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Cenomanian–Turonian Oceanic Anoxic Event (OAE2) imprint on the northwestern part of the Adriatic Carbonate Platform and a coeval intra-platform basin (Istria and Premuda Island, Croatia)

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Abstract

The Cenomanian–Turonian boundary (CTB) on the intra-Tethyan Adriatic Carbonate Platform (AdCP) is generally characterised by a transition between microbially laminated and/or bioclastic limestones to calcisphere-rich massive limestone with bioturbated intervals, organic-rich interbeds, firmgrounds, as well as neptunian dikes, carbonate turbidites, tempestites and slumped structures. Compilation of the results from two study sites in the northwestern part of the AdCP and from previous research (on Istria Peninsula and islands in the Adriatic Sea in Croatia) provides a more complete overview of geological events and paleoenvironmental conditions that transformed the formerly contiguous shallow-marine environments during this time period. For the first time, a comparison between protected inner-platform area (Barban section) and a coeval intra-platform basin (Premuda Island section) during the CTB was made. This study utilized a combination of litho-, bio-, and microfacies studies with SEM, EDS, TOC, $\delta^{13}C$ and $\delta^{18}O$ stable isotope analyses. The stratigraphic successions start with shallow-marine carbonate deposits of the Milna Formation that is conformably overlain by the drowned-platform deposits of the Sveti Duh Formation on the platform and by the Veli Rat Formation in the contemporaneously developed intraplatform basin. These deposits are in turn overlain by the Gornji Humac Formation, which represents re-establishment of shallow-marine depositional systems on the AdCP, whereas the deeper water environment persisted in the intra-platform basin until the Santonian.

Despite diagenetic modifications of shallow-marine carbonate deposits, the results of TOC and stable isotope analyses indicate the influence of global Oceanic Anoxic Event 2 (OAE2). Combination of local and regional synsedimentary tectonics and global Late Cretaceous sea-level changes accompanied by anoxic and hypoxic conditions, extinction of numerous benthic foraminifera, diversification and expansion of planktonic foraminifera and calcareous dinoflagellates, provide new insights into the character of the CTB interval in this part of the Tethyan realm.

Keywords: OAE2, Cenomanian–Turonian, Adriatic Carbonate Platform (AdCP), Sv. Duh Formation, Istria, Kvarner.

1. Introduction

This study aims to define the influence of Oceanic Anoxic Event 2 (OAE2, Jenkyns 1980, Scholle et al. 1980; Schlanger et al. 1987; Arthur et al. 1987, 1988, 1990; Tsikos et al. 2004;

Keller et al. 2004; Karakitsios et al. 2010; Pearce et al. 2009; Jarvis et al. 2011, 2015; among others) on two different sites of the generally shallow-marine intra-Tethyan Adriatic Carbonate Platform (AdCP) in present-day Croatia. OAE2 was one of the most severe and globally most extensive paleoenvironmental changes. The event occurred at the Cenomanian–Turonian boundary (CTB; about 93.9 My ago; Jarvis et al. 2011; among others). An extinction event, marine anoxia, burial of large amounts of organic carbon (Schlanger and Jenkyns 1976; Schlanger et al. 1987; Parente et al. 2008), and rise in sea level (Hardenbol et al. 1998; Miller et al. 2005; Voigt et al. 2006; Haq 2014; Sames et al. 2016) clearly define the OAE2. Present-day oceans are well oxygenated thanks to a conveyor-belt circulation and distribution of cold, oxygen-rich waters from high latitudes all the way to the abyssal zone. Approximately half of the oxygen injected into the deep-sea regions is consumed by decomposition of organic matter in the water column. Increasing ocean's nutrient content could stimulate biological productivity leading to widespread anoxia (Meyer and Kump 2008, and references therein). Cenomanian submarine volcanism was interpreted as a trigger for a chain reaction that caused OAE2 (Sinton and Duncan 1997; Kerr 1998; Larson and Erba 1999; Bralower 2008; Keller 2008; Turgeon and Creaser 2008; Du Vivier et al. 2014). One of the consequences of OAE2 was enhanced preservation and deposition of organic matter on a global scale recognized as positive shifts of $\delta^{13}C$ values of carbonate deposits. Peak of the crisis (i.e., disturbed dynamics of the global carbon cycle) lasted between 320 Ky (min.) and 1.04 ± 0.12 My (max.) (Sageman et al. 2006; Strauss 2006; Voigt et al. 2008; Gambacorta et al. 2015; Sullivan et al. 2020). Paleobiological consequences of the crisis included the extinction of approximately 26% of marine animal genera (Raup and Sepkoski 1986; Monnet 2009), and changes in diversity and abundance of planktonic foraminifera and radiolarians (Caron and Homewood 1983; Jarvis et al. 1988; Huber et al. 1999; Culver and Rawson 2004; Erba 2004; Gebhardt et al. 2010), larger foraminifera (Parente et al. 2008; Caus et al. 2009), calcareous nannoplankton (Leckie et al. 2002), as well as rudists (Philip and Airaud-Crumière 1991; Steuber and Löser 2000). Widespread dysoxic to anoxic paleoenvironmental conditions and biotic crises in the world oceans also left a significant mark on shallow-marine carbonate systems (Jenkyns 1991; Gušić and Jelaska 1993; Hilbrecht et al. 1996; Davey and Jenkyns 1999; Parente et al. 2008; Immenhauser et al. 2008; Elrick et al. 2009; Gertsch et al. 2010; Nagm 2015; Brčić et al. 2017).

This study focuses on shallow-marine carbonate deposits in the wider area of Istria and Kvarner (Barban and Premuda, Croatia, Fig. 1). Starting in early Cenomanian, the stable and uniform shallow-marine AdCP (Fig. 2a) was impacted by synsedimentary tectonism and sea-level changes, resulting in episodes of pelagic influence. Despite sea-level rise, in some parts of the study area synsedimentary tectonism overprinted eustatic changes and created emerged areas surrounding intra-platform basins (Gušić and Jelaska 1990; Vlahović et al. 1994; Tišljar et al. 1998; Korbar et al. 2012; Brčić et al. 2017; Fig. 2b). One of the main contributions of this study is a comparison between protected inner-platform area (Barban section) and a coeval intra-platform basin (Premuda Island section) during the CTB. This comparison was made possible for the first time in the study area by using an integrated litho-, bio-, and chemostratigraphic approach that allowed the recognition of characteristic signatures of the global OAE2 perturbation.

2. Geological Setting of the Study Area

Deposits of the Mesozoic Adriatic Carbonate Platform (AdCP) are currently exposed in an area approximately 800 km long and 200 km wide, from Italy in the northwest, across Croatia, and to Albania in the southeast (Jelaska 2002; Vlahović et al. 2005). These deposits are predominantly shallow-marine carbonate platform successions, typical of the intra-Tethyan realm (Fig. 2). Their maximum thickness reaches 5000-8000 m with a stratigraphic range from the upper part of lower Jurassic (Toarcian) to the Eocene (AdCP *sensu stricto*). The extensive vertical thickness is the result of synsedimentary tectonics and long-term shallow-marine sedimentation, and was also influenced by subsequent post-Cretaceous formation of thrust-nappe structures. In the study area (Istria and Kvarner, Fig. 1), one of the tectonic phases occurred during the early and late Cenomanian. At the Cenomanian–Turonian boundary, eustatic and synsedimentary tectonics locally established drowned platform environments, but at the same time caused uplift and subaerial exposure of the surrounding areas (Davey and Jenkyns 1999; Velić et al. 2002, 2003; Ćosović et al. 2004; Vlahović et al. 1994, 2002a, 2003, 2005; Korbar et al. 2012; Brčić 2015, 2017; Fig. 2). Eocene ramp-type limestones and synorogenic flysch deposits marked the onset of the Alpine orogenesis in the region (Grandić et al. 1997; Vlahović et al. 2005; Schmid et al. 2008), when the AdCP successions were strongly deformed. The compressional tectonics (Fig. 1b) resulted in the fold-and-thrust structures of the present-day External Dinarides (Tari 2002; Korbar 2009).

Paleogeographically the studied deposits belong to the northwestern part of the AdCP (Fig. 2a). During the Cenomanian the larger (mostly western) part of present-day Istria and Kvarner was subaerially exposed (Vlahović et al. 1994, 2002a, b; Brčić 2015, 2017, Fig. 2b). This study focuses on the eastern areas with deeper-marine deposits where sedimentation continued throughout the Turonian (Barban section; Fig. 2b) and until Coniacian–Santonian (Premuda section; Fig. 2c). The term “deeper-marine” is used for paleoenvironments of intraplatform basins with limited pelagic influence and water depth of less than approximately 150 m. Stratigraphic successions in both localities begin with shallow-marine, middle to upper Cenomanian skeletal mudstone-wackestone-packstone and rudist floatstone (the Milna Formation), followed by Cenomanian–Turonian deeper-marine calcisphere limestones (the Sv. Duh and Veli Rat Formations). The Barban succession ends with Turonian to Coniacian shallow-marine skeletal and peloidal mudstone-wackestone, alternating with rudist floatstone (the Gornji Humac Formation; Gušić and Jelaska 1990), while the prolonged deeper-marine sedimentation at Premuda Island resulted in the Veli Rat Formation (Fuček et al. 1991).

3. Materials and Methods

The Barban section, named after a nearby settlement of Barban, is located in the south-eastern part of peninsula Istria in Croatia (Figs. 1 and 2). This section was sampled in road cuts from Barban to the Raša river valley and in the quarry on the eastern side of the valley (Fig. 1e). The Premuda section is located on Premuda Island in the south-eastern part of Kvarner Bay. The exposures at Cape Lopata on the south-eastern tip of Premuda were examined and sampled in detail (Fig. 1d and 1f).

3.1. Fieldwork and thin-section microscopy

In the study area, the best quality exposures of continuous limestone successions were sampled (Fig. 1e and 1f). The surrounding area was mapped at a scale of 1:12.500 and 1:25.000. Two detailed stratigraphic sections were measured with a total thickness of 315 m: 175 m of the Barban section and 140 m at Premuda (Fig. 3). Selected lithotypes were sampled and a total of 237 polished slabs and 293 thin sections were made for petrographic and micropaleontological analyses in order to define lithotypes and microfossil assemblages, interpret depositional environments, document diagenetic modifications and select the most suitable samples for geochemical analyses. Biostratigraphic analyses focused on numerous species of benthic and planktonic foraminifera (Fig. 3; Croatian Geological Survey repository of the studied material).

3.2. Stable-isotope Analysis ($\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$)

Stable isotope analysis was carried out on 122 samples (81 from Barban and 41 from Premuda; Fig. 4; Table 1). Small amounts of carbonate powder (homogeneous, micritic, and non-weathered material, excluding areas with carbonate cement and skeletal fragments) were collected from polished slabs using a microscope-mounted microdrill. Stable-isotope analyses were performed using a DeltaXL mass spectrometer at the University of Massachusetts, Amherst, USA. After heating for an hour at 400°C to remove any volatile organic components, samples were reacted at 70°C with 100% anhydrous phosphoric acid (H_3PO_4) for 10 min. Standard isobaric and phosphoric acid fractionation corrections were applied to all data. Internal analytical precision, monitored through daily analysis of carbonate standards, was better than or equal to 0.1‰ for both carbon and oxygen isotope values. Results are expressed as $\delta^{13}C$ and $\delta^{18}O$ values in ‰ relative to the Vienna PeeDee Belemnite standard (VPDB).

3.3.TOC and Insoluble Residue Analyses

Total organic carbon (TOC; Fig. 5) was measured on mechanically pulverized limestone samples (i.e., bulk powdered micrite), obtained by drilling micritic limestone with a 1 mm diameter drill-bit. A representative weight (10 g) of each sample was treated with hydrochloric acid (4.2M HCl) for 24 h to eliminate carbonate fractions. To dissolve dolomite that could have been present in the samples the dissolution was performed by heating the hydrochloric acid at 80°C. The samples were filtered and washed several times in distilled water to remove the remaining acid. The insoluble residue (IR) was weighed in tin capsules and analysed using a Thermo Fisher Scientific Flash 2000 NC Elemental Analyser at the Croatian Geological Survey (HGI-CGS). Assuming a complete elimination of carbonate components during the acid treatment, the percentage of IR was calculated using the equation IR = (DM/TM) × 100, where

DM is the weight of the insoluble residue remaining after dissolution of carbonates and TM is the total weight of sample before acid treatment. The amount of TOC_{IR} (%) within IR was determined with elemental analyser and the calculated TOC_{sample} (%) for the whole sample was calculated as TOC_{sample} (%) = (DM/TM) X TOC_{IR} (%). The calibration accuracy was verified by measuring samples of certified Soil Reference Material NC (Thermo Scientific), treated in the same way as the samples. Standard quality check analysis of internal standards performed at HGI-CGS yielded a relative standard deviation (RSD) on TOC measurements of 0.4%.

4. Results

The Barban section is composed of three lithostratigraphic units: the Milna (38 m in thickness), Sv. Duh (116 m) and Gornji Humac Formations (21 m; Gušić and Jelaska 1990; Figs. 3 and 4). The Premuda section contains two lithostratigraphic units: the Milna (30 m thick; Gušić and Jelaska 1990) and Veli Rat Formations (110 m; equivalent of the Sv. Duh Formation with prolonged deeper-marine sedimentation; Fuček et al. 1991; Figs. 3 and 4).

Well-stratified, shallow-marine, middle to upper Cenomanian, foraminiferal wackestone–packstone, alternating with bioclastic (rudist and chondrodontid bivalves) floatstone and microbial laminites, represent the Milna Formation (Figs. 3, 6, 7 and 8). These deposits underlie a drowned-platform succession of the Sv. Duh Formation. Transition between the Milna and Sv. Duh (or its equivalent Veli Rat) Formations can be gradual (laminites and/or bioclastic limestone replaced with progressively thicker intercalations of calcisphere mudstone-wackestone, e.g. Barban section) or sharp (the well-stratified lithotypes overlain by massive calcisphere-rich limestone, e.g. Ćićarija sections in Brčić et al. 2017). The Sv. Duh Formation consists of 116 m of massive calcisphere wackestone with rare fine-grained bioclastic intercalations and sporadically enriched in organic matter formed in deeper-marine settings of the temporarily submerged/drowned carbonate platform with a significant open-ocean influence. Typical characteristics of these deposits are greyish to light brown erosional surfaces, poorly stratified to massive mudstone-wackestone with calcareous dinoflagellate cysts, fine-grained carbonate bioclasts, planktonic foraminifera, ostracods, pelagic crinoids, sponge spicules, echinoid spines, rare benthic foraminifera, thin-shelled bivalves, and gastropods. Other characteristics include bioturbation, dissolution seams, current microlamination, and undulated upper bedding planes. Stratigraphic range of this unit is late Cenomanian–early Turonian. Unlike the Sv. Duh Formation, the Veli Rat Formation is characterised by carbonate turbidites reflecting a different setting and prolonged deeper-marine sedimentation (late Cenomanian–early Santonian; for a more detailed explanation see Sections *4.2.* and 5). The uppermost well-stratified shallow-marine succession belongs to the Gornji Humac Formation characterised by fenestral mudstone, bioclastic-peloid-skeletal wackestone and radiolitid floatstone (with rudist debris, benthic foraminifera, echinoid spines, fine carbonate detritus, and peloids). Transition between the Sv. Duh and Gornji Humac Formations is commonly defined by a shallowing-upward trend (in some cases by oncoid and laminites facies). Deposits in the lower part of Gornji Humac contain shallow-marine bioclastic material mainly composed of rudist debris, benthic foraminifera, crinoids, echinoid spines, fine carbonate detritus, and peloids that infilled intraplatform depressions. Stratigraphic range of the Gornji Humac Formation is middle Turonian-Coniacian (Figs. 3, 6, 7 and 8; for a more detailed explanation see Sections *4.1.* and 5).

4.1. The Barban section

The Barban section (Figs. 3 and 4) starts with shallow-marine peloid-skeletal-bioclastic wackestone–packstone alternating with microbial laminites and sporadic rudist bioclastic floatstone. Dominant allochems are benthic foraminifera, rudist debris, fine-grained carbonate bioclasts and detritus, ostracods, fragments of dasycladal algae and rare *Decastronema kotori* (Radoičić) and *Thaumatoporella parvovesiculifera* (Raineri). The presence of benthic foraminifera *Pastrickella balcanica* (Cherchi, Radoičić and Schroeder) *Chrysalidina gradata* d'Orbigny, and *Vidalina radoicicae* Cherchi and Schroeder stratigraphically defines these deposits as middle to upper Cenomanian and as the uppermost part of the Milna Formation (Fig. 9).

Transition between the Milna and Sv. Duh Formations (42 m from the bottom of Barban section, Fig. 7b) begins with successive intercalations of deeper-marine fine-grained bioclastic calcisphere wackestone within predominantly shallow-marine bioclastic to skeletal packstone. Above these 2 m thick transitional deposits, the bioclastic lithofacies is replaced by thick-bedded to massive calcisphere mudstone to wackestone with planktonic foraminifera (*Rotalipora* sp., *Praeglobotruncana* sp. and *Heterohelix* sp.), ostracods, pelagic crinoids, sponge spicules, echinoid spines, bivalve bioclasts, and fine carbonate detritus. Exposures of this interval are characterised by greyish-light to brown colour, and by their brittle, fractured, partly recrystallized, and thick-bedded to massive appearance. Stratigraphically these 98 m thick deposits belong to the uppermost Cenomanian to middle Turonian and represent the deeper-marine Sv. Duh Formation (Fig. 10).

An 18 m thick interval (between 136 and 154 m of the Barban section) is characterised by a shallowing-upward trend represented by cross-bedded and fining upward grainstone followed by calcisphere wackestone. The sharp contact (at 136 m) between the grainstone and wackestone is marked by prominent stylolites (Figs. 3, 4 and 7d). This part of the section represents a transition between the Sv. Duh and Gornji Humac Formation.

The uppermost 21 m of the succession consists of shallow-marine bioclastic floatstone of the Gornji Humac Formation with radiolitid rudists *Distefanella* sp. and thin-shelled bivalves

(*Exogyra* sp.), alternating with fenestral mudstone and bioclastic-peloid-skeletal wackestone. The stratigraphic range of the Gornji Humac Formation in the wider study area is middle Turonian to Coniacian, based on the presence of *Distefanella* sp. and *Hippurites requieni* Matheron, *Decastronema kotori* (Radoičić), *Thaumatoporella parvovesiculifera*, *Moncharmontia* sp., *Pseudocyclammina sphaeroidea* Gendrot, *Scandonea samnitica* De Castro, *S. mediterranea* (De Castro), *Dicyclina schlumbergeri* Munier-Chalmas and *Murgella lata* Luperto-Sinni (Velić 2007; Figs. 3 and 4).

4.2. The Premuda section

The Premuda section (Figs. 3 and 4) starts with the Milna Formation shallow-marine peloidal-skeletal wackestone–packstone, sporadically alternating with slightly undulating microbial laminites, peloidal packstone–grainstone and rudist lithostromes (Fig. 8a). The most common skeletal allochems are benthic miliolid and nezzazatid foraminifera. Index benthic foraminifera *Pastrickella balcanica* (Cherchi, Radoičić and Schroeder), *Chrysalidina gradata* d'Orbigny, *Vidalina radoicicae* Cherchi and Schroeder, *Pseudorhapydionina dubia* De Castro (Fig. 9) clearly indicate middle to late Cenomanian age for the top of Milna Formation. Rudist debris and in places whole radiolitid shells make up the lithostrome interlayers. The remaining allochems include fine-grained carbonate bioclasts and detritus, ostracods, echinoid spines, crinoids, and fragments of dasycladal algae (*Heteroporella lepina* Praturlon). This interval also features bioturbated interlayers, a neptunian dike (at 13 m of the section) and undulated upper bedding planes.

Relative to other localities and sections in the surrounding area, the transition between Milna and Veli Rat Formations at Premuda is atypical. At 30 m of the section (Figs. 3 and 4), there is a first 2.5 m thick layer of calcisphere wackestone–packstone with increased proportion of fine bioclasts, overlain by 4 m of shallow-marine lithotypes. This pattern is repeated for the next 24

m. The proportion of fine bioclasts in the calcisphere wackestone–packstone decreases upwards and the thickness of the deeper-marine deposits increases. The shallow-marine unit becomes more thinly bedded and with a higher proportion of radiolitid bioclasts upsection. Deeper-marine limestones dominate the stratigraphic interval between 44 and 140 m. Within this interval, from 44 to 60 m, there are two up to a meter-thick lenticular intercalations of coarse-grained bioclastic-lithoclastic floatstone (Figs. 8b, 8c, 8d and 8e). Farther upsection, from 60 to 102 m, the intercalations are thinner and characterised by fine-grained bioclastic packstone (up to 0.5 m thick lenses at every 5 to 10 m of the section). From 102 m to the top of the section there are no intercalations of platform-derived bioclastic limestone and the succession contains only pelagic allochems.

Based on the first appearance of thick-bedded to massive calcisphere wackestone–packstone, the 30–140 m interval of Premuda section is attributed to the Veli Rat Formation. This interval contains calcareous dinoflagellates, planktonic foraminifera, ostracods, pelagic crinoids, sponge spicules, echinoid spines, fine bivalve bioclasts, and undefined carbonate detritus. Identified planktonic foraminifera include: *Whiteinella archaeocretacea* Pessagno, *Helvetoglobotruncana praehelvetica* (Trujillo), *Whiteinella* cf. *paradubia* (Sigal), *Dicarinella primitiva* (Dalbiez), *Dicarinella imbricata* (Monrod), *Praeglobotruncana* cf. *algeriana* (Caron), *Rotalipora* sp., *Praeglobotruncana* sp., *Praeglobotruncana gibba* (Klaus), *Helvetoglobotruncana* cf. *helvetica* (Bolli), *Marginotruncana sigali* (Reichel), *Archaeoglobigerina* cf. *cretacea* (d'Orbigny), *Archaeoglobigerina* cf. *blowi* Pessagno, and *Heterohelix* sp. (Fig. 10). Index planktonic foraminifera indicate the lower Turonian to lower Coniacian stratigraphic range (Caron 1985).

4.3. Stable-isotope Data ($\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$) of Bulk Micrite

Sampling of the stratigraphic sections for carbon and oxygen isotope analysis targeted the CTB interval with the intention of comparing the results with the European carbon-isotope reference curve from Eastbourne (Gun Gardens, England; Paul et al. 1999; Jarvis et al. 2006; Pearce et al. 2009; Figs. 4 and 5). Micritic carbonate components were sampled from the 20 to 135 m section interval at Barban, and from 18 to 97 m at Premuda. The Barban section samples have $\delta^{13}C$ values ranging between 0.71 and 3.77‰ and $\delta^{18}O$ between -5.64 and -0.98‰, and the Premuda samples yielded $\delta^{13}C$ values of -0.96 to +4.13‰ and $\delta^{18}O$ values of -6.58 to -3.48‰ (Fig. 5; Table 1). The Barban section shows a certain degree of covariance between the $\delta^{13}C$ and $\delta^{18}O$ data (for a more detailed explanation see Section 5). The Premuda section has no significant covariance between the $\delta^{13}C$ and $\delta^{18}O$ data (Fig. 5).

4.4. Carbon isotope values ($\delta^{13}C_{carb}$) of the Barban section

The first sample for stable isotope analysis was collected in the Milna Formation at 20.5 m of the Barban section. The $\delta^{13}C$ values start at about 3.0 ‰ and for the next 10 m they gradually decrease to 2.5 ‰ (Fig. 4). The 30-45 m interval (the uppermost Milna Formation) is characterised by fluctuations in $\delta^{13}C$ values between 2.0 and 4.0 ‰. At 45 m of the Barban section, in the Sv. Duh Formation, there is a steep decrease in $\delta^{13}C$ values from 3.0 to 0.75 ‰. In the overlying 10 m (45-55 m of the section) the values vary between 0.75 and 2.1‰. At 56 m of the section, the values sharply increase to 3.5 ‰. In the following 24 m (56-80 m) the values remain relatively uniform (around 3.0 ‰) and without major oscillations. At 80 m of the section there is another positive shift in $\delta^{13}C$ values from 3.0 ‰ to 4.0 ‰. The values remain relatively high (between 3.5 and 4.0 ‰) in the next 25 m (105 m of the section). The interval from 105 to 115 m of the section revealed a decline from 4.0 to 2.4 ‰ in $\delta^{13}C$ values. In the following 2 m the values increase to 3.5 ‰ (at 117 m of the section) and for the rest of the succession (117-135 m) they vary between 3.0 and 3.5 ‰ (Figs. 4 and 5; Table 1).

4.5. Oxygen isotope values ($\delta^{18}O_{carb}$) of the Barban section

Starting with -0.1 ‰ at 20.5 m in the Milna Formation of the Barban section, the $\delta^{18}O$ values decrease gradually to -3.9 ‰ for the next 13 m (Fig. 4). The interval from 33 m to 45 m of the section is characterised by significant fluctuations in $\delta^{18}O$ values between -2.7 and -5.4 ‰, with a generally decreasing-upward trend. For the next 10 m (45–55 m of the section) the $\delta^{18}O$ curve oscillates between -5.4 and -4.3 ‰. Above this interval, a general shift towards positive values is maintained for 30 m of the section. Between 55 and 85 m, the values increase upsection and vary from -5.5 to -3.2 ‰. For the rest of the section the values vary slightly between -3.9 and -3.0 ‰ (Figs. 4 and 5; Table 1).

4.6. Carbon isotope values ($\delta^{13}C_{carb}$) of the Premuda section

The first sample collected in the Milna Formation at 18 m of the Premuda section has a $\delta^{13}C$ value of -0.5 ‰ (Fig. 4). For the next 2 m the $\delta^{13}C$ values increase to 2.2 ‰ followed by a sharp decline to -0.7 ‰ (at 25 m of the section). The next 5 m record an increase to the highest $\delta^{13}C$ value of 4.0 ‰ at the transition between Milna and Veli Rat Formations. The 30-42 m interval is characterised by fluctuating, but generally decreasing values, reaching the minimum of -1.0 ‰. An upward shift to positive values (up to 4.0 ‰ at 55 m of the section) in the 42-59 m interval is also marked by pronounced fluctuations. For the next 12 m (60–72 m) the carbon-isotope curve follows a decreasing trend from 4.0 to 0.5 ‰. A recovery to a maximum value of 4.1 ‰ occurs at 74 m of the Premuda section, and the uppermost 23 m (74-97 m) show the values decline to 2.8 ‰ in an oscillating fashion (Figs. 4 and 5; Table 1).

4.7. Oxygen isotope values ($\delta^{18}O_{carb}$) of the Premuda section

The Premuda section samples show a considerable variation in their $\delta^{18}O$ values from -6.6 to -3.5 ‰. Initially the values show a slight increase from -4.5 ‰ at 18 m of the section to -3.5 ‰ at 30 m, followed by a sharp decline to -6.6 ‰ at 34 m at the transition between Milna and Veli Rat Formations (Fig. 4). In the next 18 m (30-48 m) the values fluctuate between -6.6 and -4.6 ‰. The fluctuating trend continues upward to the top of the section (48–97 m), with a change in the slope of the curve towards slightly more positive values. The lowest values (-6.0 to -5.5 ‰) are recorded at 55, 74, 84 and 92 m, and the highest values of -4.5 to -4.3 ‰ come from 68, 80 and 86 m (Figs. 4 and 5; Table 1).

4.8. TOC and Insoluble Residue Analysis

The variations in TOC and insoluble residue from the Barban section are shown in Figure 5 and Table 1. To display the relationship of TOC/insoluble residue/stable-isotope data of relatively pure carbonates (shallow-marine limestones) the TOC values are multiplied by 100 (Fig. 5). In the lowermost 23 m of the Barban section (20-43 m) the TOC values oscillate between 0.02 and 0.7 ‰. In the next 2 m (43–45 m) the TOC reaches the highest value of 1.8 ‰ at the transition between Milna and Sv. Duh Formations, followed by a sharp decline (45–47 m) to 0.2 ‰. For the next 48 m (47–95 m) the TOC curve shows fluctuations with a generally increasing upward trend from 0.2 to 0.8 ‰. For the rest of the section the TOC values show somewhat less variation and a general upward decrease from 0.8 to 0.1 ‰. The insoluble residue curve (clay minerals and quartz) coincides with the TOC one, from a minimum value of -0.13 % and the maximum of 2.47 %. Noticeable fluctuations in the insoluble residue values were observed at intervals 37–46 m, 83–96 m and 114–121 m (Fig. 5).

5. Interpretations and Discussion

Despite local and regional mid-Cretaceous synsedimentary tectonism and late Cenomanian global sea-level changes, the paleoenvironmental conditions throughout the AdCP remained relatively stable and highly productive throughout this time (Gušić and Jelaska 1990; Vlahović et al. 2005; Tišljar et al. 1998; Cvetko Tešović et al. 2011; Korbar et al. 2012; Brčić et al. 2017; Picotti et al. 2019). Post-Cenomanian tectonic changes, however, served as a prelude for a transition in depositional geomorphology from rimmed carbonate platform (Paleocene) to a ramp (Eocene). In the study area during the CTB interval, synsedimentary tectonism locally overprinted eustatic changes and laterally created uplifted areas undergoing subaerial exposure coeval with the existence of intra-platform basins (Brčić et al. 2017; Fig. 6). This caused a pronounced lateral differentiation of the AdCP facies (Tišljar et al. 1994, 1998, 2002; Vlahović et al. 1994, 2002a, b, 2005; 2011; Velić et al. 2002, 2003). The processes of karstification and the formation of paleorelief affected the emerged parts of western AdCP (upper part of the Milna Formation). Tectonically and eustatically drowned areas (i.e., intra-platform basins) experienced deeper-marine depositional conditions (see Fig. 6) as reflected in the transition into the overlying Sv. Duh and Veli Rat Formations.

5.1. Shallow-marine facies

The upper parts of the Milna Formation are characterised by intensive carbonate bioproduction (dominant contribution of biomaterial in the form of large benthic foraminifera and rudist bioclasts; Fig. 4 and Fig. 9). Cenomanian foraminiferal assemblages in the study area are probably the richest in the entire succession of shallow-marine carbonates (from the Toarcian to the Santonian; Velić 2007). Cyanobacterial laminites predominate in the top few meters of the Milna Formation, and sporadic fenestral mudstones with laminites indicate the minimum water levels in large parts of the carbonate platform (Raspini 2012). The upper part of the Milna Formation is represented by the shallow-marine carbonate platform facies in the first 42 m of the Barban section and 30 m of the Premuda section (Fig. 4; Gušić and Jelaska 1990). Peloid-skeletal wackestone–packstone alternating with microbial laminites and sporadic rudist bioclastic floatstone with fine-grained carbonate bioclasts, ostracods, fragments of dasycladal algae and crinoids were formed in protected environments, ranging from shallow subtidal, across intertidal to tidal flats (Fig. 6a). Detailed descriptions of this paleoenvironment are provided by Korbar et al. (2001), Steuber et al. (2005), and Korbar and Husinec (2003; Kvarner area; Fig. 1).

Late Cenomanian in the study area is characterised by the presence of benthic foraminifera *Pastrickella balcanica* (Cherchi, Radoičić and Schroeder), *Vidalina radoicicae* Cherchi and Schroeder, *Chrysalidina gradata* d'Orbigny, and *Pseudorhapydionina dubia* De Castro (Fig. 9). In addition, there are also *Cisalveolina* sp., *Peneroplis planatus* (Fichtel & Moll), *Scandonea* sp., *Cuneolina* cf. *pavonia* (d'Orbigny) *Pseudonummoloculina heimi* (Bonet), *Idalina* cf. *antiqua* (Munier-Chalmas et Schlumberger), *Nezzazata* cf. *gyra* (Smout), and *Nezzazata simplex* (Omara). Following the biozonations of Velić (2007), Chiocchini (2008) and Frijia et al. (2015), this interval belongs to the *Chrysalidina gradata* benthic foraminifera biozone.

At the Barban section, following the carbonate platform drowning at the CTB, a minor regressive phase and infilling of intraplatform basins with shallow-marine paleoenvironmental conditions were re-established in middle Turonian (Fig. 6c). The stratigraphic interval from 154 to 175 m in the Barban section belongs to the Gornji Humac Formation. Its middle Turonian to Coniacian age is defined by the presence of *Distefanella* (Henhöfer et al. 2014) and *Hippurites requieni* Matheron rudists, *Moncharmontia* sp., *Pseudocyclammina sphaeroidea* Gendrot, *Scandonea samnitica* De Castro, S. *mediterranea* (De Castro), *Dicyclina schlumbergeri* Munier-Chalmas and *Murgella lata* Luperto-Sinni benthic foraminifera, but also *Decastronema* *kotori* (Radoičić) and *Thaumatoporella parvovesiculifera*. Coniacian limestones of the Gornji Humac Formation at the Barban section represent the last deposits of the AdCP in this area. Unlike the above, the Veli Rat Formation at the Premuda section continued with deeper-marine sedimentation into the Santonian (see Section *5.3.* Figs. 3 and 6).

5.2. Transition from shallow-marine to deeper-marine facies

In contrast with the Cenomanian, the Turonian on AdCP (and surrounding shallow-marine carbonate platforms) is characterised by a decrease in the diversity and abundance of benthic foraminiferal assemblages as a consequence of global sea-level rise in the latest Cenomanian and earliest Turonian (Gušić and Jelaska 1990; Velić 2007; Parente et al. 2008). Transition between the Milna and Sv. Duh Formations at the Barban section is a typical example of oscillatory transgression (series of cyclic steps generally showing a deepening upward trend). The stratigraphic interval between 40 and 44 m contains several successive repetitions of shallow-marine bioclastic material and micritic intercalations with pelagic influence. The same transition in the Premuda section has characteristic features of the proximal part of the carbonate turbidite facies with reworked, poorly sorted bioclastic breccias found inside the deeper-marine calcisphere mudstone-wackestone (Colacicchi and Baldanza 1986; Fuček et al. 1991; Moro and Ćosović 2013). These changes are repeated throughout the 30–54 m interval of the Premuda section. Occasionally there are slope-derived slump structures associated with fine-grained, reworked benthic platform bioclasts and autochthonous pelagic material with the appearance of neptunian dykes. These deposits indicate that Premuda, unlike the Barban section, was located on the intraplatform basin margins during the CTB (Figs. 2a and 6). Benthic fossils in bioclastic input within the transitional zone are represented with index foraminifera *Pastrickella balcanica* (Cherchi, Radoičić and Schroeder), *Vidalina radoicicae* Cherchi and Schroeder, *Chrysalidina gradata* d'Orbigny, *Cisalveolina* sp., and *Pseudorhapydionina dubia* De Castro. The CTB is also characterised by resedimented upper Cenomanian index benthic foraminifera within autochthonous pelagic layers of the transitional zone with planktonic foraminifera (*Whiteinella archaeocretacea*, *W. praehelvetica*, *W.* cf. *paradubia*, *Rotalipora* sp. and *Praeglobotruncana* sp.).

5.3. Deeper-marine facies

The total thickness of the Sv. Duh Formation deposits in the Barban section is 116 m. Stratigraphically these deposits are entirely Turonian, and have a sharp transition into the overlying shallow-marine Gornji Humac Formation (Turonian–Coniacian). Unlike Barban, the Premuda section reveals a prolonged deeper-marine sedimentation (the Veli Rat Formation). The youngest pelagic fossils from the upper part of the Premuda section are of Coniacian age (*Marginotruncana sigali*, *Dicarinella* sp., *Archaeoglobigerina* cf. *cretacea*, *A. blowi*; Fig. 10). Geological mapping of the wider area of the island also revealed some even younger pelagic deposits (Santonian; Moro and Ćosović 2013; Fuček et al. 2018). The difference in paleogeographic location of the individual sections is also evident in the dominance of pelagic components at Premuda (dinoflagellate cysts and planktonic foraminifera; Figs. 4 and 6). The pelagic deposits are about 100 m thick in both stratigraphic sections. At Barban the complete pelagic interval formed during the latest Cenomanian and almost the entire Turonian (in the span of approximately 5 million years, Cohen et al. 2018). At the Premuda section, the same interval was deposited from the latest Cenomanian through the beginning of Coniacian (approximately 6 million-year span, Cohen et al. 2018). The main reason for lower depositional rates and/or smaller thickness of the Premuda deposits (i.e., the Veli Rat Formation) is the difference in their paleoenvironment. The Premuda section was situated on the margin of an intraplatform basin, which resulted in greater accommodation space and stronger open ocean influence, but was characterised by lower depositional rates (see Fig. 3 for the relationship between thickness and stratigraphic intervals). In contrast, the Barban section was likely located in a more protected intraplatform area where high bioclastic production (see Figs. 2 and 6) and small accommodation space resulted in faster infilling and shallowing of the drowned platform facies (i.e., the Sv. Duh Formation). Thus, Barban is characterised by a greater thickness of the CTB drowned platform succession (constant backfill of fine bioclastic material from the surrounding areas resulted in thicker pelagic successions).

Early–middle Turonian global eustatic sea-level fall (Hardenbol et al. 1998; Miller et al. 2005; Voigt et al. 2006; Haq 2014; Sames et al. 2016) caused a faster backfill of intraplatform depressions with bioclastic material (mainly fragments of rudist colonies and benthic foraminifera) from the surrounding shallow-marine areas (Gušić and Jelaska 1993; Korbar et al. 2001). This process is clearly visible in the Barban section at the 136–175 m interval (transition between the Sv. Duh and Gornji Humac Formations). The re-establishment of shallow marine depositional environments in the late Turonian was characterised by gradual recolonization of rudists and benthic foraminifera, but with lower richness of taxa and smaller number of specimens relative to the Cenomanian (Velić 2007). At the Premuda section, the shallow-marine deposits of the Gornji Humac Formation (the upper boundary of the Veli rat Formation) are buried under the recent Adriatic Sea deposits (Fig. 1f) and are thus inaccessible for direct observation.

5.4. Stable isotope, TOC and insoluble residue data

Chronostratigraphic calibration of Upper Cretaceous shallow-marine carbonate platform deposits of the Tethyan area is commonly hindered by low-resolution stratigraphic schemes due the lack of chronostratigraphic markers such as ammonites, planktonic foraminifera and calcareous nannoplankton (Fleury 1980; De Castro 1991; Chiocchini et al. 2008; Velić 2007). For this reason, isotope geochemistry ($\delta^{13}C$ and $\delta^{18}O$) is currently the best available stratigraphic tool (Frijia et al. 2015; Brčić et al. 2017). The results of stable isotope analysis (Table 1; Fig. 5) were used to improve stratigraphic interpretations and global correlation of the studied deposits. The challenging aspects of this part of the research were the limited number of samples, tectonically disturbed successions, and diagenetic modifications. Recrystallization of carbonate mud is the main diagenetic process that impacted the carefully selected micritic samples without obvious carbonate cement and skeletal fragments. Nevertheless, the study produced isotope curves that show significant correlation with the informal reference curves of basinal successions (Paul et al. 1999; Jarvis et al. 2006; Pearce et al. 2009; Fig. 5). During the Cenomanian and Turonian there was no terrigenous input to the north-western part of the isolated AdCP (Fig. 2a). Even though the interiors of large carbonate platform are commonly isolated and subject to localized environmental fluctuations, global events such as OAE2 (Jenkyns 1980, 2010; Schlanger et al. 1987; Arthur et al. 1987, 1988, 1990; Paul et al. 1999; Tsikos et al. 2004; Keller et al. 2004; Pearce et al. 2009; Jarvis et al. 2011; among others) and sea level maxima (Haq 2014) were large enough in scope to overprint local influences and get recorded and preserved in the depositional succession of the AdCP shallow-marine settings regardless of diagenetic modifications (Jenkyns 1991; Gušić and Jelaska 1993; Hilbrecht et al. 1996; Davey and Jenkyns 1999; Parente et al. 2008; Immenhauser et al. 2008; Elrick et al. 2009; Gertsch et al. 2010; Nagm 2015; Brčić et al. 2017). These influences are evident in the drowned platform facies of the northwestern part of the AdCP (Fig. 6b), oxygen-restricted paleoenvironmental conditions and intervals of carbonate factory crisis reflected in bioturbation (Fig. 3), sulphate reduction, synsedimentary pyrite and greenish glauconite (other sections in Istria, Ćićarija, Brčić et al. 2017). The nearest previously examined OAE2 sedimentary successions are carbonate-free black shales in Italy (Gubbio; Coccioni and Luciani 2005), Austria (Rehkogelgraben; Wagreich et al. 2008) and Greece (Ionian zone; Karakitsios et al. 2007, 2010). However, the results of carbon and oxygen isotope analyses were here compared to chalk deposits from Eastbourne Gun Gardens (Fig. 5) because they currently represent the best reference curve for this stratigraphic interval. This reference curve records the pre-excursion levels, the first build up (or peak *a*), the trough, the second build-up (peak *b*), and the plateau (ending with peak *c*; Paul et al. 1999; Tsikos et al. 2004).

Facies variation and diagenesis may limit the reliability of $\delta^{13}C$ data from the same interval within a single section (Immenhauser et al. 2008; Wendler 2013; Jarvis et al. 2015). The covariance between $\delta^{13}C$ and $\delta^{18}O$ data (correlation coefficient is 0.74) observed in the Barban section (Fig. 5) suggests that carbon isotope values here may have been affected by diagenetic modifications (such as recrystallization in the presence of meteoric fluids; Swart and Oehlert 2018). Despite this diagenetic potential, the similarity with Premuda carbon-isotope record, which shows less covariance with $\delta^{18}O$ values (correlation coefficient is 0.19), and the ability to correlate these local sections with the global reference curve, regardless of major differences in their thickness and lithology (Figs. 3 and 5), supports the application of carbon-isotope stratigraphy in this research regardless of its limitations. Such application was made possible by careful integration of chemostratigraphy with detailed litho- and biostratigraphic data (Figs. 3-5 and 7-10), and was also aided by TOC and insoluble residue data.

The $\delta^{18}O$ values of diagenetically modified carbonates are mainly controlled by fluid composition, temperature and water/rock ratios (Brand and Veizer 1981). In most Cretaceous carbonates (Scholle and Arthur 1980), the $\delta^{18}O$ data show significant depletion at CTB, suggesting meteoric water influence (Hajikazemi et al. 2010). Similary, the $\delta^{18}O$ values of the Barban section are diagenetically modified, but the $\delta^{18}O$ values of Premuda section generally coincide with the global trend interpreted to reflect the warmest conditions at end of Cenomanian (Jarvis et al. 2011). Despite diagenetic modifications of oxygen-isotope values that limit their potential as paleoenvironmental proxies, the carbon-isotope ratios of the same samples are expected to be more resilient to diagenetic resetting and to more closely resemble the original depositional signatures (Marshall 1992; Parente et al. 2007). Departures towards more negative $\delta^{13}C$ values are interpreted as a consequence of interaction with fluids enriched in ^{12}C derived from organic-matter degradation (Irwin et al. 1977). Compared to Eastbourne $\delta^{13}C$ curve, both research sections show large amplitude in $\delta^{13}C$ variations. The end of peak *a* in both sections is marked by a very abrupt, rapid shift to low $\delta^{13}C$ values, followed by very low values between *a* and *b* peaks. A possible explanation for the observed trends is condensed sedimentation. The rich carbonate production reflected in bioclastic lithotypes of the Milna Formation was abruptly replaced with drowned platform facies (Sv. Duh and Veli Rat Formations) of mudstones with rare dinoflagellate cysts and planktonic foraminifera. These events are closely related to the sharp rise in sea level at the very end of the Cenomanian (Haq 2014). Similar examples of condensed sedimentation at CTB can be found locally (Brčić et al. 2017), but also in other parts of Tethys realm (Gambacorta et al. 2015; Wohlwend et al. 2015). Furthermore, deposition on carbonate platform shoals and intraplatform basins (depths up to 150 m) is highly sensitive to eustatic and tectonic events as reflected, for example, in carbonate turbidite facies of the Veli Rat Formation at Premuda section and bioclastic intercalations of the Sv. Duh Formation at Barban section. This may account for some of the observed fluctuations in $\delta^{13}C$ values (e.g., due to variable rates of organic matter respiration; Patterson and Walter 1994).

The results of TOC and insoluble residue analyses (Fig. 5) of shallow-marine deposits from the Barban section indicate low amounts of non-carbonate components (less than 1% on average of clay minerals and quartz), as expected for shallow parts of isolated carbonate platforms. The slightly elevated TOC values at 45 m of the Barban section correlate with the transition from the first build up to the second build-up on the isotope curves (transition Milna–Sv. Duh

Formation; Figs. 3 and 5). A similar, but less pronounced change occurred at 81 m of the section and correlates with the transition from the second isotope build-up to the plateau. Stratigraphically, this transition also closely corresponds with the Cenomanian–Turonian boundary and can help determine and position the CTB in the study area (Fig. 5). Correlation coefficient between the TOC and carbon-isotope record at the Barban section is 0.27 (Fig. 5), which suggests that post-depositional alteration in the presence of organic matter played a role in diagenetic history of these deposits (Irwin et al. 1977; Oehlert and Swart 2014). Despite these challenges, the integration of detailed biostratigraphy with TOC/insoluble residue and carbon-isotope records helped determine and position the CTB in the study area, as well as improve stratigraphic resolution through placing stage boundaries and global correlation of Barban and Premuda sections. The first OAE2 geochemical imprint (positive carbon isotope values in response to enhanced organic carbon burial) was detected in uppermost Milna Formation deposits (i.e., the first build up, see Section *5.4* and Fig. 4), preceded by a global rise in sea level at the end of the Cenomanian (Haq 2014). The strongest OAE2 geochemical imprint is recorded in transition from shallow-marine to deeper-marine facies (uppermost Milna Formation deposits to Sv. Duh/Veli rat Formation; peak *b*; see Section *5.4* and Figs. 4 and 5). The OAE2 geochemical imprint within deeper-marine facies interval (Sv. Duh/Veli rat Formation) is represented with the carbon-isotope *c* plateau phase (see Section *5.4* and Figs. 4 and 5).

6. Conclusions

1) The Milna, Sv. Duh, Veli Rat and Gornji Humac Formations reflect distinct paleoenvironments that existed at the Cenomanian–Turonian boundary (CTB) in

western part of the Adriatic Carbonate Platform (AdCP; Barban and Premuda sections in present-day Croatia). Their deposition was impacted by eustatic sea level changes and synsedimentary tectonics (folding and faulting) resulted in facies differentiation and karstification through uplifts and lowering of individual local platform areas. The Premuda section reveals such tectonic influence (initial forming of intraplatform basins) in combination with sea level rise (pelagic influence).

2) The late Cenomanian sea-level rise lead the AdCP into a carbonate factory crisis and condensed sedimentation**.** Bottom and top layers of the intraplatform basin facies of the Veli Rat Formation and the inner platform drowning facies of the Sv. Duh Formation reflect the interplay between the platform drowning and growth (accumulation and aggradation of lateral shallow-marine sediment). Variations in subsidence and accommodation space fine-tuned the depositional processes and stratigraphic record within the research area.

3) Global oceanic anoxic event (OAE2) at the CTB left its mark starting from the shallow-marine facies (SMF, Milna Formation), through transitional (TF), and ending in deeper-marine facies (DMF, Sv. Duh and Veli Rat Formations) of the study area. The $\delta^{13}C$ values of Barban and Premuda sections indicate that OAE2 impacted the north-western part of AdCP almost entirely in the latest Cenomanian. The observed fluctuations in $\delta^{13}C$ values are evidence of condensed sedimentation and shallow-marine influence. The covariance between $\delta^{13}C$ and $\delta^{18}O$ values at Barban section indicate meteoric diagenesis, but $\delta^{18}O$ values of Premuda section coincide with the global trends interpreted to represent the warmest conditions at the end of Cenomanian. The elevated TOC values at 45 m of the Barban section correlate with the AdCP drowning and a shift to very low $\delta^{13}C$ values. Integration of litho-, bio-, microfacies, and TOC, insoluble residue and stable isotope data indicated a carbonate factory crisis (low sedimentation

rate, drowned platform facies) and geochemical OAE2 imprint at the boundary between the Milna and Sv. Duh/Veli Rat Formations (the latest Cenomanian) in the eastern Istria and southern Kvarner area.

4) Carbon-isotope values from the CTB interval of Barban and Premuda sections in western AdCP represent a combination of global paleoceanographic effects, local environmental factors and diagenetic alteration, and are correlative with the reference curve from English Chalk (Eastbourne, Gun Gardens, England). These correlations contribute towards fine-tuning and calibration of biostratigraphy based on benthic and planktic foraminifera in the study area.
5) Detailed facies interpretations concluded that the Premuda section was located on the margin of an intra-platform basin during the CTB, and the Barban section was in the inner protected areas of the north-western parts of the AdCP. This research contributes an example of integrating the evidence for the influence of global paleoceanographic perturbations on two different (protected platform interior and intra-platform basin) relatively restricted shallow-marine environments with detailed paleogeographic information (emerged, shallow-marine, and drowned platform area) during the CTB in the Tethyan realm.

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Fig. 1: Study area. a) Global position of the study area in Croatia; b) Regional setting including location of previous OAE2-related research areas; c) Local position of the Barban section; d) Local position of the Premuda section; e) Orthophoto (with Digital Relief Model - DRM) of the Barban section exposure (A – starting point, D – end point); f) Orthophoto (with DRM) of the Premuda section exposure (A – starting point, B – end point).

Fig. 2: Paleogeographic setting of the study area. a) The wider Perimediterranean region (prior to approximately 100 Mya) with paleogeographically reconstructed locations of the Barban (BS) and Premuda (PS) sections within the Adriatic Carbonate Platform (AdCP) (modified after Blakey 2010, and references therein); b) Peninsula Istria during the late Cenomanian to early Turonian (Brčić et al. 2017) with location of the Barban section; c) Premuda island during the late Cenomanian to Santonian with location of the study section.

Fig. 3: Detailed measured stratigraphic sections at the Barban and Premuda sites, indicating rock formations names (lithostratigraphy), age, and lithologies and fossils present.

Fig. 4: Detailed stratigraphic sections measured at Barban and Premuda with photomicrographs of the typical facies present (SMF – shallow-marine facies, TF – transition shallow-marine to deeper-marine facies, DMF – deeper-marine facies; see Section 5), correlated (grey interval) on the basis of their carbon isotope compositions. Isotope curves were constructed by connecting all individual data points. Photomicrograph scale = 1 mm.

Fig. 5: Correlation of the Barban and Premuda sections with the reference Eastbourne section (Pearce et al. 2009) using stable-isotope data and benthic/planktonic foraminifera biozones.

Green dotted line represents CT boundary. TOC and insoluble residue data for the Barban section are also shown.

Fig. 6: Block diagrams of paleoenvironmental conditions from late Cenomanian to early Coniacian in the wider research area: NWI – North-western Istria; BS – paleogeographic location of the Barban section; PS – paleogeographic location of the Premuda section (see text for details).

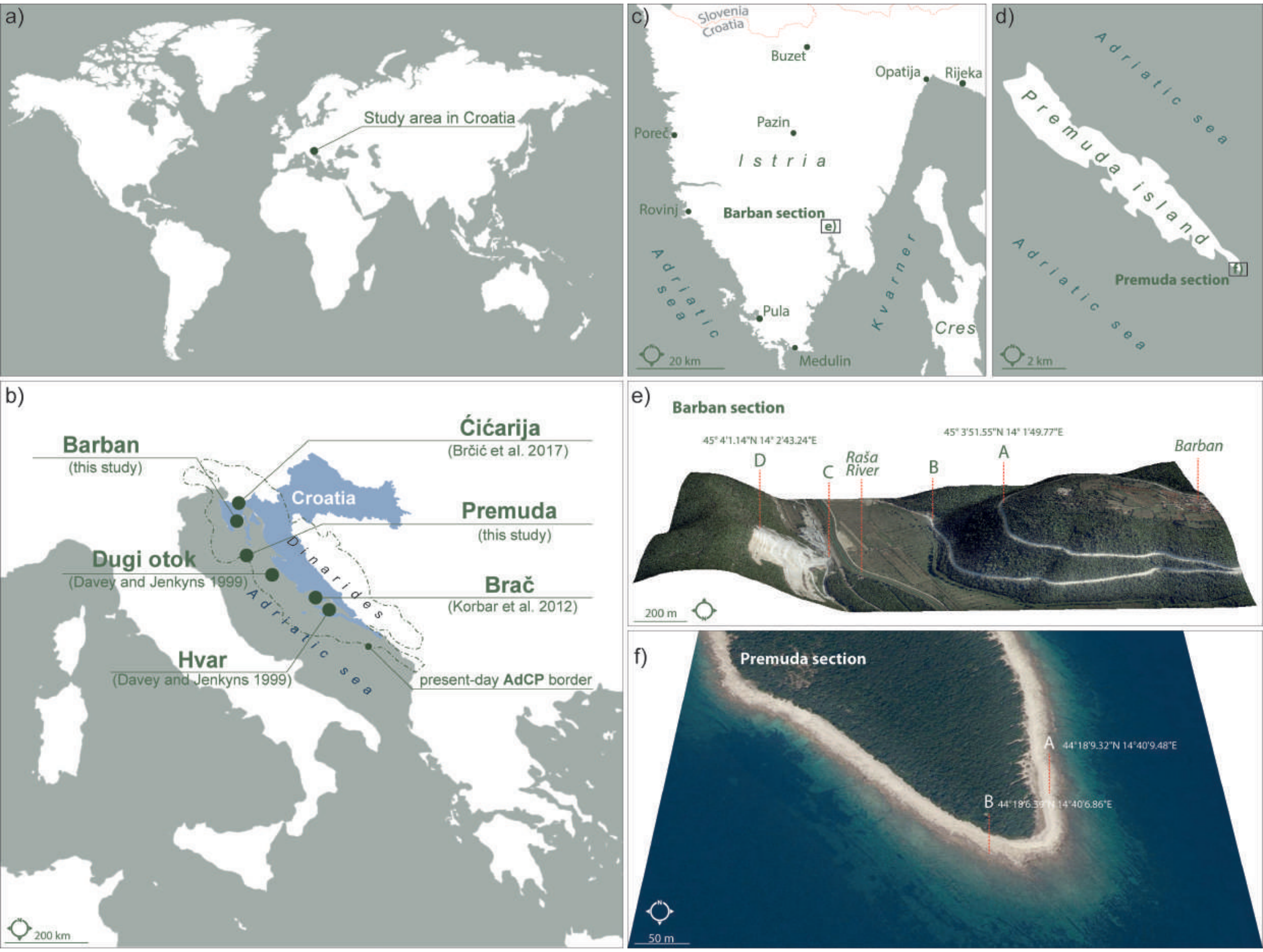
Fig. 7: Field photographs of the Barban section: **a)** Thin-bedded upper Cenomanian deposits at the western part of the Barban section (see Fig. 1e); **b)** Thin-layered transition between the Milna (shallow-marine) and Sv. Duh (with pelagic influence) Formations (oscillating transgression, see Section *5.2.*; hammer for scale is 32 cm long); **c)** Radiolitid rudist biostrome of the Milna Formation (upper Cenomanian); **d)** Transition shallow-marine to deeper-marine facies with a stylolite (black dotted line) between the Sv. Duh (SD, calcisphere wackestone) and Gornji Humac Formations (GH, peloidal grainstone).

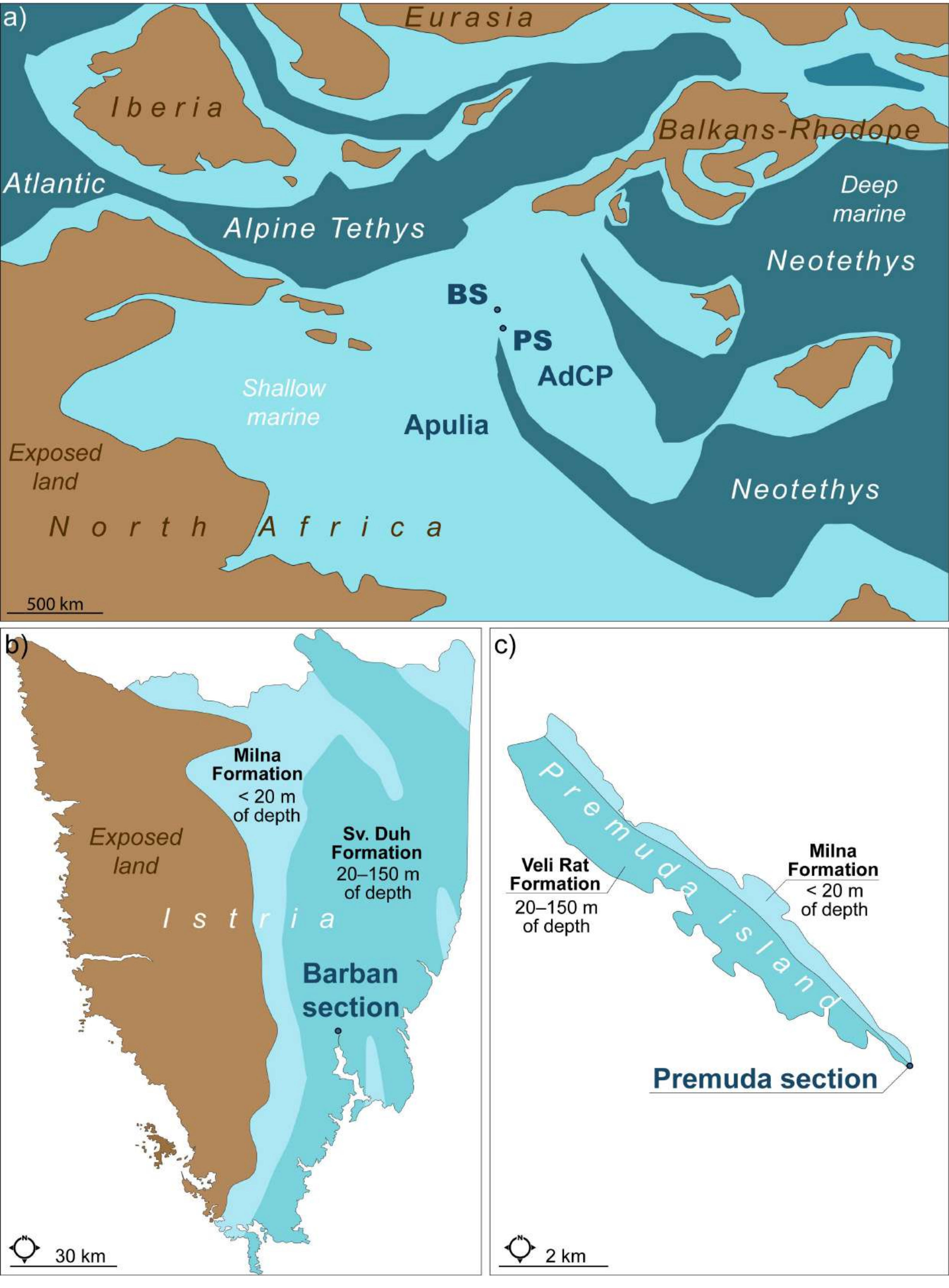
Fig. 8: Field photographs of the Premuda section: **a)** Radiolitid (Ra) and chondrodontid (Ch) lithostrome floatstone of the Milna Formation; **b)** Coarse lithoclasts (lth) and other shallow-marine material re-deposited in bioclastic-lithoclastic lithosome intercalated within the calcisphere wackestones in the lower part of the Veli Rat Formation; **c)** and **d)** Lithoclasts (lth) of the shallow-marine Milna Formation deposits within the deeper-marine Veli Rat Formation deposits; **e)** subvertical layers (interval between 44 and 60 m) of the Premuda section (view to the east; see Figs. 1 and 3).

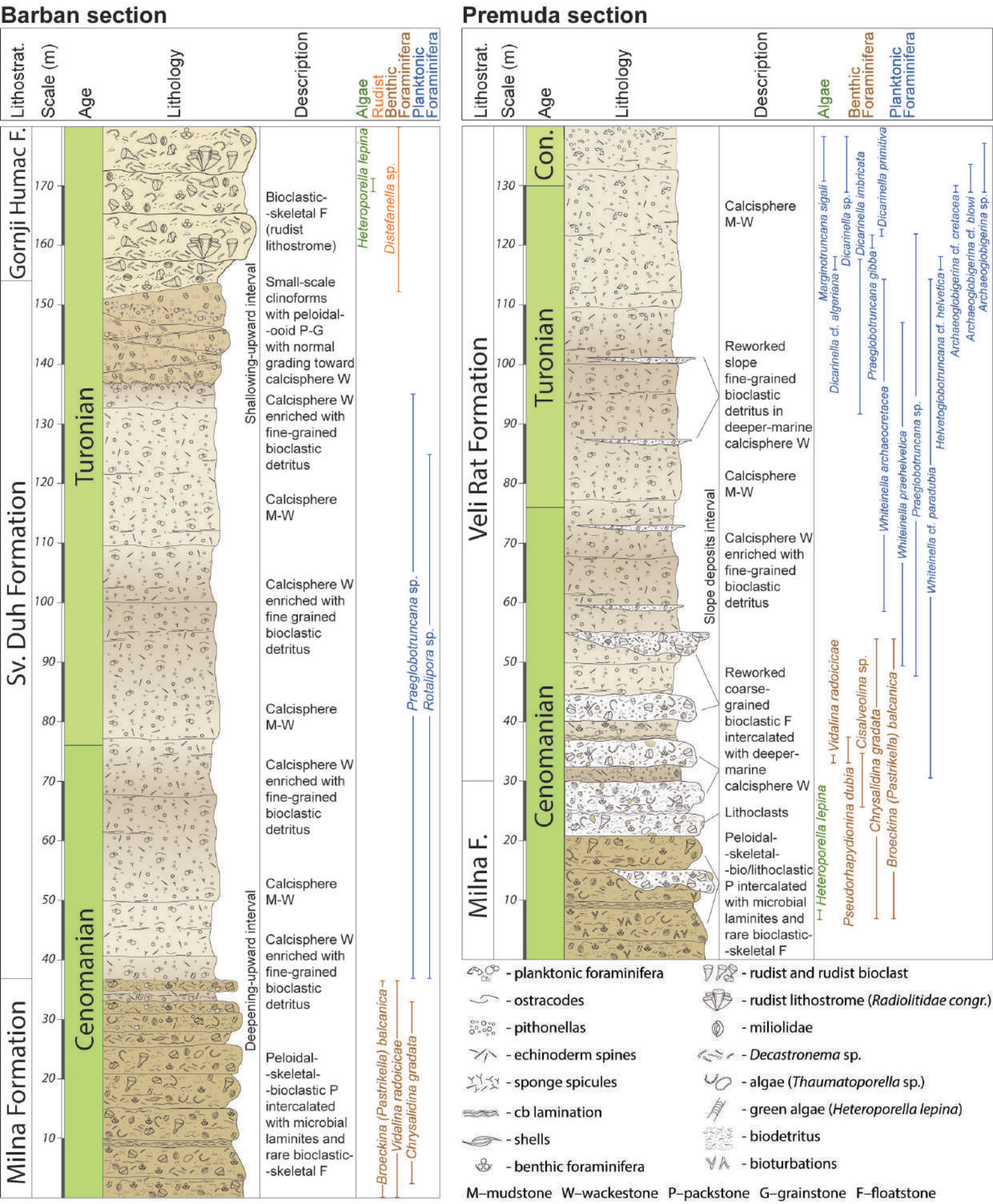
Fig. 9: Photomicrographs of benthic foraminifera from the Barban and Premuda sections (scale = 0.5 mm): **a)** and **b)** *Pastrickella balcanica* (Cherchi, Radoičić and Schroeder), samples Plo-26b and BB-6; **c)** and **d)** *Heteroporella lepina* Praturlon, sample BB-32; **e)** *Heteroporella lepina* Praturlon, sample BB-32; **f)** *Thaumatoporella parvovesiculifera* (Raineri), sample Plo-37a; **g)** and **h)** *Cisalveolina* sp., samples Plo-16b and Plo-24 ; **i)** *Peneroplis planatus* (Fichtel and Moll), sample Plo-34; **j)** *Scandonea* sp., sample BB-11; **k)**, **l)** and **m)** *Cuneolina* cf. *pavonia* (d'Orbigny), samples BB-06 and BB-04; **n)** *Vidalina radoicicae* Cherchi and Schroeder, sample BB-11; **o)** *Pseudonummoloculina heimi* (Bonet), sample BB-06; **p)**, **q)** and **r)** *Chrysalidina gradata* d'Orbigny, samples BB-06 and Plo-03; **s)** *Pseudorhapydionina dubia* De Castro, sample BB-06; **t)** *Idalina* cf. *antiqua* (Munier-Chalmas et Schlumberger), sample BB-06; **u)** *Nezzazata* cf. *gyra* (Smout), sample BB-06; **v)** *Nezzazata simplex* Omara, sample BB-04.

Fig. 10: Photomicrographs of planktonic foraminifera from the Barban and Premuda sections (scale = 200 μm): **a)** *Marginotruncana* cf. *renzi* (Gandolfi), sample Plo-72; **b)** *Heterohelix* sp., sample Plo-71; **c)** *Marginotruncana sigali* (Reichel), sample Plo-70; **d)** *Dicarinella* sp., sample Plo-70; **e)** *Marginotruncana schneegansi* (Sigal), sample Plo-70; **f)** *Archaeoglobigerina* cf. *blowi* Pessagno, sample Plo-65; **g)** *Praeglobotruncana gibba* (Klaus), sample Plo-61; **h)** *Helvetoglobotruncana* cf. *helvetica* (Bolli), sample Plo-59; **i)** *Helvetoglobotruncana praehelvetica* (Trujillo), sample Plo-53; **j)** *Whiteinella* cf. *paradubia* (Sigal), sample Plo-52a; **k)** *Helvetoglobotruncana praehelvetica* (Trujillo), sample Plo-52a; **l)** *Dicarinella imbricata* (Monrod), sample Plo-51; **m)** *Whiteinella* cf. *archaeocretacea* Pessagno, sample Plo-42b; **n)** *Helvetoglobotruncana praehelvetica* (Trujillo), sample Plo-37b; **o)** *Whiteinella* cf. *paradubia* (Sigal), sample Plo-22.

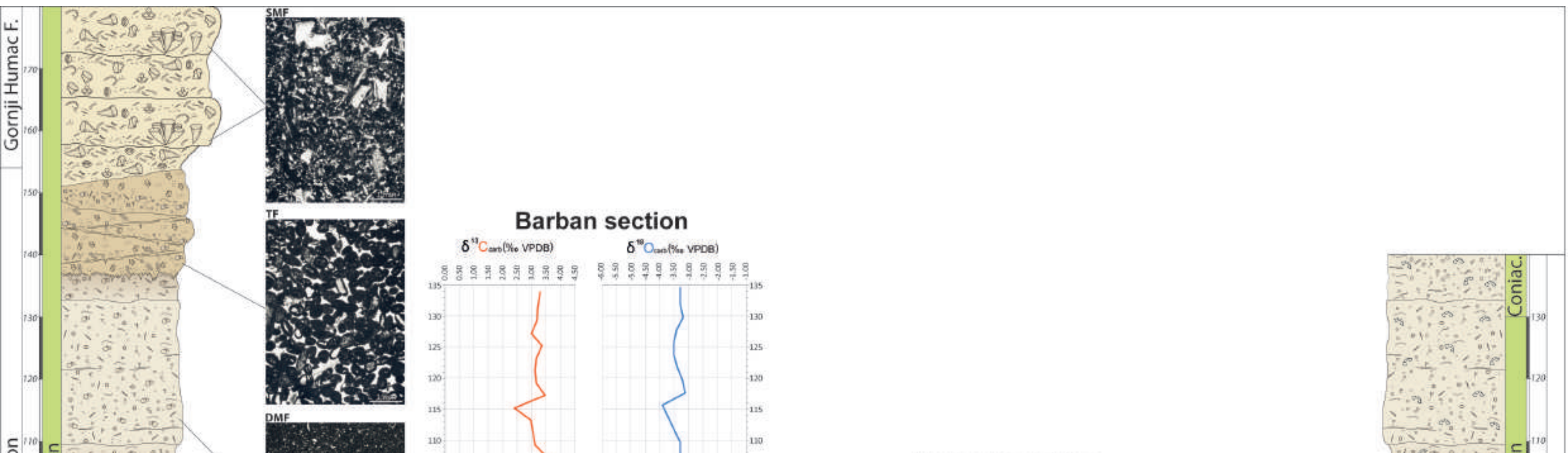
Table 1: Results (values) of stable isotope analysis of 122 samples (81 from Barban and 41 from Premuda section) and TOC and Insoluble Residue Analyses (81 samples from Barban section). - *Appendix/supplement*


a)
Study area in Croatia
b)
Barban
(this study)
Ćićarija
(Brčić et al. 2017)
Croatia
Premuda
(this study)
Dugi otok
(Davey and Jenkyns 1999)
Dinarides
Brač
(Korbar et al. 2012)
Adriatic sea
Hvar
(Davey and Jenkyns 1999)
present-day AdCP border
200 km
c)
Slovenia
Croatia
Buzet
Opatija
Rijeka
Poreč
Pazin
Istria
Rovinj
Barban section
e)
Adriatic sea
Kvarner
Pula
Cres
Medulin
20 km
d)
Adriatic sea
Premuda island
Premuda section
f)
Adriatic sea
2 km
e)
Barban section
45° 4'1.14"N 14° 2'43.24"E
45° 3'51.55"N 14° 1'49.77"E
D
C
Raša River
B
A
Barban
200 m
f)
Premuda section
A 44°18'9.32"N 14°40'9.48"E
B 44°18'6.39"N 14°40'6.86"E
50 m

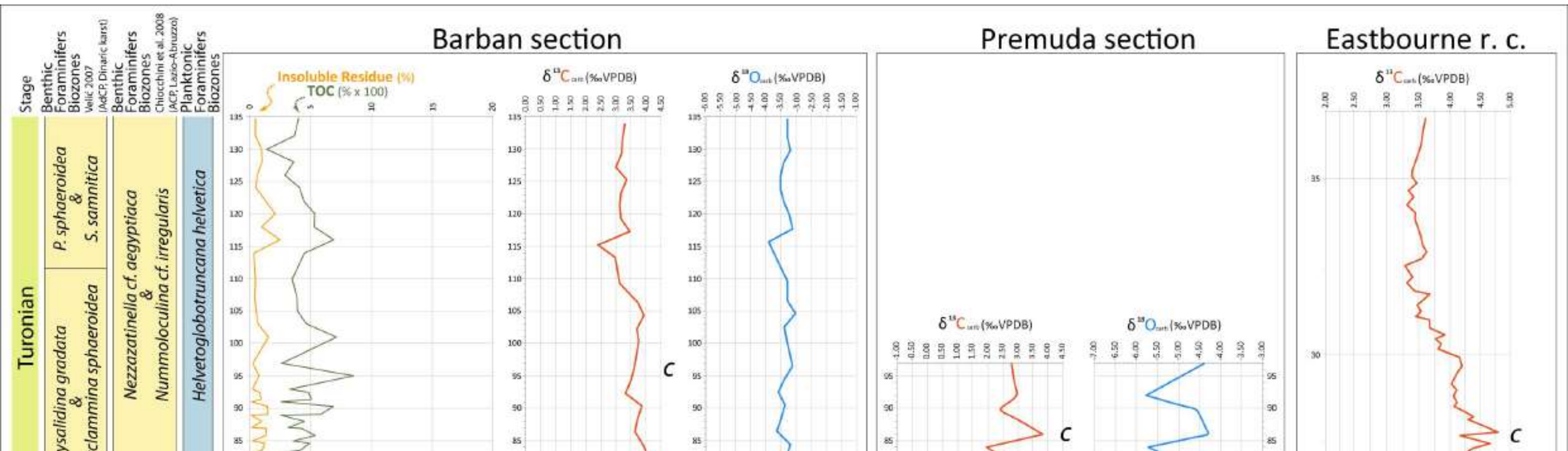

a)
Eurasia
Iberia
Balkans-Rhodope
Atlantic
Deep marine
Alpine Tethys
Neotethys
BS
PS
AdCP
Shallow marine
Apulia
Exposed land
Neotethys
North Africa
500 km
b)
Milna Formation
< 20 m of depth
Exposed land
Sv. Duh Formation
20–150 m of depth
Istria
Barban section
30 km
c)
Premuda island
Milna Formation
< 20 m of depth
Veli Rat Formation
20–150 m of depth
Premuda section
2 km



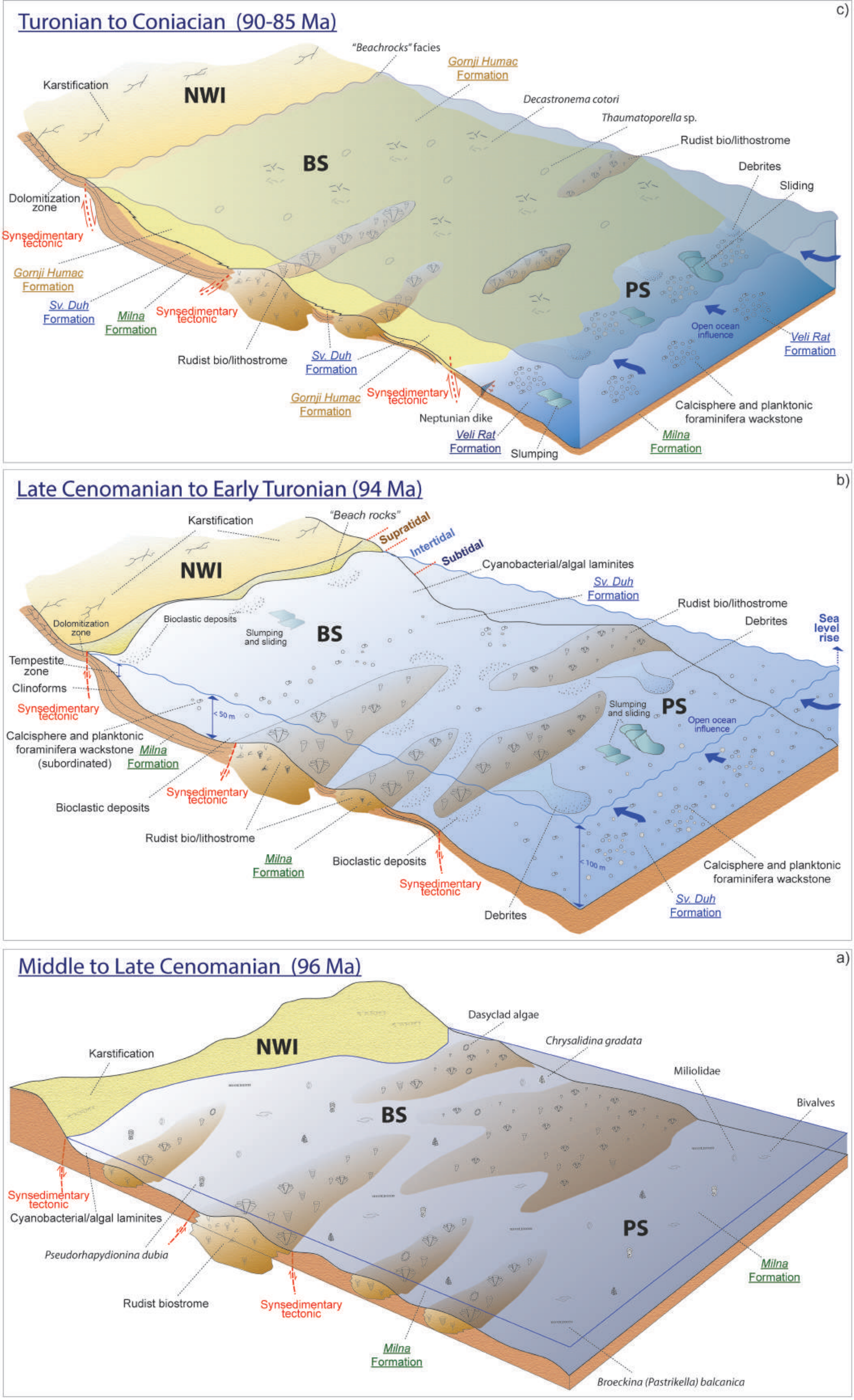
Barban section
Lithostrat.
Scale (m)
Age
Lithology
Description
Algae
Rudist
Benthic Foraminifera
Planktonic Foraminifera
Gornji Humac F.
Sv. Duh Formation
Milna Formation
Turonian
Cenomanian
Bioclastic-
-skeletal F
(rudist
lithostrome)
Small-scale
clinoforms
with peloidal-
-ooid P-G
with normal
grading toward
calcisphere W
Calcisphere W
enriched with
fine-grained
bioclastic
detritus
Calcisphere
M-W
Calcisphere W
enriched with
fine grained
bioclastic
detritus
Calcisphere
M-W
Calcisphere W
enriched with
fine-grained
bioclastic
detritus
Calcisphere
M-W
Calcisphere W
enriched with
fine-grained
bioclastic
detritus
Peloidal-
-skeletal-
-bioclastic P
intercalated
with microbial
laminites and
rare bioclastic-
-skeletal F
Shallowing-upward interval
Deepening-upward interval
Heteroporella lepina
Distefanella sp.
Praeglobotruncana sp.
Rotalipora sp.
Broeckina (Pastrikella) balcanica
Vidalina radoicicae
Chrysalidina gradata
Premuda section
Lithostrat.
Scale (m)
Age
Lithology
Description
Algae
Benthic Foraminifera
Planktonic Foraminifera
Veli Rat Formation
Milna F.
Con.
Turonian
Cenomanian
Calcisphere
M-W
Reworked
slope
fine-grained
bioclastic
detritus in
deeper-marine
calcisphere W
Calcisphere
M-W
Calcisphere W
enriched with
fine-grained
bioclastic
detritus
Reworked
coarse-
grained
bioclastic F
intercalated
with deeper-
marine
calcisphere W
Lithoclasts
Peloidal-
-skeletal-
-bio/lithoclastic
P intercalated
with microbial
laminites and
rare bioclastic-
-skeletal F
Slope deposits interval
Heteroporella lepina
Pseudorhapydionina dubia
Vidalina radoicicae
Cisalveolina sp.
Chrysalidina gradata
Broeckina (Pastrikella) balcanica
Marginotruncana sigali
Dicarinella cf. algeriana
Dicarinella sp.
Dicarinella imbricata
Dicarinella primitiva
Praeglobotruncana gibba
Whiteinella archaeocretacea
Whiteinella praehelvetica
Praeglobotruncana sp.
Whiteinella cf. paradubia
Helvetoglobotruncana cf. helvetica
Archaeoglobigerina cf. cretacea
Archaeoglobigerina cf. blowi
Archaeoglobigerina sp.
- planktonic foraminifera
- ostracodes
- pithonellas
- echinoderm spines
- sponge spicules
- cb lamination
- shells
- benthic foraminifera
- rudist and rudist bioclast
- rudist lithostrome (Radiolitidae congr.)
- miliolidae
- Decastronema sp.
- algae (Thaumatoporella sp.)
- green algae (Heteroporella lepina)
- biodetritus
- bioturbations
M–mudstone W–wackestone P–packstone G–grainstone F–floatstone



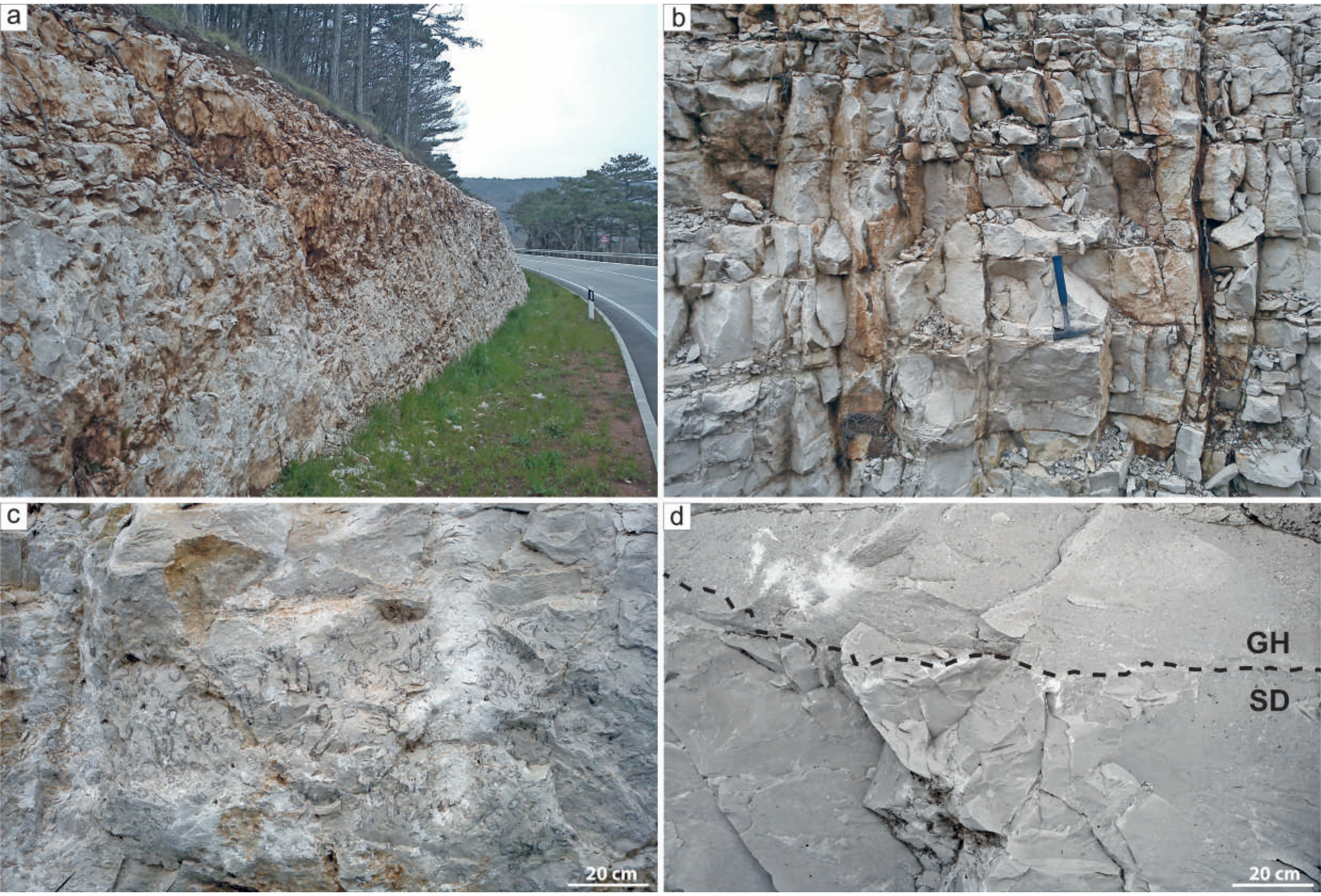
Barban section
Premuda section
$\delta^{13}C_{carb}$ (‰ VPDB)
$\delta^{18}O_{carb}$ (‰ VPDB)
Scale (m)
a
b
c
SMF
TF
DMF
Gornji Humac F.
Sv. Duh Formation
Milna Formation
Turonian
Cenomanian
Coniac.
Veli Rat Formation
Milna F.

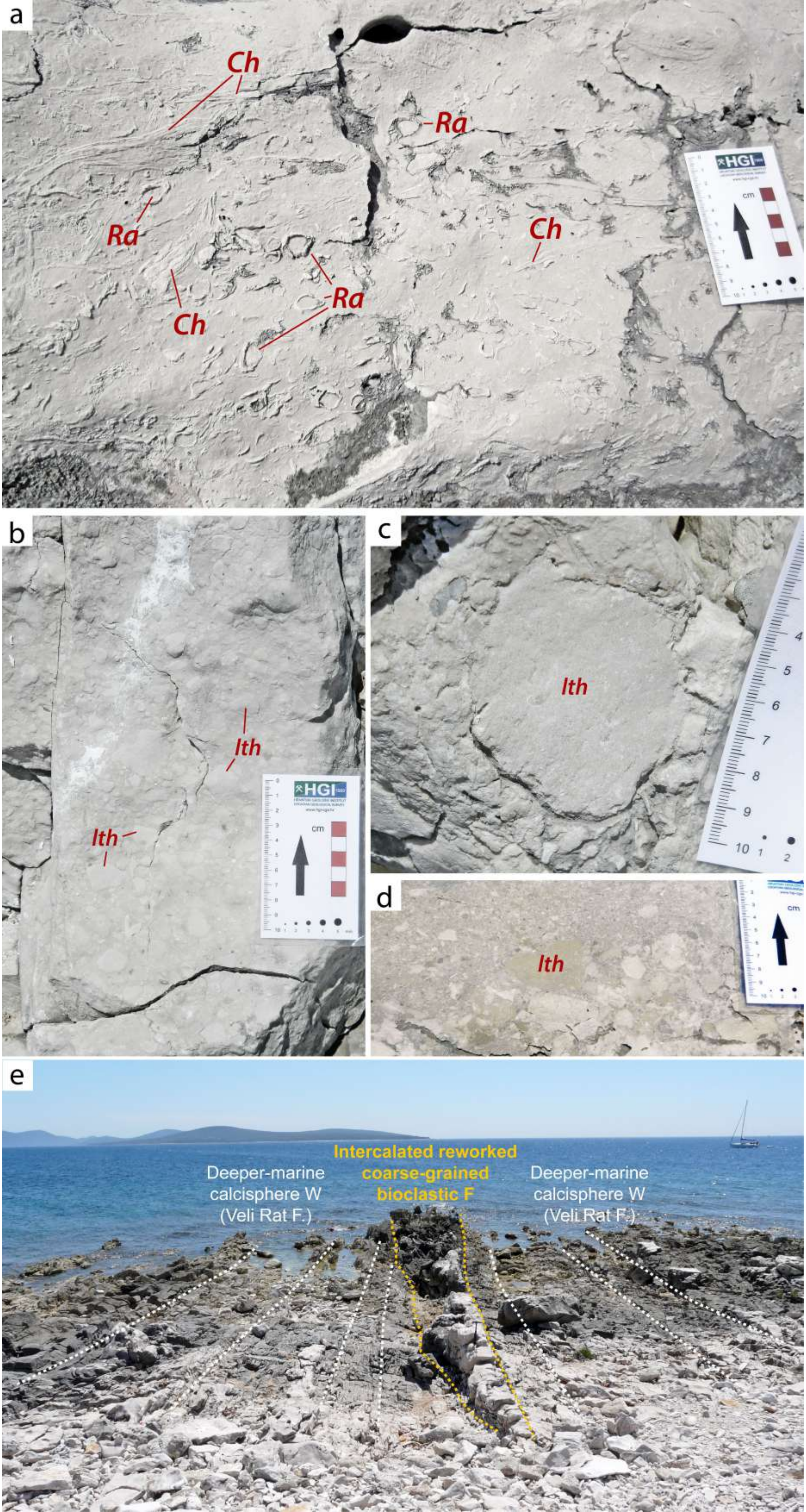


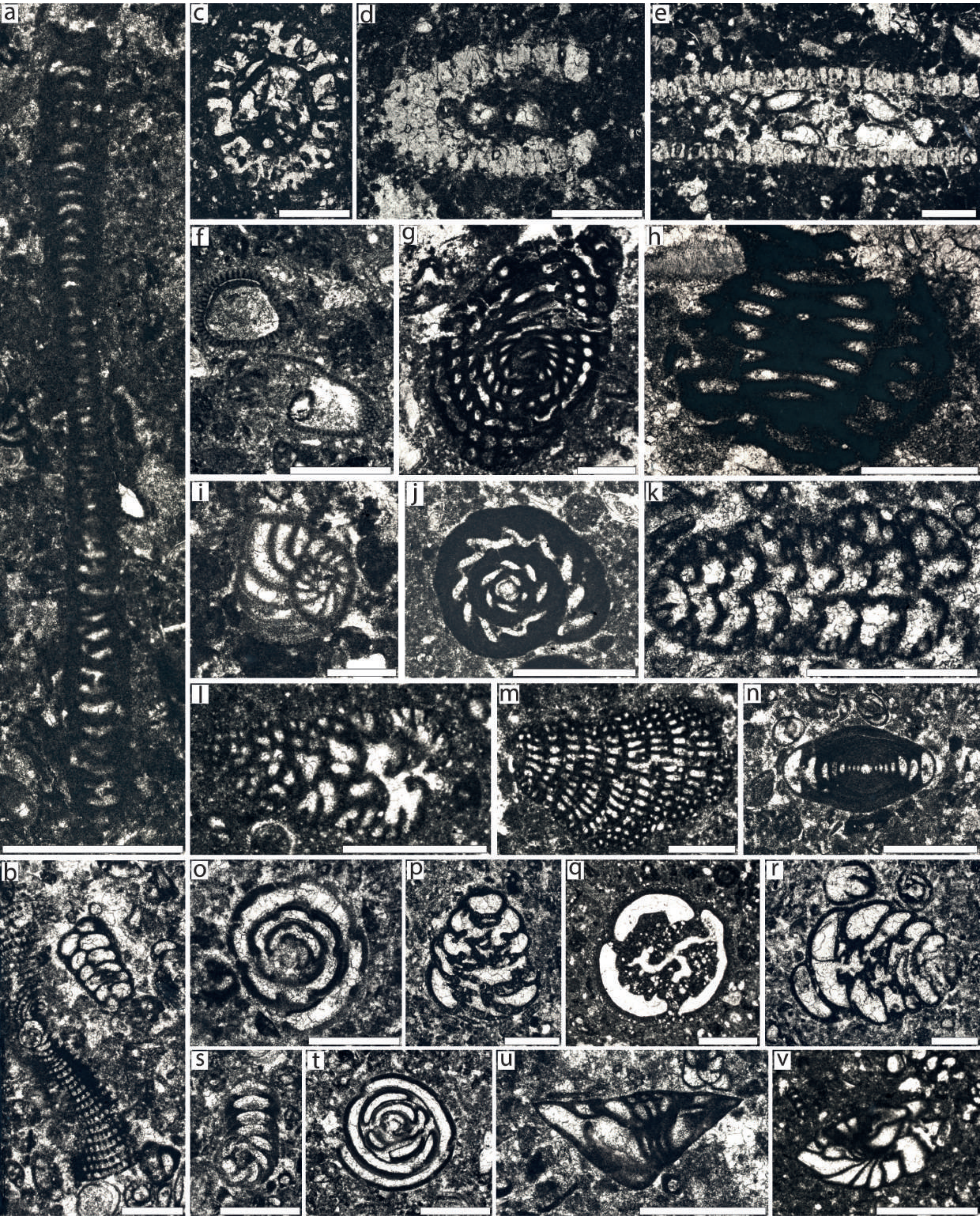
Barban section
Premuda section
Eastbourne r. c.
Stage
Turonian
Cenomanian
Insoluble Residue (%)
TOC (% x 100)
Helvetoglobotruncana helvetica
Whiteinella archaeocretacea
R. cushmani
a
b
c



Turonian to Coniacian (90-85 Ma)
c)
"Beachrocks" facies
Gornji Humac Formation
Karstification
NWI
Decastronema cotori
Thaumatoporella sp.
Rudist bio/lithostrome
BS
Debrites
Sliding
Dolomitization zone
Synsedimentary tectonic
Gornji Humac Formation
Sv. Duh Formation
Milna Formation
Synsedimentary tectonic
PS
Open ocean influence
Veli Rat Formation
Rudist bio/lithostrome
Sv. Duh Formation
Gornji Humac Formation
Synsedimentary tectonic
Neptunian dike
Veli Rat Formation
Slumping
Calcisphere and planktonic foraminifera wackstone
Milna Formation
Late Cenomanian to Early Turonian (94 Ma)
b)
"Beach rocks"
Karstification
Supratidal
Intertidal
Subtidal
NWI
Cyanobacterial/algal laminites
Sv. Duh Formation
Rudist bio/lithostrome
Debrites
Sea level rise
Dolomitization zone
Bioclastic deposits
Slumping and sliding
BS
Tempestite zone
Clinoforms
Synsedimentary tectonic
< 50 m
Slumping and sliding
PS
Open ocean influence
Calcisphere and planktonic foraminifera wackstone (subordinated)
Milna Formation
Synsedimentary tectonic
Bioclastic deposits
Rudist bio/lithostrome
Milna Formation
Bioclastic deposits
Synsedimentary tectonic
< 100 m
Calcisphere and planktonic foraminifera wackstone
Sv. Duh Formation
Debrites
Middle to Late Cenomanian (96 Ma)
a)
Dasyclad algae
NWI
Chrysalidina gradata
Karstification
Miliolidae
BS
Bivalves
Synsedimentary tectonic
Cyanobacterial/algal laminites
PS
Pseudorhapydionina dubia
Milna Formation
Rudist biostrome
Synsedimentary tectonic
Milna Formation
Broeckina (Pastrikella) balcanica


a
b
c
20 cm
d
GH
SD
20 cm


a
Ch
Ra
Ra
Ch
Ch
Ra
b
lth
lth
c
lth
d
lth
e
Intercalated reworked coarse-grained bioclastic F
Deeper-marine calcisphere W (Veli Rat F.)
Deeper-marine calcisphere W (Veli Rat F.)


a
b
c
d
e
f
g
h
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k
l
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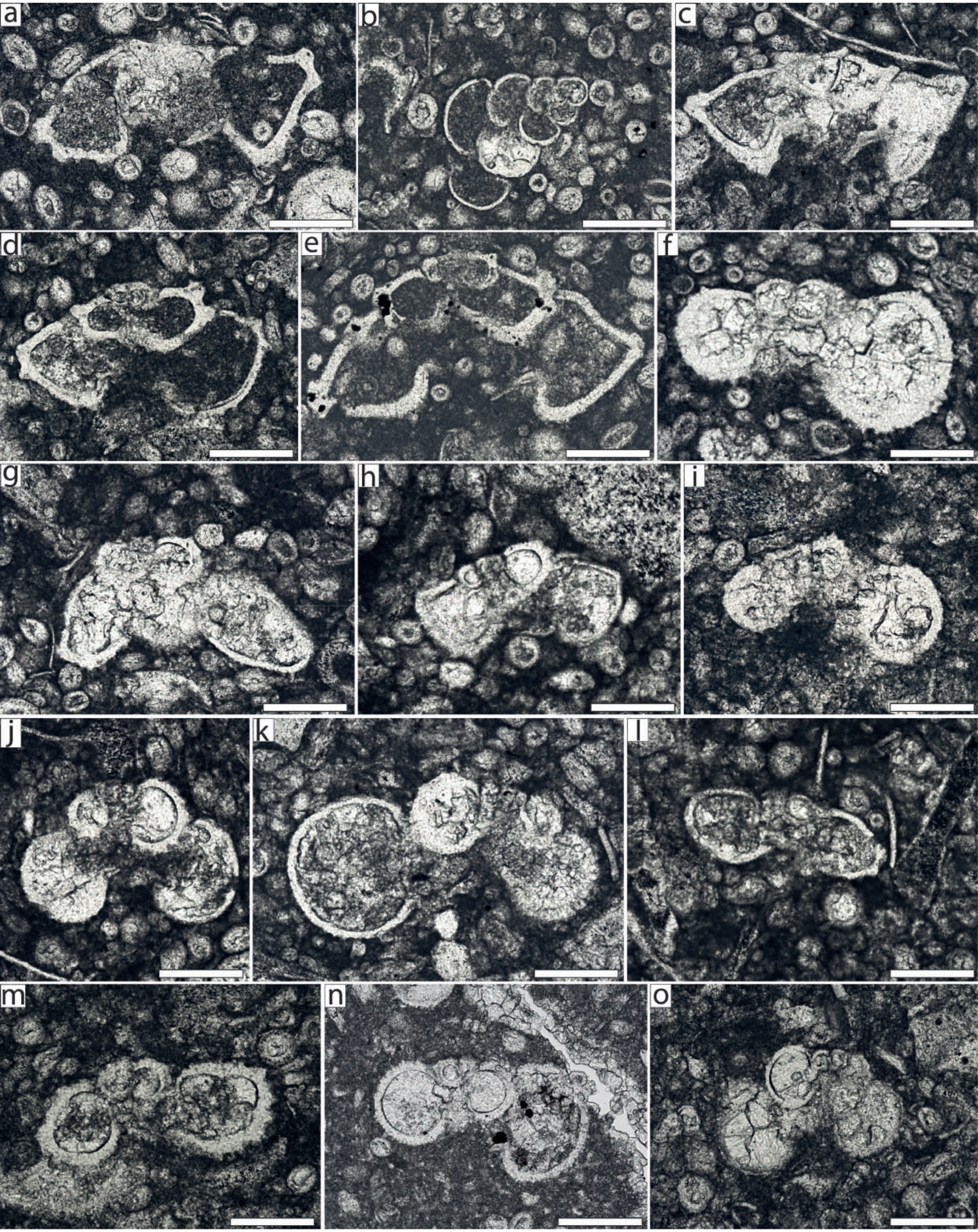
v


a
b
c
d
e
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g
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i
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k
l
m
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o