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The Miocene "Pteropod event" in the SW part of the Central Paratethys (Medvednica Mt., northern Croatia)

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This paper was inspired by the scientific opus of Professor Vanda Kochansky-Devidé, the first woman elected to the Croatian Academy of Sciences and Arts, whose 100th birthday we celebrated in 2015.

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Abstract: Deep marine Miocene deposits exposed sporadically in the Medvednica Mt. (northern Croatia) comprise pelagic organisms such as coccolithophores, planktic foraminifera and pteropods. The pteropod fauna from yellow marls at the Vejalnica locality (central part of Medvednica Mt.) encompasses abundant specimens of *Vaginella austriaca* Kittl, 1886, accompanied with scarce *Clio fallauxi* (Kittl, 1886). Calcareous nannoplankton points to the presence of NN5 nannozone at this locality. Highly fossiliferous grey marls at the Marija Bistrica locality (north-eastern area of Medvednica Mt.) comprise limacinid pteropods: *Limacina valvatina* (Reuss, 1867), *L. gramensis* (Rasmussen, 1968) and *Limacina* sp. Late Badenian (NN5 to NN6 nannozone) age of these marls is presumed on the basis of coccolithophores. Most of the determined pteropods on species level, except *V. austriaca* have been found and described from this region for the first time. New pteropod records from Croatia point to two pteropod horizons coinciding with the Badenian marine transgressions in Central Paratethys. These pteropod assemblages confirm the existence of W–E marine connection ("Transtethyan Trench Corridor") during the Badenian NN5 nannozone. Limacinids point to the possible immigration of the "North Sea fauna" through a northern European marine passage during the Late Badenian (end of NN5- beginning of NN6 zone), as previously presumed by some other authors.

Keywords: Planktic gastropods, palaeoenvironment, Middle Miocene, Badenian, Central Paratethys, northern Croatia.

Introduction

Pteropoda are marine gastropods adapted to a holoplanktic way of life by transforming their foot into the "wings" (parapodia) for buoyancy and swimming. They live in oceans around the world at various depths. Most of them are epi- or mesopelagic (up to 1000 m), but some species live bathypelagic, at depths of 1000 m or more. During the day, they float at greater depths, and at sunset they rise up near the surface (negative fototaxis). Pteropods are divided into two orders: Thecosomata de Blainville, 1824 ("sea butterflies") and Gymnosomata de Blainville, 1824 ("sea angels"). Thecosomata include mainly forms with aragonitic shell in the adult stage, but in Gymnosomata a shell is only present in the larval stage (e.g., Herman 1998; Janssen & Little 2010; Corse et al. 2013; Janssen & Peijnenburg 2014 and references therein).

The most abundant occurrences of pteropods in Paratethys are recorded from the Middle Miocene deposits (e.g., Bohn-Havas & Zorn 1993, 1994, 2002; Bohn-Havas et al. 2004), coinciding with peak marine transgressions. The genera *Limacina* Bosc, 1817, *Vaginella* Daudin, 1800 and *Clio* Linnaeus, 1767 are the most diverse and numerous taxa (Janssen 1984; Zorn 1991, 1995, 1999; Bohn-Havas & Zorn 1993, 1994, 2002; Bohn-Havas et al. 2004). In northern Croatia, on the south-western margin of the Central Paratethys, Miocene planktic gastropods were recorded by Gorjanović-Kramberger (1908, p. 36), Kochansky (1944), Kochansky-Devidé (1973), Basch (1983b, p. 29), Magaš (1987, p. 19), Pikija (1987, p. 20), Korolija & Jamičić (1989, p. 16) and Avanić et al. (1995). Although pteropods were not studied in detail by the aforementioned authors, we were able to conclude from their records that *Vaginella austriaca* Kittl, 1886 was the most widely distributed pteropod species (Gorjanović-Kramberger 1908; Kochansky-Devidé 1973; Basch 1983b; Korolija & Jamičić 1989; Avanić et al. 1995), sporadically associated with *Clio pedemontana* (Mayer, 1868) (Kochansky 1944; Kochansky-Devidé 1973; Basch 1983b), "*Spiratella* sp." (Magaš 1987; Pikija 1987) and "*Spirialis* (=*Limacina*) *andrussowi* Kittl, 1886" (Kochansky-Devidé 1973).

A significant number of pteropods were collected during the recent field research in central and north-eastern parts of Medvednica Mt. in northern Croatia. This paper describes the Middle Miocene pteropod assemblages and palaeoenvironments with implications for the wider palaeogeographical area (Central Paratethys), and indicates possible faunal "migration routes".

Abbreviations used in this article are as follows (alphabetical order): A — aperture diameter; A_1/A_2-ratio — aperture diameters ratio; α — apical angle; $α_1$ — aperture angle; CNHM — Croatian Natural History Museum, Zagreb, Croatia; H — shell height; H/W-ratio — shell height and width ratio; Inv. No. — inventory number; H_t — height of teleoconch; MB — Marija Bistrica locality; UZFS-DG — University of Zagreb, Faculty of Science, Department of Geology, Croatia; V — Vejalnica locality; W — shell width.

Geological setting

The investigated localities are situated in the northern Croatia: Vejalnica locality in the central part of the Medvednica Mt. (45°54'17" N, 16°4'19" E) and the Marija Bistrica locality in the north-eastern part of the Medvednica Mt. (45°58'56" N, 16°6'52" E), near Zagreb (Fig. 1).

During the Miocene, the area of northern Croatia formed the south-western margin of the Central Paratethys, and geotectonically belonged to the Pannonian Basin System (Pavelić 2001, 2002, 2005; Kováč et al. 2007). The Paratethys sea flooded different types of basement in northern Croatia, and significant palaeogeographic changes occurred during the Middle Miocene (Badenian), when the marine transgressions affected the Central Paratethys area (e.g., Rögl 1998; Rögl et al. 2007; Kováč et al. 2007). There are disputes regarding age estimations of the first Miocene marine transgression in northern Croatia. It was initially dated as the Early Miocene (Karpatian) transgression (e.g., Šikić et al. 1977, 1979; Basch 1983 a, b; Pavelić 2001), and recently some authors have considered it to be of the Middle Miocene (Badenian) age (Ćorić et al. 2009; Pavelić 2015).

The Middle Miocene deposits crop out along the Medvednica Mt. slopes (Kochansky 1944; Kochansky-Devidé 1957; Šikić et al. 1977, 1979; Kochansky-Devidé & Bajraktarević 1981; Basch 1983a,b; Avanić et al. 1995, 2003; Sremac et al. 2005; Vrsaljko et al. 2006; Pezelj et al. 2007; Pezelj 2015; Brlek et al. 2016 and references therein; Sremac et al. 2016 and references therein; Pezelj et al. 2016) (Fig. 1A). Kochansky (1944) described three types of Middle Miocene (Badenian) marine developments on the Medvednica Mt. ("South-western", "Central" and "North-eastern" development), and areas studied in this paper belong to the "Central" or "Čučerje" development (Vejalnica outcrop), and to the "North-eastern" or "Zelina" development (Marija Bistrica outcrop) (Fig. 1B). The "Central-" part is characterized by the Miocene marl deposits with open sea organisms (nautiloids, pteropods, planktic foraminifers, nannoplankton) and rare specialized benthic bivalve genus *Solemya* Lamarck, 1818 (Gorjanović-Kramberger 1908; Kochansky 1944; Kochansky-Devidé 1957; Basch 1983 b; Avanić et al. 1995). In contrast, the "North-eastern" development is marked with rich planktic associations of foraminifera and calcareous nannoplankton, and benthic molluscs findings (Kochansky 1944; Avanić et al. 2003). Regarding the character of Miocene marine deposits on Medvednica Mt., pteropods were expected and found in both the "Central-" and "North-eastern" development.

Material and methods

The study areas presented here were chosen according to the previously published data (Kochansky 1944; Kochansky-Devidé 1957; Avanić et al. 1995, 2003). Furthermore, Miocene marine fauna from investigated localities studied by V. Kochansky-Devidé (Kochansky 1944; Kochansky-Devidé 1957) is housed at CNHM and has recently been undergoing revision (M. Bošnjak, doctoral thesis).

Research methods included field and laboratory work. Field work conducted between 2014 and 2016 included collecting fossil fauna and recording geological columns. For this research, the authors chose the outcrops of the Middle Miocene deep marine marls in the central area of the Medvednica Mt., and north-eastern Medvednica Mt. (for more information see Basch 1983 a, b; Avanić et al. 2003; Sremac et al. 2016) (Fig. 1).

During field work, marls from Vejalnica and Marija Bistrica localities were collected for more detailed analyses, and 0.3 kg of each sample were collected for the wet sieving technique. From the Vejalnica locality, Miocene sediments alongside the forest road crop out over a length of app. 15 m, and the total thickness of layers is app. 2 m, of which 1.50 m is visible in the road cutting, and 0.50 m is in the gully. We recognized 12 layers, each around 1 to 3 cm thick, and the majority of pteropods were collected from the middle part of the gully. At the second locality, Marija Bistrica, we investigated an outcrop of sediments app. 10 m in length and 5 m in height. They are less distributed and more eroded than the Vejalnica sediments, and following the changes in lithology 4 layers could be distinguished. From these layers, samples for laboratory work were collected for the purpose of another research, and during the analyses of the washed material the limacinids presented here were recognized.

Laboratory work included the wet sieving technique, analyses and determination of molluscs and calcareous nannofossils. Soft marls were crushed and soaked in water. After twenty-four hours, samples were washed over meshes of 0.5, 0.2, 0.125 and 0.63 mm. After drying, the residue was studied using stereo-microscope Olympus−SZX10 and polarizing microscope Leica Laborlux 11, photographed by a Canon EOS 1100 camera and saved through the Quick PHOTO CAMERA 3.0 programme at UZFS-DG. Samples with fossil molluscs were cleaned and photographed by a Canon EOS 6D camera at CNHM. Pteropod specimens were photographed under a TESCAN VEGA TS 5136 MM/Oxford scanning electron microscope at UZFS-DG. Calcareous nannofossil probes were prepared by standard method (after Bown & Young 1998) in the Wet Laboratory of UZFS-DG. Thin sections were studied at UZFS-DG by "Zetoplan Reichert" polarizing microscope, using the 1250× and 1600× magnification, and photographed by a Canon EOS 400D camera. Nannofossils were determined according to Perch-Nielsen (1985), Bown (1998), Bartol (2009) and Young et al. (2014).

Pteropod samples are housed at CNHM, with assigned temporary inventory numbers: CNHM MBa-LV 1 to 21 and

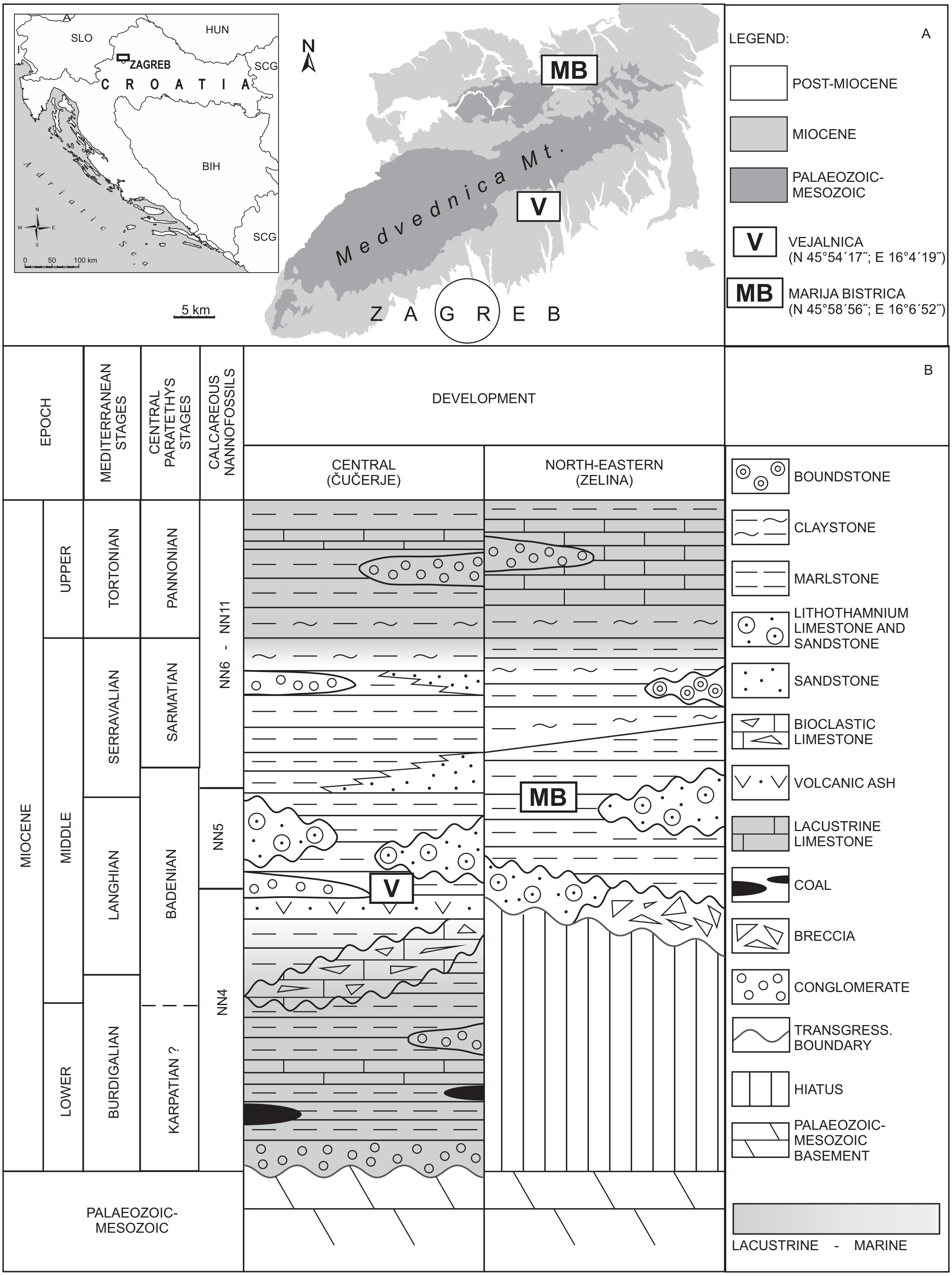

Fig. 1. A — Location of the investigated area on the Medvednica Mt., northern Croatia. **B** — Schematic geological columns of the studied outcrops (after Vrsaljko et al. 2015). Calcareous nannofossils after Harzhauser & Piller (2007), Kováč et al. (2007), Piller et al. (2007) and Pezelj et al. (2013).

CNHM MBb-LV 1 to 14 (*Limacina valvatina*, Marija Bistrica locality), CNHM MB-LG 1 to 6 (*Limacina gramensis*, Marija Bistrica locality), CNHM MB-L 1 to 2 (*Limacina* sp. (? nov.), Marija Bistrica locality), CNHM V-CF 1 to 5 (*Clio fallauxi*, Vejalnica locality) and CNHM V-VA 1 to 17 (*Vaginella austriaca*, Vejalnica locality). Due to the importance of new records of the Middle Miocene (Badenian) pteropods on the Medvednica Mt., we present planktic gastropods together with the biostratigraphically important nannoplankton. Other fossil fauna will be addressed in future studies.

Systematic Palaeontology

Phylum: Mollusca Linnaeus, 1758
Class: Gastropoda Cuvier, 1795
Subclass: Heterobranchia Burmeister, 1837
Superorder: Pteropoda Cuvier, 1804
Order: Thecosomata de Blainville, 1824
Suborder: Euthecosomata Meisenheimer, 1905

Family: Limacinidae Gray, 1847
Genus: *Limacina* Bosc, 1817

Type species: *Limacina helicina* (Phipps, 1774)

Three limacinid species were recognized: *Limacina valvatina* (Reuss, 1867), *Limacina gramensis* (Rasmussen, 1968) and *Limacina* sp. (? nov.). For measurements see Fig. 2.

Limacina valvatina (Reuss, 1867)

1867 *Spirialis valvatina* – Reuss, p. 32, 146, pl. 6, fig. 11 a−b.
1886 *Spirialis valvatina* Reuss – Kittl, p. 69, pl. 2, fig. 38.
1981 *Spirialis valvatina* (Reuss) 1867 – Krach, p. 125, pl. 3, figs. 2−4, 7−8, pl. 5, figs. 1−2, ?9, 10−11, pl. 6, figs. 1−2.
1984 *Spirialis valvatina* Reuss, 1867 – Janssen, p. 72.
1991 *Limacina valvatina* (Reuss, 1867) – Zorn, p. 97, pl. 1, figs. 1–6, pl. 10, figs. 1, 2, pl. 11, figs. 4, 5.
1993 *Limacina valvatina* (Reuss, 1867) – Janssen & Zorn, p. 179, pl. 1, figs. 4–11, pl. 2, figs. 1–11, pl. 3, figs. 1–12.
1999 *Limacina valvatina* (Reuss, 1867) – Zorn, p. 728, pl. 1, figs. 4, 6–10.
2005 *Limacina valvatina* (Reuss, 1867) – Suciu et al., p. 455, pl. 1, figs. 15–17.
2010 *Limacina valvatina* (Reuss, 1867) – Cahuzac & Janssen, p. 47, pl. 12, figs. 6–12.

Material examined: Thirty-five casts from grey marls, Marija Bistrica locality (temporary inventory numbers CNHM MBa-LV 1 to 21 and CNHM MBb-LV 1 to 14).

Description: Shells with low spire, up to 4 whorls (Fig. 3). Height/width-ratio is below 110, a value considered a reliable distinguishing characteristic between *L. valvatina* and *L. gramensis* (Janssen & Zorn 1993). The apical angle varies from ≤88° to max ≤158°. Dimensions of shell height, width and apical angles are given in Table 1 and Fig. 4. Measured specimens show normal variability in H/W-ratio (Fig. 4A, B), but in the histogram of apertural shape variability is larger (Fig. 4C). This variability of measurement span could be partly result from a compression.

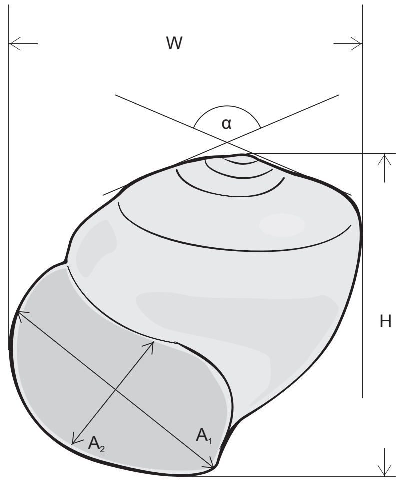

Fig. 2. Measured elements of *Limacina* shell (after Zorn 1991). Abbreviations: H — shell height; W — shell width; *α* — apical angle; A_1, A_2 — aperture diameters.

Remarks: Specimens are pyritized. The shape of fossil Limacinidae species, including *L. valvatina*, is more diverse than in the few existing recent species, as demonstrated, for example, by the missing umbilicus in some species, size and shape of body whorl and the morphology of the apertural margin, or ornamentation of the shell (Janssen 2003). Specimens shown on Fig. 3 could be juvenile, and are very low spired. Similar forms identified as "*Spiratella (Spiratella) krutzschi* Tembrock, 1989" were found in northern Germany (Gorlosen, south of Ludwigslust) (Tembrock 1989), which Janssen (1999) considered a junior synonym of *Limacina valvatina*.

Occurrence: These are the first records of *Limacina valvatina* from the Badenian sediments of northern Croatia. Its occurrence in the Middle Miocene of Paratethys has been documented from the Early to the Late Badenian, and records from the Lower Sarmatian deposits are mentioned (Bohn-Havas & Zorn 2002), e.g., in Romania (Bohn-Havas & Zorn 1994, p. 78, Abb. 4) and in Bulgaria (Nikolov 2010). However, the species was most widely distributed during the Badenian (Bohn-Havas & Zorn 2002). Paratethyan records are available from Hungary (Bohn-Havas & Zorn 1993, 1994; Bohn-Havas et al. 2004) in the NN5 nannozone after Bohn-Havas & Zorn (1993) and Selmeczi et al. (2012), Austria (Zorn 1991; Bohn-Havas & Zorn 1993, 1994), Poland (Bohn-Havas & Zorn 1993, 1994; Janssen & Zorn 1993; Janssen 2012), Czech Republic (Bohn-Havas & Zorn 1994; Zorn 1999), Slovakia (Zorn 1999), Romania (Bohn-Havas & Zorn 1994; Suciu et al. 2005), Bulgaria (Nikolov 2010) and Ukraine (Janssen & Zorn 1993; Bohn-Havas & Zorn 1994). The largest specimens are recorded in Poland (Janssen & Zorn 1993). Outside Paratethys, *L. valvatina* is known from younger Miocene deposits of the North Sea Basin (Zorn 1999; Bohn-Havas & Zorn 2002;

Janssen 2012), Early and Middle Miocene of the Aquitaine Basin, France (Cahuzac & Janssen 2010; Janssen 2012), Langhian of northern Italy and Sicily (Jannsen 2012), and Miocene deposits of the Maltese Archipelago (Janssen 2012) and Germany (Tembrock 1989; Jannsen 1999). Also, *Limacina* cf. *valvatina* is known from the older Miocene sediments of Val Ceppi, Italy (Janssen 1995; Zorn 1999).

Limacina gramensis
(Rasmussen, 1968)

1886 *Spirialis stenogyra* (Philippi) – Kittl, p. 67, text-figs. 35, 36 (*non* Philippi).
1968 *Spiratella gramensis* – Rasmussen, p. 244, pl. 27, figs. 4–7.
1984 *Spirialis stenogyra* (Philippi, 1844) – Janssen, p. 71, pl. 3, figs. 1, 2 (*non* Philippi).
1993 *Limacina gramensis* (Rasmussen, 1968) – Janssen & Zorn, p. 175, pl. 3, figs. 13, pl. 4, figs. 1–9, pl. 5, figs. 1–3.
1999 *Limacina gramensis* (Rasmussen, 1968) – Zorn, p. 726, pl. 1, figs. 1–3, 5.

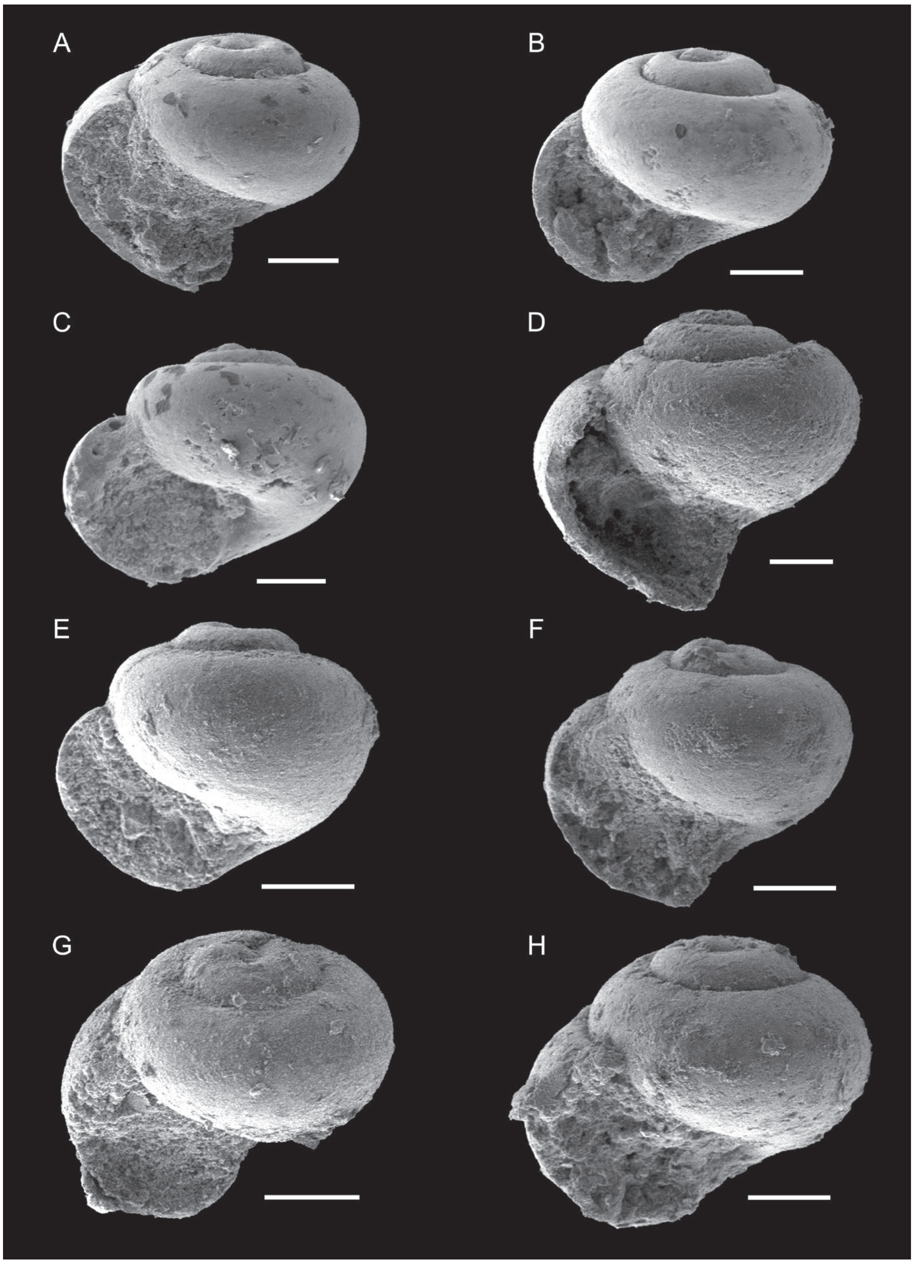

Fig. 3. *Limacina valvatina* (Reuss, 1867) from the Marija Bistrica locality. **A** — CNHM MBa-LV 6; **B** — CNHM MBa-LV 8; **C** — CNHM MBa-LV 10; **D** — CNHM MBa-LV 14; **E** — CNHM MBa-LV 18; **F** — CNHM MBb-LV 3; **G** — CNHM MBb-LV 6; **H** — CNHM MBb-LV 12. Scale bars 100 µm.

Material examined: Six casts from grey marls at the Marija Bistrica locality (temporary inventory numbers CNHM MB-LG 1 to 6).

Description: Slender small shells (possibly juvenile) with high spire, 3 to 5 whorls (Fig. 5A,B). Height/width-ratio above 110. Apical angle varying from ≤44° to ≤80° may be consequence of compression. Straight spire tangents. Dimensions of shell height, width and apical angle are given in Table 2. Fig. 6 shows shell height and width relationship of studied specimens.

Remarks: Casts are pyritized and slightly deformed by pressure. Fig. 6 shows shell height/width-ratio of *L. gramensis*, but the number of collected specimens is too small to perform conclusive statistical analyses.

Occurrence: The sporadic presence of pteropods (determined as *Spiratella* and *Spirialis*) in the Middle Miocene deposits of northern Croatia were reported by Magaš (1987) and Pikija (1987), during the preparation of the Basic Geological Map, sheets Sisak and Osijek. Unfortunately, this material was not studied later and is today unavailable. The present research proves the first record of *Limacina gramensis* in the Badenian deposits of northern Croatia. Up to today the occurrence of *L. gramensis* within the Central Paratethys is limited to the Upper Badenian deposits and the species is considered to be an index fossil (e.g., Bohn-Havas & Zorn 2002). It is known from Poland (Bohn-Havas & Zorn 1993; Janssen & Zorn 1993; Zorn 1999), Czech Republic (Zorn 1999), Romania (Janssen & Zorn 1993; Zorn 1999), Bulgaria (Nikolov 2010) and Ukraine (Janssen & Zorn 1993; Zorn 1999). Outside Paratethys, this species is known from Miocene of the North Sea Basin (Zorn 1999; Bohn-Havas & Zorn 2002).

Table 1: Measurements of *Limacina valvatina* (Reuss, 1867) from the Marija Bistrica locality. Abbreviations: Inv. No. — inventory number; H — shell height; W — shell width; H/W-ratio — shell height and width ratio; α — apical angle; A_1 and A_2 — aperture diameters; A_1/A_2-ratio — aperture diameters (A_1 and A_2) ratio.

Inv. No.	H (in mm)	W (in mm)	H/W-RATIO	α	A_1 (in mm)	A_2 (in mm)	A_1/A_2 - RATIO
MBa-LV 1	0.255	0.288	0.885	≤119°	0.21	0.105	2
MBa-LV 2	0.317	0.399	0.794	≤120°	0.279	0.168	1.661
MBa-LV 3	0.238	0.3	0.793	≤133°	0.196	0.098	2
MBa-LV 4	0.301	0.409	0.736	≤93°	0.257	0.112	2.295
MBa-LV 5	0.267	0.337	0.792	≤118°	0.219	0.095	2.305
MBa-LV 6	0.265	0.343	0.773	≤98°	0.196	0.098	2
MBa-LV 7	0.284	0.341	0.833	≤116°	0.223	0.123	1.813
MBa-LV 8	0.367	0.437	0.84	≤107°	0.278	0.122	2.279
MBa-LV 9	0.282	0.328	0.86	≤102°	0.179	0.089	2.011
MBa-LV 10	0.211	0.262	0.805	≤120°	0.152	0.076	2
MBa-LV 11	0.24	0.273	0.879	≤113°	0.156	0.095	1.642
MBa-LV 12	0.206	0.265	0.777	≤97°	0.145	0.089	1.629
MBa-LV 13	0.272	0.358	0.76	≤106°	0.19	0.078	2.436
MBa-LV 14	0.257	0.282	0.911	≤119°	0.19	0.101	1.881
MBa-LV 15	0.259	0.294	0.881	≤107°	0.179	0.101	1.772
MBa-LV 16	0.352	0.399	0.882	≤105°	0.246	0.156	1.577
MBa-LV 17	0.257	0.29	0.886	≤124°	0.195	0.116	1.681
MBa-LV 18	0.382	0.426	0.897	≤122°	0.267	0.124	2.153
MBa-LV 19	0.331	0.368	0.899	≤102°	0.246	0.101	2.436
MBa-LV 20	0.185	0.257	0.72	≤158°	0.143	0.067	2.134
MBa-LV 21	0.243	0.331	0.734	≤154°	0.21	0.095	2.211
MBb-LV 1	0.262	0.334	0.784	≤126°	0.214	0.129	1.659
MBb-LV 2	0.278	0.349	0.797	≤114°	0.223	0.134	1.664
MBb-LV 3	0.239	0.286	0.836	≤110°	0.193	0.1	1.93
MBb-LV 4	0.27	0.303	0.891	≤111°	0.204	0.107	1.907
MBb-LV 5	0.267	0.326	0.819	≤125°	0.2	0.1	2
MBb-LV 6	0.249	0.313	0.796	≤98°	0.184	0.112	1.643
MBb-LV 7	0.23	0.294	0.782	≤126°	0.179	0.101	1.772
MBb-LV 8	0.238	0.279	0.853	≤92°	0.171	0.1	1.71
MBb-LV 9	0.269	0.319	0.843	≤132°	0.19	0.112	1.696
MBb-LV 10	0.259	0.302	0.858	≤95°	0.134	0.101	1.327
MBb-LV 11	0.282	0.355	0.794	≤119°	0.2	0.114	1.754
MBb-LV 12	0.349	0.375	0.931	≤88°	0.229	0.114	2.009
MBb-LV 13	0.401	0.445	0.901	≤101°	0.271	0.171	1.585
MBb-LV 14	0.249	0.271	0.919	≤120°	0.184	0.112	1.643

Limacina sp. (? nov.)

Material examined: Two casts from grey marls at the Marija Bistrica locality (temporary inventory numbers CNHM MB-L 1 and 2).

Description: Small shells (possibly juvenile), oval-conical shaped with high spire and 3 preserved whorls (Fig. 5C,D). Apical region blunt; aperture not preserved. Height/width-ratio above 110. Straight spire tangents. Dimensions of shell height, width and apical angle are given in Table 2.

Remarks: Casts are pyritized and slightly deformed by pressure. These two specimens (MB-LG 1 and 2, Fig. 5C,D) differ from the other six *L. gramensis* specimens by shape, which is more rounded than in *L. gramensis* (Fig. 5A,B) and lacks lateral widening of last whorls. The described two specimens are indicated as *Limacina* sp. (? nov.), but their number is not sufficient for a valid description of a new species.

Representatives of the families Cliidae and Cavoliniidae were also determined and presented in this paper. The measured elements are shown on Fig. 7.

Family: Cliidae Jeffreys, 1869
Genus: *Clio* Linnaeus, 1767

Type species: *Clio pyramidata* Linnaeus, 1767

Clio fallauxi (Kittl, 1886)

1886 *Balantium Fallauxi* Kittl, p. 62, pl. 2, figs. 23–26.
1984 *Balantium fallauxi* Kittl, 1886 – Janssen, p. 65.
1993 *Clio fallauxi* (Kittl, 1886) – Janssen & Zorn, p. 195, pl. 8, figs. 1–9, pl. 9, figs. 1–3.
1999 *Clio fallauxi* (Kittl, 1886) – Zorn, p. 730, pl. 2, figs. 3–5.

Material examined: Five casts with preserved ornament (inner shell ornament) on yellow marls at the Vejalnica locality (temporary inventory numbers CNHM V-CF 1 to 5). The measured elements are shown on Fig. 7.

Description: Elongated triangular shell sculptured with transversal ribs overrun by multiple riblets. The ribs are flattened, but in the lateral parts of the shell they are flexuous. Measurements of specimens are shown in Table 3.

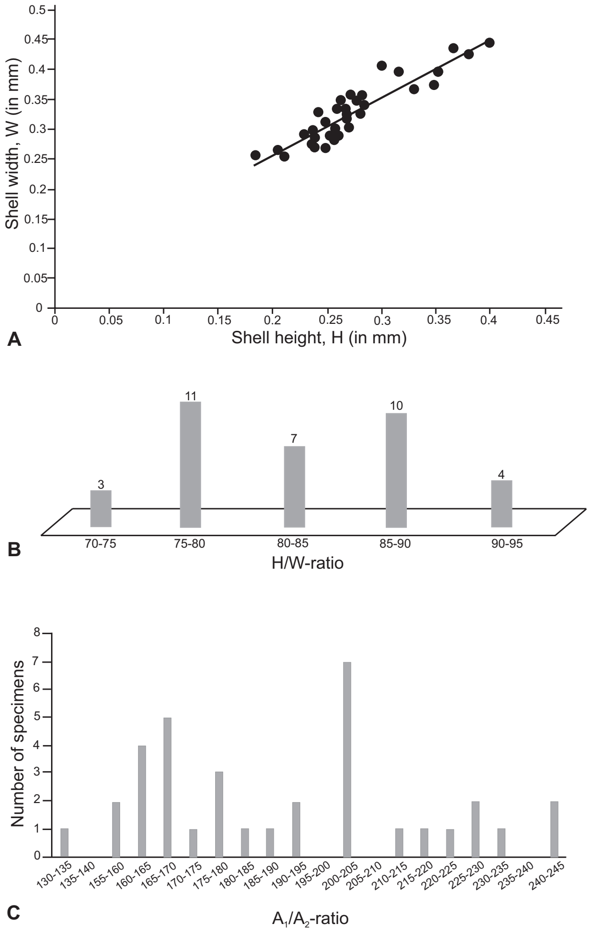

Fig. 4. A — Shell height and width diagram of *Limacina valvatina* (Reuss, 1867) from the Marija Bistrica locality. **B** — Shell height/width ratio of collected specimens with number of *L. valvatina* belonging to each H/W range (70–75, 75–80, 80–85, 85–90, 90–95). **C** — Aperture diameters (A_1/A_2) ratio of presented *L. valvatina* with number of specimens from each range. Abbreviations: A_1/A_2-ratio — aperture diameters A_1 and A_2 ratio; H/W-ratio — shell height and width ratio.

Remarks: The pteropod casts here presented resemble the species *Clio fallauxi* (Kittl, 1886). Kochansky (1944) listed *Clio pedemontana* (Mayer, 1868) from the Medvednica Mt. ("Central" or "Čučerje" area), but unfortunately her original material is missing. The species *C. fallauxi* resembles *C. pedemontana*, but it differs from the latter in its larger apical angle and presence of riblets (e.g., Janssen & Zorn 1993; Zorn 1999). In Tables 3 and 4, and Figs. 8 and 9, we present specimens of *C. fallauxi* from selected Paratethyan localities (see Table 4). Based on the morphology, measurements and comparison of the investigated *Clio* specimens from the Medvednica Mt. with other records from the Central Paratethys, we identify the sculpted casts as *C. fallauxi*. As shown on Fig. 9, shell height and width fits the trend line of other Central Paratethys specimens. The apical angle is variable in comparison to other specimens, but that might be a preservation artifact.

One specimen (V-CF 5, Fig. 8 D) could only be determined as *Clio* cf. *fallauxi* due to its deviating apical angle value, although its aperture angle is similar to the other collected specimens, and the ribs and riblets are present.

Occurrence: In the Central Paratethys the occurrence of *Clio fallauxi* was documented only in the Lower Badenian deposits (e.g., Zorn 1999; Bohn-Havas & Zorn 2002; Selmeczi et al. 2012). It was known from Hungary (Bohn-Havas & Zorn 1993, 1994; Zorn 1999; Bohn-Havas et al. 2004) in NN5 nannozone after Bohn-Havas & Zorn (1993) and Selmeczi et al. (2012), Poland (Bohn-Havas & Zorn 1993, 1994; Janssen & Zorn 1993; Zorn 1999), Czech Republic (Janssen & Zorn 1993; Zorn 1999), Romania (Bohn-Havas & Zorn 1994; Zorn 1999), Bulgaria (Zorn 1999; Nikolov 2010) and possibly Slovenia (NN5 nannozone after Mikuž et al. 2012). *C. fallauxi* locally occurs together with *C. pedemontana* (see Bohn-Havas & Zorn 1993, 1994; Zorn 1999; Bohn-Havas et al. 2004) in NN5 nannozone after Bohn-Havas et al. (2004).

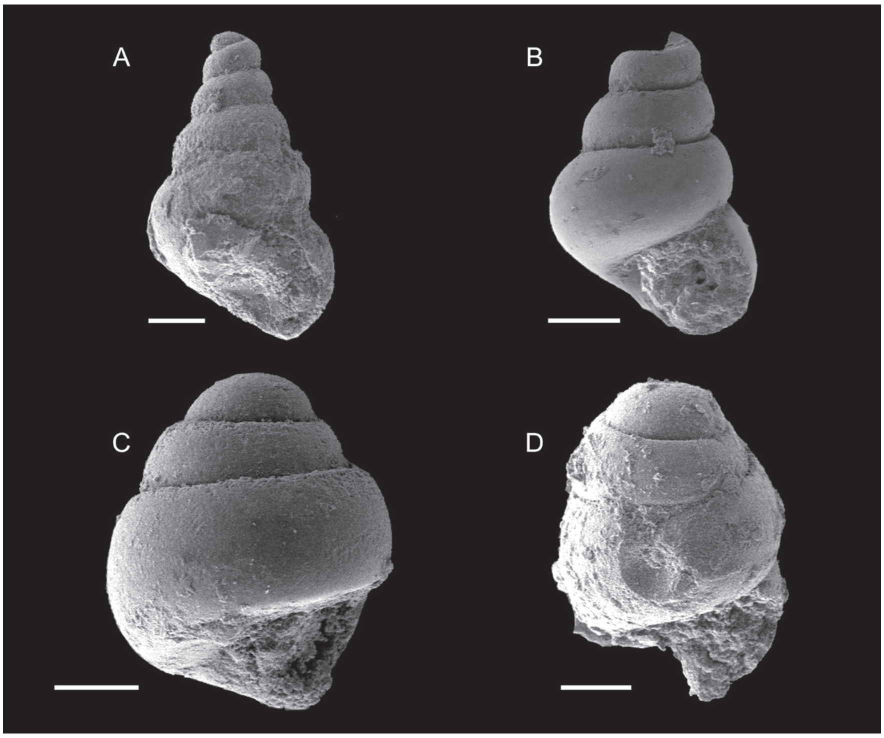

Fig. 5. A–B: *Limacina gramensis* (Rasmussen, 1968) from the Marija Bistrica locality. **A** — CNHM MB-LG1; **B** — CNHM MB-LG 8. **C-D:** *Limacina* sp. (? nov.) from the Marija Bistrica locality. **C** — CNHM MB-L 1; **D** — CNHM MB-L 2. Scale bars 100 µm.

Family: Cavoliniidae Gray, 1850 (1815)
(=Hyalaeidae Rafinesque, 1815)
Genus: *Vaginella* Daudin, 1800

Type species: *Vaginella depressa* Daudin, 1800

Vaginella austriaca Kittl, 1886

1886 *Vaginella austriaca* Kittl, p. 54, pl. 2, figs. 8–12.
1981 *Vaginella austriaca* Kittl, 1886 – Krach, p. 124, pl. 1, figs. 15−18, 20; pl. 2, figs. 1−3, 21−24; pl. 4, fig. 2.
1984 *Vaginella austriaca* Kittl, 1886 – Janssen, p. 73, pl. 4, figs. 1–8.
1991 *Vaginella austriaca* Kittl, 1886 – Zorn, p. 120, pl. 6, figs. 1–6, pl. 7, figs. 1–9, pl. 12, figs. 4, 5, pl. 14, figs. 1–8, pl. 16, figs. 1–4.

Table 2: Measurements of *Limacina gramensis* (Rasmussen, 1968) from the Marija Bistrica locality. *Measurements of *Limacina* sp. (? nov.) from the same locality. Abbreviations: Inv. No. — inventory number; H — shell height; W — shell width; H/W-ratio — shell height and width ratio; α — apical angle.

Inv. No.	H (in mm)	W (in mm)	H/W-RATIO	α
MB-LG 1	0.394	0.246	1.602	≤44°
MB-LG 2	0.259	0.228	1.136	≤80°
MB-LG 3	0.281	0.23	1.222	≤70°
MB-LG 4	0.31	0.254	1.22	≤61°
MB-LG 5	0.288	0.243	1.185	≤53°
MB-LG 6	0.294	0.271	1.085	≤46°
MB-L 1 *	0.344	0.25	1.376	≤62°
MB-L 2 *	0.292	0.232	1.259	≤65°

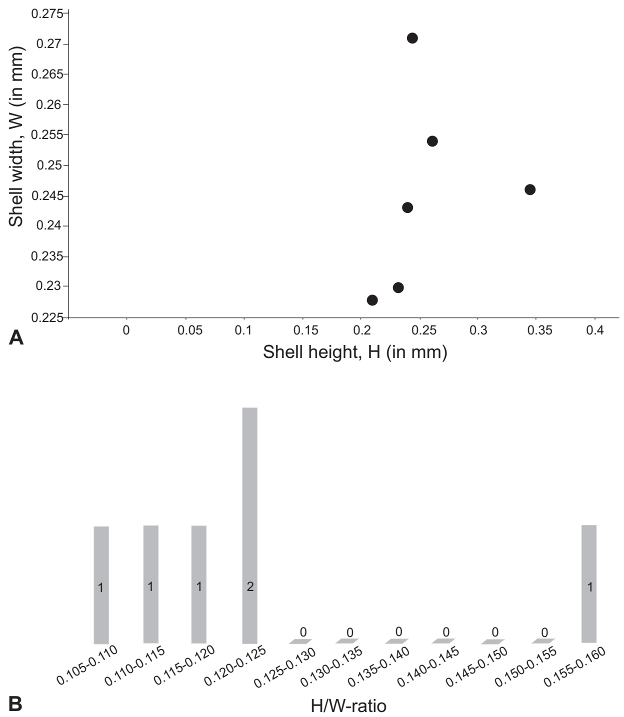

Fig. 6. *Limacina gramensis* (Rasmussen, 1968) from the Marija Bistrica locality. **A** — Shell height and width relationship. **B** — Shell height/width-ratio with marked number of collected specimens belonging to each range (after Table 2). Abbreviation: H/W-ratio — shell height and width ratio.

1993 *Vaginella austriaca* Kittl, 1886 – Janssen & Zorn, p. 203, pl. 6, figs. 8–15, pl. 10, figs. 1–5, pl. 11, figs. 1–6.
1999 *Vaginella austriaca* Kittl, 1886 – Zorn, p. 732, pl. 4, figs. 1–3, pl. 5, figs. 1, 2.

Material examined: Casts and imprints found in yellow marls at the Vejalnica locality (temporary inventory numbers CNHM V-VA 1 to 17) (Fig. 10, Table 5).

Description: Lance-shaped specimens with smooth shell surface, widest in the aperture area. Absence or presence of lateral carinae could not be determined since the material is preserved as casts and imprints. Pre-apertural constriction is not visible. The middle part of two shell casts is widened and these specimens are identified as *Vaginella* cf. *austriaca*, due to the lack of diagnostic elements for precise determination, and are not included in statistical analyses presented in this paper. Dimensions of the studied specimens (Vejalnica locality) are shown in Table 5. Measurements of the specimens presented in this paper are shown in Fig. 11, together with other *Vaginella austriaca* specimens from the selected Paratethyan localities (Table 6).

Remarks: Different species of the genus *Vaginella* Daudin, 1800 such as *V. depressa* Daudin, 1800, *V. austriaca* Kittl, 1886, *V. acutissima* Audenino, 1897 and *V. lapugyensis* Kittl, 1886 are similarly shaped, developing more elongated shells during their evolution. Therefore it can be difficult to determine them to species level, particularly in poorly preserved specimens with the apical part with protoconch missing, and damaged apertural part. Beside general shape differences, the apical angle is used as a distinguishing criterion, which can also be misleading due to the curvature of shell sidelines. *V. depressa* has the widest apical angle of ≥40°, *V. austriaca* c. ≥20°, *V. acutissima* c. 15–18° and V. *lapugyensis* c. 8–13° (Cahuzac & Janssen 2010, p. 100). Apical angle comparison of *V. austriaca* from the Vejalnica locality and selected available Paratethyan specimens is shown in Fig. 12.

Occurrence: *Vaginella austriaca* from the Medvednica Mt. was recorded by Gorjanović-Kramberger (1908), Kochansky (1944), Basch (1983b) and Avanić et al. (1995). In the Central Paratethys *V. austriaca* is known from the Karpatian and Badenian deposits in Austria (Janssen 1984; Bohn-Havas & Zorn 1993, 1994; Janssen & Zorn 1993; Zorn 1991, 1999), Poland (Lower and Middle Badenian) (Zorn 1991, 1999; Bohn-Havas & Zorn 1993, 1994; Janssen & Zorn 1993), Hungary (Lower Badenian) (Zorn 1991; Bohn-Havas & Zorn 1993, 1994; Bohn-Havas et al. 2004) in NN5 nannozone after Bohn-Havas & Zorn (1993), Bohn-Havas et al. (2004) and Selmeczi et al. (2012), Czech Republic (Karpatian and Lower Badenian) (Zorn 1991, 1999), Slovenia (Mikuž et al. 2012 and references therein), Serbia (Stevanović 1974), Romania (Lower Badenian) (Zorn 1991, 1999; Janssen & Zorn 1993; Bohn-Havas & Zorn 1994) and Bulgaria (Badenian) (Zorn 1999; Nikolov 2010). Outside the Paratethys, *Vaginella austriaca* is known from Middle Miocene deposits in the Mediterranean area (Zorn 1991, 1999 and references therein; Bohn-Havas & Zorn 2002; Janssen & Little 2010; Janssen 2012), Miocene deposits in the North Sea Basin (Zorn 1991, 1999 and references therein; Bohn-Havas & Zorn 2002; Cahuzac & Janssen 2010; Janssen & Little 2010; Janssen 2012), and the Aquitaine Basin (Cahuzac & Janssen 2010; Janssen & Little 2010; Janssen 2012).

Regardless of the poor preservation of *Vaginella* specimens from the Medvednica Mt. the authors consider casts to belong to *Vaginella austriaca*. The apical angle can be used as a reliable determination criterion characteristic for *Vaginella* species only in very well-preserved specimens (Janssen & Zorn 1993; Cahuzac & Janssen 2010). Since the specimens presented here are preserved as casts, measurements of the apical angle could be uncertain and unreliable for the specific determination (e.g., Fig. 12). Therefore the authors based their identification on the morphology, previously known data and comparison with available data from the neighbouring area. As seen in Fig. 11, studied specimens fit the trend line of the shell width and height diagram of the compared Paratethyan material (see Table 6), which confirmed our determination.

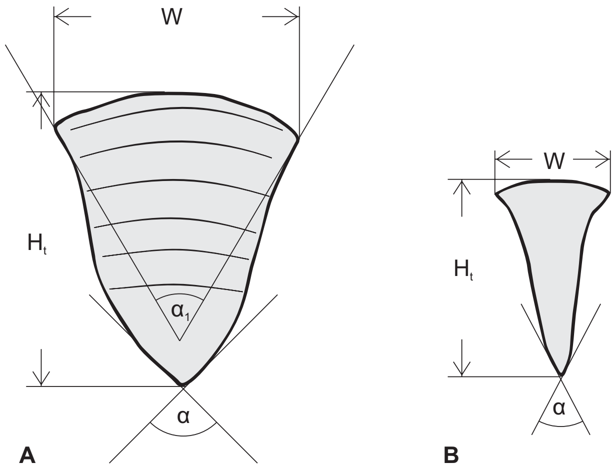

Fig. 7. Measured elements of **A** — *Clio fallauxi* (Kittl, 1886) and **B** — *Vaginella austriaca* Kittl, 1886 (after Zorn, 1991). Abbreviations: H_t — height of teleoconch; W — shell width; α — apical angle; α_1 — aperture angle.

Calcareous nannoplankton

Calcareous nannoplankton is found at both of the investigated localities on the Medvednica Mt., as shown in Table 7 and Figs. 13 and 14. Table 7 shows comparison with available data covering pteropod and nannoplankton assemblages (after Chira et al. 2000; Suciu et al. 2005; Vulc & Silye 2005; Ćorić et al. 2009; Bartol 2009; Mikuž et al. 2012 and this paper). Different nannoplankton assemblages of high stratigraphic range are here recorded, and the time span of the deteremined taxa is from NN4 to NN6. The age of deposits cropping out at Vejalnica has been determined by the occurrence of *Sphenolithus heteromorphus* as the NN5 Zone. Nannoplankton

Table 3: Measurements of *Clio fallauxi* (Kittl, 1886) from the Vejalnica locality (Medvednica Mt., northern Croatia). **Clio* cf. *fallauxi*. Abbreviations: Inv. No. — inventory number; H_t — height of teleoconch; W — shell width; α — apical angle; α_1 — aperture angle.

Inv.No.	H_t (in mm)	W (in mm)	α	α_1	1st ORDER RIBS	RIBS WIDTH (in mm) MACRORIBS convex	RIBS WIDTH (in mm) MICRORIBS concav	CONVEX / CONCAV RATIO
V-CF 1	10	7.3	≤74°	≤28°	≥11	0.54	0.27	2
V-CF 2	5.78	5.22	not saved	≤33°	≥9	0.33	0.22	1.5
V-CF 3	6.81	5.42	≤68°	≤32°	≥9	0.42	0.28	1.5
V-CF 4	6.5	5.63	≤72°	not saved	≥5	0.25	0.13	1.92
V-CF 5*	10.15	7.12	≤58°	≤37°	≥9	0.45	0.3	1.5

Table 4: Measurements of *Clio fallauxi* (Kittl, 1886) from the Badenian deposits of the Central Paratethys (after literature data). *Note that the measures are obtained from published photos, not the original specimens. **Measurements from cited papers. ***Material mentioned by Krach (1981) derived from boreholes. Abbreviations: H_t — height of teleoconch; W — shell width; α — apical angle.

REFERENCES	SPECIMEN	LOCALITY	H_t (in mm) *	W (in mm) *	α *	1^{st} ORDER RIBS *
Kittl (1868)	Figs. 23–25	Peterswald, Czech Republic	13.7 **	10 **		
Janssen & Zorn (1993)	Pl. 8, Fig. 1	Dębowiec, Poland***	13.14	9.71	39°–49° **	≥12
	Pl. 8, Fig. 2		10.29	8.29		≥12
	Pl. 8, Fig. 3	Simoradz, Poland***	6.6	7.6		≥7
	Pl. 8, Fig. 4	Roczyny, Poland***	7.82	6.55		≥6
	Pl. 8, Fig. 5		8.6	7.2		?
	Pl. 8, Figs. 6	Dębowiec, Poland***	13.71	8.57		≥12
	Pl. 8, Figs. 8	Roczyny, Poland***	13.14	8.57		≥12
	Pl. 9, Fig. 1	Dombrau, Czech Republic	7.27	6.91	45° **	≥7
Bohn-Havas & Zorn (1994)	Pl. 3, Fig. 13	Sopron well, Hungary	6.38	4.75	≤38°	≥7
Zorn (1999)	Pl. 2, Fig. 3	Dražovice, Czech Republic	4.5	2.63	≤48°	≥ 13
			4.75	2.25	≤37°	≥ 15
			4.88	2.38	≤36°	≥ 7
			4	2.38	≤36°	?
			5.63	3.38	≤40°	≥ 15
	Pl. 2, Fig. 4		11.54	6	≤41°	≥ 13

assemblages from the Marija Bistrica locality indicate younger horizons, on the transition from the NN5 to NN6 Zone. Coccoliths are abundant and comprise some reworked specimens.

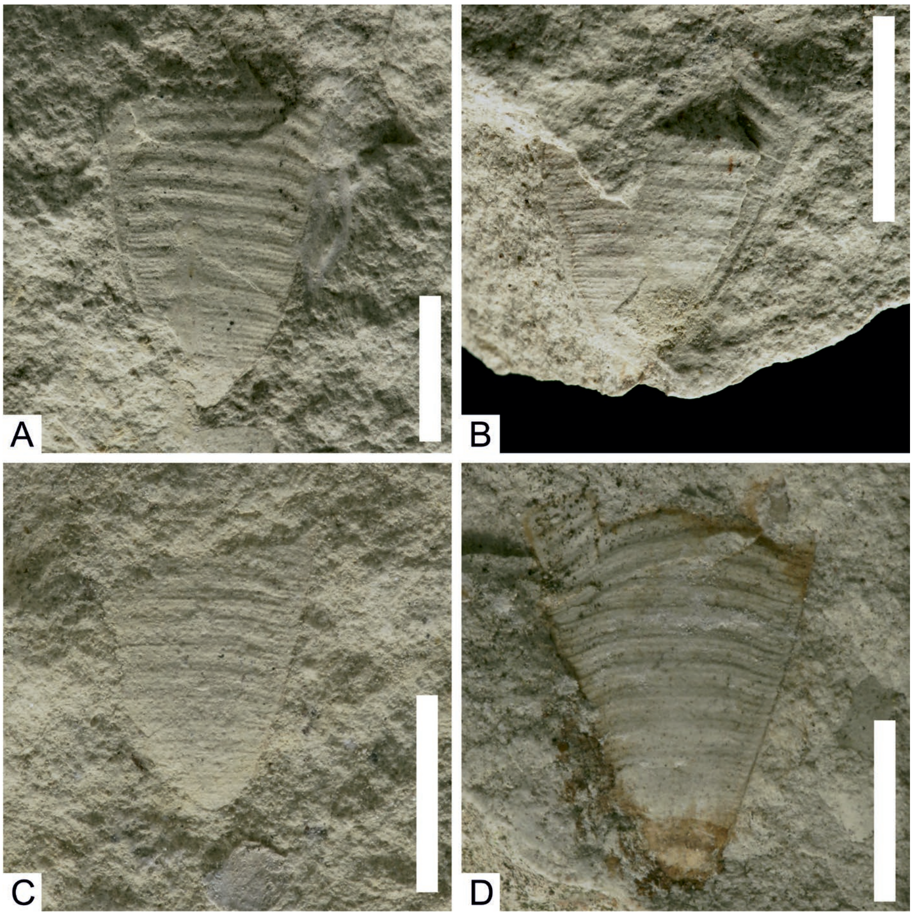

Fig. 8. *Clio fallauxi* (Kittl, 1886) from the Vejalnica locality. **A** — CNHM V-CF 1; **B** — CNHM V-CF 2; **C** — CNHM V-CF 3; **D** — *Clio* cf. *fallauxi*, CNHM V-CF 5. Scale bars 5 mm.

Discussion

Pteropod ecology

Pteropods show horizontal distribution along climate zones, depending on temperature, salinity, food, oxygen, water depth, ocean currents etc., with temperature as the main factor of their distribution. They are limited to narrow salinity ranges and can tolerate slight salinity deviations, e.g., according to Ivanova (1983) up to 28–30 ‰, 35 to 36 ‰ (Herman 1998) and 39 ‰ (Velcescu 1997). Pteropods also have a limited tolerance to temperature change, with exceptions, for example, of recent representatives of the genus *Creseis* Rang, 1828 and *Limacina trochiformis* (d'Orbigny, 1834) (see Herman 1998). Recent pteropods are distributed in worldwide seas (e.g., Hunt et al. 2010). Most species live in tropical and subtropical regions, however, they are also represented in polar regions (e.g., Velcescu 1997; Herman 1998; Janssen & Peijnenburg 2014).

Pteropod species diversity in tropical seas is high and they are concentrated at greater depths than temperate and high-latitude species (Bednaršek et al. 2012b and references therein), and in colder and polar waters pteropods are particularly abundant and represented by two species, *Limacina helicina* (Phipps, 1774) and *Limacina retroversa* (Fleming, 1823) (e.g., Hunt et al. 2010; Lischka & Riebesell 2012). *Limacina helicina* is a polar pteropod species, a main component of the polar zooplankton (Hunt et al. 2010; Lischka & Riebesell 2012). *Limacina retroversa* is a boreal-temperate species of subpolar and transitional waters of the North Atlantic (Lischka & Riebesell 2012).

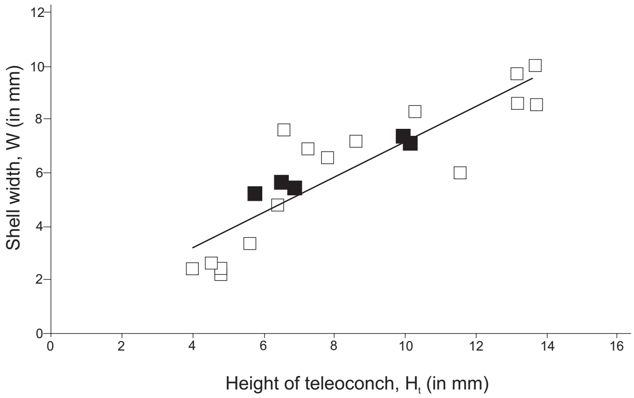

Fig. 9. Comparison of shell height and width of *Clio fallauxi* (Kittl, 1886) specimens described in previously published papers (references in Table 4 — white) and from the Medvednica Mt. (this study — black).

Modern pteropods nowadays are widely used as first indicators of ocean acidification effects on marine communities, due to their aragonitic shell (e.g., Hunt et al. 2010; Bednaršek et al. 2012a; Burridge et al. 2015). The process of ocean acidification (reducing pH value) and reduction with a lowering of the $CaCO_3$ saturation as a result affects marine organisms building their skeletons from aragonite, a more soluble form of $CaCO_3$ than calcite. The consequences of the ocean acidification process are expected to be visible first in the polar region, due to the higher solubility of CO_2 in colder waters, which impacts organisms with calcified shells, particularly pteropods (e.g., Lischka & Riebesell 2012). Due to the higher aragonite undersaturation, pteropods can migrate in the aragonite saturated waters changing their depth strata (Lischka & Riebesell 2012),

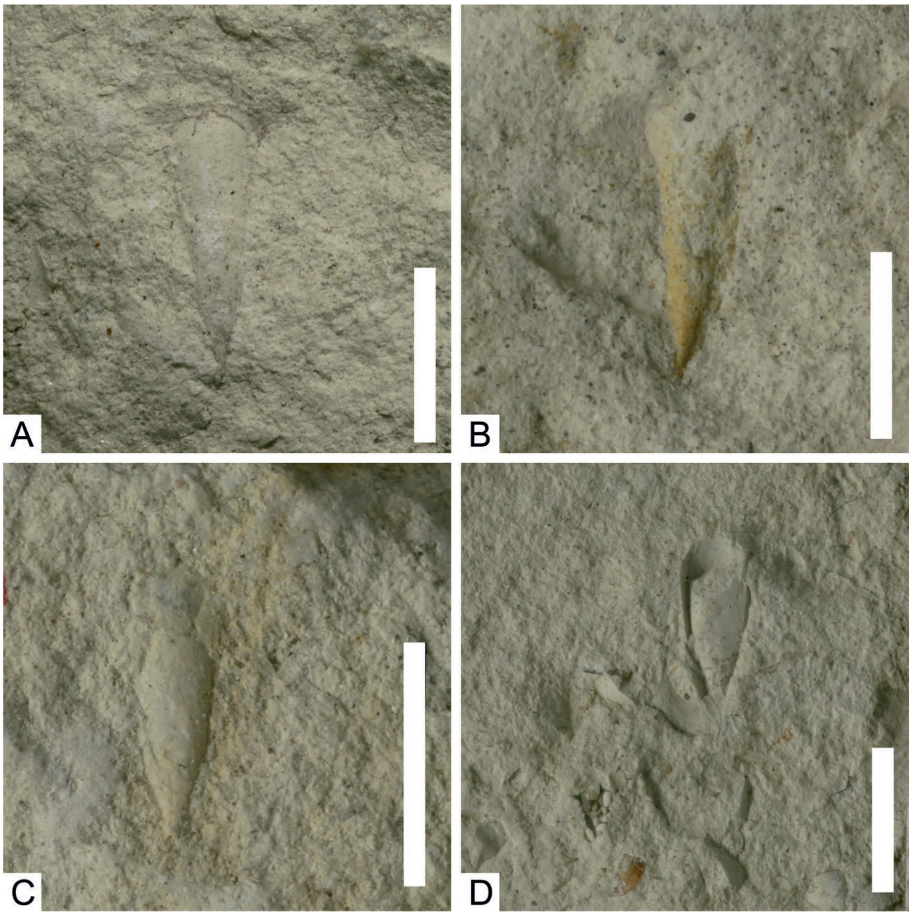

Fig. 10. *Vaginella austriaca* Kittl, 1886 from the Vejalnica locality. **A** — CNHM V-VA 2; **B** — CNHM V-VA 7; **C** — CNHM V-VA 11; **D** — CNHM V-VA 19. Scale bars 5 mm.

Table 5: Measurements of *Vaginella austriaca* Kittl, 1886 from the Vejalnica locality (Medvednica Mt., northern Croatia). Abbreviations: Inv. No. — inventory number; H_t — height of teleoconch; W — shell width; α — apical angle.

Inv. No.	H_t (in mm)	W (in mm)	α
V-VA 1	4.38	1.69	≤27°
V-VA 2	6.88	2.38	≤19°
V-VA 3	3.62	1.16	≤28°
V-VA 4	3.5	1.5	≤21°
V-VA 5	3.5	1.5	≤24°
V-VA 6	7.43	2.71	≤20°
V-VA 7	4.56	1.62	≤20°
V-VA 8	2.5	1.05	≤26°
V-VA 9	4.36	1.54	≤20°
V-VA 10	4.29	1.43	≤21°
V-VA 11	4.19	1.63	≤15°
V-VA 12	4.07	1.05	≤14°
V-VA 13	4.65	2.21	≤22°
V-VA 14	4.25	1.5	≤18°
V-VA 15	4.23	1.41	≤13°
V-VA 16	2.56	1.28	≤24°
V-VA 17	5	2.1	≤28°

which means that their migration is not influenced only by surface water temperature (e.g, research presented in Oliveira-Koblitz & Larrazábal 2014).

“Pteropod events” in the Paratethys

Pteropods inhabited the Paratethys Sea from its early days (Rögl 1999), but their abundance varied in different horizons, with two peaks during the Middle Miocene (e.g., Bohn-Havas et al. 2003). *Vaginella austriaca* Kittl, 1886 is the most abundant pteropod species in the Middle Miocene of this area (Janssen & Zorn 1993; Bohn-Havas & Zorn 1993, 1994, 2002; Bohn-Havas et al. 2003, 2004). It first appeared in the Karpatian NN4 nannozone and only a small number can be found in the Early Badenian, about 14.9 Ma ago (Bohn-Havas et al. 2003). According to the magnetostratigraphic data from Hungary, mixed pteropod fauna, comprising *Clio pedemontana* (Mayer, 1868), *Clio fallauxi* (Kittl, 1886) and *Limacina valvatina* (Reuss, 1867) appeared in that area 14.5 Ma ago, in the Badenian NN5 nannozone, marking the general bloom of planktic molluscs, which lasted till about 14.2 Ma ago (Bohn-Havas et al. 2003; Selmeczi et al. 2012).

Mass occurrences of limacinids (*Limacina* or, previously, “*Spiratella*” horizon), were recorded in the Upper Badenian deposits throughout the Central Paratethys, except in Hungary (e.g., Rögl 1998, 1999; Bohn-Havas et al. 2004; Kováč et al. 2007; Śliwiński et al. 2011). This horizon comprises the species *L. valvatina* and the Upper Badenian index fossil, *L. gramensis.* In Poland this horizon is positioned within the “Pecten Beds”, in the uppermost Badenian NN6 zone, aged 13.06 Ma (Śliwiński et al. 2011). Limacinid bloom coincides with the Middle Miocene climatic transition and cooling event, when CO_2 pressure was in decline (e.g., Zhang et al. 2013).

Recent and fossil limacinids are usually abundant in cold, even polar waters and represented by a small number of species. Mass mortality of *Limacina* from the older, Oligocene deposits was attributed to a short-term decrease in surface water salinity, or rise of H_2S and oxygen depleted environments (Rögl 1998; Báldi 2006 and references therein; Studencka et al. 2016 and references therein). Similar environmental conditions could have triggered the Late Badenian limacinid crisis (e.g., Báldi 2006 and references therein), or we can explain this event with the influx of colder ocean waters into the Paratethys during the Middle Miocene (e.g., Kováč et al. 2007).

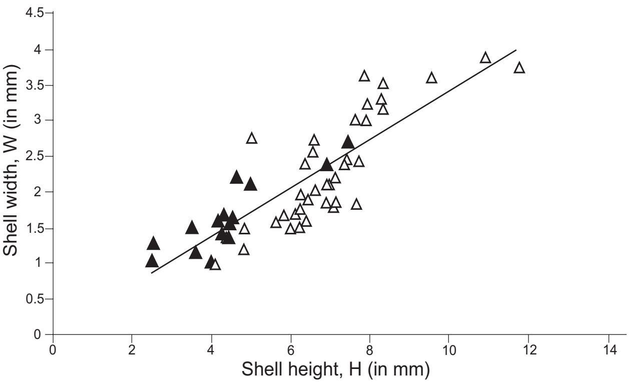

Fig. 11. Comparison of shell height and width of *Vaginella austriaca* Kittl, 1886 from the Medvednica Mt. (black triangels; after Table 5) and the comparative material from the Central Paratethys (white triangels; after Table 6).

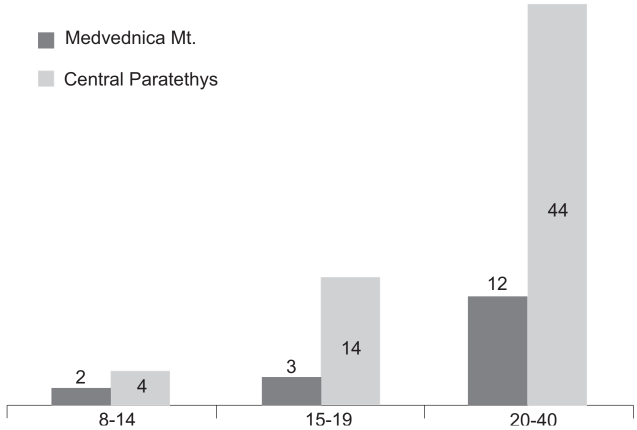

Fig. 12. Apical angle values of *Vaginella austriaca* Kittl, 1886 from the Vejalnica locality, and comparative material from the Central Paratethys (after Table 6). Numbers above the columns mark number of specimens within three ranges of measured apical angles (8°–14°, 15°–19°, 20°–40°).

Table 6: Measurements of *Vaginella austriaca* Kittl, 1886 from the Badenian deposits of the Central Paratethys (after literature data). *Note that the measures are obtained from published photos, not the original specimens. **Lectotype. Abbreviations: H_t — height of teleoconch; W — shell width; α — apical angle.

REFERENCES	SPECIMEN	LOCALITY	H_t (in mm) *	W (in mm) *	α *
Janssen (1984)	Pl. 4, Fig. 1 **	Baden, Austria	7.67	1.83	≤20°
	Pl. 4, Fig. 3		6.33	1.58	≤23°
	Pl. 4, Fig. 4		6.92	1.83	≤23°
	Pl. 4, Fig. 7	Lapugy, Rumania	4.08	1	≤22°
	Pl. 4, Fig. 8		4.83	1.17	≤22°
Zorn (1991)	Pl. 6, Fig. 3	Bad Vöslau, Austria	6.37	1.95	≤27°
	Pl. 6, Fig. 4		7	2.09	≤25°
	Pl. 6, Fig. 5		6.91	2.09	≤29°
	Pl. 6, Fig. 6		7.09	2.18	≤30°
	Pl. 7, Fig. 2		7.74	2.43	≤23°
	Pl. 7, Fig. 3		7.17	1.83	≤18°
	Pl. 14, Fig. 1	Baden, Austria	7.13	1.75	≤21°
	Pl. 14, Fig. 2		6.25	1.75	≤24°
	Pl. 14, Fig. 3		6	1.5	≤24°
	Pl. 14, Fig. 4		6.5	1.88	≤21°
	Pl. 14, Fig. 5	Bad Vöslau, Austria	6.19	1.5	≤18°
	Pl. 14, Fig. 6	Sooss, Austria	4.44	1.38	≤18°
Janssen & Zorn (1993)	Pl. 6, Fig. 8	Korytnica, Poland	5.67	1.58	≤24°
	Pl. 6, Fig. 9		5.83	1.67	≤15°
	Pl. 6, Fig. 12		4.83	1.5	≤29°
	Pl. 10, Fig. 1	Brzeszcze, Poland	7.63	3	≤28°
	Pl. 10, Fig. 2	Międzyrzecze, Poland	6.63	2.75	≤33°
	Pl. 10, Fig. 3	Łapczyca, Poland	7.38	2.38	≤34°
	Pl. 10, Fig. 4	Brzeszcze, Poland	6.38	2.38	≤25°
	Pl. 10, Fig. 5		6.63	2	≤30°
	Pl. 11, Fig. 1	Poremba, Czech Republic	7.94	3.25	≤24°
	Pl. 11, Fig. 2	Grudna Dolna, Poland	8.31	3.5	≤31°
	Pl. 11, Fig. 3		7.88	3.63	≤37°
	Pl. 11, Fig. 4		5	2.75	≤38°
	Pl. 11, Fig. 5		10.94	3.88	≤34°
	Pl. 11, Fig. 6		11.81	3.75	≤27°
Bohn-Havas & Zorn (1994)	Pl. 2, Fig. 5	Vöslau, Austria	6.2	1.67	≤24°
	Pl. 3, Fig. 3		6.55	2.55	≤15°
	Pl. 3, Figs. 4		7.54	2.45	≤21°
Zorn (1999)	Pl. 4, Fig. 1	Tučapy, Czech Republic	9.6	3.6	≤26°
	Pl. 4, Fig. 2		7.9	3	≤38°
	Pl. 4, Fig. 3a		8.33	3.17	≤24°
	Pl. 4, Fig. 3b		8.33	3.33	≤27°

Table 7: Comparison of the Medvednica Mt. Badenian nannoplankton findings with available data on pteropod and calcareous nannoplankton assemblages from Slovenia (Bartol 2009; Mikuž et al. 2012), Croatia (Čučerje locality after Ćorić et al. 2009, *this research) and Romania (Cepari after Vulc & Silye 2005; Cluj-Napoca after Chira et al. 2000, Suciu et al. 2005).

SPECIES	REGION/LOCALITY					
	CENTRAL PARATETHYS				EASTERN PARATETHYS	
	NE SLOVENIA	NW CROATIA - Medvednica Mt.			ROMANIA	
		Central		Eastern		
		Čučerje	Vejalnica*	M. Bistrica*	Cluj-Napoca	Cepari
Calcidiscus permacintyrei Theodoridis	■			■	■	
C. tropicus (Kamptner)	■			■		
Coccolithus miopelagicus Bukry	■	■	■		■	■
C. pelagicus (Wallich) Schiller	■	■	■		■	■
Cycliargolithus abisectus Muller (Wise)	■		■		■	
Discoaster formosus Martini & Worsley	■		■			
Helicosphaera carteri (Wallich) Kamptner	■		■	■	■	■
H. intermedia Martini	■			■		
H. perch-nielseniae (Haq) Jafar & Martini	■			■		
Pontosphaera multipora (Kamptner) Roth	■	■	■		■	■
P. plana (Bramlette & Sullivan) Haq	■			■		
Reticulofenestra bisecta (Hay, Mohler & Wade) Roth	■			■		
*R. dictycoda (*Deflandre) Stradner				■		
R. minuta Roth	■	■	■		■	
R. perplexa (Burns) Wise	■		■	■		
R. pseudoumbilicus (Gartner) Gartner	■	■	■	■	■	■
Sphenolithus heteromorphus Deflandre	■	■	■		■	■
S. moriformis (Bronniman & Stradner) Bramlette & Wilcoxon	■	■		■	■	■
Umbilicosphaera rotula (Kamptner) Varol	■			■	■	

Pteropods from Mt. Medvednica

During this research, pteropods were collected from two different areas and associated with different biota, indicating two different stratigraphic horizons (Table 8).

Yellow marls from the Vejalnica locality belong to the “Central” Miocene belt (sensu Kochansky 1944). Deposits from this area yielded the first record of pteropods (*Vaginella austriaca* Kittl, 1886) in the Medvednica Mt. (Gorjanović-Kramberger 1908). This finding was later supported by a record of *Clio pedemontana* (Mayer, 1868) mentioned by Kochansky (1944) and Basch (1983b, p. 29). Unfortunately, the original specimens from these studies are missing. Species *C. fallauxi*, collected during this study, occurs in the same area as the above mentioned *C. pedemontana*. These records support the existence of marine environments on the Medvednica Mt. prior to the Late Badenian, and are in accordance with the pteropod bloom positioned by Bohn-Havas et al. (2003) between the 14.5 and 14.2 Ma (Table 9).

The age of the yellow marls from the “Central” Miocene belt, previously compared to the Austrian “Schlier”, was additionally estimated on the basis of calcareous nannoplankton, pointing to the probable Badenian NN5 nannozone, although the time span of the most determined taxa ranges from NN4 to NN6.

Pteropods in the northeastern part of the Medvednica Mt. (“Zelina” development) were found in grey marls exposed near Marija Bistrica, and comprise only limacinids (*L. valvatina*, *L. gramensis*, *Limacina* sp. ?). *Limacina gramensis* was present in the Central Paratethys only during the Late Badenian (Table 10), which points to the younger transgressive cycle (probably NN6 Zone) than the one visible at Vejalnica locality.

Due to the small size and poor preservation potential of pteropods, it is possible that during the previous investigations pteropods were not recorded, or remained unpublished. In addition, some older fossil collections are not available, so part of the information may be missing.

“Migration routes”

Despite the fact that pteropods are not active swimmers and their distribution depends on ocean currents and available seaways, we discuss here about their possible “migration routes” based on their recorded geographical distribution in the Paratethys during the Badenian. Open seaways are connected with maximum flooding, tectonic events and climatic conditions and it is not easy to position them in time and space. New pteropod findings from this study contribute to the palaeobiogeographic reconstructions, indicating the possible seaway connections during the different Miocene transgressive cycles, but they do not provide clear evidence for the “migration routes”. We hope that our further research will give us more insight on this subject.

Available data on the geographical distribution of *C. fallauxi*, *C. pedemontana*, *V. austriaca*, *L. valvatina* and *L. gramensis* in the Paratethys during the Miocene are shown on Figs. 15 and 16. There are additional pteropod records (*Vaginella*

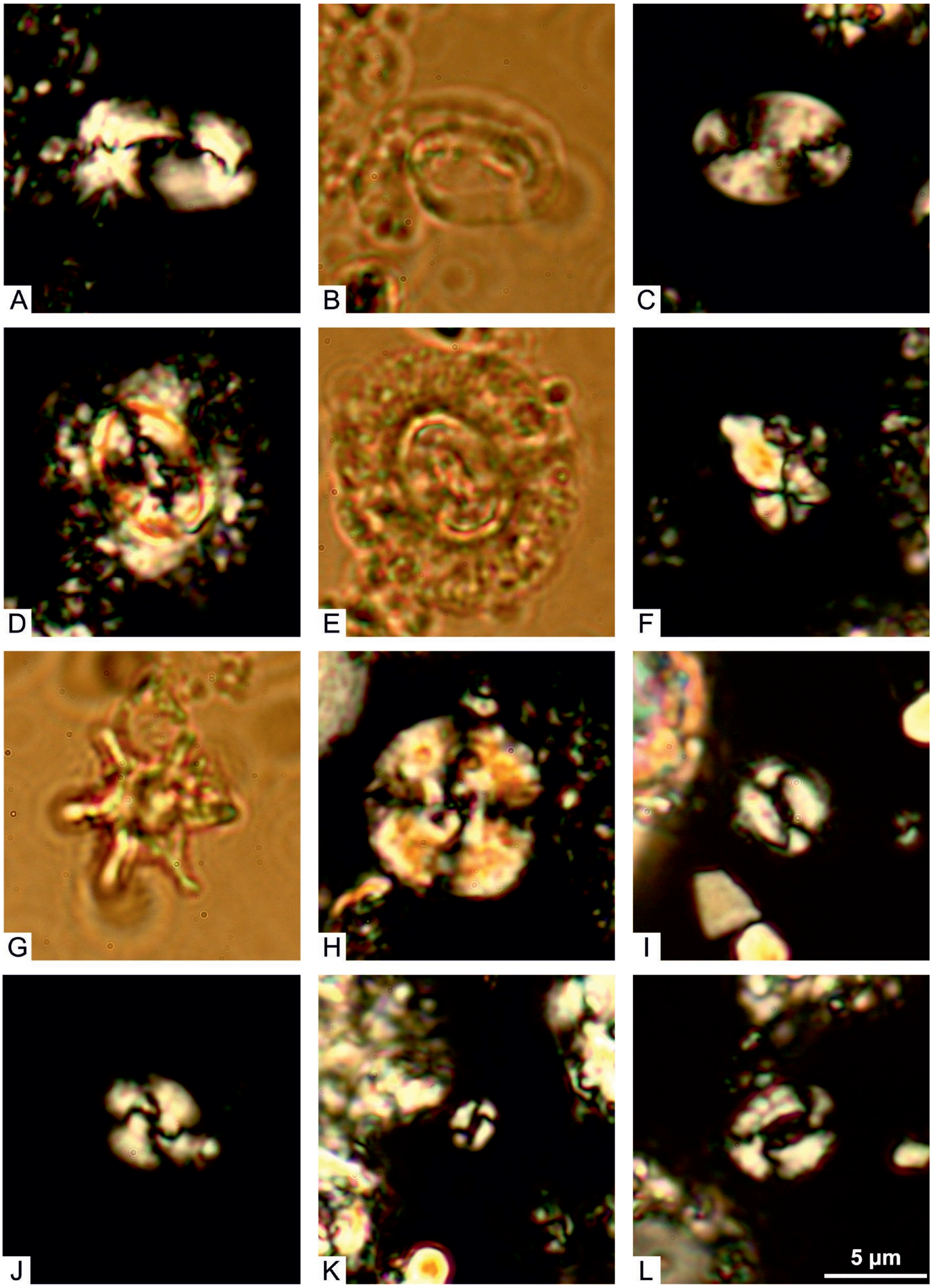

Fig. 13. Vejalnica locality. **A** — *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954; **B** — *H. carteri* (Wallich, 1877) Kamptner, 1954; **C** — *Pontosphaera multipora* (Kamptner, 1948 ex Deflandre in Deflandre and Fert, 1954) Roth, 1970; **D** — *Coccolithus miopelagicus* Bukry, 1971; **E** — *C. miopelagicus* Bukry, 1971; **F** — *Sphenolithus heteromorphus* Deflandre, 1953; **G** — *Discoaster formosus* Martini and Worsley, 1971; **H** — *Cyclicargolithus abisectus* (Muller, 1970) Wise, 1973; **I** — *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930; **J** — *Reticulofenestra perplexa* (Burns, 1975) Wise, 1983; **K** — *Reticulofenestra minuta* Roth, 1970; **L** — *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969. Figs. B, E, G PPL, others XPL. Scale bars 5 µm.

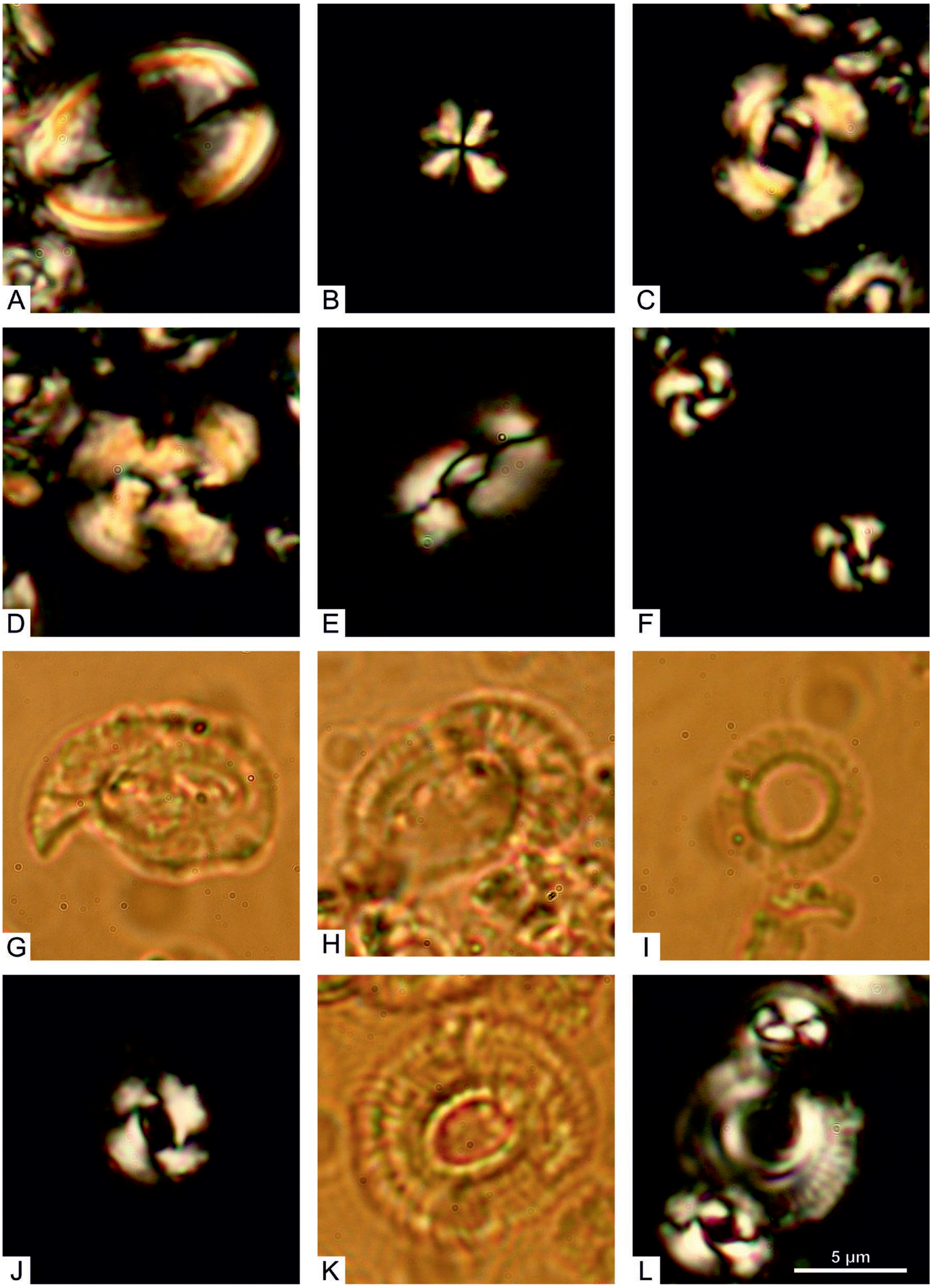

Fig. 14. Marija Bistrica locality. **A** — *Pontosphaera plana* (Bramlette and Sullivan, 1961) Haq, 1971; **B** — *Sphenolithus moriformis* (Bronnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967; **C** — *Reticulofenestra dictyoda* (Deflandre in Deflandre and Fert, 1954) Stradner in Stradner and Edwards, 1968; **D** — *Reticulofenestra bisecta* (Hay, Mohler and Wade, 1966) Roth, 1970; **E** — *Helicosphaera intermedia* Martini, 1965; **F** — *Reticulofenestra perplexa* (Burns, 1975) Wise, 1983; **G** — *Helicosphaera perch-nielseniae* (Haq, 1971) Jafar and Martini, 1975; **H** — *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954; **I** — *Umbilicosphaera rotula* (Kamptner, 1956) Varol, 1982; **J** — *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969; **K** — *Calcidiscus premacintyrei* Theodoridis, 1984; **L** — *Calcidiscus tropicus* (Kamptner, 1956) Varol 1989 sensu Gartner, 1992. Figs. G, H, I and K PPL, others XPL. Scale bars 5 µm.

Table 8: List of the collected fossil fauna presented in this paper. Abbreviations: V — Vejalnica locality; MB — Marija Bistrica locality.

	Species	Locality	
		V	MB
Pteropoda	*Limacina valvatina* (Reuss)		■
	Limacina gramensis (Rasmussen)		■
	Clio fallauxi (Kittl)	■	
	Vaginella austriaca Kittl	■	?
Coccolithales	*Calcidiscus premacintyrei* Theodoridis		■
	C. tropicus (Kamptner)		■
	Coccolithus miopelagicus Bukry	■	
	C. pelagicus (Wallich) Schiller	■	
	Cyclicargolithus abisectus Muller (Wise)	■	
	Discoaster formosus Martini & Worsley	■	
	Helicosphaera carteri (Wallich) Kamptner	■	■
	H. intermedia Martini		■
	H. perch-nielseniae (Haq) Jafar & Martini		■
	Pontosphaera multipora (Kamptner) Roth	■	
	P. plana (Bramlette & Sullivan) Haq		■
	Reticulofenestra bisecta (Hay, Mohler & Wade) Roth		■
	R. dictyoda (Deflandre) Stradner		■
	R. minuta Roth	■	
	R. perplexa (Burns) Wise	■	■
	R. pseudoumbilicus (Gartner) Gartner	■	■
	Sphenolithus heteromorphus Deflandre	■	
	S. moriformis (Bronniman & Stradner) Bramlette & Wilcoxon		■
	Umbilicosphaera rotula (Kamptner) Varol		■
Other	Foraminifera	■	■
	Ostracods		■
	Bivalves	■	■
	Benthic gastropods	■	
	Scaphopods	■	■
	Bryozoans		■
	Fish remains	■	■

Table 9: Regional distribution and stratigraphic range of *Clio fallauxi* (Kittl, 1886), *Clio pedemontana* (Mayer, 1868) and *Vaginella austriaca* Kittl, 1886 in the Paratethys during the Badenian (Middle Miocene). *Badenian threefold subdivision sensu Piller et al. (2007). Palaeogeographic map of distribution is shown on Fig. 15.
References: [1]Gorjanović-Kramberger 1908; [2]Kochansky 1944: [3]Basch 1983; [4]Janssen 1984; [5]Zorn 1991; [6]Bohn-Havas & Zorn 1993; [7]Janssen & Zorn 1993; [8]Bohn-Havas & Zorn 1994; [9]Avanić et al. 1995; [10]Zorn 1999; [11]Bohn-Havas et al. 2011; [12]Janssen & Little 2010; [13]Nikolov 2010; [14]Mikuž et al. 2012; [15]Selmeczi et al. 2012; [16]this paper.

References	Species	Sedimentological basin	Country	MIOCENE / MIDDLE MIOCENE / Badenian	
				Lower-Middle *	Upper
6; 8; 10; 11; 15	*Clio fallauxi*	Central Paratethys	Hungary	■ ?	
6; 7; 8; 10			Poland	■	
7; 10			Czech Republic	■	
14			Slovenia	■	
16			Croatia	■	
8; 10		Eastern Paratethys	Romania	■	
10; 13			Bulgaria	■	
6; 8; 12; 15	*Clio pedemontana*	Central Paratethys	Hungary	■	
6; 7; 12			Poland	■	
14			Slovenia	■	
2; 3			Croatia	■	
6; 12		Eastern Paratethys	Romania	■	
13			Bulgaria	■	
4; 6; 8; 5; 10	*Vaginella austriaca*	Central Paratethys	Austria	■	
5; 6; 8; 11; 15			Hungary	■	
5; 6; 7; 8; 10			Poland	■	
5; 10			Czech Republic	■	
14			Slovenia	■	
1; 2; 9			Croatia	■	
6; 5; 10		Eastern Paratethys	Romania	■	
10; 13			Bulgaria	■	

austriaca and "*Spiratella* sp.") from the eastern part of northern Croatia (Magaš 1987; Pikija 1987) and vicinity of Belgrade, Serbia (Stevanović 1974), but we did not include them in Figures 15 and 16, since we do not know the exact stratigraphic position of those findings.

In the Early-Middle Badenian (e.g., Rögl 1998; Harzhauser & Piller 2007) fauna may have migrated in a northwestern–southeastern direction. Mikuž et al. (2012) described *C. pedemontana* and possibly *C. fallauxi* in the Badenian NN5 nannozone deposits of Slovenia, and indicated the existence of a marine connection between the Central Paratethys and the Mediterranean during the Early Badenian transgression ("Transtethyan Trench Corridor", e.g., Rögl 1998). Absence of *C. fallauxi* in the Eastern Paratethys may indicate the existence of a palaeogeographical barrier between the Central and Eastern Paratethys during that period, as described in Studencka et al. (1998). Rögl (1998) discussed an open marine connection between the Central and Eastern Paratethys, and the existence of a southern marine connection to the Mediterranean and Central Paratethys through the area between the Black Sea and the Pontids.

Recent studies show different interpretations of the Badenian subdivision, the age of the NN5 zone, and number and timing of Badenian marine transgressions in the Paratethys (Harzhauser & Piller 2007; Piller et al. 2007; Kováč et al. 2007; Rögl et al. 2007; Kováč et al. 2008; Pezelj et al. 2013; Bartol et al. 2014; Hohenegger et al. 2014). Therefore, the stratigraphic range of *Clio fallauxi* should be extended to the lower part of the Middle Badenian (Badenian subdivision sensu Papp & Cicha 1968 and Piller et al. 2007). Considering the appearance of *C. fallauxi* in the NN5 nannozone e.g., Mikuž et al. (2012) and Selmeczi et al. (2012) (Early Badenian sensu Kováč et al. 2007, i.e. Early-Middle Badenian sensu Piller et al. 2007), our new records, together with previous research from Croatia (Kochansky 1944) contribute to the possible suggested northwestern-southeastern fauna migration direction in the Paratethys.

The existence of the seaway between the Mediterranean and the Central Paratethys ("Transtethyan Trench Corridor") during

Table 10: Regional distribution and stratigraphic range of *Limacina valvatina* (Reuss, 1867) and *Limacina gramensis* (Rasmussen, 1968) in the Paratethys area during the Badenian (Middle Miocene). *Badenian threefold subdivision sensu Piller et al. (2007). Palaeogeographic map of distribution is shown on Fig. 16. References: [1]Zorn 1991; [2]Bohn-Havas & Zorn 1993; [3]Janssen & Zorn 1993; [4]Bohn-Havas & Zorn 1994; [5]Zorn 1999; [6]Bohn-Havas et al. 2004; [7]Suciu et al. 2005; [8]Nikolov 2010; [9]Selmeczi et al. 2012; [10]this paper.

References	Species	Sedimentological basin	Country	MIOCENE	
				MIDDLE MIOCENE	
				Badenian	
				Lower-Middle *	Upper
1; 2; 4	*Limacina valvatina*	Central Paratethys	Austria		
2; 4; 6; 9			Hungary		
2; 3; 4;			Poland		
4; 5			Czech Republic		
5			Slovakia		
10			Croatia		
4; 7		Eastern Paratethys	Romania		
8			Bulgaria		
3; 4			Ukraine		
2; 3; 5	*Limacina gramensis*	Central Paratethys	Poland		
5			Czech Republic		
10			Croatia		
5		Eastern Paratethys	Romania		
8			Bulgaria		
3; 5			Ukraine		

the Late Badenian is debated in several papers. According to some authors (e.g., Rögl 1998; Harzhauser & Piller 2007; Piller et al. 2007; Kováč et al. 2007), the “Transtethyan Trench Corridor” was closed during the Late Badenian, so the migration of fauna from west-northwestern direction would not be possible. Rögl (1998) assumes the re-opening of the southern Early Badenian passage. Based on a bivalve fauna, Studencka et al. (1998) conclude on a connection of the Central and Eastern Paratethys and existence of a corridor between the Paratethys and the Eastern Mediterranean. Bartol et al. (2012, 2014) considered the connection between the Mediterranean and the Central Paratethys through the “Transtethyan Trench Corridor” during the Late Badenian, in contrast to some previous studies (Bistričić & Jenko 1985; Rijavec 1985; Rögl 1998;

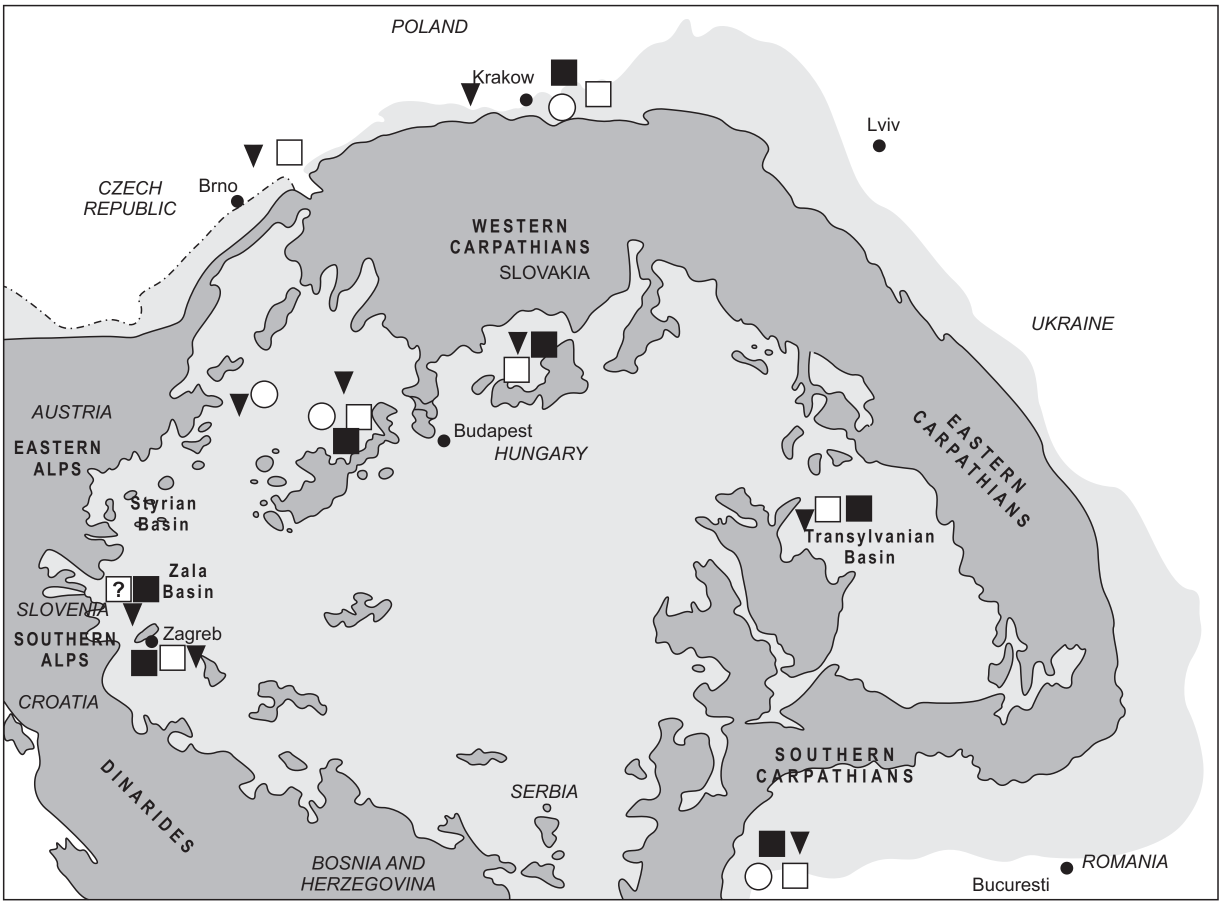

Fig. 15. Palaeogeographic distribution of *Limacina valvatina* (Reuss, 1867) (white circles), *Clio fallauxi* (Kittl, 1886) (white rectangulars), *Clio pedemontana* (Mayer, 1868) (black rectangulars) and *Vaginella austriaca* Kittl, 1886 (black triangels) during the Early−Middle Badenian sensu Piller et al. (2007) in the Paratethys. For references and localities see Tables 9 and 10. Palaeogeographic map after Kováč et al. 2007.

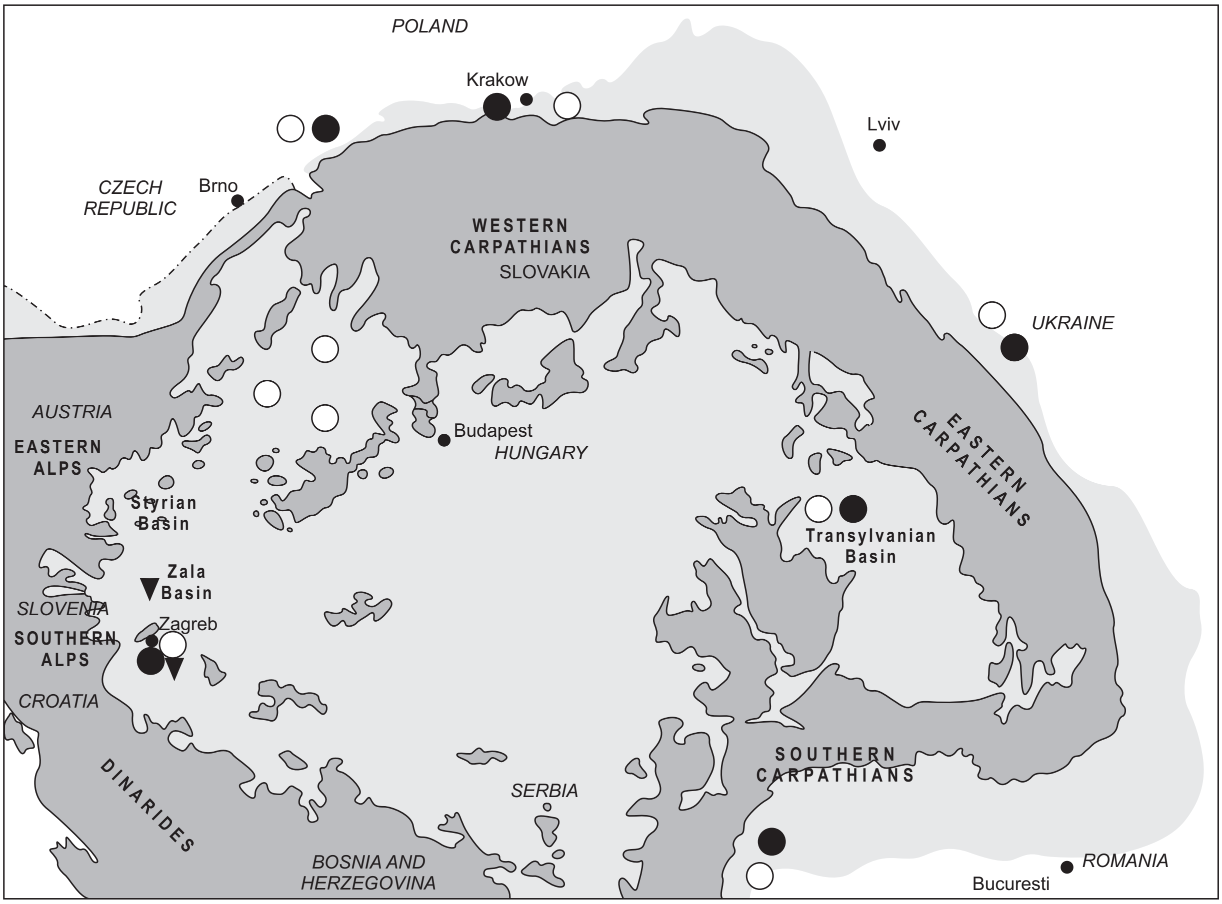

Fig. 16. Palaeogeographic distribution of *Limacina valvatina* (Reuss, 1867) (white circles) and *Limacina gramensis* (Rasmussen, 1968) (black circles) during the Late Badenian in the Paratethys. For references and localities see Table 10. Palaeogeographic map after Kováč et al. 2007.

Kováč et al. 2007). Spreading of pteropod fauna (*Limacina* horizon) during the Late Badenian in the eastern part of the Paratethys is shown on Fig. 16. *L. gramensis* and *L. valvatina* are also recorded from northern palaeogeographical areas (Tembrock 1989; Janssen & Zorn 1993; Janssen 1999). Bearing that in mind, their distribution could possible point to a connection or brief existence of a northern European passage between the Central Paratethys and the North Sea Basin during the Miocene.

Conclusions

Middle Miocene marls from Mt. Medvednica (northern Croatia) comprise two different pteropod assemblages.

The pteropod fauna at the locality Vejalnica (central part of the Medvednica Mt.) is characterized by low pteropod diversity and predominance of the species *Vaginella austriaca* Kittl, 1886, accompanied by *Clio fallauxi* (Kittl, 1886). Yellow marls additionally comprise other pelagic and deep marine biota.

Grey Miocene marls at the locality Marija Bistrica (north-eastern area) are highly fossiliferous and, among other fossils, comprise limacinid pteropods: *Limacina valvatina* (Reuss, 1867), *L. gramensis* (Rasmussen, 1968) and *Limacina* sp.

Determined pteropod taxa, except *V. austriaca* and *Limacina* sp. have been found in this region for the first time. Pteropods *Clio pedemontana* (Mayer, 1868) and *Limacina andrussowi* (Kittl, 1886) (in original: "*Spirialis*" or "*Spiratella*") were recorded in the same region by previous authors.

Pteropod marls at the Vejalnica locality were deposited during the older Badenian transgressive cycle, and grey marls with limacinids from the north-eastern part of the Medvednica Mt. are dated to the Late Badenian.

Pteropod records from Croatia, compared with other published data, indicate pteropod immigration into the Paratethys from the west during the Badenian NN5 nannozone. Therefore the Mediterranean connection ("Transtethyan Trench Corridor"), proposed by previous authors, could be a possible immigration seaway. A northern European marine passage may have been active during the Late Badenian, enabling the immigration of the "North Sea fauna" (including limacinid pteropods) into the Paratethys. Such theory was presumed by several authors during the 1990s (e.g., Janssen & Zorn 1993), but has not been confirmed, due to the lack of fossil evidence.

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Erratum

'The Miocene "Pteropod Event" in the SW part of the Central Paratethys (Medvednica Mt., Northern Croatia)' by MARIJA BOŠNJAK, JASENKA SREMAC, DAVOR VRSALJKO, ŠIMUN AŠČIĆ and LUKA BOSAK published in *GEOLOGICA CARPATHICA* Vol. 68, No. 4, 2017, pages 329–349, doi: 10.1515/geoca-2017-0023, error in the Figure 5 on page 335, Table 8 on page 344, Table 10 on page 345 and Figure 16 on page 346:

In Fig. 5, determinations of gastropods are erroneous and the figure caption is incorrect.

Fig. 5. A–B: *Limacina gramensis* (Rasmussen, 1968) from the Marija Bistrica locality. **A** — CNHM MB-LG1; **B** — CNHM MB-LG 8. **C-D:** *Limacina* sp. (? nov.) from the Marija Bistrica locality. **C** — CNHM MB-L 1; **D** — CNHM MB-L 2. Scale bars 100 µm.

The corrected Figure caption is shown below:

Fig. 5. Juvenile benthic gastropods from the Marija Bistrica locality. **A** — CNHM MB sp. A-1; **B** — CNHM MB sp. A-2; **C** — CNHM MB sp. B-1; **D** — CNHM MB sp. B-2. Scale bars 100 µm.

Specimens illustrated in Fig. 5 as the pteropods *Limacina gramensis* and *Limacina* sp. (nov. ?) do not represent pteropod species, but juvenile benthic gastropods. Description of *Limacina gramensis* and *Limacina* sp. (nov.?) should be excluded from the chapter Systematic Palaeontology, p. 333–334, as well as Table 2 and Fig. 6, page 336.

This change affects the following tables/figures:

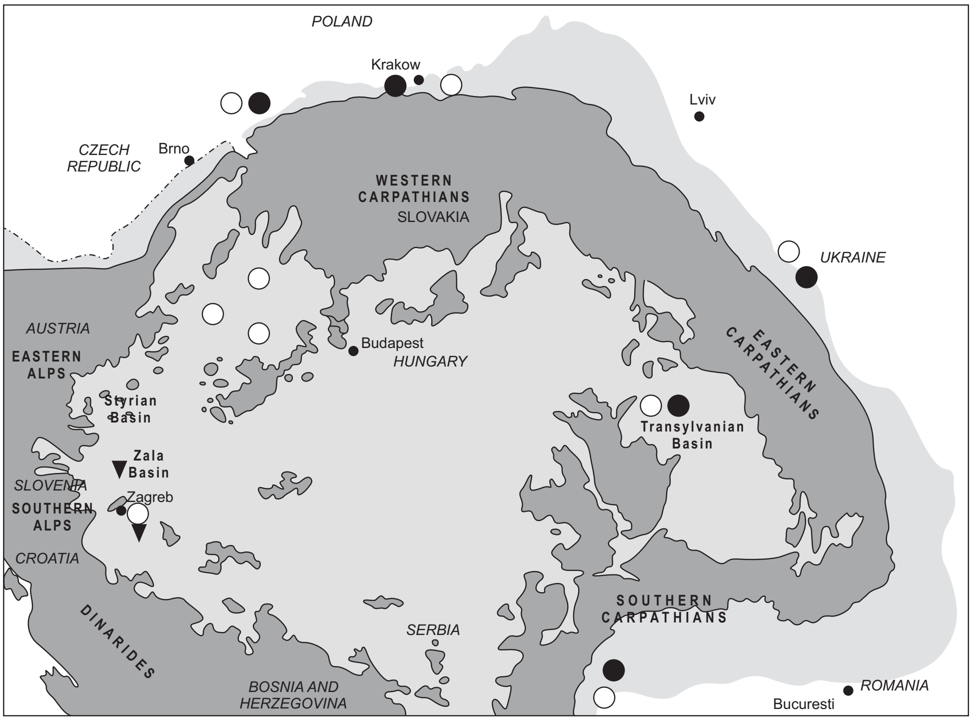
In Table 8 *Limacina gramensis* and *Limacina* sp. should be excluded from pteropod list. Benthic gastropoda from the Marija Bistrica locality are added among the category: Other. The corrected Table 8 is shown below:

	Species	Locality	
		V	MB
Pteropoda	*Limacina valvatina* (Reuss)		■
	Clio fallauxi (Kittl)	■	
	Vaginella austriaca Kittl	■	■ ?
Coccolithales	*Calcidiscus premacintyrei* Theodoridis		■
	C. tropicus (Kamptner)		■
	Coccolithus miopelagicus Bukry	■	
	C. pelagicus (Wallich) Schiller	■	
	Cyclicargolithus abisectus Muller (Wise)	■	
	Discoaster formosus Martini & Worsley	■	
	Helicosphaera carteri (Wallich) Kamptner	■	■
	H. intermedia Martini		■
	H. perch-nielseniae (Haq) Jafar & Martini		■
	Pontosphaera multipora (Kamptner) Roth	■	
	P. plana (Bramlette & Sullivan) Haq		■
	Reticulofenestra bisecta (Hay, Mohler & Wade) Roth		■
	R. dictyoda (Deflandre) Stradner		■
	R. minuta Roth	■	
	R. perplexa (Burns) Wise	■	■
	R. pseudoumbilicus (Gartner) Gartner	■	■
	Sphenolithus heteromorphus Deflandre	■	
	S. moriformis (Bronniman & Stradner) Bramlette & Wilcoxon		■
	Umbilicosphaera rotula (Kamptner) Varol		■
Other	Foraminifera	■	■
	Ostracods		■
	Bivalves	■	■
	Benthic gastropods	■	■
	Scaphopods	■	■
	Bryozoans		■
	Fish remains	■	■

In Table 10, distribution of *Limacina gramensis* in Central Paratethys is incorrect. The corrected Table 10 is shown below:

References	Species	Sedimentological basin	Country	MIOCENE MIDDLE MIOCENE Badenian	
				Lower-Middle *	Upper
1; 2; 4	*Limacina valvatina*	Central Paratethys	Austria		
2; 4; 6; 9			Hungary		
2; 3; 4;			Poland		
4; 5			Czech Republic		
5			Slovakia		
10			Croatia		
4; 7		Eastern Paratethys	Romania		
8			Bulgaria		
3; 4			Ukraine		
2; 3; 5	*Limacina gramensis*	Central Paratethys	Poland		
5			Czech Republic		
5		Eastern Paratethys	Romania		
8			Bulgaria		
3; 5			Ukraine		

In Fig. 16. palaeogeographic distribution of *Limacina gramensis* in Croatia is incorrect. The corrected Figure 16 is shown below:



Although *L. gramensis* was not found in the research area, the species is considered to be a Late Badenian index fossil, therefore it is important for the discussion regarding the Badenian palaeogeography (parts of Discussion and Conclusion, Fig. 16, Table 10).

The erroneous determination of gastropods on Fig. 5 does not significantly affect presented discussion and conclusions, since the age of the investigated sites was based on the nannoplankton assemblages as well as on pteropods.