potkula – Slatina and in the quarry Slatina (Figs. 1 and 6, profiles and geological columns marked by 3, 4, 5 and 6). Succession comprises an alternation of thick-bedded and massive limestones of wackestone, bioclastic and peloidal packstone and bioclastic (frequently rudist) floatstone types, with local occurrences of rudist rudstone and algal oncoids. Limestones contain well-preserved radiolitid and hippuritid shells, as well as the remains of foraminifera and algae (Fig. 3f). Bioclastic wackestone and packstone occur as individual beds or as a floatstone matrix.

Well-preserved shells of *Vaccinites taburni* Guiscardi and *Vaccinites cornuvaccinum* Bronn, or fragmented shells of *Vaccinites atheniensis* Ktenas and *Sauvagesia tenuicostata* Polšak were identified, as well as bioclasts of other rudists and echinoderms (Božović, 2016). The assemblage of benthic foraminifers *Moncharmontia apenninica* De Castro, *Scandonea mediterranea* De Castro and Miliolidae, as well as calcareous algae *Salpingoporella donatae* Sokač and microproblematicum *Thaumatoporella parvovesiculifera* Raineri have been also found**.** Coupled microfossil and macrofossil assemblage indicates a late Santonian age of the limestones of the facies D. Carbonate deposits of the facies D are interpreted as shallow-marine carbonates of platform-margin to outer shelf environment.

4.5. Facies E: pelagic limestones

These carbonates were analyzed along several profiles such as: Vučica – Taraš, Međice – Lubovo, Potkula – Slatina and Slap – Vinići (Figs. 1 and 6, profiles and geological columns 4, 5, 6 and 8). The unit is typically represented by thick-bedded and massive micrites and biomicrites of mudstone, mudstone–wackestone, and less common wackestone types. Chert nodules and infrequent chert intercalations with radiolarians occur locally within the succession, as well as smaller lenses of graded bioclastic allodapic limestones. Pelagic limestones contain numerous planktonic and benthic foraminifers (Figs. 3a and 3b), preserved or fragmented calcisphaerulids, radiolarians, and very scarce tiny bioclasts of rudists and echinoderms.

Limestones contain the association of planktonic foraminifers *Globotruncanita stuartiformis* Dalbiez, *Globotruncana lapparenti* Brotzen, *Globotruncana arca* Cushman, *Globotruncana linneiana* d'Orbigny, *Globotruncanita elevata* Brotzen, *Globotruncana bulloides* Vogler and subordinated benthic foraminifers *Navarella joaquini* Ciry and Rat, *Rotorbinella lepina* Consorti et al., *Tekkeina anatoliensis* Farinacci and Yeniay, *Minouxia lobata* Gendrot and calcisphaerulids *Pithonella ovalis* Kaufmann, *Pithonella sphaerica* Kaufmann and *Pithonella multicava* Borza. The defined microfauna indicates the early Campanian age of the limestones of the facies E. Micritic carbonates with prevailing planktonic foraminifers, calcisphaerulids, radiolarians, nodules and intercalations of chert suggest deposition within the generally deep-water and low-energy environment.

4.6. Facies F: allodapic limestones

Allodapic limestones of the facies F were studied along the profiles Gornji Rsojevići and Slap – Vinići (Figs. 1 and 6, profiles and geological columns 7 and 8) and could be divided into three packages. In the base of the first package occur thick-bedded floatstone, bioclastic packstone and wackestone in alternation (Fig. 4c). The lower part of graded beds, of floatstone type, gradually transitions into bioclastic packstone, whereas the upper part is of wackestone type. Bioclastic packstone contains rudist and echinoderm bioclasts, with rudist bioclasts as the main constituent in some beds. Rare intercalations and nodules of radiolarian chert can also be observed within the succession. Gradation of carbonate particles was observed macroscopically as well as microscopically. Laminated biocalcarenites and biocalcilutites alternate with pelag-

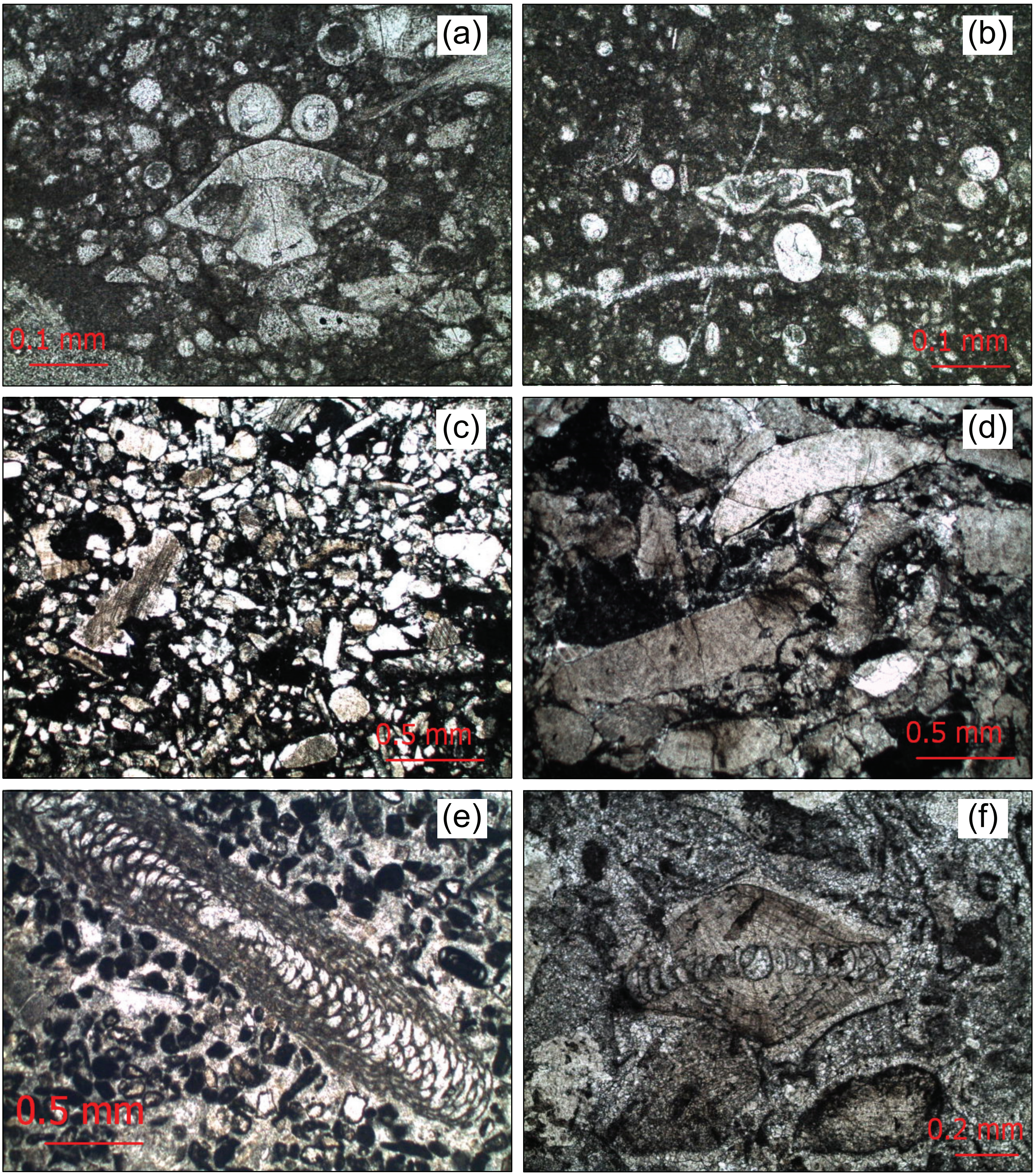

Figure 4: Microphotographs of the Upper Cretaceous limestones of Bjelopavlići: **(a)** Bioclastic biomicrite with *Rotorbinella lepina* Consorti et al. and *Pithonella sphaerica* Kaufmann, facies E. **(b)** Biomicrite with *Globotruncana linneiana* d'Orbigny and pithonellas, facies E. **(c)** Bioclastic biointramicrite with rudist bioclasts, facies F. **(d)** Biocalcarenite with bioclasts from rudists, facies G. **(e)** Foraminiferal biointrasparite with *Orbitoides tissoti* Schlumberger, facies H. **(f)** Biointrasparite with *Orbitoides media* d'Archiac, facies H.

ic and hemipelagic mud. The presence of pithonellas and calcispheres indicates deeper parts of the open sea. The microfossil assemblage includes calcisphaerulids *Pithonella ovalis* Kaufmann and *Pithonella multicava* Borza, benthic foraminifers *Minouxia lobata* Genrot and *Pararotalia minimalis* Hofker and subordinated planktonic foraminifers *Globotruncana hilli* Pessagno and *Globotruncana linneiana* d'Orbigny. These limestones conformably overlie pelagic limestones of the facies E. Microfauna association and superposition of limestones of the facies F indicate a middle Campanian age.

Carbonate sediments of the facies F are typical allodapic limestones, which form when shelf biogenic debris is re-sedimented by turbiditic currents and mass-flow mechanisms into a deeper environment. Graded bedding displayed by bioclasts within beds reflects gravity driven debris along the steep peripheral part of the platform. Biogenic remains in these limestones are of planktonic as well as of benthic origin.

Allodapic carbonates display several standard microfacies: floatstone, wackestone, bioclastic wackestone and bioclastic packstone. Bioclastic carbonates are commonly built by rounded and graded rudist fragments. Floatstone is a typical sediment of a reef slope facies, with large rudist fragments embedded in micrite matrix. Bioclastic wackestone consists of bioclasts of rudists, gastropods, foraminifers, calcisphaerulids and other occasionally almost completely recrystallized organisms.

4.7. Facies G: rudist limestones

Profiles with these limestones were analyzed in the area Slap-Vinići and in the quarries Vinići, Maljat and Radujev krš (Fig. 1, profiles 8 and 10). Carbonates are represented by thick-bedded and massive bioclastic wackestone, foraminiferal wackestone, rudist floatstone and rudstone with packstone matrix, small rudist biostrome, and rarely bioclastic, foraminiferal and rudist packstone (Fig. 4d). Coarse to tiny fragments of rudists, less frequent echinoderms and other bioclasts are embedded in the micrite matrix, rarely cemented by sparite. Biosparites of grainstone, and subordinate rudstone lithofacies build the base and top packages of the succession. Geopetal fabric, internal sediments and rare fenestral cavities filled with sparite are observed in these sediments.

In addition to fragments of *Pironaea* sp., *Sabinia* sp. and *Vaccinites* sp., these limestones contain the association of benthic foraminifers *Moncharmontia apenninica* De Castro, *Dicyclina schlumbergeri* Munier-Chalmas, *Pseudocyclammina sphaeroidea* Gendrot and *Rotorbinella scarsellai* Torre. These, along with superposition relations indicate a late Campanian age. Carbonate sediments of the facies G were deposited in the rudist inhabited platform-margin to upper slope depositional environment. The material for their formation comes mainly from eroded rudist biostromes that were located nearby. Their proximity is indicated by a large percentage of angular fragments or bioclasts of rudist shells. The accumulating bioclastic shallow-water rudist debris is associated with bioclasts of benthic foraminifers and echinoderms, as well as with peloids and rare intraclasts.

4.8. Facies H: bioclastic limestones

Bioclastic limestones of the facies H were studied in the quarry Visočica (Fig. 1, profile 11). They are overlying the upper Campanian limestones of the facies G and are unconformably overlain by Paleogene flysch sediments. The unit is built by thick-bedded and massive biopelsparites of grainstone and rudstone microfacies that sometimes display imbrication, graded bedding, and lamination, then foraminifera-bearing wackestone, packstone, bioclastic-intraclastic grainstone, floatstone, rudist rudstone, and rarely mudstone. Dolomitic limestones and dolomites are also present (Figs. 3e and 3f). Hence, biogenic limestones formed by skeletal remains of benthic foraminifers, rudists and other bivalves prevail. In the upper part of the column, interbeds and lenses with "black pebbles", birdseye structures, numerous extraclasts and intraclasts and vadose pisoids are frequent. Desiccation pores, solution cracks and micro-karst surfaces filled up by vadose cement and vadose silt during emersion phases are also noted in sediments (Fig. 5a). In this type of limestones besides foraminifers that have been already identified in other shallow-water carbonates in this area, the presence of *Orbitoides tissoti* Schlumberger and *Orbitoides media* d'Archiac was recorded, which determined the late Campanian to possibly early Maastrichtian age of the unit.

Carbonates of the facies H were deposited in a shallow-marine environment characterized by frequent sea-level oscillations (shallowing-upward cycles?). The calm environment, marked by accumulation of bioclastic debris, comprises: wackestone, packstone and floatstone. Periods of higher energy are marked by biosparites, such as grainstone and rudstone. Beds of the latter commonly display imbrication, graded bedding, and lamination. The most abundant limestone microfacies is foraminiferal grainstone. Limestones of rudstone and floatstone types occur as intraformational breccias that derive through erosion, short transport and intrabasinal re-deposition of marine deposits. Dried mud characterizes the birdseye structure. The presence of black pebbles, desiccation breccia and disrupted beds inside shallow-marine deposits indicate the existence of coastal marshes as well as on the erosion of biogenic deposits during emersion. Emersion periods led to the development of solution cavities, corrosive voids and pores with cement characteristic for submarine and vadose environments (Fig. 5a). The early-diagenetic dolomites, along with the pattern of discussed facies, further indicate a peritidal environment.

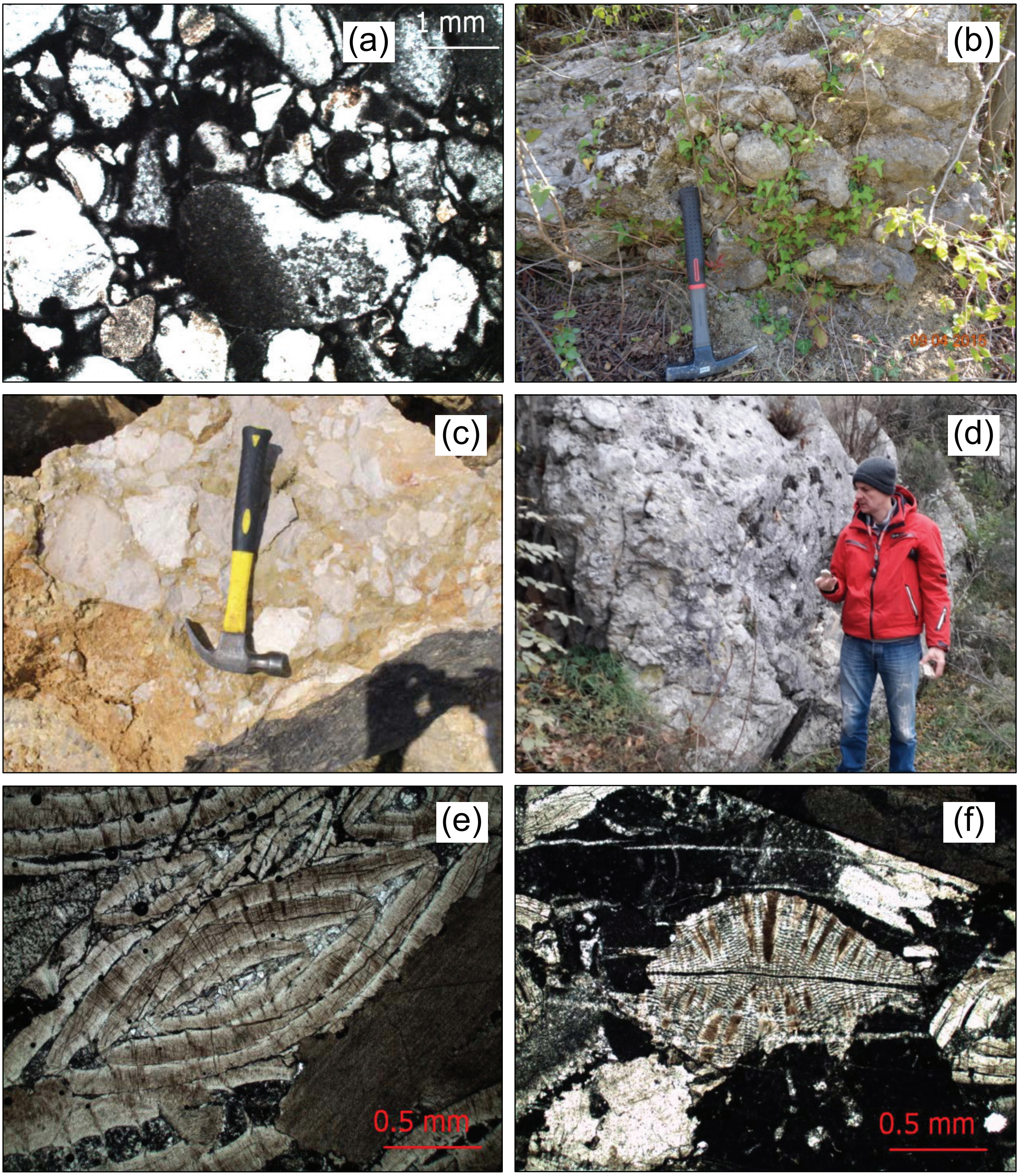

Figure 5: (a) Dissolution cavities in limestone of facies H with multiple infills: A type of cement (sparite) along the edges of the cavities, and internal micrite enriched with Fe and organic matter. **(b)** Conglomerates in the base of Paleocene pre-flysch clastites in Pješivački do, **(c)** Paleogene breccia of Visočica, **(d)** Thick-bedded Paleogene breccia with cherts (sector Dugačke glavice-Donje selo), **(e)** *Nummulites* sp. within transitional beds of pre-flysch into flysch sediments nearby Bare Šumanovića (Figs. 1 and 6, profile and column 9), **(f)** *Discocyclina* sp. from the same transitional beds.

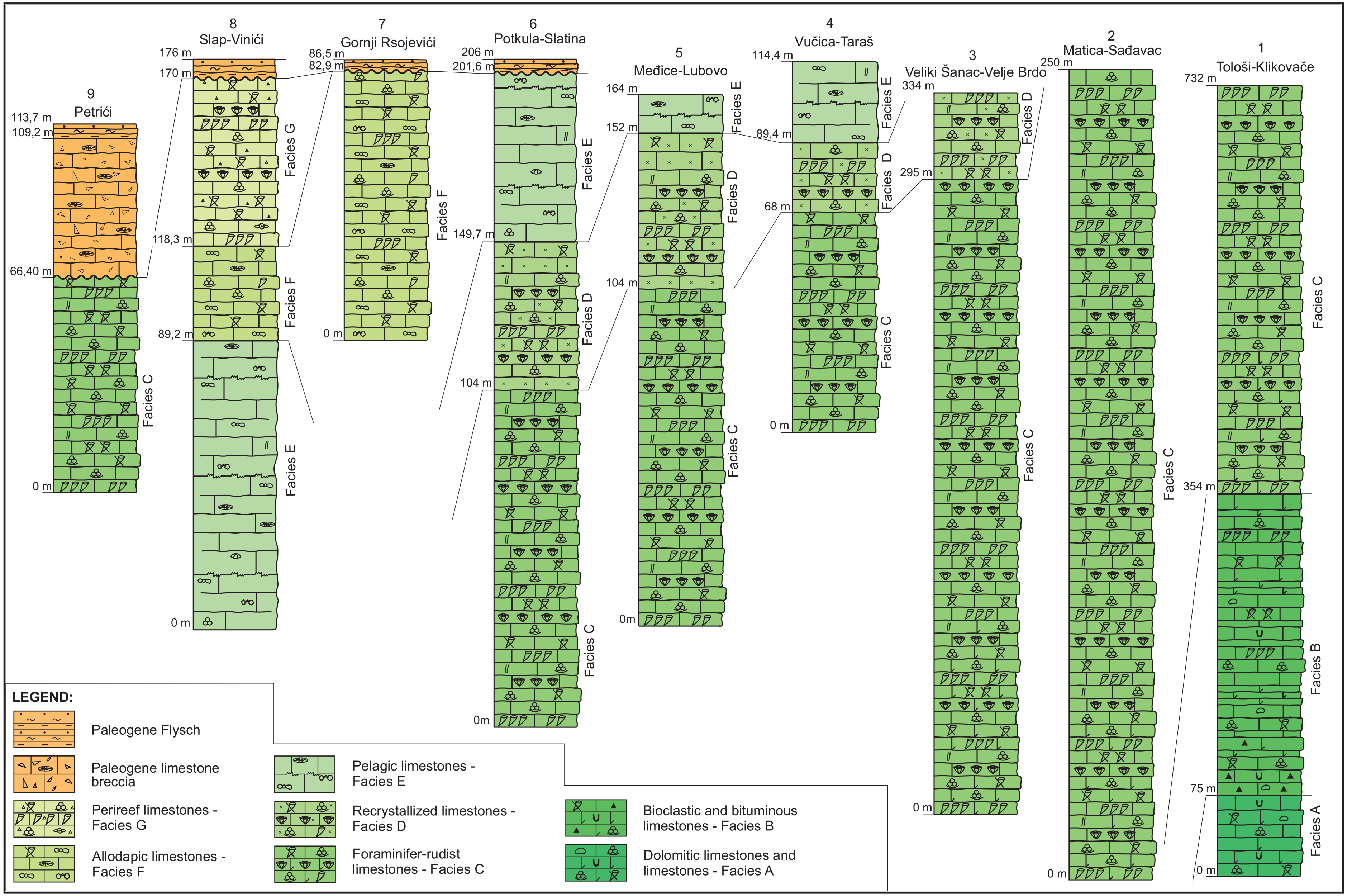

Figure 6: Correlation of geological columns of the Upper Cretaceous carbonates and Paleogene clastic-carbonate sediments in Bjelopavlići area. Numbers of geological columns coincide with profile numbers in the Figure 1.

5. Paleogene sediments of Bjelopavlići

Paleogene sediments have a limited distribution and have been discovered in a few spatially separated zones. The largest exposure is northeast of Bjelopavlići, in the footwall of the basal thrust of the Pre-Karst unit (Božović, 2016; Schmid et al., 2020). The rest is located in the northwestern part of Bjelopavlići (Fig. 1) following the strike of local reverse faults. The basal part of the series, composed of conglomerate, carbonate breccia and sandstone (Figs. 5a, 5b, and 5c), transitioning upwards into the sandy limestones and marlstones bearing *Discocyclina seunesi* (Živaljević et al., 1967). The appearance of Upper Paleocene and Lower Eocene marlstone, sandstone, coarse-grained breccia, and conglomerate within the Paleogene series in the Zeta River valley was recorded and confirmed by foraminifers (Pavić, 1970). The same author considered them to be part of the flysch series that was discordantly developed above the Upper Cretaceous limestones.

The base of the Paleogene sediments in the profile Petrići (Figs. 1 and 6, profile and geological column 9) is represented by a 40 m-thick package of brecciated limestones is overlain by marly-clayey turbidites. A Paleogene microfauna has been identified in the lower part of marly deposits (Figs. 5d and 5e). In the profiles Potkula – Slatina, Gornji Rsojevići, and Slap – Vinići (Figs. 1 and 5, profile and geological columns 6, 7 and 8), siliciclastics of Paleogene age overlay Upper Cretaceous limestones of a different facies.

6. The Upper Cretaceous depositional environments

Based on data obtained from coupled field and laboratory investigations of carbonate rocks in Bjelopavlići, the three paleogeographic domains of the Upper Cretaceous deposition were identified. The majority of carbonates represent shallow-marine products of the inner AdCP. Some of them are associated with deep-water, pelagic environments, while others formed on the platform slope.

6.1. The Upper Cretaceous shallow-water carbonates

Shallow-water conditions were established in the area of Bjelopavlići within the AdCP from the late Turonian to the onset of the Campanian, resulting in the formation of carbonate rocks belonging to facies A, B, C and D. Similar conditions were re-established in the late Campanian and Maastrichtian when limestones of facies G and H were deposited. Lithological properties, faunal content, and diagenesis have led to the recognition of Upper Cretaceous shallow-water carbonates formed in different sub-environments, such as shallow subtidal and intertidal to supratidal (Flügel, 2010).

Typical intertidal sediments are thinly laminated muddy carbonates with LLH-type stromatolites. Microbial carbonates are deposited in an environment inhabited by cyanobacteria. Stromatolites display wavy laminas of small thickness, which commonly occur together with fenestrae and shrinkage pores, such as in the case of limestones of the facies A. Significant amounts of peloids, bioclasts of benthic foraminifers, molluscs and echinoderms are characteristic for these carbonates. Bituminous laminated limestones in the lower part of section of facies B point to a calm depositional environment with a stratified water body and anoxic conditions. Shallow-marine limestones contain rudist colonies forming biostromes, as recognized in facies C and D. Similar shallow-water conditions were re-established in the late Campanian, leading to the development of rudist limestones of facies G. Limestones of the facies H, deposited during the late Campanian to possibly early Maastrichtian, refer to peritidal environments. The main sediments in such environments are laminated and stromatolitic limestones, including the early diagenetic dolomites. The desiccation pores, breccias, vadose pisoids, dissolution cracks, and microkarst surfaces, together with intercalations of black pebbles, suggest a supratidal zone (Flügel, 2010).

6.2. The Upper Cretaceous deep-water carbonates

The deep-water conditions were established in the area of Bjelopavlići during the early to middle Campanian, facilitating the deposition of pelagic and platform slope carbonates.

6.2.1. The pelagic carbonates

Pelagic carbonates of Bjelopavlići were deposited during the early Campanian. Biomicrites with shells or fragments of planktonic organisms are prevailing in pelagic carbonates of the facies E. The main benthic constituents are benthic foraminifers and bioclasts of rudists, echinoderms and gastropods. Bioclasts of benthic fossils are most often found in intercalations and lenses of allodapic limestones. In addition, these carbonates contain chert nodules and thinner chert interbeds with radiolarians. Carbonates of the facies E were deposited in a deep-water pelagic environment within the basin floor domain attached to a lower slope of the platform margin (Playton et al., 2010). The presence of planktonic foraminifers microfauna, siliceous intercalations, and lenses of allodapic limestones, along with significant amounts of benthic bioclasts and substantial bed thickness, suggest on their deposition in epipelagic to mesopelagic environments at depths ranging from 150 to 800 m (Flügel, 2010).

6.2.2. The slope carbonates

These deposits refer to re-sedimented carbonates that originated from a deep-water environment on the platform slope. As a consequence of shallowing in the middle Campanian, the pelagic limestones of facies E were overlain by allodapic limestones of facies F. Carbonate turbidites that resemble properties of allodapic limestones were deposited at the base of the platform slope and on the peripheral basin plain. Allodapic limestones comprise skeletal and non-skeletal carbonate detritus originating from shallow platform environments. The flat base of thick beds, gradation of bioclasts, imbrication and lamination imply gravity-driven transport and turbiditic re-deposition of carbonate debris in a deeper part of the basin attached to the platform periphery.

7. Cretaceous-Paleogene transition

The character of contact between Cretaceous and Paleogene sediments in the southwestern Dinarides is important for discussions regarding platform evolution towards its terminal phase and for tectonic and paleogeographic correlations across the orogen. Relationships of the Upper Cretaceous and Paleogene sediments around Bjelopavlići were observed at several profiles and local outcrops. The Upper Cretaceous limestones, which exhibit distinct lithological and stratigraphic characteristics, are overlain by Paleogene carbonate breccias and siliciclastic sediments (Figs. 1 and 5). In the Petrići profile (Figs. 1 and 6, profile and geological column 9), Paleogene deposits are underlain by carbonate rocks of the facies C, while in Slap-Vinići they are underlain by limestones of the facies G, in Gornji Rsojevići profile by limestones of the facies F, and in the Potkula-Slatina profile by limestones of the facies E (Figs. 1, 5, and 6).

All observed relationships clearly indicate the lack of conformity between the Upper Cretaceous and Paleogene sediments. To be more precise, the obtained stratigraphic data support an unconformity between Campanian-lower Maastrichtian platform limestones and the overlying upper Paleocene-lower Eocene calcrudites and siliciclastic sediments.

8. Stratigraphic significance of the fauna and age of carbonates

Detailed stratigraphic subdivision of the Upper Cretaceous sediments, particularly those previously considered Senonian, was insufficiently reliable due to the wide stratigraphic ranges of benthic foraminifera used for age determination. Although the stratigraphic range of the Upper Cretaceous benthic foraminifera in the area enclosed by the AdCP has been compiled and explained by Velić (2007), pelagic forms remained insufficiently reviewed. The age of the carbonate rocks of Bjelopavlići has been determined based on data from this study coupled with the available references.

The dolomitic limestones of the facies A contain a middle to upper Cenomanian foraminiferal assemblage identified as *Chrysalidina gradata* superzone, distinguished by Velić (2007). Limestones of the facies B contain forms of a wide stratigraphic range, but also species such as *Moncharmontia apenninica* and *Pseudocyclammina sphaeroidea* that occurred in the upper Turonian at the AdCP. Suggested Turonian and Coniacian stages coincide with zones 5–8, distinguished by Velić (2007) i.e., *Chrysalidina gradata-Pseudocyclammina sphaeroidea* interval zone to *Dicyclina schlumbergeri-Murgella lata* interval zone. The first appearance of *Rotalispira scarsellai* in rudist limestones of the facies C indicates a Santonian age. According to Velić (2007), these forms were first observed in the upper Santonian on the AdCP. However, Brandano and Loche (2014) documented these species in Italy as early as the Coniacian, extending their stratigraphic range beyond the interpretations of Velić (2007). The late Santonian age of limestones of the facies D was determined by benthic foraminifers such as *Scandonea mediterranea* and dasyclad alga *Salpingoporella donatae*, and macrofossils (*Vaccinites* and other rudists).

Microfauna in pelagic limestones of facies E and allodapic limestones of facies F include foraminifers, which are generally indicative of the early-middle Campanian. The planktonic association with *Globotruncanita stuartiformis*, *Globotruncana arca*, *Globotruncana bulloides* and *Globotruncanita elevata* indicates the early Campanian age of the facies E carbonates. The microfaunal assemblage of limestone facies F does not include index fossils with a short stratigraphic range. The age of these limestones is derived from published data (Radoičić et al., 2010; Velić, 2007; Pejović and Radoičić, 1987). These data, together with the age of carbonates of the facies E, support the interpretation of the facies F limestones as middle Campanian.

The lack of characteristic forms in limestones of the facies G required the determination of their age by superposition. However, the absence of species such as *Biconcava bentori* or *Pseudonummoloculina heimi*, which, according to Velić (2007) disappear before the late Campanian, confirm the age inferred by superposition. The presence of the species *Orbitoides tissoti* and *Orbitoides media* in bioclastic limestones of the overlying facies H, including foraminifers that were already recorded in limestones of the facies G, suggests a late Campanian, and probably early Maastrichtian age of these carbonates.

9. Upper Cretaceous limestones of Bjelopavlići within the Adriatic carbonate platform

The Upper Cretaceous sediments of Bjelopavlići display significant facies variation due to changes in the depositional environment. Analyzed facies and depositional environments of carbonate sediments of Bjelopavlići are correlative with sediments in central and northward parts of the Adriatic Carbonate Platform. The early Cenomanian dolomitic limestones, underlying facies A limestones, exhibit properties of deep-water carbonates (Živaljević et al., 1967), and could be in part correlated with sediments related to temporary deepening and drowning of the platform in the Croatian part of the AdCP (Vlahović et al., 2005). Middle to upper Cenomanian shallow-water limestones of the facies A are correlative with contemporaneous platform carbonates across the External Dinarides (Dragićević and Velić, 2002; Velić et al., 2002; Vlahović et al., 2005). Turonian to Santonian carbonates of facies B, C and D and limestones of facies G accumulated under shallow-marine conditions within an intertidal lagoon that was connected to the open sea. These carbonates are correlative with synchronous shallow-marine deposits of central and northern parts of the AdCP (Vlahović et al., 2005).

The thick sequence of pelagic limestones of the facies E reflects significant basin deepening in the early Campanian. These micritic limestones with pelagic microfauna accumulated in an elongated and deeper environment established to the southeast platform periphery. Micrites and biomicrites with pelagic foraminifera and radiolarians, as well as interbeds and concretions of chert, suggest deposition in a calm pelagic marine environment. Depths can vary (Flügel, 2010; Playton et al., 2010) but typically exceed the depth of several hundred meters, where there are no pronounced waves or currents to disturb the deposition of fine-grained sediments. Considering that the limestones of facies E locally contain re-deposited benthic bioclasts and lenses of allodapic limestones, this environment was still relatively close to the carbonate platform. Hence, the water depth where the pelagic limestones were deposited likely did not exceed 800 meters.

Summarizing microfossil associations and lithologies, the carbonate rocks of facies E correlate with the upper parts of the Dol Formation, i.e., micrites and biomicrites of "Sivac", which are exposed on the Brač island (Gušić and Jelaska, 1990; Cvetko Tešović et al., 2001; Bucković et al., 2010). It should be emphasized that the deep-water carbonates of Brač and Bjelopavlići did not form in a unique deep-water basin but in two separate settings. The former was deposited within a narrow and isolated intraplatform trough, while the latter formed in a subbasin developed along the north-eastern platform periphery throughout the Dinarides (for the spatial distribution of subbasins, see Fig. 12 in Vlahović et al., 2005).

The middle Campanian deposits shifted towards the accumulation of allodapic limestones instead of pelagic carbonates, likely due to the progradation of the platform slope (Flügel, 2010). The migration of the platform periphery was followed by re-deposition of the platform limestones and faunal fragments, supporting the development of bioclastic allodapic limestones of the facies F. Therefore, the pelagic and allodapic carbonates of the facies E and F represent the deep-water facies, which are in superposition with limestones of the facies G, showing the upward shallowing trend.

Comparison of the deep-water sediments of Bjelopavlići with the synchronous sediments in the AdCP indicates that deep-water sediments of the Brač island (Cvetko Tešović et al., 2001; Vlahović et al., 2005; Prtoljan et al., 2007) are correlative with the analyzed, spatially separated deposits on the south-eastern platform part. Next to limestones of the facies E that are correlative with limestones of the Dol Formation, carbonates of the facies F and G are correlative with Pučišća Formation (Cvetko Tešović et al., 2001) and carbonates of the Čiovo Formation (Brlek et al., 2013). In addition, the Upper Cretaceous slope and pelagic carbonates that are exposed along the northeast platform margin (Dragičević and Velić 2002; Velić et al., 2005) are genetically and temporally correlative with deep-water carbonates of Bjelopavlići.

The Upper Cretaceous shift of depositional environments between shallow- to deep-water has often been interpreted as the carbonate platform response to a global sea-level change (Gušić and Jelaska, 1993; Brlek et al., 2013). The deepening of the environment in Bjelopavlići, which started in the early Campanian, recorded peak moments at the early/middle Campanian boundary. The deepening could be a result of a global sea-level rise (Brlek et al., 2013) accompanied by tectonic activity (Otoničar, 2007; Korbar, 2009; Božović, 2016). The recent revision of Cretaceous eustasy (Wagreich et al., 2020) indicates the absence of significant global sea-level rise during the Campanian period. The long-term sea level changes from the Coniacian to the Campanian were estimated to be only around 20 m (Haq, 2014). However, in the study area, the evidence of the extensive early Campanian tectonic events that could have led to notable subsidence was not recorded. In the region northeast of Bjelopavlići, extending northwest through the Dinarides during the Campanian, Maastrichtian, and Paleogene, existing basins were predominantly filled with deep-water carbonates and flysch deposits. These basins were formed as a result of regional flexural subsidence of the continental lithosphere and developed in front of the regional thrust separating the High Karst Units, the Pre-Karst and Bosnia Flysch Zone and the East Bosnian-Durmitor Zone (Dimitrijević, 1997; Schmid et al., 2020).

Additionally, in Slovenia, they developed in front of the thrust separating the Southern Alps Units and the High Karst Units (Buser 1986; Goričan et al., 2022). In the north-eastern syncontractional basin in Montenegro and Bosnia and Hercegovina, sediments of the Durmitor Flysch were deposited (Mirković et al., 1997; Mikes et al., 2008; Ćorić and Benić, 2014; Jolović et al., 2016). This basin, which developed in front of the thrust separating the Pre-Karst and Bosnia Flysch Zone from the High Karst Unit, was directly connected with AdCP. The flexural bending of the lithosphere in front of the regional thrust resulted in tectonic and depositional separation, leading to the formation of a deep basin attached to the periphery of the AdCP. In Bjelopavlići, the platform periphery experienced drowning in the lower Campanian, followed by the establishment of pelagic depositional conditions.

The middle and late Campanian, as well as the Maastrichtian, were periods of gradual shallowing of depositional environments within the entire AdCP. This was a consequence of a gradual sea-level fall (e.g., Brlek et al., 2013; Haq, 2014), accompanied by deformation in the foreland of propagated thrusts (Otoničar 2007). These processes ultimately resulted in regional basin exhumation by the end of Maastrichtian (Vlahović et al., 2005; Brlek et al., 2013; Božović, 2016). Furthermore, in the north and central parts of the AdCP, frequent emersions of varying duration were reconstructed (Velić et al., 2002), whereas in the carbonate succession of Bjelopavlići, evidence for significant breaks in deposition was not recorded.

10. Conclusion

In the Upper Cretaceous, the area of Bjelopavlići was on the south-eastward periphery of the vast Adriatic Carbonate Platform and represented the area of locally varying conditions. The deposits display transitions from shallow- to deep-water environments, followed by the return of shallow-water conditions that persisted until the complete exhumation of this area by the end of Maastrichtian.

Carbonates of facies A were deposited in a shelf lagoon of restricted circulation; limestones of facies B in an open-marine shelf lagoon with restricted circulation. Limestones of the facies C and D derived from a restricted shelf area on the platform margin that gradually passed into an open marine environment. The described transitions of facies reflect a gradual upward deepening of the depositional environment. Deep-water conditions favoured the accumulation of pelagic limestones of the facies E. The carbonates above pelagic limestones exhibit facial characteristics typical of sediments derived in upward-shallowing environments. Limestones of facies F developed on the basin and platform slope. Limestones of facies G originated from an open-marine shelf lagoon, while limestones of facies H were deposited within a peritidal environment.

The Campanian subsidence of the platform along its north-eastern margin, as well as its subsequent gradual exhumation, could be attributed to the tectonic mobilization of the foreland associated with the fold-thrust belt, located northeast of the Adriatic Carbonate Platform.

Carbonate sediments of Bjelopavlići are correlative with carbonate facies of the central and north-westeren part of the AdCP. Therefore, the shallow-water limestones of the latest Cretaceous are correlative with synchronous sediments from AdCP, while deep-water sediments of Bjelopavlići, limestones of facies E and F, are correlative with synchronous deep-water limestones of Brač. Along the north-eastern margin of AdCP, stretching from north-western Montenegro, through Bosnia and Herzegovina, Croatia, and Slovenia, basins developed that were characterized by transitions from shallow-water to deep-water sedimentation. The sediments deposited in these basins, located in front of the regional thrusts, are temporally and genetically correlative with the discussed deep-water sediments of Bjeopavlići. Apparently, during the late Late Cretaceous, a regional deep-water basin existed along the north-eastern margin of the AdCP. Its depositional dynamics, including the drowning of the attached platform and its subsequent exhumation, were predominantly controlled by the evolution of regional thrusts in the Dinarides. The continuous transition from the Upper Cretaceous into the Paleogene sediments is lacking in the area of Bjelopavlići. Paleocene-Eocene sediments discordantly overlie facially diverse Upper Cretaceous limestones.

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