New biostratigraphic interpretation of the Middle Miocene (Badenian) transgression in the southern margin of the Pannonian Basin (Hrvaćani, northern Bosnia, Central Paratethys), based on the fossil assemblages

GORDANA JOVANOVIĆ[1,✉], DRAGANA ĐURIĆ[1], SEJFUDIN VRABAC[2], STJEPAN ĆORIĆ[3], JOVICA JOVANOVIĆ[4] and ZORAN BOJIĆ[4]

[1]Natural History Museum, Belgrade, Serbia; ✉gordana.j@nhmbeo.rs, djuric.dragana@nhmbeo.rs
[2]University of Tuzla, Tuzla, Bosnia and Herzegovina; sejfudin.vrabac@untz.ba
[3]Geological Survey of Austria, Vienna, Austria; stjepan.coric@geologie.ac.at
[4]Geological Survey of Serbia, Belgrade, Serbia; jovica.jovanovic@gzs.gov.rs, zoran.bojic@gzs.gov.rs

(Manuscript received December 14, 2020; accepted in revised form July 1, 2021; Associate Editor: Natália Hudáčková)

Abstract: This paper focuses mainly on the representatives of calcareous nannofossils and invertebrates from the Hrvaćani section of the Middle Miocene (Badenian) (Prnjavor Basin, southern margin of Pannonian Basin), and it defines the time of Badenian transgression in this area. Rich resources of fossil mollusk species, isolated parts of coral colonies, and other invertebrate remains were found in the investigated section. Moreover, turtle remains from marine sediments at the southern margin of Central Paratethys were recorded for the first time. Calcareous nannofossil biostratigraphy has established an NN5 Zone by the presence of *Sphenolithus heteromorphus* and the absence of *Helicosphaera ampliaperta*. The foraminifera associations from the analyzed sandstones belong to the Lower Badenian, namely the older zones of *Ammonia viennensis* and *Elphidium crispum* (the equivalent of Lagenidae Zone of Vienna Basin). The specimen of a turtle is currently attributed to order Testudines (suborder Pleurodira). From a stratigraphic and paleoecological point of view, all the fossil assemblages showed similar patterns for the subject of study, reflecting favorable conditions for developing a subtropical fauna in the open shallow marine environment. Consequently, by combining nannofossils, foraminifers, corals, malacological, and herpetological data, we can conclude that the early Middle Miocene (Badenian) in Hrvaćani (Bosnia) corresponds to the Lagenidae Zone (NN5 Zone) and was characterized by a relatively warm climate.

Keywords: Badenian (Central Paratethys, Bosnia), calcareous nannofossils, foraminifera, corals, mollusks, turtle.

Introduction

The village of Hrvaćani is located in the central part of northern Bosnia. During the Miocene, this locality belonged to the Prnjavor Basin, situated on the southern margin of Central Paratethys. In this area, Badenian sediment contains numerous fossils. The paleontological features of Badenian were investigated by Eremija (1969, 1970, 1971); Mojićević et al. (1976, 1977); Petrović & Atanacković (1976), and Atanacković (1984). In the area of Hrvaćani, southwest of the Crkvena River, in the form of erosion Rags, outcropping Badenian sediments are represented by clastics and limestones (Fig. 1C). The outcrop located in the creek bed, about 1.5 km west of the school in Hrvaćani, one of the richest macrofossil associations on the southern margin of Central Paratethys were described by Atanacković (1984, 1985). Among the mentioned fossil associations by Atanacković (1984), 243 species and subspecies of gastropods, 46 species, and subspecies of bivalves, as well as numerous corals, annelids, bryozoa, brachiopods, echinoderms, and vertebrate remains collected from "coral reef", and associated clastites (basal conglomerate, gravel, and sand clays, of total thickness about 10 m) were determined. These deposits are being attributed (Petrović & Atanacković 1976) to the Upper Badenian (*Rotalia beccarii* Zone). Eremija (1970) attributed the clastites of Rogić Jaruga, which were lying transgressively over the Jurassic diabase-chert Formation, to the same Late Badenian age (issue No. 108). During oil prospecting in Northern Bosnia in the seventies, considerable work was undertaken by geologists on the boreholes. Calcareous nannofossils and foraminifers were investigated for the stratigraphical framework of this area. Much of this work is summarized in Jerković & Ćorić (2006); Ćorić et al. (2009). In October 2019, a new outcrop of Badenian deposits, situated about 1.5 km east of the famous Badenian fossil site, depicted by Atanacković (1984), was described and sampled (Fig. 1A, B, C). In addition to highly diverse molluskan fauna, nannofossils, serpulids, bryozoans, cirripedes, ostracods, foraminifera, corals, echinoid spines, fishes, and turtle remains occur in this area. To establish the stratigraphic affiliation of these deposits, we analyzed the collected fossil material.

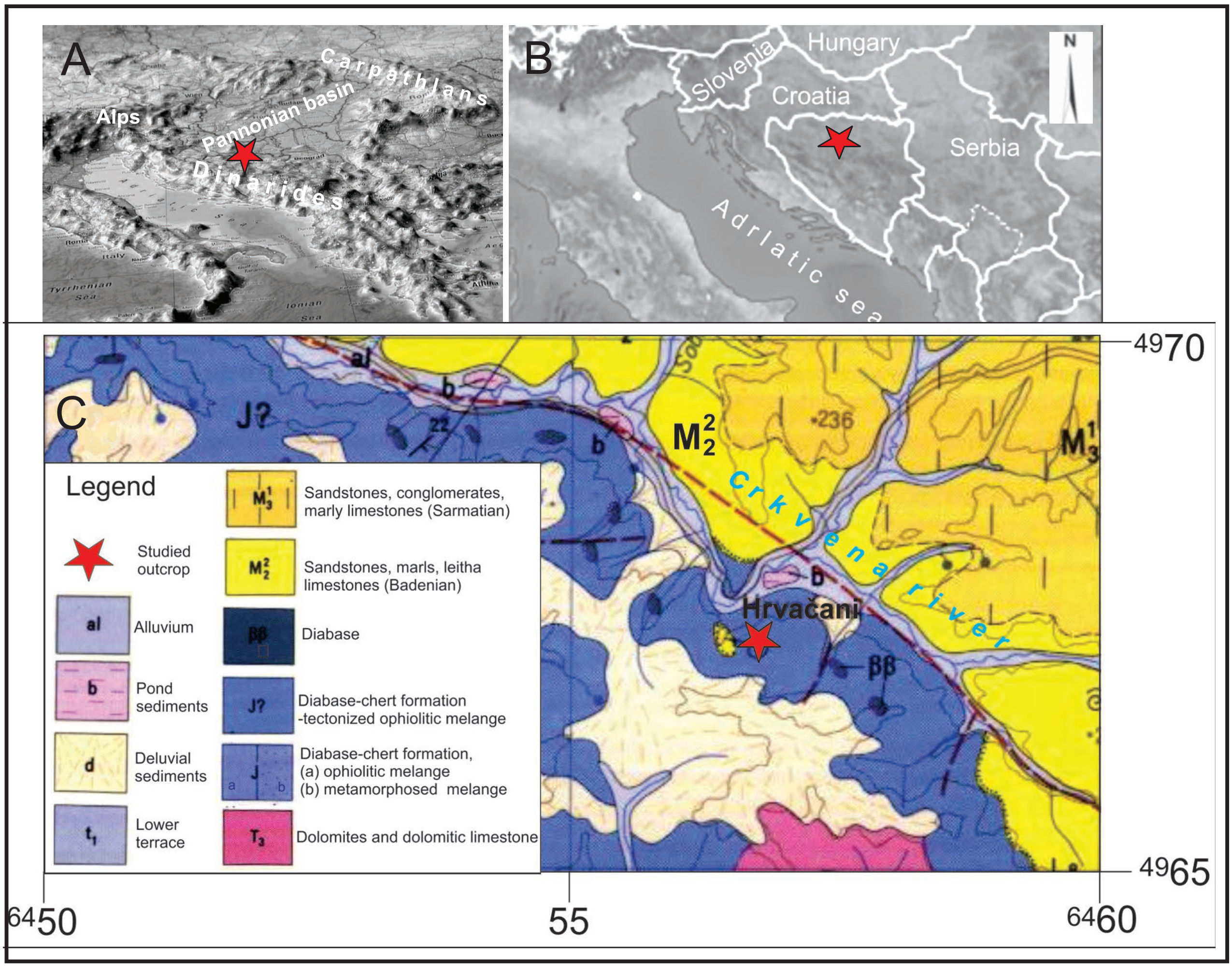

Fig. 1. A — Geographical position of the studied area in Pannonian Basin; **B** — Location of the studied area in Bosnia and Herzegovina; **C** — Geological map of the Hrvaćani area, after map of Bosnia and Herzegovina 1: 100,000, sheet Banjaluka (according to Mojićević et al. 1976).

Geological settings

During the Langhian (Early Badenian), the Central Paratethys Sea reached its maximal extent, and the (southern) margin in several sites was flooded. Previous research indicates that the flooding had an impact on the Central Paratethys via the Slovenian corridor, probably functioning as the connecting sea strait (Bistričić & Jenko 1985; Kováč et al. 2017a, b; Sant et al. 2017). At this time, the investigated area was located at the southern margin of the Prnjavor Basin, which represents the southern edge of the Pannonian Basin and the Central Paratethys Basin. Several basins with predominant shallow-water sedimentation were formed in Bosnia. The village of Hrvaćani is situated in the central part of northern Bosnia, in front of the Inner Dinaric Mountains. Middle Miocene (Badenian) deposits lie transgressively over the Jurassic diabase-chert Formation (Fig. 2B). Decades ago, several different opinions were mentioned regarding age estimates of the first Miocene marine transgression in this area. Recently, other authors proved that the Middle Miocene (Early Badenian NN5 Zone) (Ćorić et al. 2009; Pezelj et al. 2013) in Bosnia corresponds to initial Badenian transgression. The Middle Miocene (Badenian, NN5 Zone) deposits are marine and associated with the extensive early Badenian transgression, which flooded large areas of northern Bosnia. In contrast, the Early Miocene and the oldest Lower Badenian sediments are primarily terrestrial in origin. Based on calcareous nannoplankton, the Badenian sediments from northern Bosnia were attributed to the nannoplankton zones NN5 and NN6 (Jerković & Ćorić 2006; Ćorić et al. 2009) (Fig. 3A, B).

Material and methods

A described section of Hrvaćani has been recorded and subjected to detailed investigation and sampling. The outcrop located in the creek about 1.5 km east of the famous Badenian fossiliferous site was described by Atanacković (1984) on

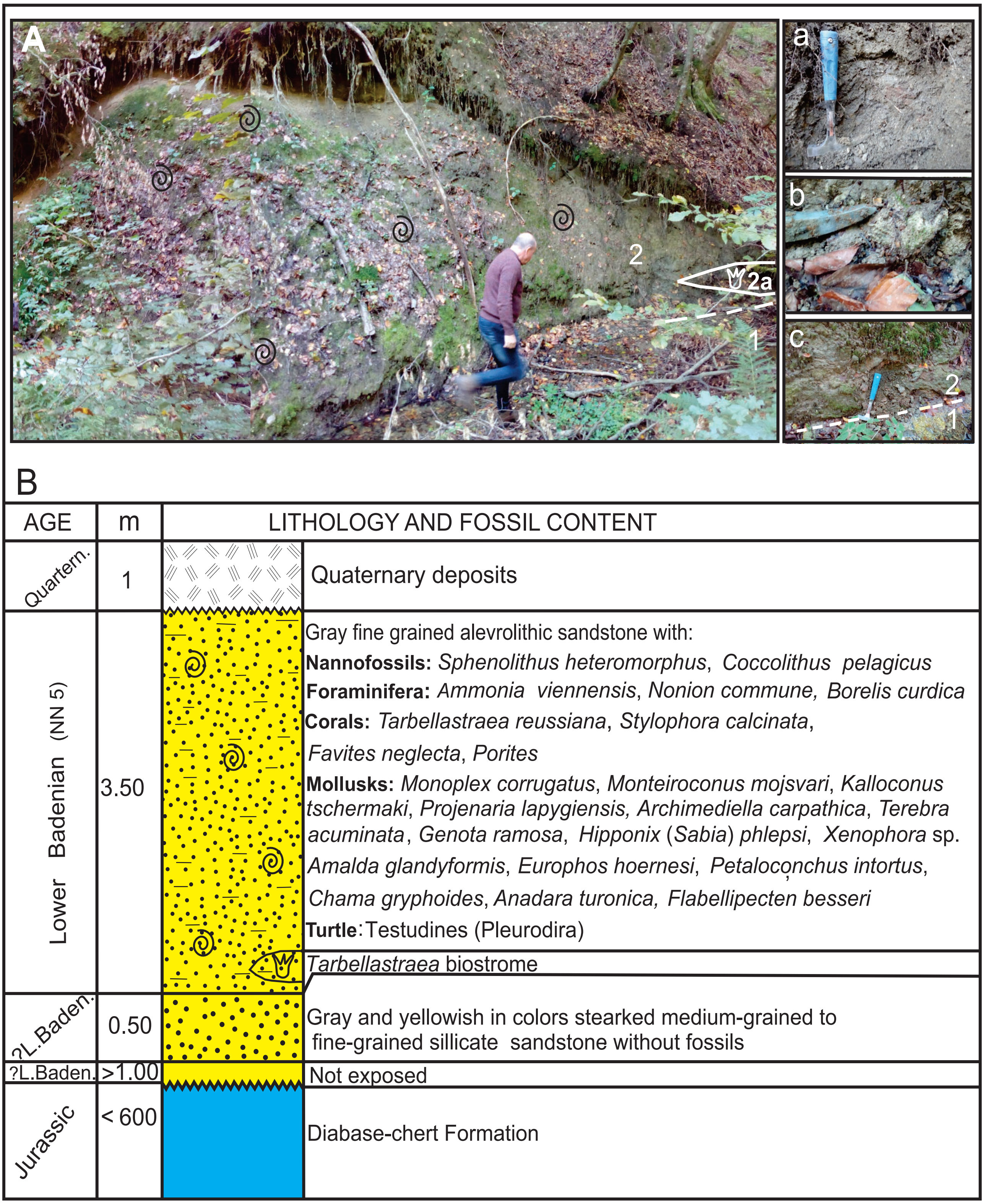

Fig. 2. A — The Lower Badenian sediments in Hrvaćani: Bed 2; a — detail of the picture A; 2a — coral biostrome; b — detail of the picture A, 2a — *Tarbellastraea reussiana* (Milne-Edwards & Haime, 1850); c — contact between the Bed 1 and the Bed 2. **B** — Stratigraphic column of the Lower Badenian deposits at Hrvaćani section with the fossil content.

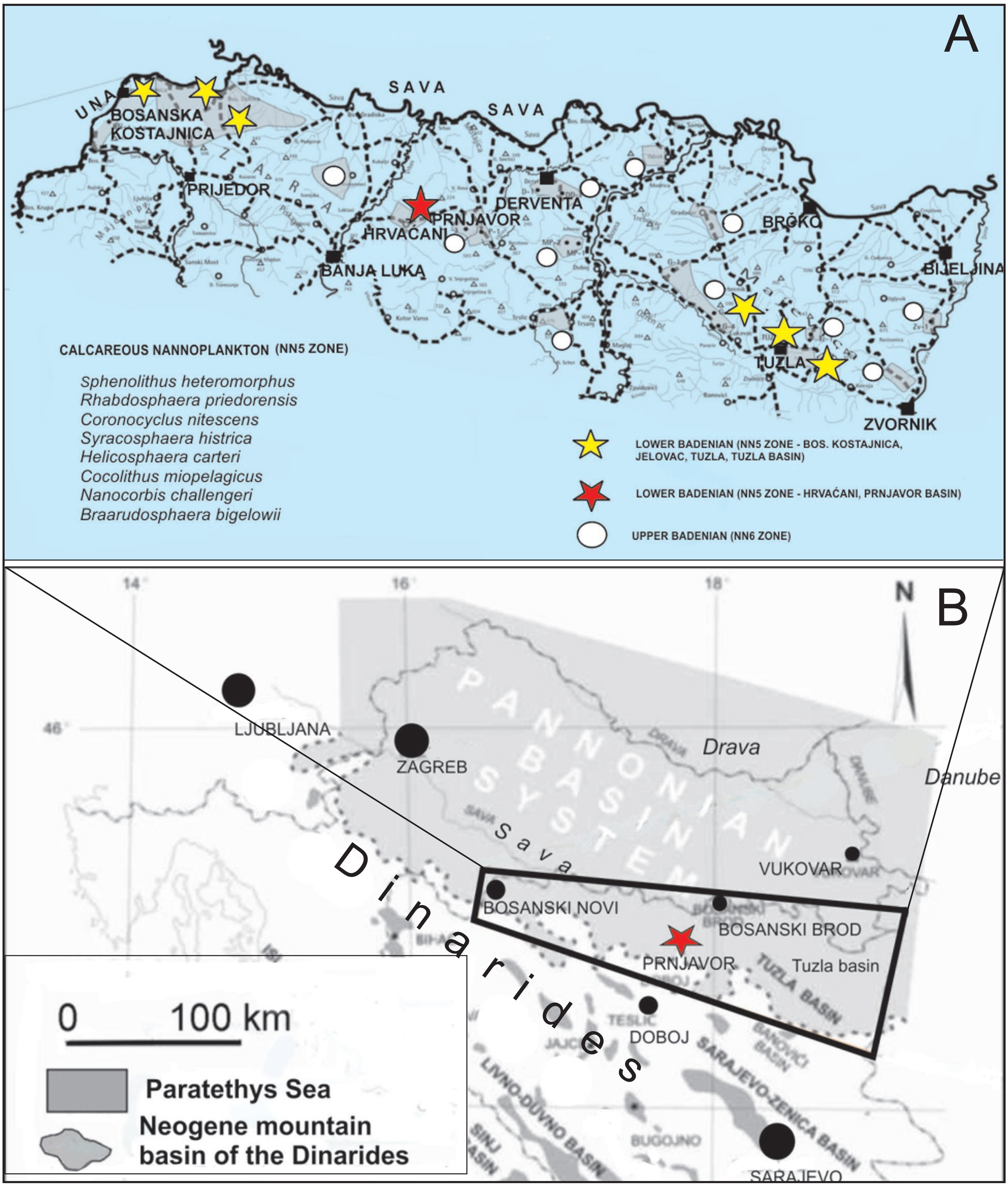

Fig. 3. A, B — Middle Miocene (Badenian) calcareous nannoplankton (northern Bosnia), according (Ćorić et al. 2009; modified). Red star shows the position of Hrvaćani locality. Yellow stars and white circles display position of boreholes.

the right bank of the stream, exposing deposits of at least 4.5 m thickness, while the length of the section is about 25 m. The Badenian sediments base is not exposed, but we can conclude that the Badenian deposits in this part of the terrain also lie transgressively over the Jurassic diabase-chert Formation discovered on the left bank of the stream, across from the exposed fossil layer. Described sediments declined by the fault being thus brought into contact with Jurassic diabase-chert

Formation. Based on field observations and lithology, two beds can be distinguished (Fig. 2A). The falling angle of the Miocene sediments is about 20° (Fig. 2A, c). The same angle of decline for the Neogene sediments of the Prnjavor Basin was noted by Mojićević et al. (1977).

The thickness of visible beds was measured, and several samples from different lithologies were chosen for paleontological analysis. Smear slides for calcareous nannoplankton analysis were prepared using the standard procedures described by (Perch-Nielsen 1985) and examined under Leica DMLP light microscope (cross and parallel nicols) with 1000× magnification. An amount of 100 specimens were counted and inverted in percentages to show the composition of calcareous nannofossil assemblages from the sample Hrvaćani 2 (Fig. 4). The foraminifera and other small specimens were recovered from over a 0.1 mm fraction-sieve and picked under the microscope. Eight samples were crushed and disaggregated by hydrogen peroxide solution and washed through a 0.1 mm sieve. The nannoplankton zonation of Martini (1971) was used for the stratigraphical analyses, while the standard foraminiferal zonation was used according to (Grill 1943). Particular attention was paid to the coral specimens, as they are one of the main groups in the collected material. One sediment sample with a turtle shell was subjected only to mechanical cleaning using various needles, brushes, and a microscope. In terms of numbers, there is a particularly opulent presence of mollusks, especially gastropods. Materials were prepared in the laboratory of the Natural History Museum in Belgrade (mollusks and turtle), University of Tuzla (foraminifers), Geological Survey of Serbia (corals), Geological Survey of Austria, Vienna (calcareous nannofossils). Several samples *Cubitostrea*, *Conus*, Turritellidae, Cerithidae, and some corals collected by Suzana Bojić, have been investigated. The collected material is stored in the collections of the Natural History Museum in Belgrade (Serbia).

Results

Fossil content and biostratigraphy

Bed 1, approximately 0–0.5 m thick, visible on the surface only in one part of the section (Fig. 2A – 1, c – 1), exposes streaked, medium-grained to fine-grained, silicate sandstone, gray and yellowish. The angled, matte, and shiny grains of quartz strongly dominate after being washed through a sieve. Three samples were taken from Bed 1 and processed for nannoplankton, foraminiferal, and mollusks content, using the microscope and other standard procedures but were barren. Bed 2 (Fig. 2A, a) is built of gray, fine-grained aleurolithic sandstone with abundant fossil remains. Quartz grains dominate in the material washed through a sieve. Mollusks fauna with aragonitic skeletons prevails, while biota with calcite skeletons are rare. Five samples from Bed 2 were chosen for nannoplankton, foraminiferal, and mollusks analyses. A 3.5 m thick aleurolihic sandstone (Fig. 2A, a) contains fairly preserved nannofossil as well as highly species diverse foraminiferal and molluscan assemblages, corals fauna, bryozoa, and others. Remains of the turtle were found in this part of the profile. There is no clear internal stratification at this level. However, their lowermost part includes gray sandstone with remains of diverse fossils and the appearance of coral biostrome consisting of *Tarbellastraea reussiana* (Milne-Edwards & Haime, 1850). The thickness of the exposed biostrome is about 30 cm (Fig. 2A – 2a, b). In addition, Bed 2 is the richest in fossils in its upper part. This lithological unit is overlain by the Quaternary deposits. It can be concluded that the majority of the identified mollusk shells from the private collection of Suzana Bojić originate from debris or from the uppermost part of the outcropped Miocene sediments.

Calcareous nannofossils

Sediment from Bed 1 is barren of calcareous nannofossils. Overlaying sediments (Sample 2) contain well-preserved, rare nannofossil assemblage (Fig. 4). This assemblage is dominated by *Sphenolithus heteromorphus, Coccolithus pelagicus* and reticulofenestrids (*Reticulofenestra perplexa*, *R. haqii, R. minuta* and *R. pseudoumbilicus*). Long-range species *Sphenolithus moriformis* and *Triquetrorhabdulus milowii* were observed too.

Reworking from the uppermost Maastrichtian was documented by the presence of *Micula prinsii* occurring together with *Arkhangelskiella cymbiformis* and *Watznaueria barnesiae*. Besides nannofossils, common didemnid ascidian spicules occur too (Fig. 4 – 28).

Foraminifera

Foraminifers are rare, being presented exclusively by benthic forms: *Ammonia viennensis*, *Elphidium crispum*, *Biasterigerina planorbis*, *Nonion commune*, *Pseudotriloculina consobrina*, *Cibicidoides ungerianus ungerianus*, *Planostegina costata*, *Triloculina gibba* and at the southern part of Central Paratethys by rare alveolinoid *Borelis melo* subsp. *curdic*a (Fig. 5). Only rare juvenile planktic forms were observed (Fig. 4 – 29). Large foraminifer *Borelis melo* subsp. *curdica* has been found for the first time in the area of the Prnjavor Basin (Fig. 6).

Corals

The investigated section contains isolated parts of colonial corals (Figs. 7, 8) found in a sandstone bed (Bed 2). The sediment, laterally and above the biostrome coral, contains numerous mollusk shells and other invertebrates of different ages, ranging from juveniles to adults. A new fossil corals fauna comprises the following taxa: *Tarbellastraea reussiana*, *Stylophora calcinata*, *Stylophora depauperata*, *Heliastraea defrancei*, *Favites neglecta*, *Favites neugeboreni*, *Plesiastraea* (*Paleoplesiastraea*) cf. *tazarinensis*, *Porites maigensis*, *Porit*es sp., ?*Favites* sp., *Siderastrea* sp., ?Scleractinia (indet.).

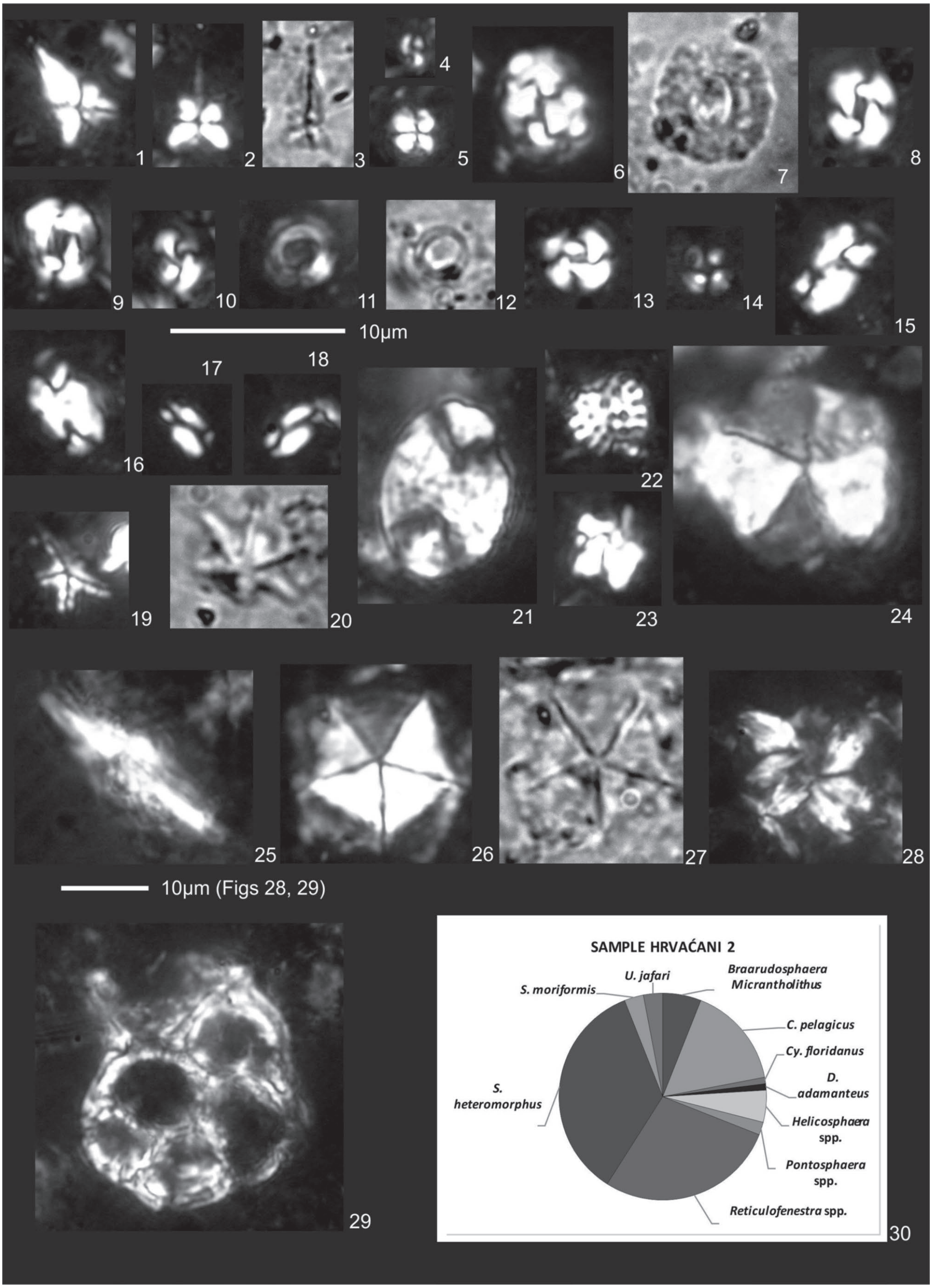
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
10μm
16
17
18
19
20
21
22
23
24
25
26
27
28
10μm (Figs 28, 29)
29
SAMPLE HRVAĆANI 2
U. jafari
S. moriformis
Braarudosphaera Micrantholithus
C. pelagicus
Cy. floridanus
D. adamanteus
S. heteromorphus
Helicosphaera spp.
Pontosphaera spp.
Reticulofenestra spp.
30

Fig. 4. Association of calcareous nannoplankton species from Hrvaćani section: 1–3 — *Sphenolithus heteromorphus* Deflandre 1953; 4 — *Reticulofenestra minuta* Roth, 1970; 5 — *Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967; 6, 7 — *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930; 8, 9 — *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969M; 10 — *Reticulofenestra perplexa* (Burns, 1975) Wise, 1983; 11, 12 — *Umbilicosphaera rotula* (Kamptner, 1956) Varol, 1982; 13 — *Cyclicargolithus floridanus* (Roth & Hay, *in* Hay et al., 1967) Bukry, 1971; 14 — *Umbilicosphaera jafari* Muller, 1974; 15 — *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954; 16 — *Helicosphaera* cf. *waltrans* Theodoridis, 1984; 17, 18 — *Helicosphaera walbersdorfensis* Muller, 1974; 19 — *Micrantholithus vesper* Deflandre 1950; 20 — *Discoaster adamanteus* Bramlette & Wilcoxon 1967; 21 — *Pontosphaera discopora* Schiller, 1925; 22 — *Pontosphaera multipora* (Kamptner, 1948 ex Deflandre *in* Deflandre & Fert, 1954) Roth, 1970; 23 — *Micula prinsii* Perch-Nielsen, 1979; 24 — *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947; 25 — *Triquetrorhabdulus milowii* Bukry, 1971; 26, 27 — *Micrantholithus* cf. *flos* Deflandre *in* Deflandre & Fert, 1954; 28 — Didemnid ascidian spicules; 29 — juvenile planktonic foraminifera; 30 — Composition of calcareous nannofossil assemblage from Sample Hrvaćani.

Massive colonies of *Tarbellastraea reussiana* prevail. The *Tarbellastraea* biostrome appears at the base of Bed 2 and seems to consist almost exclusively of *Tarbellastraea* sp. (Fig. 2A – 2a, b). A specimen of *Tarbellastraea* sp. inhabits Cirripedia (Fig. 7 – 8). Cirripedia represent mandatory symbionts of scleractinian and fire corals. Some corals appear recrystallized or preserved as moulds (Fig. 7 – 5, 6; Fig. 8 – 1, 11, 12). Only small colonies of *Porites* coral are preserved. A turtle shell's plastron is covered by the evolved colony of small encrusting thin branched *Porites* corals. As for *Favites* sp. and ?Scleractinia indet., belonging to the collection of Suzana Bojić, we can say they are probably of sub-autochthonous origin.

Mollusks

The locality described here contains a large number of mollusk taxa reported by Atanacković (1984, 1985). However, it is unfortunate that the original locality of her collection is not available today. From the sediments of here presented locality, gastropods are predominant. We were able to identify several distinct taxa (Figs. 9, 10): *Amalda glandiformis*, *Monoplex corrugatus*, *Thetystrombus* sp., *Ocinebrina* cf. *coellata*, *Genota ramosa*, *Perrona taurienensis*, *Perrona* sp., *Projenneria lapugyensis*, *Phasmoconus fuscocingulatus*, *Monteiroconus mojsvari*, *Kalloconus tschermaki*, *Lautoconus* cf. *bitorosus,*

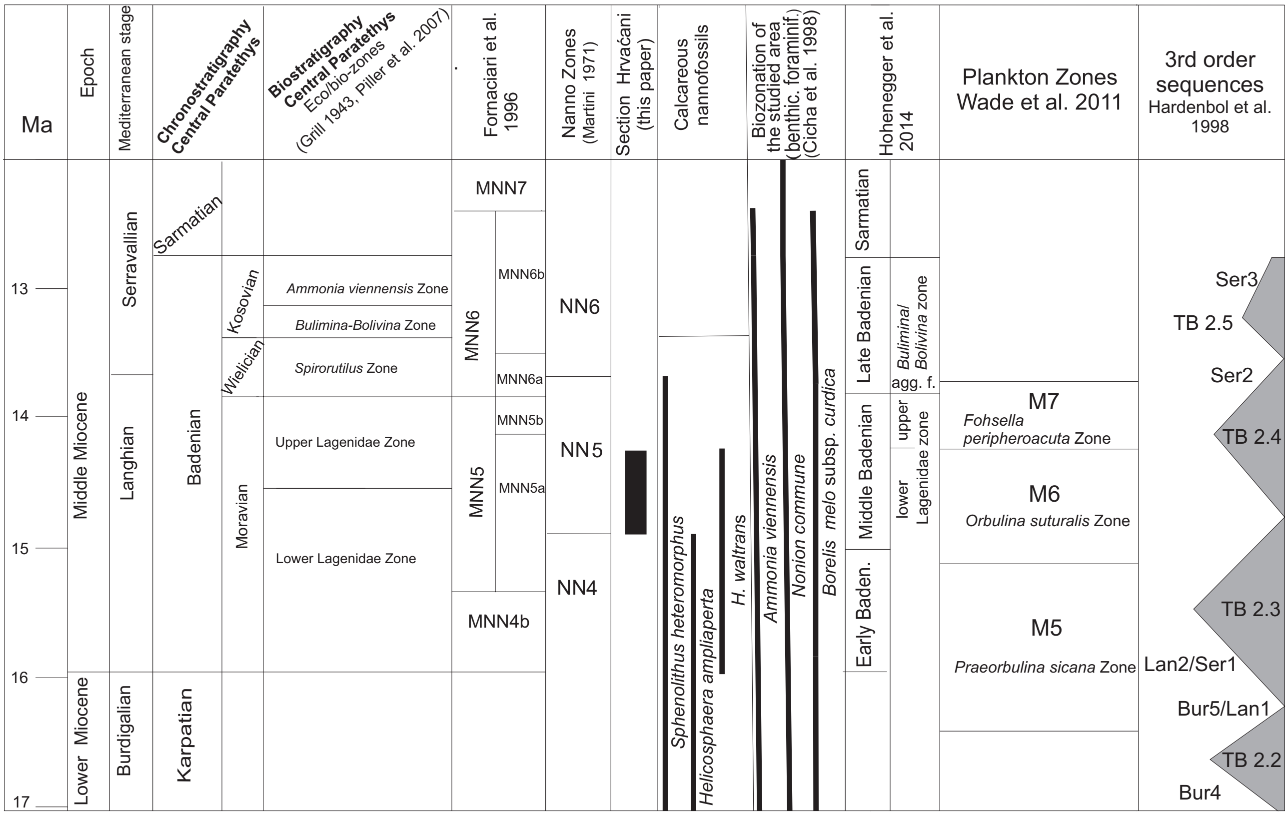

Fig. 5. Stratigraphic distribution of the calcareous nannofossils and foraminifera on the Hrvaćani section (northern Bosnia) and correlation of the investigated area with the global 3rd order sequences. Foraminiferal biozonation in the Central Paratethys (Grill 1943). Stratigraphic correlation table and global chronostratigraphy after Hilgen et al. (2009); Gradstein et al. (2012), NN zone after Lourens et al. (2004); Hohenegger et al. (2014).

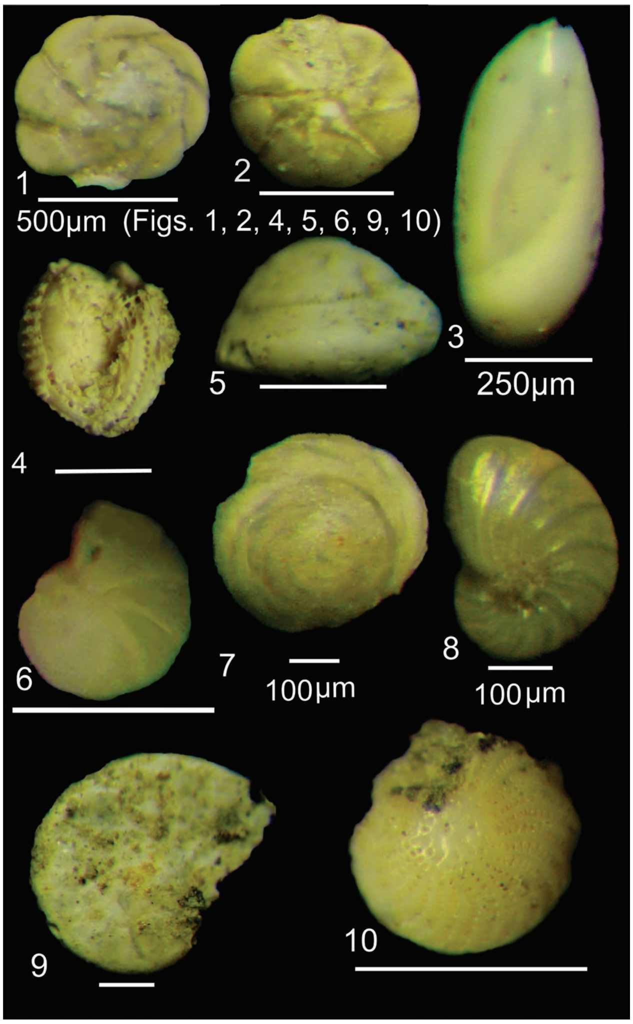

Fig. 6. Association of foraminifera from Hrvaćani: 1, 2 — *Ammonia viennensis* (d'Orbigny, 1846); 3 — *Pseudotriloculina consobrina* (d'Orbigny, 1846); 4 — *Borelis melo* subsp. *curdica* (Reichel, 1937); 5 — *Triloculina gibba* (d'Orbigny, 1846); 6 — *Cibicidoides ungerianus ungerianus* (d'Orbigny, 1846); 7 — *Biasterigerina planorbis* (d'Orbigny, 1846); 8 — *Nonion commune* (d'Orbigny, 1846); 9 — *Planostegina costata* (d'Orbigny, 1846); 10 — *Elphidium crispum* (Linnaeus, 1758).

Kalloconus sp., *Oligodia bicarinata*, *Archimediella carpathica*, *Terebra acuminata, Sandbergeria perpusilla*, naticids *Neverita josephinia*, *Polinices redemptus*, *Cypraea ovulinae*, *Xenophora* sp., *Tritia* sp., *Europhos hoernesi*, *Paroxystele orientalis*, *Seila turritissima*, *Petaloconchus intortus*, *Cylichna clathrata*, *Roxania utriculus*, *Alvania miocenica*, *Hipponix* (*Sabia*) *phlepsi*, *Thala obsolete*, ?*Conomitra* sp., ?*Mitromorpha* sp., *Caecum trachea*, *Pyrunculus elongatus*. Among bivalves, the following are present: *Psammobia uniradiata*, *Aequipecten malvinae*, *Chama gryphoides*, *Anadara fichtelli*, *Flabellipecten besseri, Corbula carinata*, *Tellina* sp., *Anadara turonica*, *Venus nux*, *Clausinella basteroti*, *Microloripes dentatus*, *Cubitostrea digitalina*, etc. Our research also shows the predominance of thermophilic elements in the section of Hrvaćani (*Petaloconchus*, *Genota*, *Xenophora*, *Amalda,* and several genera of Conidae, Veneridae, Turritellidae, etc.). Almost all specimens are well preserved. In contrast, the fragmented shell of *Xenophora* may have been transported from the adjacent coastal area. Agglutinate taxon *Xenophora* can cement foreign objects (gastropod and bivalve shells, pebbles) to the dorsal surface of their shell (Fig. 9 – 5, 6).

Turtle

The occurrence of fossil turtles at the Central Paratethys margin of Bosnia is unknown. The described specimen was embedded in a sandstone matrix containing small shells of marine gastropods. The colonial corals, small gastropods, and sediments associated with the remains of the turtle are utilized to infer its stratigraphic provenience and the depositional conditions in which it was preserved. The investigated material is presented by the right parts of small-bodied turtle, several (4) cm long, clearly visible of a carapace with several scutes and a part of the plastron, as well as one marginal scute (Fig. 11 – 1). The size of the shell indicates that it may be a juvenile specimen. Both the carapace and plastron are thick bony structures that seemed to be hooked to each other. The plastron is visible only on the lateral margin because the ventral surface is overgrown with colonial *Porites* coral and immersed in sediment (Fig. 11 – 1, 2). Some features as pelvic elements, shell shape, etc., indicate that the specimen could belong to the order Testudines, suborder Pleurodira. It is known that the pelvic elements of Pleurodira turtles are extensively sutured to both the carapace and plastron, whereas the pelvic elements of cryptodire are not (Williams & Stayton 2019). These distinctive features in Pleurodira probably contributed to the preservation of both carapace and plastron in our specimen. Pleurodira of carapace shells is also generally flatter than those of cryptodires (Fig. 11 – 2, 3). Similar form in most podocnemidids (Pleurodira) is mentioned by Cadena et al. (2010). In addition, on the anterior margin of the plastron, two triangular fragments of scutes in the gular region are preserved (Fig. 11 – 4).

Paleoenvironmental–climatic interpretation

All the fossil assemblages showed similar patterns for the Hrvaćani site, reflecting favorable conditions in the open shallow marine environment with normal salinity and influx from the Indo–Pacific bioprovince during early Badenian. Fossil remains from the Hrvaćani locality indicate the influence of this warm period that is probably related to the Middle Miocene Climate Optimum, evidenced in the whole Paratethys. The upper sediment bed (Bed 2) from the Hrvaćani locality contains taxa typical of early Badenian successions. The fossil assemblages characterized by abundant and diverse thermophilic mollusks fauna (*Amalda*, *Genota*, *Clavatula*, *Xenophora,* and several genera of Conidae, Turritelidae, etc.) indicated shallow water and favorable conditions. Representatives of recent genera gastropod *Genota* of West African genus are not found further north from Western Sahara (Ardovini & Cossignani 2004). Some species as well as *Vaginella austriaca* and rare finds of *Costellamussiopecten* shells (Eremija 1970), then benthic foraminifera (*Cibicidoides ungerianus ungerianus*, *Borelis melo*, *Borelis melo* subsp. *curdica*), gastropods (*Archimediella carpathica, Amalda glandiformis*), bivalvia

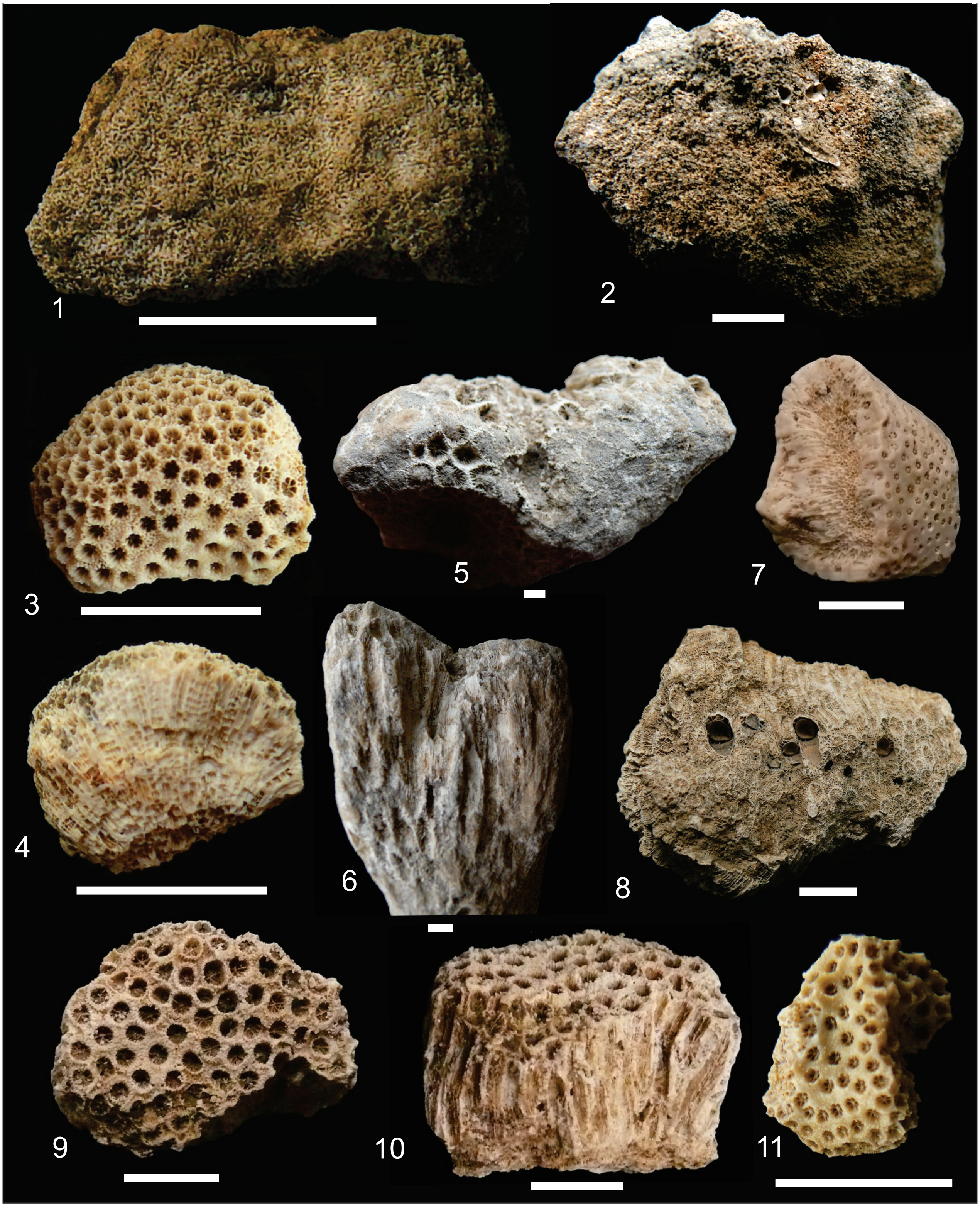

Fig. 7. Detailed view to corals assemblages, scale bar 1 cm: 1 — *Porites maigensis* Kühn, 1925; 2 — *Porites* sp.; 3, 4 — *Stylophora depauperata* (Reuss, 1867); 5, 6 — *Siderastrea* sp.; 7 — *Stylophora calcinata* (Mayer, 1864); 8 — symbiotic association of a Cirripedia with corals *Tarbellastraea* sp.; 9 10 — *Heliastraea defrancei* (Milne-Edwards & Haime, 1850); 11 — *Stylophora* sp.

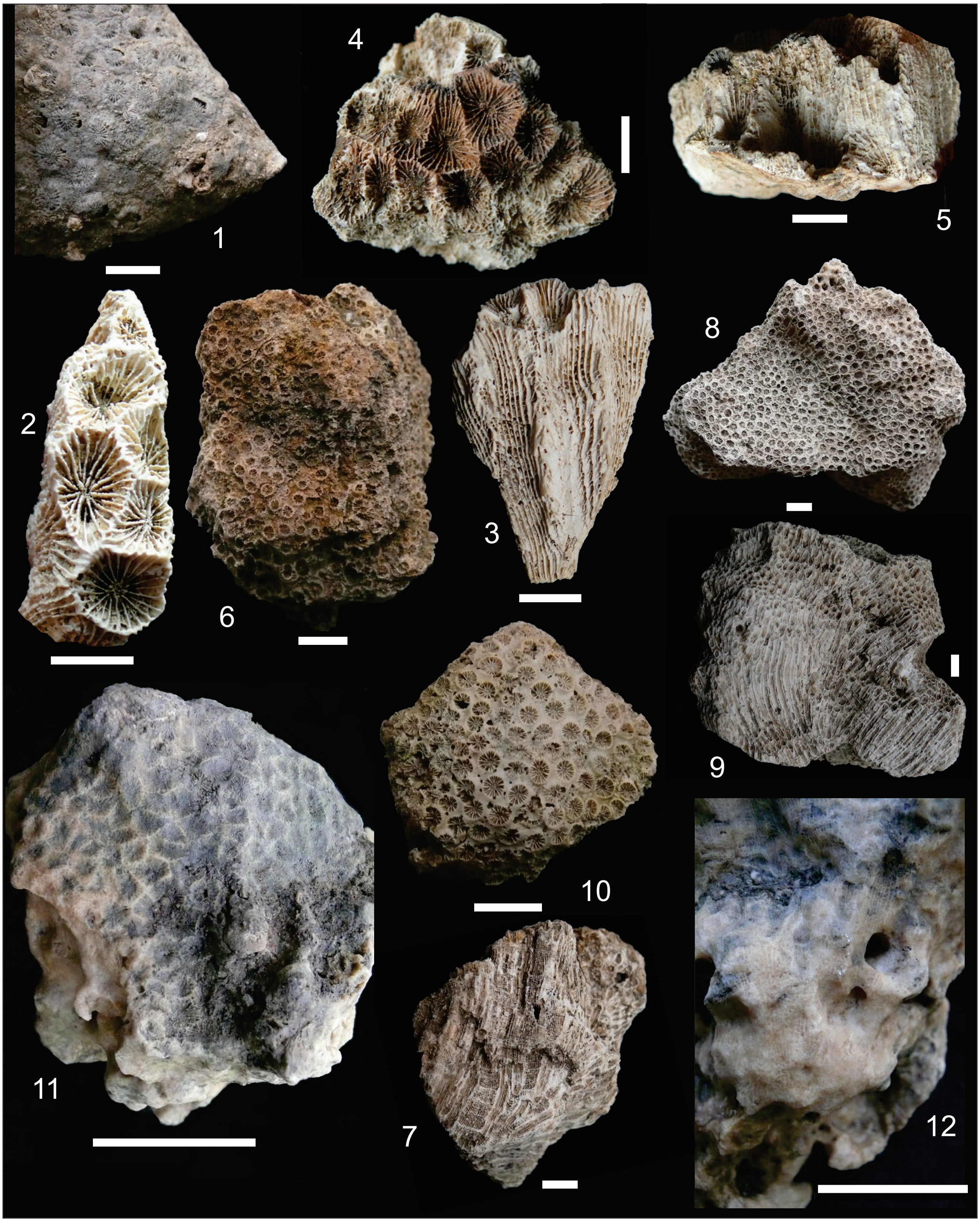

Fig. 8. Detailed view to corals assemblages, scale bar 1 cm: 1 — mould of Scleractinia indet.; 2, 3 — *Favites neugeboreni* (Reuss, 1871); 4, 5 — *Favites neglecta* (Michelotti *in* d'Achiardi, 1868); 6, 7 — ?*Heliastraea* sp.; 8, 9 — *Tarbellastraea* sp.; 10 — *Plesiastraea* (*Paleoplesiastraea*) cf. *tazarinensis* (Chevalier, 1962); 11, 12 — ?*Favites s*p.

Fig. 9. Detailed view to mollusks assemblages, scale bar 1 cm: 1, 2 — *Phasmoconus fuscocingulatus* (Hoernes, 1851); 3 — *Chama gryphoides* Linnaeus, 1758; 4 — *Cubitostrea digitalina* (Dubois, 1831); 5, 6 — *Xenophora* sp.; 7, 8 — *Kalloconus* sp.; 9, 10 — *Lautoconus* cf. *bitorosus* (Fontannes, 1880); 11, 12 — *Amalda glandiformis* Lamarck, 1810; 13, 14 — *Monteiroconus mojsvari* (Hoernes & Auinger, 1879); 15, 16 — *Aequipecten malvinae* (Dubois, 1831); 17, 18 — ?*Conomitra* sp.

(*Flabellipecten besseri*, *Aequipecten malvinae*), etc. suggest the Prnjavor Basin being well-connected to open sea. Shallow water forms predominated. Rare small colonies of coral *Porites* indicate slightly deeper water. Migrations and extinctions of thermophilic taxa such as mollusks (Harzhauser et al. 2003), then corals fauna, and thermophilic ectothermic vertebrates (turtles), have been documented in Central Europe as a result of the events after the Middle Miocene Climate Optimum (MMCO). Langhian expansion of the tropics during the Middle Miocene Climate Optimum (MMCO) enabled

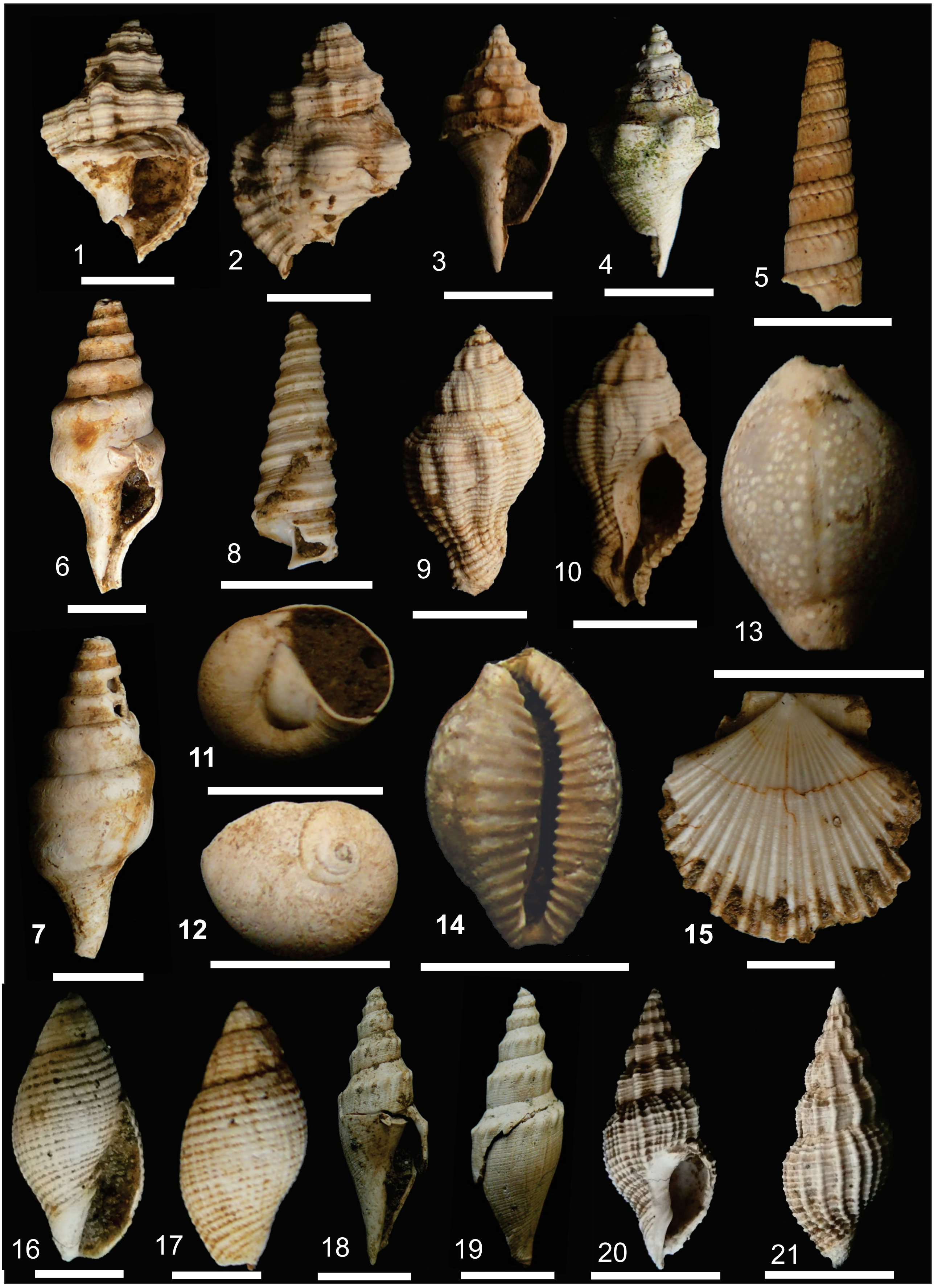
1
2
3
4
5
6
8
9
10
13
7
11
14
15
12
16
17
18
19
20
21

Fig. 10. Detailed view to mollusks assemblages, scale bar 1 cm: 1, 2 — *Monoplex corrugatus* (Lamarck, 1816); 3, 4 — *Thetystrombus* sp.; 5 — *Terebra acuminata* Borson, 1820; 6, 7 — *Perrona* sp.; 9, 10 — *Ocinebrina* cf *coellata* (Dujardin, 1837); 8 — *Archimediella carpathica* Harzhauser & Landau, 2019; 11, l2 — *Neverita josefinia* Risso, 1826; 13, 14 — *Projenneria lapugyensis* (Sacco, 1894); 15 — *Flabellipecten besseri* (Andrzejowski, 1830); 18, 19 — *Genota ramosa* (Basterot, 1825); 20, 21 — *Europhos hoernesi* (Semper, 1861); scale bar 0.5 cm: 16, 17 — ?*Mitromorpha* sp.

the distribution of corals (Riegl & Piller 2000; Perrin & Bosellini 2012; Wiedl et al. 2013; Sremac et al. 2016; Chaix et al. 2018). In this respect, the Prnjavor Basin situated at the southern edge of the Central Paratethys preserves a relatively rich coral fauna. Atanacković (1984) recorded an occurrence of corals in the Badenian of the Hrvaćani though he used the term "coral reef". The reef is 5 m thick and inserted into arenaceous and gravel clays. The well-preserved coral colonies were noticed: *Favia, Helliastraea*, *Lithophyllia*, *Prionastraea*, *Solenastraea*. Besides corals, the reef contains hydrozoans, bryozoans, and sponges mentioned (Krumpholz 1916; Atanacković 1984, 1985; Soklić 2001).

Biostratigraphic interpretation

Calcareous nannofossil biostratigraphy has established NN5 Zone by the presence of *Sphenolithus heteromorphus* Deflandre, 1953 and the absence of *Helicosphaera ampliaperta* Bramlette & Wilcoxon, 1967. The presence of *Pontosphaera desuetoidea* described from NN5 (3rd order cycles TB 2.4) Zone from Mura Depression (Slovenia) by Bartol (2010) supports this biostratigraphic attribution. A common occurrence of *S. heteromorphus* (35 %) within the investigated assemblage from Hrvaćani allows the correlation with *Sphenolithus heteromorphus* Partial-range Zone (MNN5) of Mediterranean nannofossil zonation described by Fornaciari et al. (1996). The occurrence of *H*. cf. *waltrans* points to the lower part of NN5 Zone that can be correlated with the lower Lagenidae Zone (Hohenegger et al. 2014) (Fig. 5).

The record of some foraminiferal species suggests their biostratigraphic and paleoecological usefulness; namely, they belong to the Lower Badenian, the older zone of *Ammonia viennensis* and *Elphidium crispum* (the equivalent of Lagenidae Zone of Vienna Basin) (Jovanović et al. 2020). This includes *Ammonia viennensis*, *Borelis melo* subsp. *curdica* etc.

Based on available data, a difference in the richness of the major testudinate clades through time is noticed. The European records had a mixture of both cryptodires and pleurodires, yet cryptodires were predominant (Cleary et al. 2020).

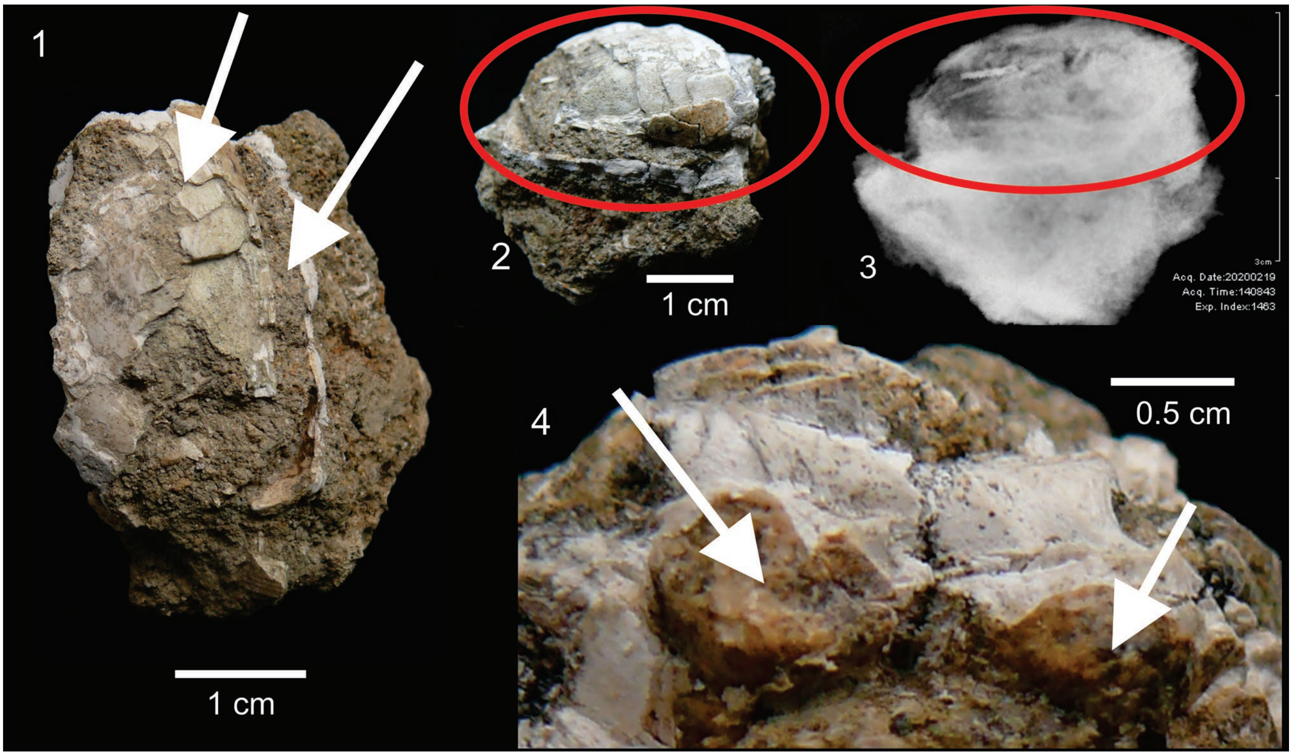

Fig. 11. Detailed view to shell turtle, scale bar 1 cm (figs. 1, 2) and 0.5 cm (4): 1 — part of carapace of shell in dorsal views. The white arrow (left) shows the plates; the white arrow (right) shows the rim of the plastron; 2 — carapace of shell in lateral view; 3 — X-ray photography of shell in lateral view; 4 — parts of plastron in gular region (the white arrows).

The Eocene was a particularly favorable time for the development of littoral turtles in Europe, while there is only one finding in Miocene presently (Georgalis et al. 2013). Extant pleurodires live in relatively warm regions. Pleurodira is less rich in species and confined to freshwater in the southern hemisphere today, while cryptodires contribute most of the richness record to non-marine turtles. These generally cold-intolerant turtles (Bourque 2016) are indicators that paleoclimate in the southern margin of Central Paratethys was warm enough during the Middle Miocene, as pointed out by Eremija (1970). The colonial corals and sediments associated with the remains of a turtle are utilized to infer its stratigraphic provenience and the depositional conditions in which it has been preserved. The accompanying fossil assemblages include nannoplankton, foraminifera, juvenile and adult stenohaline, and thermophilic mollusks. The new turtle is therefore confidently interpreted as originating from shallow water with normal salinity. As the only specimen found in the marine sediments of Bosnia, the rest of the turtle needs to be studied in more detail due to the possibility that it represents a new taxon. A detailed description of these remains of a turtle shell will be the subject of another paper.

Fossil remains from Hrvaćani locality indicate the influence of the warm period that is probably related to the Middle Miocene Climate Optimum evidenced in the whole Paratethys, as pointed (Eremija 1970). All the fossil assemblages showed similar patterns for the described site, reflecting favorable conditions in the open shallow marine environment influenced by normal salinity. Therefore, our age estimate differs from other authors, and we propose Middle Miocene (early Badenian) age (NN5 Zone) TB 2.4, cycles for the Hrvaćani deposits.

Discussion

At the southern margin of the Pannonian Basin (Croatia, Bosnia, and Serbia), after the continental sedimentation phase, the Badenian transgressive phase is easily recognized by the abundance of marine fossils such as calcareous nannofossils, foraminifera, and mollusks. However, this area has a very complex geological past that is largely still unclear. In addition to the specific geographical and geotectonic position, unclear connections with other basins, the misinterpretation of the stratigraphic affiliation of the microfauna (e.g., foraminifera) present additional problems.

During the Langhian (Early Badenian, 15.97–13.8 Ma according to Gradstein et al. 2012), the Central Paratethys Sea reached its maximal extent, and their southern margin in several sites was flooded. The onset of the widespread open marine "Badenian Sea" is recognized in western and eastern terrains of Northern Bosnia nannofossils of the NN5 (Martini 1971) biozone (Ćorić et al. 2009) (Fig. 3), while in all previously investigated localities of the central part of northern Bosnia (Prnjavor Basin, etc.) nannofossils of the NN6 (Martini 1971) biozone are recognized (Jerković & Ćorić 2006). Changes in the layout and characteristics of these sedimentary basins, situated in front of the Dinaric Mountains, reflect the local and regional tectonic and paleogeographic settings (Ćorić et al. 2009). According to our results, during this period, there were no drastic climate changes on the southern margin of Central Paratethys. Still, there were obvious changes in the composition of the communities associated with different facies and local paleogeography. Therefore, biostratigraphic correlations within this region remain unclear. The middle Miocene experienced two climate periods known as the Middle Miocene Climate Optimum (MMCO) and Middle Miocene Climate Transition (MMCT), linked to highly enigmatic processes such as sea-level change, and ocean currents, etc. (Flower & Kennett 1994; Zachos et al. 2001). The Middle Miocene (Badenian) period was marked in Central Paratethys by developing thermophilic stenohaline species and invasion of Mediterranean fauna (Harzhauser et al. 2003). In addition, rich fauna that prefers warm water and many marine mollusks display a peak in diversity during the warm Lower Badenian. The recognition of an understanding of these events in the geological past is of general interest to understanding the evolution and distribution of biota over time, as well as biostratigraphic and biogeographic correlations (Harzhauser & Piller 2007; Kováč et al. 2017 b), paleogeographic reconstruction, as well as the definition of regional time scale (Kováč et al. 2018).

The nannoplankton assemblages enabled the biostratigraphic correlation of the investigated section with other fossiliferous sites in the region. Hrvaćani is situated in the central part of northern Bosnia (Fig. 2). The age of these deposits corresponds to the zone of calcareous nannoplankton NN5, first reported in this part of Bosnia. Our research and marker fossils prove the early Badenian age in the Hrvaćani site for the first time when the climate in the Central Paratethys was mainly subtropical (Kováč et al. 2007, 2017a). The similar Badenian nannoplankton bioevents at the southern margin of Central Paratethys (Tuzla Basin in Bosnia, then Sumijevac stream near Koceljeva and Rakovica stream near Belgrade (in Serbia) were established by Vrabac et al. 2007; Jovanović et al. 2019, 2020.

Benthic foraminifera of the Hrvaćani section comprise taxa that are important biostratigraphical markers, particularly at the southern boundary of the Central Paratethys. Correlations with other localities such as Sumijevac stream near Koceljeva and Rakovica stream near Belgrade (in Serbia) (Jovanović et al. 2020) are possible. *Borelis melo* range at least throughout the Miocene while *B. melo* subsp. *curidica* is restricted to the late Early to the Middle Miocene (Jones et al. 2006). *Borelis melo* and *B. melo* subsp. *curdica* bear a very important stratigraphic value and can be used for the correlation with the Mediterranean Sea, as well as paleoecological information (Gagić 1984; Barjaktarević 1986; Jones et al. 2006; Bassi et al. 2019). In addition, the authors reported on paleobiogeographical significance of *Borelis melo* and *B. melo* subsp. *curdica* as well as their paleobathymetry in both the Indo–Pacific and Mediterranean. *B. melo* subsp. *curdica*, which occur in shallow water tropical, carbonate coral reef related settings and indicate shallow water with a depth of up to 35 m and temperature around 30 °C (Bignot & Guernet 1976; Barjaktarević 1986). During the Miocene, the "Trans-Tethyan Trench Corridor" via Slovenia was open and connected the Mediterranean Sea with the Pannonian Basin (Rögl 1998, 1999). The foraminifera associations from the analyzed sandstones of Hrvaćani belong to the Lower Badenian, namely the older zone of *Ammonia viennensis* and *Elphidium crispum* (the equivalent of Lagenidae Zone of Vienna Basin). The occurrence of *Planostegina costata* allows correlation with the "Moravian Substage" (NN5 Zone) of the Badenian (Grill 1943).

Corals lived in larger or smaller colonies. Although corals were exposed to diverse influences depending on the type of sedimentation, location, distance from shore and proximity to river mouths, different geochemical properties, etc., many species indicate favorable conditions for the development of a subtropical fauna, such as the hermatypic corals (Chaix & Saint Martin 2008; Duckworth et al. 2017; Chaix et al. 2018) and are represented in the Central Paratethys during the Lower Badenian (Saint Martin et al. 2007). The taxa identified here are common in the Miocene deposits of the Central Paratethys (e.g., Reuss 1871; Oosterbaan 1990; Rus & Popa 2008; Chaix et al. 2018; Kleprlíková 2018) or the Mediterranean realm (e.g., Chaix & Saint Martin 2008) etc. Some species such as *Favites neglecta* and *Tarbellastraea reussiana* were recorded previously from the early Middle Miocene (Badenian) sites from Serbia, Romania, Hungary, then from the Miocene deposits of Portugal, Spain, Greece, France, Egypt, Iran, Saudi Arabia (El-Sorogy et al. 2020). Compared to some Late Badenian localities, the coral community is quite diverse in species, but compared to the Transylvanian Basin (Romania) (Rus & Popa 2008; Chaix et al. 2018) and Styrian Basin (Austria) Riegl & Piller (2000) studied coral fauna is poor. The low diversity of the scleractinian corals may be interpreted as the influence of diverse paleoecological and paleogeographical conditions in the Prnjavor Basin surrounded by several mountains. Due to living conditions that remained fairly favorable to them, the late Badenian coral fauna has a relatively low diversity, comprised of only several genera, in which the *Tarbellastraea* and *Porites* predominate (Górka 2018). As mentioned earlier, the coral fauna of Hrvaćani consists primarily of massive *Tarbellastraea reussiana* and *Favites* sp. and several specimens of smaller colonies Scleractinia indet. The amount of terrigenous input and inhabiting Cirripedia affected the growth of some coral morphology. Although *Porites* are resistant to sediment, only small colonies of coral are preserved. Isolated parts of colonies or biostromes may be found occasionally in Badenian deposits in Vojilovo (surroundings of Golubac, Serbia), as well as in Badenian sediments of Rakovica near Belgrade and Negotin (eastern Serbia, Dacian Basin) (Pavlović 1908; Jovanović et al. 2020). According to the previous data, it may be concluded that the Badenian sediments in the vicinity of Negotin in Serbia (Pavlović 1908; Jovanović 2011) and Hrvaćani in Bosnia were the richest sediments with corals fauna of Middle Miocene in the southern margin of Central Paratethys. From a stratigraphic perspective, fossiliferous sediments from Negotin have been classically attributed to the Middle Miocene (Lower Badenian) (Stevanović 1977). From a stratigraphic and paleoecological point of view, many species indicate favorable conditions for developing subtropical fauna such as the hermatypic corals (Chaix et al. 2018).

Abundant and diversified mollusks fauna has been recorded from the investigated outcrop. A paleontological data suggest that the Middle Miocene Climatic Optimum was reflected in mollusks abundance and distribution, not only in Central Paratethys (Sacco 1897–1901; Malatesta 1974; Studencka 1986, etc.). Many species are well represented in tropical and subtropical water during the lower Miocene or Middle Miocene period. Numerous widespread species have hither been known in the Lower Badenian localities of Central Paratethys. Mollusks assemblages are very similar to those found in Rakovica and Golubac sites in Serbia as well and other coeval localities of the Central Paratethys (Korytnica Basin, Făget Basin, Vienna Basin) (Baluk 1975, 2003, 2006; Studencka 1986; Studencka et al. 1998; Landau et al. 2013; Popa et al. 2014; Jovanović et al. 2020). Similar or identical fossil mollusks occur in the Hrvaćani site described by Atanacković (1984, 1985), pointing out that the Badenian mollusks from Hrvaćani correlate most to fauna from the Transylvanian Basin (Romania). Interestingly, the assemblage contains very rare *Projenneria lapugyensis* that occurs only in the Lower Badenian of Romania (Popa et al. 2014) and Bulgaria (Dacian Basin), according to Kojumdgieva & Strachimirov (1960).

Conclusion

This paper is based on lithostratigraphic and biostratigraphic data derived from investigations of Middle Miocene (Badenian) strata at Hrvaćani (Northern Bosnia). Their systematic excavation started in 2019. Our biostratigraphy inferences are based on the analyses of calcareous nannofossil, foraminifers, and mollusks assemblages. Additionally, we also investigated other fossils sampled from the Hrvaćani site. Calcareous nannofossil biostratigraphy has established an NN5 Zone based on the presence of *Sphenolithus heteromorphus* and the absence of *Helicosphaera ampliaperta*. Except for rare juvenile planktic forms, microfossils in these samples are represented by benthic foraminifera. The foraminifera associations belong to the Lower Badenian, zone of *Ammonia viennensis* and *Elphidium crispum* (the equivalent of Lagenidae Zone of Vienna Basin). Lower Badenian age is supported by the presence of *B. melo* subsp. *curidica*, which is restricted to the late Early to the Middle Miocene (Jones et al. 2006). The fossil assemblages are characterized by diverse thermophilic corals (*Plesiastraea*, *Favites, Stylophora*), and abundant mollusks fauna (*Amalda*, *Clavatula*, *Petalocochnus*, *Genota, Xenophora*, several genera of Conidae, Turritellidae, etc.) indicate shallow water and favorable conditions.

The fossil of a small-bodied turtle from Hrvaćani improves our knowledge of fossil turtle paleobiodiversity, being the first record of a fossil turtle in the Bosnian and neighboring regions. This fossil find shows the high potential that the southern margin middle Miocene (Badenian) outcrop of Central Paratethys has in order to explore paleobiogeography distribution of numerous fossils assemblages, including littoral turtles currently attributed to Testudines (Pleurodira).

The discovery of Lower Badenian deposits in Hrvaćani provides new insights into our knowledge of the paleogeographic situation of Bosnia. Our own and the private fossil collections presented here give a more detailed picture of the Badenian fauna diversity and paleoenvironment in the southern margin of the Pannonian Basin. It can be concluded by combining data of nannoplankton, foraminifers, corals, malacological, and herpetological remains that the early Middle Miocene (Badenian) in Hrvaćani (Bosnia) corresponds to Lagenidae Zone (NN5 Zone) and indicate the warm period related to the Middle Miocene Climate Optimum, known from the entire Paratethys. Therefore, as our age estimate diverges markedly from other authors, we propose Middle Miocene Badenian age, calcareous nannofossil Lagenidae zone (NN5 Zone) for the Hrvaćani deposits.

Acknowledgments: We are very grateful to the reviewers Michal Jamrich (Comenius University, Bratislava), Radoslav Biskupič (Poprad, Slovakia), Ljupko Rundić (University of Belgrade), who contributed to the quality of this paper with their advice. We would also like to thank the editors Natália Hudáčková (Comenius University, Bratislava), and Silvia Antolíková (Slovak Academy of Sciences, Bratislava) for their constructive instructions.

References

Ardovini R. & Cossignani T. 2004: West African seashells (including Azores, Madeira and Canary Is.) [Conchiglie dell'Africa Occidentale (incluse Azzorre, Madeira e Canarie)]. *English-Italian edition*. Ancona (L'Informatore Piceno), 1–319.

Atanacković M. 1984: Fossil assemblages of Middle Miocene (Badenian) marine deposits near the village of Hrvaćani (northwestern Bosnia). *Akademija nauka i umjetnosti Bosne i Hercegovine, Odjeljenje tehničkih nauka* 8, Sarajevo, 1–12 (in Serbo-Croatian).

Atanacković M. 1985: Molluscs of the marine Miocene of Bosnia. *Geoinženjering*, Sarajevo, 1–305 (in Serbo-Croatian).

Baluk W. 1975: Lower Tortonian gastropods from Korytnica, Poland; Part 1. *Palaeontologia Polonica* 32, 1–186.

Baluk W. 2003: Middle Miocene (Badenian) gastropods from Korytnica, Poland; Part IV. Turridae. *Acta Geologica Polonica* 53, 29–78.

Baluk W. 2006: Middle Miocene (Badenian) gastropods from Korytnica, Poland; Part V. Addenda et Corrigenda ad Prosobranchia. *Acta Geologica Polonica* 56, 177–220.

Barjaktarević Z. 1986: *Borelis curdica* (Reichel) in the Upper Badenian sediments of North-Western Croatian Paratethys. *Geološki vjesnik* 39, 7–9 (in Serbo-Croatian with English summary).

Bartol M. 2010: *Pontosphaera geminipora* n. sp. and *Pontosphaera desuetoidea* n. sp., new calcareous nannoplankton species from the Middle Miocene of the Mura Depression (Slovenia, Central Paratethys). *Micropaleontology* 56, 509–516. https://doi.org/10.2307/40983738

Bassi D., Braga C.J., Di Domenico G., Pignatti J., Abramovich S., Hallock P., Könen K., Kovács Z., Langer R.M., Pavia G. & Iryu Y. 2019: Palaeobiogeography and evolutionary patterns of the larger foraminifer Borelis de Montfort (Borelidae). *Papers in Paleontology* 1–3. https://doi.org/10.5061/dryad.st65n12

Bignot G. & Guernet C. 1976: Sur la presence de Borelis curdica (Reichel) dans le Miocène de l'ile de Kos (Grèce). *Géologie Méditerranéenne* 3, 15–25.

Bistričić A. & Jenko K. 1985: Area No. 224 b1: Transtethyan Trench "Corridor", YU. In: Steininger F.F., Senes J., Kleemann K. & Rögl F. (Eds.): Neogene of the Mediterranean Tethys and Paratethys. Stratigraphic correlation tables and sediment distribution maps. *University of Vienna,* Vienna, 1, 72–73.

Bourque J.R. 2016: Side necked turtles (Testudines, Pleurodira) from the ancient Gulf Coastal Plain of Florida during middle Cenozoic megathermals. *Chelonian Conservation & Biology* 15, 23–35. https://doi.org/10.2744/CCB-1159.1

Cadena A.E., Bloch I.J. & Jaramillo A.C. 2010: New Podocnemidid Turtle (Testudines: Pleurodira) from the Middle-Upper Paleocene of South America. *Journal of Vertebrate Paleontology* 30, 367–382. https://doi.org/10.1080/02724631003621946

Chaix C. & Saint Martin J.P. 2008: Les faunes de scléractiniaires hermatypiques dans les plates-formes carbonatées méditerranéennes au Miocène supérieur. *Geodiversitas* 30, 181–209.

Chaix C., Saint Martin J.P., Merle D., Saint Martin S. & Caze B. 2018: Biodiversité des coraux scléractiniaires du Langhien (Badénien, Miocène moyen) de Lăpugiu de Sus (Roumanie). *Geodiversitas* 40, 321–353. https://doi.org/10.5252/geodiversitas2018v40a14

Cicha I., Rögl F., Rupp Ch. & Čtyroká J. (Eds.) 1998: Oligocene–Miocene foraminifera of the Central Paratethys. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft* 549, 1–325.

Cleary T.J., Benson R., Holroyd P.A. & Barrett P.M. 2020: Tracing the patterns of non marine turtle richness from the Triassic to the Palaeogene: from origin to global spread. *Palaeontology* 63, 753–774. https://doi.org/10.1111/pala.12486

Ćorić S., Pavelić D., Rögl F., Mandic O., Vrabac S., Avanić R. Jerković L. & Vranjković A. 2009: Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geologica Croatica* 62, 31–43. https://doi.org/10.4154/GC.2009.03

Duckworth A., Giofre N. & Jones R. 2017: Coral morphology and sedimentation. *Marine Pollution Bulletin* 125, 15, 289–300. https://doi.org/10.1016/j.marpolbul.2017.08.036

El-Sorogy A.S., Tsaparas N. & Al-Kahtany K. 2020: Middle Miocene corals from Midyan area, Northwestern Saudi Arabia. *Geological Journal* 55, 5594–5605. https://doi.org/10.1002/gj.3761

Eremija M. 1969: Neogene between Motajica and Ljubić (Prnjavor Basin). *Geološki glasnik* 13, 1–140 (in Serbo-Croatian).

Eremija M. 1970: Neogene between Motajica and Ljubić (I). Biostratigraphic analysis of Miocene deposits and fauna in the Prnjavor basin. *Geološki anali Balkanskoga poluostrva* 35, 25–117 (in Serbo-Croatian).

Eremija M. 1971: Miocene molluscs of the Prnjavor basin (Bosnia). *Geološki anali Balkanskoga poluostrva* 36, 51–85 (in Serbo-Croatian).

Flower B.P. & Kennett J.P. 1994: The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation and global carbon cycling. *Palaeogeography, Palaeoclimatology, Palaeoecology* 108, 537–555.

Fornaciari E., Di Stefano A., Rio D. & Negri A. 1996: Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. *Micropaleontology* 42, 37–63. https://doi.org/10.2307/1485982

Gagić N. 1984: Borelis curdica (Reichel) from Badenian sediments of Yugoslavia. *Vesnik Zavod za geološka i geofizička istraživanja* 42, 119–123 (in Serbo-Croatian).
Georgalis G.L., Velitzelos E., Velitzelos D.E. & Kear B.P. 2013: *Nostimochelonelampra* gen. et sp. nov., an Enigmatic new Podocnemidoidean Turtle from the Lower Miocene of Northern Greece. In: Brinkman D.B., Holroyd P.A. & Gardner J.D. (Eds.): Morphology and Evolution of Turtles. *Springer*, 277–287. https://doi.org/10.1007/978-94-007-4309-0_17
Górka M. 2018: Late Badenian zooxanthellate corals of the Medobory Hills (western Ukraine) and their environmental significance. *Annales Societatis Geologorum Poloniae* 88, 243–256. https://doi.org/ 10.14241/asgp.2018.011
Gradstein F.M., Ogg J.G., Schmitz M.D. & Ogg G. 2012: The Geologic Time Scale 2012. *Elsevier,* Amsterdam, 1–1144.
Grill R. 1943: Über mikropaläontologische Gliederungsmöglichkeiten im Miozän des Wiener Beckens. *Mitteilungen des Reichsanst für Bodenforschung* 6, 33–44.
Hardenbol J., Thierry J., Farley M.B., Jacquin T., de Graciansky P.C. & Vail P. 1998: Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: Graciansky P.C. et al. (Eds): Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. *SEPM Special Publication* 60, 3–13.
Harzhauser M. & Piller W. 2007: Benchmark data of a changing sea. Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene. *Palaeogeography Palaeoclimatology, Palaeoecology* 253, 8–31. https://doi.org/10.1016/j.palaeo.2007.03.031
Harzhauser M., Mandic O. & Zuschin M. 2003: Changes in Paratethyan marine molluscs at the Early/Middle Miocene transition: diversity, palaeogeography and palaeoclimate. *Acta Geologica Polonica* 53, 323–339.
Hilgen F.J., Abels H.A., Iaccarabino S., Krijgsman W., Raffi I., Sprovieri R., Turco E. & Zachariasse W.J. 2009: The Global Stratotype Section and Point (GSSP) of the Serravallian Stage (Middle Miocene). *Episodes* 32, 152–166. https://doi.org/10.18814/epiiugs/2009/v32i3/002
Hohenegger J., Ćorić S. & Wagreich M. 2014: Timing of the Middle Miocene Badenian Stage of the Central Paratethys. *Geologica Carpathica* 65, 55–66. https://doi.org/10.2478/geoca-2014-0004
Jerković L. & Ćorić S. 2006: Middle Miocene (Badenian/Sarmatian) Calcareous Nannoplankton from the Southern Margin of the Central Paratethys (Northern Bosnia). *Journal of Nannoplankton Research* (Program with Abstracts, INA11 Conference, Lincoln, Nebraska) 31–33, 52.
Jones R.W., Simmons M.D. & Whittaker J.E. 2006: On the stratigraphical and palaeobiological significance of *Borelis melo melo* (Fichtel & Moll, 1798) and *B. melo curdica* (Reichel, 1937) (Foraminifera, Miliolida, Alveolinidae). *Journal of Micropalaeontology* 25, 175–190. https://doi.org/10.1144/jm.25.2.175
Jovanović G. 2011: Badenian fauna of corals in vicinity of Negotin (NE Serbia). In: Kyška-Pipík R., Starek D. & Staňová S. (Eds.): The 4th International workshop on the Neogene from the Central and South-Eastern Europe (NCSEE), September, 12–16, 2011 Banská Bystrica, Slovakia. Abstracts and Guide of Excursion. *Geological Institute of the Slovak Academy of Sciences*, 20.
Jovanović G., Ćorić S. & Vrabac S. 2019: First evidence of the marine Badenian transgression Badenian near Koceljeva (western Serbia). *Geološki anali Balkanskoga poluostrva* 80, 1–15. https://doi.org/10.2298/GABP1901001J
Jovanović G., & Vrabac S. & Ćorić S. 2020: Stratigraphy revision of Upper Badenian of Rakovica stream near Belgrade (Central Paratethys, Serbia). *Geološki anali Balkanskoga poluostrva* 81, 11– 30. https://doi.org/10.2298/GABP200213005J
Kleprlíková L. 2018: Scleractinia from a new locality Borač–Podolí (southern Part of the Carpathian foredeep, Czech Reupbilc). *Acta Musei Moravie Scientiae geologicae* 103, 59–66 (in Czech, with English abstract).
Kojumdgieva E. & Strachimirov B. 1960: Les fossiles de Bulgarie. VII. Tortonien. *Academie Bulgare des Sciences*, Sofia, 1–246 (in Bulgarian, with French summary).
Kováč M., Andreyeva-Grigorovich A., Bajraktarević Z., Brzobohatý R., Filipescu S., Fodor L., Harzhauser M., Nagymarosy A., Oszczypko N., Pavelić D., Rögl F., Saftić B., Sliva Ľ. & Studencka B. 2007: Badenian evolution of the Central Paratethys Sea: paleogeography, climate and eustatic sea-level changes. *Geologica Carpathica* 58, 579–606.
Kováč M., Hudáčková N., Halásová E., Kováčová M., Holcová K., Oszczypko-Clowes, M., Báldi K., Less Gy., Nagymarosy A., Ruman A., Klučiar T. & Jamrich M. 2017a: The Central Paratethys palaeoceanography: a water circulation model based on microfossil proxies, climate, and changes of depositional environment. *Acta Geologica Slovaca* 9, 75–114.
Kováč M., Márton E., Oszczypko N., Vojtko R., Hók, J., Králiková S., Plašienka D., Klučiar, T., Hudáčková N. & Oszczypko-Clowes M. 2017b: Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global and Planetary Change* 155, 133–154.
Kováč M., Halásová E., Hudáčková N., Holcová K., Hyžný M., Jamrich M. & Ruman A. 2018: Towards better correlation of the Central Paratethys regional time scale with the standard geological time scale of the Miocene Epoch. *Geologica Carpathica* 69, 283–300. https://doi.org/10.1515/geoca-2018-0017
Krumpholz F. 1916: Miozane Korallen aus Bosnien. *Verhandlungen des Naturforschenden Vereines in Brünn* 54, 26–50.
Landau B.M., Harzhauser M., İslamoğlu Y. & da Silva C.M. 2013: Systematics and paleobiogeography of the gastropods of the middle Miocene (Serravallian) Karaman Basin, Turkey. *Cainozoic research* 11–13, 3–576.
Lourens L., Hilgen F., Shackleton N.J., Laskar J. & Wilson D. 2004: The Neogene Period. In: Gradstein F.M., Ogg J.G. & Smith A.G. (Eds.): A geologic time scale 2004. *Cambridge University Press*, Cambridge, 409–440.
Malatesta A. 1974: Malacofauna Pliocenica umbra. *Memorie per servire alla descrizione della Carta Geologica D'ltalia* 13, 1–498 (in Italian).
Martini E. 1971: Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Proceedings of the II Planktonic Conference. *Tecnoscienza,* Roma, 739–785.
Mojićević M., Vilovski S. & Tomić B. 1976: Basic Geological Map of SFRY 1:100,000, sheet Banjaluka. *Federal Geological Survey,* Belgrade (in Serbo-Croatian).
Mojićević M., Vilovski S. & Tomić B. 1977: Explanatory notes for the sheet Banjaluka. Basic Geological map of the SFRY 1:100,000. *Federal Geological Survey* Belgrade (in Serbo-Croatian with English summary).
Oosterbaan A.F.F. 1990: Notes on a collection of Badenian (Middle Miocene) corals from Hungary in the National Museum of Natural History at Leiden (The Netherlands). *Contributions to Tertiary and Quaternary Geology* 27, 3–15.
Pavlović S.P. 1908: Corals from the Second Mediterranean beds in Serbia. *Rad JAZU* 175, 81–86 (in Serbian).
Perch-Nielsen K. 1985: Cenozoic calcareous nannofossils. In: Bolli H.M., Saunders J.B. & Perch-Nielsen K. (Eds.): Plankton Stratigraphy. *Cambridge University Press*, Cambridge, 427–554.
Perrin C. & Bosellini F.R. 2012: Paleobiogeography of scleractinian reef corals: Changing patterns during the Oligocene–Miocene climatic transition in the Mediterranean. *Earth-Science Reviews* 111, 1–24. https://doi.org/10.1016/j.earscirev.2011.12.007
Petrović M. & Atanacković M. 1976: Biostratigraphy of the Tortonian stage of the northern Potkozarje and the surroundings of the

village Hrvaćani based on foraminifera (northwestern Bosnia). *Geološki anali Balkanskoga poluostrva* 40, 65–102 (in Serbo-Croatian).

Pezelj D.J., Mandic O. & Ćorić S. 2013: Paleoenvironmental dynamics in the southern Pannonian Basin during initial Middle Miocene marine flooding. *Geologica Carpathica* 64, 81–100. https://doi.org/10.2478/geoca-2013-0006

Piller E., Harzhauser M. & Mandic O. 2007: Miocene Central Paratethys stratigraphy – current status and future directions. *Stratigraphy* 4, 151–168.

Popa V.M., Duma A. & Săplăcan A. 2014: Badenian gastropods from the collections of the Mureş County Museum. *Analele Stiintifi ceale Universitatii "Al. I. Cuza" din Iasi,* Seria Geologie 60, 5–30.

Reuss A.E. 1871: Die fossilen Korallen des österreichisch-ungarischen Miocäns. *Denkschriften der Kaiserlichen Akademie der Wissenschaften*, *Mathematisch-Naturwissenschaftlichen Klasse* 31, 197–270.

Riegl B. & Piller W.E. 2000: Reefs and coral carpets in the Miocene Paratethys (Badenian, Leitha Limestone, Austria). In: Moosa M.K. et al. (Eds.): *Proceedings of the Ningth International Coral Reef Symposium*, Bali, 1, 211–216.

Rögl F. 1998: Palaeogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). *Annalen des Naturhistorischen Museums in Wien* 99A, 279–310.

Rögl F. 1999: Mediterranean and Paratethys. Facts and hypotheses of an Oligocene to Miocene Paleogeography (short overview). *Geologica Carpathica* 59, 339–349

Rus M. & Popa M. 2008: Taxonomic notes on the Badenian corals from Lăpugiu de Sus (Făget Basin, Romania). *Acta Palaeontologica Romaniae* 6, 325–337.

Sacco F. 1897–1901: The molluscs of the Tertiary terrain of Piedmont and Liguria. *Memoirie della Reale Accademi delle Sciense di Torino* 23, 1–42 (1897); 24, 1–26, 1–64 (1898); 27, 1–74 (1899); 29, 1–159 (in Italian).

Saint Martin J.P., Merle D., Cornée J.J., Filipescu S., Saint Martin S. & Bucur I.I. 2007: Les constructions coralliennes du Badénien (Miocène moyen) de la bordure occidentale de la Dépression de Transylvanie (Roumanie). *Comptes Rendus Palevol* 6, 37–46. https://doi.org/10.1016/j.crpv.2006.07.006

Sant K., Palcu D., Mandic O. & Krijgsman W. 2017: Changing seas in the Early–Middle Miocene of Central Europe: a Mediterranean approach to Paratethyan stratigraphy. *Terra Nova* 29, 273–281. https://doi.org/10.1111/ter.12273

Soklić I. 2001: Fossil Flora and Fauna of Bosnia and Herzegovina. *Akademija Nauka i Umjetnosti Bosne i Hercegovine* 10, 1–861 (in Bosnian).

Sremac J., Bošnjak Makovec M., Vrsaljko D., Karaica B., Tripalo K., Fio Firi K., Majstorović Bušić A. & Marjanac T. 2016: Reefs and bioaccumulations in the Miocene deposits of the North Croatian Basin – Amazing diversity yet to be described. *The Mining–Geology–Petroleum Engineering Bulletin* 31, 19–29. https://doi.org/10.17794/rgn.2016.1.2

Stevanović P. 1977: Carpathian foothills from Kladovo to Negotin and Štubik. In: Petković K. (Ed.): Geology of Serbia (Stratigraphy, Cenozoic) 2, 3. *Zavod Regionalnu geologiju i paleontologiju Rudarsko-geološkog fakulteta Univerziteta u Beogradu,* Belgrade, 35–47 (in Serbo-Croatian).

Studencka B. 1986: Bivalves from the Badenian (Middle Miocene) marine sandy facies of southern Poland. *Palaeontologia Polonica* 47, 3–128.

Studencka B., Gontsharova I.A. & Popov S. 1998: The bivalve faunas as a basis for reconstruction of the Middle Miocene history of the Paratethys. *Acta Geologica Polonica* 48, 285–342.

Vrabac S., Ferhatbegović Z. & Đulović I. 2007: The stratigraphic position of the local foraminifer zone *A. viennensis* and *N. commune* in the Miocene sediments of the Tuzla Basin. *Zbornik radova RGGF* 31, 23–27 (in Bosnian).

Wade B.S., Pearson P.N., Berggren W.A. & Pälike H. 2011: Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth-Science Reviews* 104, 111–142.

Wiedl T., Harzhauser M., Kroh A., Ćorić S. & Piller E.W. 2013: Ecospace variability along a carbonate platform at the northern boundary of the Miocene reef belt (Upper Langhian, Austria). *Palaeogeography, Palaeoclimatology, Palaeoecology* 370, 232–246. https://doi.org/10.1016/j.palaeo.2012.12.015

Williams C & Stayton C.T. 2019: Effects of Sutured Pelvic Elements on Turtle Shell Strength: A Comparison of Pleurodire and Cryptodire Shell Mechanics. *Herpetologica* 75, 123–133. https://doi.org/10.1655/D-17-00066

Zachos J., Pagani M., Sloan L., Thomas E. & Billups K. 2001: Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292, 686–93. https://doi.org/10.1126/science.1059412

Supplementary material

Supplementary Table S1 is available online at http://geologicacarpathica.com/data/files/supplements/GC-72-4-Jovanovic_TableS1.docx.

Supplement

Table S1: List of the all taxa cited in the text and figures.

	Badenian taxa	Reworked taxa from a Cretaceous deposits
Calcareous nannoplankton	*Sphenolithus heteromorphus* Deflandre, 1953 *Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967 *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930 *Reticulofenestra perplexa* (Burns, 1975) Wise, 1983 *R. haqii* Backman, 1978 *R. minuta* Roth, 1970 *R. pseudoumbilicus* (Gartner, 1967) Gartner, 1969) *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954 *H. walbersdorfensis* Muller, 1974 *H.* cf. *waltrans* Theodoridis, 1984 *Coronocyclus nitescens* (Kamptner, 1963) Bramlette & Wilcoxon 1967 *Cyclicargolithus floridanus* (Roth & Hay, in Hay et al. 1967) Bukry, 1971 *Umbilicosphaera jafari* Muller, 1974 *U. rotula* (Kamptner, 1956) Varol, 1982 *Pontosphaera desuetoidea* Bartol, 2010 *P. discopora* Schiller, 1925 *P. multipora* (Kamptner, 1948 ex Deflandre in Deflandre & Ferth, 1954) Roth, 1970 *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 *Micrantholithus vesper* Deflandre, 1950 *M.* cf. *flos* Deflandre in Deflandre & Fert, 1954 *Discoaster adamanteus* Bramlette & Wilcoxon, 1967 *Triquetrorhabdulus milowii* Bukry, 1971	*Micula prinsii* Perch-Nielsen, 1979 *Arkhangelskiella cymbiformis* Vekshina, 1959 *Watznaueria barnesiae* (Black in Black & Barnes, 1959) Perch-Nielsen, 1968
Foraminiera	*Ammonia viennensis* (d'Orbigny, 1846) *Elphidium crispum* (Linnaeus, 1758) *Biasterigerina planorbis* (d'Orbigny, 1846) *Nonion commune* (d'Orbigny, 1846) *Pseudotriloculina consobrina* (d'Orbigny, 1846) *Cibicidoides ungerianus ungerianus* (d'Orbigny, 1846) *Planostegina costata* (d'Orbigny, 1846) *Triloculina gibba* (d'Orbigny, 1846) *Borelis melo* subsp. *curdica* (Reichel, 1937) Planktic form	
Cirripedia	Indet.	
Spongia	Didemnid ascidian spicules	
Corals	*Tarbellastraea reussiana* (Milne-Edwards & Haime, 1850) *Stylophora calcinata* (Mayer, 1864) *Stylophora depauperata* (Reuss, 1867) *Heliastraea defrancei* (Milne-Edwards & Haime, 1850) *Favites neglecta* (Michelotti in d'Achiardi, 1868) *Favites neugeboreni* (Reuss, 1871) ?*Favites* sp. *Plesiastraea* (*Paleoplesiastraea*) cf. *tazarinensis* (Chevalier, 1962) *Porites maigensis* Kühn, 1925 *Porites* sp. *Siderastrea* sp. ?Scleractinia (indet.)	
Gastropoda	*Amalda glandiformis* (Lamarck, 1810) *Monoplex corrugatus* (Lamarck, 1816) *Thetystrombus* sp. *Ocinebrina* cf. *coellata* (Dujardin, 1837) *Genota ramosa* (Basterot, 1825) *Perrona taurienensis* (Bellardi, 1877) *Perrona* sp. *Projenneria lapugyensis* (Sacco, 1894) *Phasmoconus fuscocingulatus* (Hoernes 1851) *Monteiroconus mojsvari* (Hoernes & Auinger, 1879) *Kalloconus tschermaki* (Hoernes & Auinger, 1879) *Kalloconus* sp.; *Lautoconus* cf. bitorosus (Fontannes, 1880) *Oligodia bicarinata* (Eichwald, 1830) *Archimediella carpathica* Harzhauser & Landau, 2019 *Terebra acuminata* Borson, 1820 *Sandbergeria perpusilla* (Grateloup, 1827) *Neverita josephinia* Risso, 1826	

Table S1 (continued)

	Badenian taxa	Reworked taxa from a Cretaceous deposits
Gastropoda	*Polinices redemptus* (Michelotti, 1847) *Cypraea ovulinae* Schilder, 1925 *Europhos hoernesi* (Semper, 1861) *Paroxystele orientalis* (Cossmann & Peyrot, 1917) *Seila turritissima* Sacco, 1895 *Petaloconchus intortus* (Lamarck, 1818) *Cylichna clathrata* (Defrance, 1825) *Roxania utriculus* (Brocchi, 1814) *Alvania miocenica* Sacco, 1895 *Hipponix (Sabia) phlepsi* (Boettger, 1896) *Thala obsoleta* (Brocchi, 1814) *Caecum trachea* (Montagu, 1803) *Pyrunculus elongatus* (Eichwald, 1830 *Xenophora* sp. Tritia sp. *Conomitra* sp. *?Mitromorpha* sp.	
Bivalvia	*Cubitostrea digitalina* (Eichwald, 1830) *Psammobia uniradiata* (Brocchi, 1814) *Aequipecten malvinae* (Dubois, 1831) *Chama gryphoides* Linnaeus, 1758 *Anadara fichtelli* (Deshayes, 1850) *Anadara turonica* (Dujardin, 1837) *Flabellipecten besseri* Andrzejowski, 1830 *Corbula carinata* Dujardin, 1837 *Venus nux* Gmelin, 1791 *Clausinella basteroti* (Deshayes, 1850) *Microloripes dentatus* (Defrance, 1823) *Tellina* sp	
Turtles	Testudines Batsch 1788	