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Upper Miocene Pannonian sediments from Belgrade (Serbia): new evidence and paleoenvironmental considerations

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Abstract: The Late Miocene sublittoral marls of the Pannonian Stage (the long-lived Lake Pannon) were studied. From neotectonic point of view, the investigated area represents a natural border between two different morphostructural domains: the Pannonian Basin to the north and the Peri-Pannonian Realm to the south. More than 20 mollusc and 34 ostracod species were identified which indicate the upper part of the Lower Pannonian and the lower part of the Middle Pannonian ("Serbian") predominantly. The identified dinoflagellate cyst assemblage (21 taxa) hinders assignment of the studied samples to a Pannonian substage but supports the high endemism of the Pannonian flora. The lithostratigraphical, paleontological, and paleoecological analyses indicate a mesohaline (8–16 ‰), sublittoral (< 90 m deep) environment of the early Lake Pannon. The estimated stratigraphic range for the investigated deposits is 9.8–11.4 Ma.

Key words: Late Miocene, Lake Pannon, Belgrade, sublittoral environment, endemism.

Introduction

The Pannonian Basin is a large internal basin structure within continental Europe surrounded by the Alps, Dinarides, and Carpathians. It resulted from back-arc basin extension during the Miocene and subsequent compression during the Pliocene to Quaternary (Horváth & Cloetingh 1996; Cloetingh et al. 2006; Horváth et al. 2006). At about the Middle–Late Miocene boundary (ca. 11.6 Ma), following the demise of the Central Paratethys Sea a long-lived Lake Pannon was formed (Magyar et al. 1999; Piller et al. 2007; Harzhauser & Mandic 2008). It shows high endemism in both fauna and flora (e.g. Müller et al. 1999; Harzhauser & Piller 2007). Lake Pannon enabled a spectacular adaptive radiation of molluscs including over 900 described species and many endemic genera (e.g. the families Cardiidae with more than 220 species and Dreissenidae with more than 130 species, Geary et al. 2000). Among gastropods, the prosobranch families Hydrobiidae (~180 species) and Melanopsidae (~100 species) are dominant (Geary et al. 2000). Many of the ostracod, nannoplankton, dinoflagellate, diatom, and other fossil species are also recognized as endemic.

During the last couple of decades, many new data on Lake Pannon have been published. Application of an integrated stratigraphic approach led to modification of the previously accepted concept concerning the chronostratigraphic division (Papp et al. 1985; Magyar 1995; Rögl 1999; Magyar et al. 1999; Harzhauser et al. 2002, 2004; Magyar et al. 2006, 2007 and reference therein). Despite the well-known facts about the paleogeographical evolution of the Pannonian Basin, there are still many open questions. The scarcity and endemism of dinoflagellates as well as calcareous nannoplankton in Lake Pannon sediments

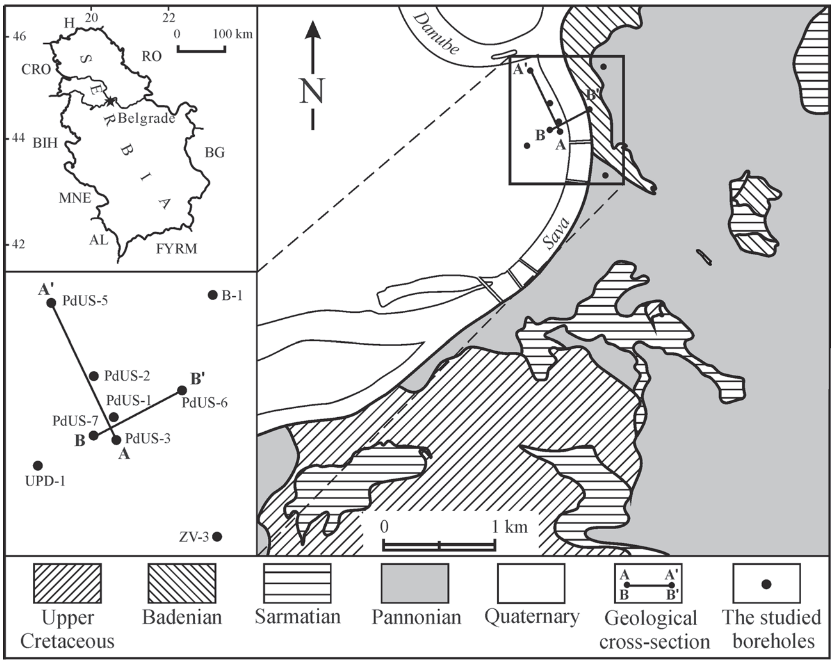

Fig. 1. Geological sketch map of the Belgrade City area and the position of geological cross-sections and the studied boreholes. Note: Quaternary deposits with small thickness are ommited (the right bank of the Sava River).

made biostratigraphic correlation to the Late Miocene marine sequences impossible.

The intention of this study was to explain: (1) the general distribution and structure of the Pannonian sediments from the Belgrade City area in order to determine the paleogeography at the time of deposition; (2) paleontological analysis in order to determine biostratigraphic position and the depositional environment. In addition, estimated time span is discussed in terms of the different chronostratigraphic divisions of the Late Miocene in the Pannonian realm (Magyar et al. 1999; Harzhauser & Mandic 2008; Harzhauser et al. 2008).

Geological framework

More than 70 % of all Miocene sediments in the Belgrade City area (Fig. 1) correspond to the Pannonian Stage. The Pannonian deposits occur at the top of the borehole sections under a thin layer of loess sediments and alternating loess deposits. In some places, they cover older rocks (Badenian reef deposits, borehole B-1) or they continue from Sarmatian sandstones and sandy limestone. The contact between the Sarmatian and Pannonian is conformable in general, but there are localities where the Pannonian deposit lies transgressively over the Sarmatian sediments. In the City centre, numerous shallow boreholes and outcrops revealed Pannonian deposits overlain by a thin cover of loess deposits (Knežević & Šumar 1993, 1994). Along other localities and the street outcrops, very similar stratigraphic positions of the investigated deposits were noted (Krstić 1973). The total thickness of the Pannonian sediments is more than 50 m (Stevanović 1977; Eremija 1989).

Material and methods

The data acquired from the different core samples of the PdUS set of boreholes have been used for the construction of two geological cross-sections (Table 1, Fig. 2). Stratigraphic correlation of the Pannonian deposits from an additional three boreholes is shown in Fig. 3.

Molluscs were analysed from fifteen core samples of the boreholes B-1 (Kalemegdan), ZV-3 (Zeleni venac), PdUS-3 and PdUS-7 (Sava River banks).

For analysis of the ostracods, seven dried samples from borehole ZV-3 were washed using dilute hydrogen peroxide and standard 63–500 μm sieves. The specimens were picked out from the residue and stored in the collection of the Department of Geology and Paleontology, Faculty of Mining and Geology, University of Belgrade.

Four samples from the borehole ZV-3 were selected for the contents of dinoflagellate cysts. Approximately 15 grams

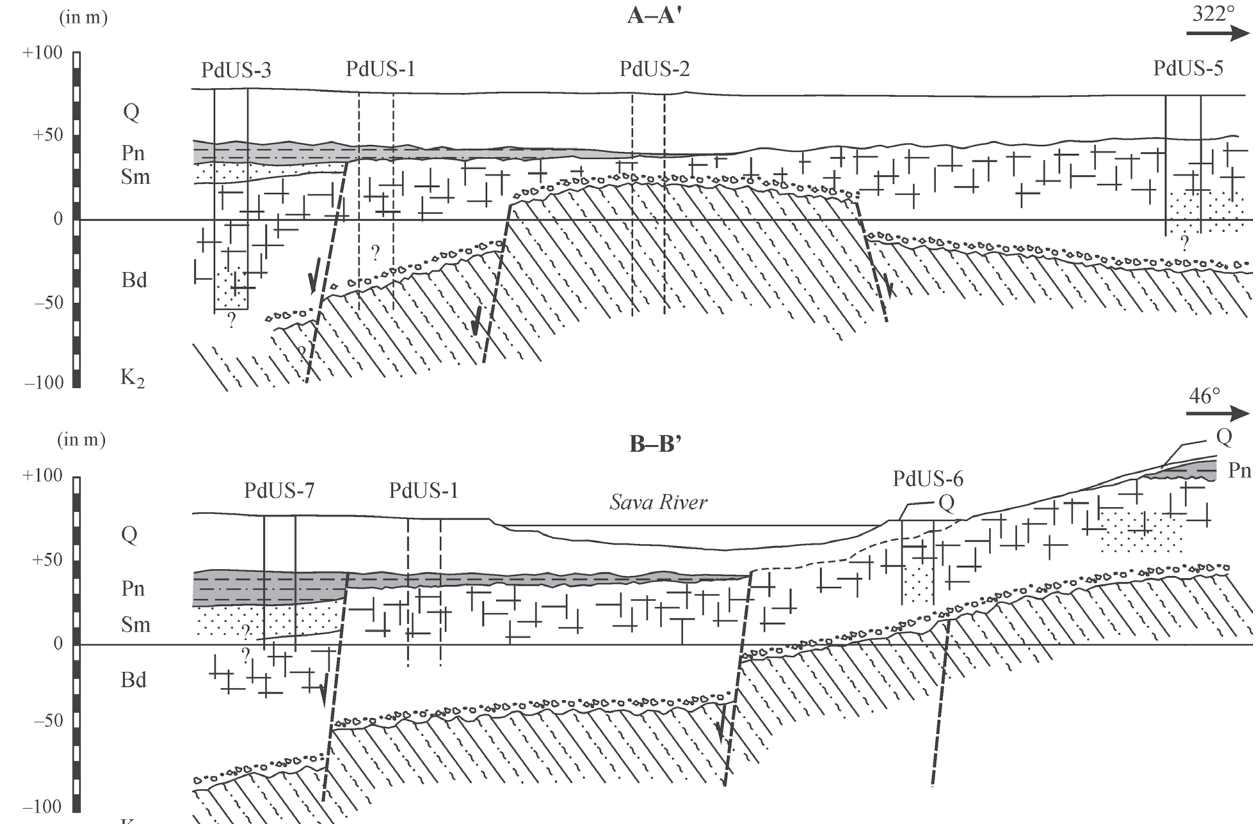

Fig. 2. Geological cross-sections through the Miocene sediments near the Sava-Danube confluence: **A–A'** — along the left bank of the Sava River, **B–B'** — across the Sava River, $\mathbf{K_2}$ — Upper Cretaceous, **Bd** — Badenian limestone and sand, **Sm** — Sarmatian sand, marl and limestone, **Pn** — Pannonian marl and silty marl, **Q** — Loess and other soft deposits.

Table 1: Geographical position of the investigated boreholes.

No.	Boreholes	Coordinates (WGS84)	
1	PdUS-1	N 44º 49' 00.8"	E 20º 26' 41.5"
2	PdUS-2	N 44º 49' 07.0"	E 20º 26' 38.2"
3	PdUS-3	N 44º 48' 57.4"	E 20º 26' 42.4"
4	PdUS-5	N 44º 49' 18.3"	E 20º 26' 28.0"
5	PdUS-6	N 44º 49' 06.1"	E 20º 26' 59.3"
6	PdUS-7	N 44º 48' 58.2"	E 20º 26' 38.9"
7	UPD-1	N 44º 48' 59.8"	E 20º 26' 29.9"
8	B-1	N 44º 48' 57.4"	E 20º 26' 42.4"
9	ZV-3	N 44º 48' 48.9"	E 20º 27' 24.3"

were treated with cold HCl (34 %) to remove carbonates. Then after washing with distilled water, the residue was treated with HF (48 %) and cold HCl to fully remove silicates and colloids. The residue was ultrasonicated (ca. 30°) and sieved at 125 μm and 20 μm. No oxidation at all was applied. The residue was washed and stained with Safranine "O". Two microscope slides were made from each sample using glycerin jelly as the mounting medium. The first 300 dinoflagellate cysts were counted using a Zeiss Axioplan 2 microscope fitted with a Leica DFC 320 digital camera. Additionally, two SEM stubs were prepared from a sample of 21.60 m and scanned with DSM Gemini SEM operating at a working voltage of 10 kV. The dinoflagellate cyst nomenclature generally followed that of Fensome et al. (2008), namely, the new online version of DINOFLAG2, http://dinoflaj.smu.ca.

Structural and stratigraphic setting

The first structural stage forms the substrate for the Miocene and Quaternary cover (Fig. 2) in Belgrade City and its vicinity. It occurs on elevated structures such as small highs represented by Jurassic serpentinite; Jurassic and Cretaceous carbonate rocks and rare igneous rocks. The second structural stage is composed of Miocene deposits, the most widespread rocks in the investigated area on the right bank of the Sava and Danube Rivers. The last structural stage corresponds to the Quaternary sediments. These are various alluvial deposits on the left bank of the Sava River, covering the older formations. The older rocks have very complex structural settings as a result of long-range tectonic activities (Marović et al. 2007). For these reasons, there are big differences in the core sections between boreholes PdUS-1, PdUS-2, and PdUS-3 (Fig. 2). Core analysis of the last borehole as well as the borehole UDP-1 showed complete successions of the Badenian, Sarmatian, and Pannonian deposits (Fig. 3). On the contrary, a prior study shows that the Miocene sediments are thinner and the Sarmatian sediments are missing (Knežević & Ganić 2008).

Detailed analysis of the geological cross-section B-B' in the NE direction (across the Sava River, borehole PdUS-1 to the Kalemegdan Fortress) showed that there was a strong vertical movement of up to 75 m along the fault zone. Similar data was obtained by core analysis of other PdUS boreholes. However, it is noticed that the sinking is more evident towards the center of the basin (borehole PdUS-7). It could be supposed that there was a cascade fault system that separated different rock units and shifting along the main fault that followed the Sava River. In addition, a transversal fault cuts pre-Quaternary sediments. It was documented by longitudinal cross-section analysis (A–A', Fig. 2) between the boreholes PdUS-3 and PdUS-5. A very marked subsurface horst-like structure was identified by core analysis of borehole PdUS-2. Away from

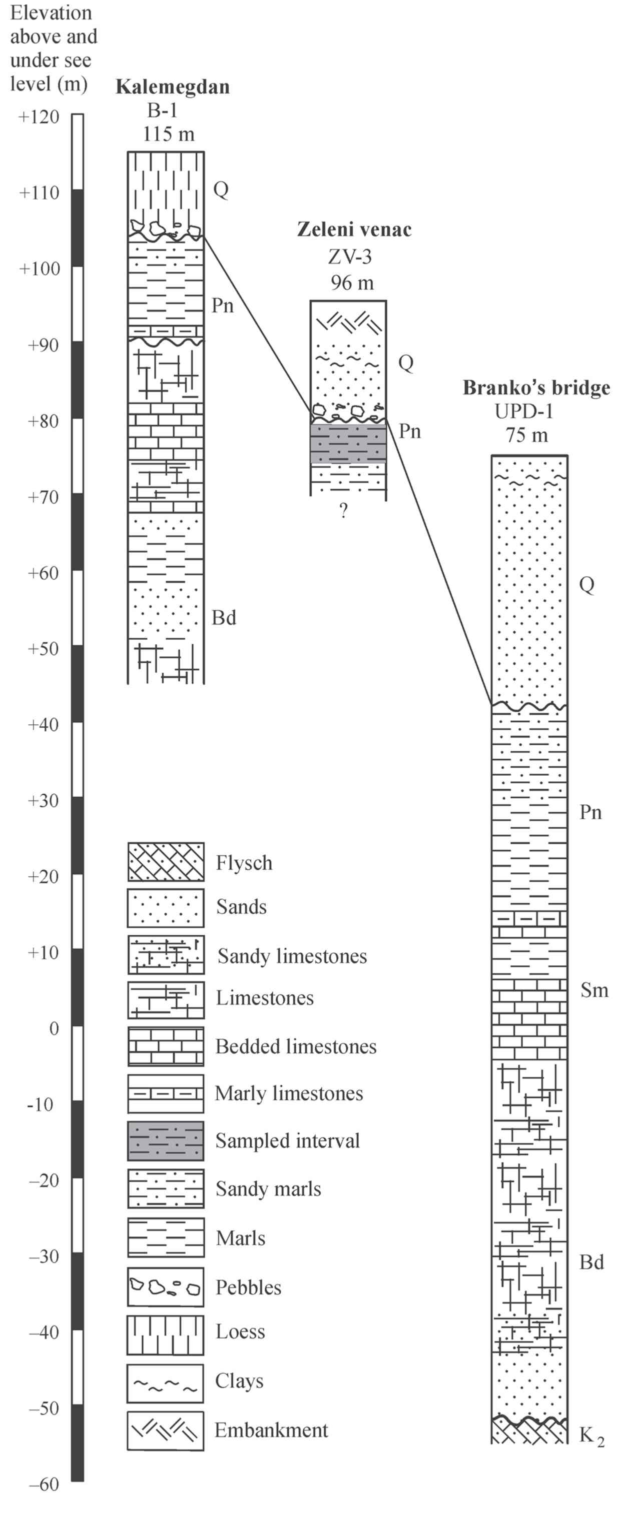

Fig. 3. Stratigraphic columns of the investigated boreholes and position of the Pannonian deposits. For stratigraphic abbreviations, see Fig. 2.

both sides of this location, there is a trend towards increased thickness of the Miocene deposits.

In the lower part of borehole B-1 (Fig. 3), the Pannonian marly limestone and marl transgressively lay over the Middle Miocene Badenian reef sediments. The inhomogeneous marl has a thickness of up to 10 m. The uppermost part of that marl section is marked by marly clay. Core samples from the borehole ZV-3 represented by silty marl contain very scarce and damaged molluscs (depth ca. 17–24 m). Above, there is a 2 m thick zone of deformed and altered silty marl. Core section analysis shows that the maximal thickness of the Pannonian sediments is up to 30 m as recorded in the borehole UDP-1.

Paleontological analysis

For the appropriate biostratigraphic and paleoenvironmental interpretations, the Late Miocene Lake Pannon division after Magyar et al. (1999) was used as well as the modern chronostratigraphic and biostratigraphic correlation scheme for the Mediterranean and Paratethys (Gradstein et al. 2004; Vasiliev et al. 2004; Kováč et al. 2006; Piller et al. 2007; Harzhauser & Mandic 2008 — Fig. 4).

Molluscs

New data obtained by stratigraphic and paleontological analysis of fifteen core samples from boreholes B-1 (Kalemegdan), ZV-3 (Zeleni venac), PdUS-3 and PdUS-7 from both sides of the Sava River are discussed here. Although certain specimens were put in open nomenclature, 20 mollusc species were determined.

The Pannonian marl in the borehole B-1 contains a poor but very characteristic mollusc association with *Paradacna cekusi* (Gorjanović-Kramberger), *Gyraulus praeponticus* (Gorjanović-Kramberger), *Congeria* sp., *Micromelania* sp. Shells are relatively small, broken and without prevailing orientation. Biostratigraphically, another more important assemblage was recorded. It corresponds to the uppermost part of the Lower Pannonian where *Congeria banatica* (R. Hoernes), *Paradacna syrmiense* (R. Hoernes), *Parvidacna laevicostata* (Wenz), *Orygoceras fuchsi* (Kittl) and *Gyraulus* cf. *praeponticus* (Gorjanović-Kramberger) were recognized.

Most evidence concerning the Pannonian molluscs was collected from boreholes PdUS-3 and PdUS-7. Ten core samples from both boreholes were analysed. The basal part of the Pannonian in the borehole PdUS-3 is represented by grey marl with abundant small limnocardids such as *Limnocardium maorti* Strausz, *L. winkleri lukae* Stevanović, *L.* gr. *praeponticum* Gorjanović-Kramberger, *Paradacna lenzi* (R. Hoernes), *P. syrmiense* (R. Hoernes), as well as *Mytilopsis zujovici* Brusina and *Congeria banatica* (R. Hoernes). Above the fossiliferous marl, there is a thin marly bed with imprints of different small limnocardids without prevailing orientation of the shell remains. The upper part contains grey, silty marl with *Mytilopsis subdigitifera* (Stevanović), *Paradacna syrmiense* (R. Hoernes), *Paradacna lenzi* (R. Hoernes), *Paradacna* sp., *Monodacna vienensis* Papp, and *Gyraulus praeponticus* (Gorjanović-Kramberger). Additionally, it contains numerous *Mytilopsis czjzeki* M. Hoernes and *Congeria zsigmondyi* Halaváts (Figs. 5, 6).

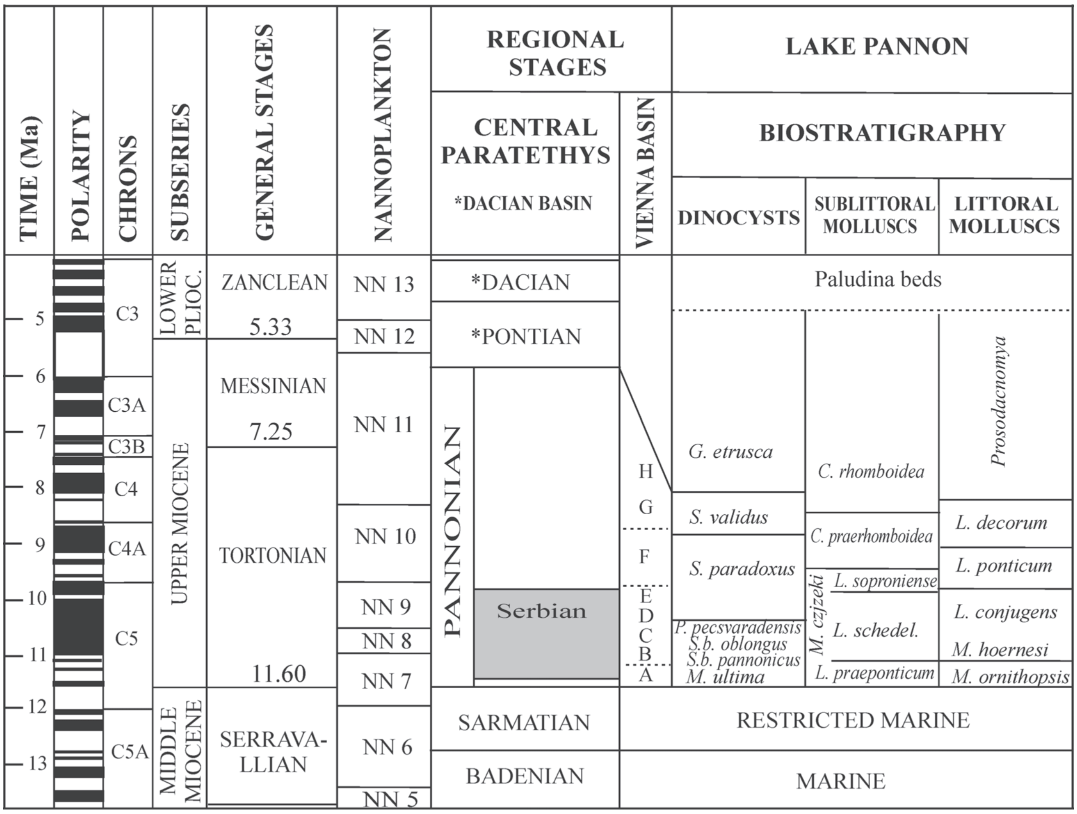

Fig. 4. A stratigraphic correlation scheme for the Miocene of Central Paratethys and the Lake Pannon biostratigraphy (after Magyar et al. 1999; Gradstein et al. 2004; Kováč et al. 2006; Piller et al. 2007; Harzhauser & Mandic 2008 — modified). Time span for the Pontian and Dacian according to Vasiliev et al. (2004). A light grey area marks the stratigraphical range of the investigated Lake Pannon deposits.

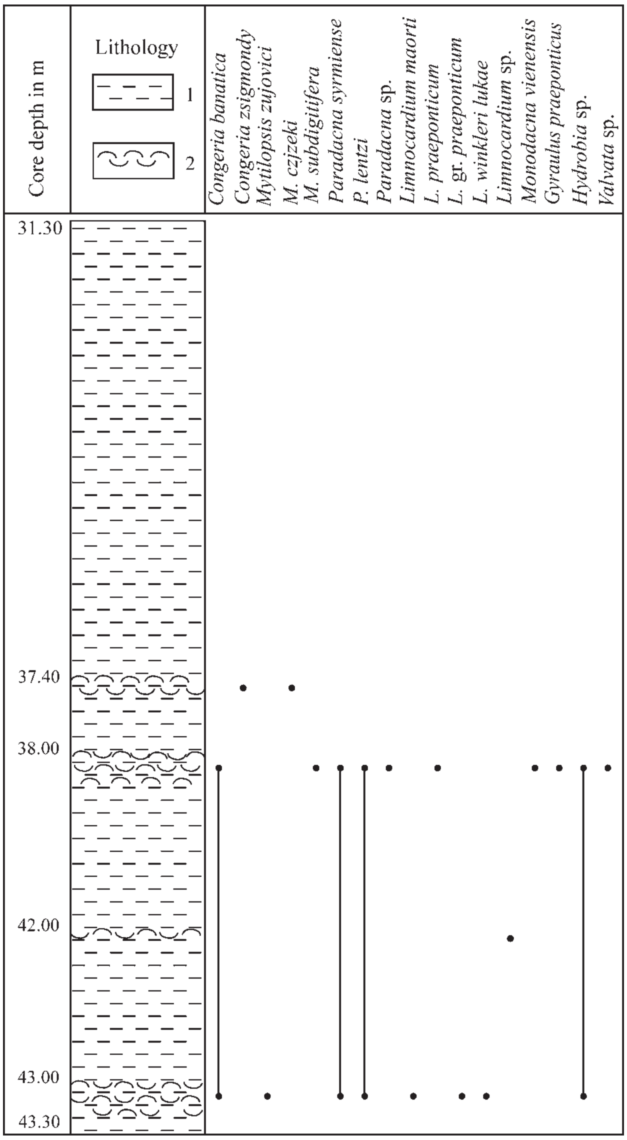

Fig. 5. PdUS-3 borehole section and distribution of the mollusc fauna. **1** — marls, **2** — mollusc shells.

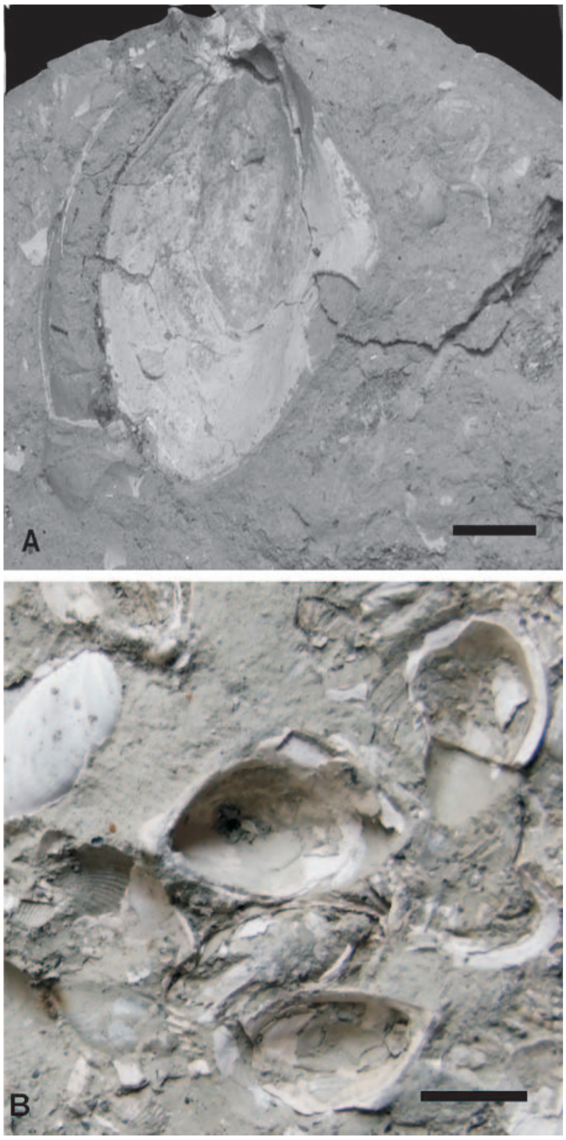

Fig. 6. Molluscs from the borehole PdUS-3: **A** — *Mytilopsis zujovici*, **B** — *Mytilopsis czjzeki.* Scale bar: 1 cm.

Pannonian sediments in the lower part of borehole PdUS–7 (Figs. 7, 8) start with *Undulotheca pancici* Brusina and *Mytilopsis* gr. *czjzeki* M. Hoernes. From the upper parts of this borehole, three marly samples were taken. The lowermost one, greyish blue marl contains abundant specimens of *Paradacna lenzi* (R. Hoernes), *Congeria banatica* (R. Hoernes), and *Mytilopsis czjzeki* M. Hoernes. The central part contains a small lens with *Paradacna cekusi* (Gorjanović-Kramberger), *Parvidacna laevicostata* Wenz, and *Gyraulus praeponticus* (Gorjanović-Kramberger) and finally, the uppermost one, silt and sandy silt has numerous *Paradacna syrmiense* (R. Hoernes) and *Paradacna cekusi* (Gorjanović-Kramberger). As opposed to borehole PdUS-3, it was noticed that the marker zone of the Middle Pannonian, *M. czjzeki–C. zsigmondyi* is missing here.

Biostratigraphically, the above-mentioned associations of molluscs correspond to the *M. czjzeki* Zone (Magyar et al. 1999). Moreover, this zone can be divided into two subzones: a) the lower, small limnocardids subzone with *Limnocardium* gr. *praeponticum*, *L. winkleri lukae*, *L. maorti*, *Paradacna lenzi*, etc. and b) the upper, *czjzeki–zsigmondyi* Subzone. According to the previous biozonation, the investigated Pannonian sediments from the Belgrade City area correspond to the zones B, C, D and the lowermost part of zone E (Papp 1953; Papp et al. 1985).

Ostracods

The current study of seven silty marl samples taken between 17.10 to 21.60 m of the upper part of the borehole ZV-3 made it possible to identify 34 species of ostracods (see position in Fig. 1). Core sediment shows minor evidence of taphonomic processes (e.g. bioturbations, pyrite occurrences). The ostracod association consists of, mainly, numerous candonids, including *Reticulocandona reticulata* (Méhes), *Zalanyiella rurica* Krstić, *Z. venustoidea* Krstić, *Z. buchii* Krstić, *Serbiella* cf. *bacevicae* Krstić, *S. maxiunguiculata* Krstić, *Turkmenella* sp., *Typhlocyprella* cf. *ankae* Krstić, *T.* cf. *lineocypriformis* Krstić, *Typhlocyprella* sp., *Fabaeformiscandona lineata* Krstić, *Camptocypria subpontica* Krstić, *C. praebalcanica* Krstić, *C. alasi alasi* Krstić, *Serbiella sagitosa* Krstić, *S. unguiculus* (Reuss). Most of them have a thin, more or less transparent, and elongated carapace (e.g. *Camptocypria*, *Typhlocyprella*, *Zalanyiella*, and *Serbiella*). Among cytherids, the genus *Cyprideis* is represented by three taxa (*C. longa* Krstić, *C. longitesta* Krstić, and *C.* cf. *brevis* Krstić) that dominate the assemblages. All the other species of ostracods make another important part of the Pannonian assemblages in these core samples. They are represented by large *Hungarocypris hierogliphica* (Méhes) — genus *Herpetocyprella* after Danielopol et al. (2007) as well as *Amplocypris major* Krstić, *Hemicytheria croatica* Sokač and *H. marginata* Sokač. Small forms of *Loxoconcha rhombovalis* Pokorny, *L. granifera* (Reuss), *L. fistulosa* Krstić, *L. subrugosa* Zalanyi, *Loxocorniculina hodonica* Pokorny, *Amnicythere naca* (Méhes), *A. lacunoidea* Krstić, *A. larga* Krstić, *A.* cf. *stanchavae* Krstić, *Cypria dorsoconcava* Krstić, *C.* cf. *siboviki* Krstić are present, too. Adult valves of the two large species *H. hierogliphica* and *A. major*

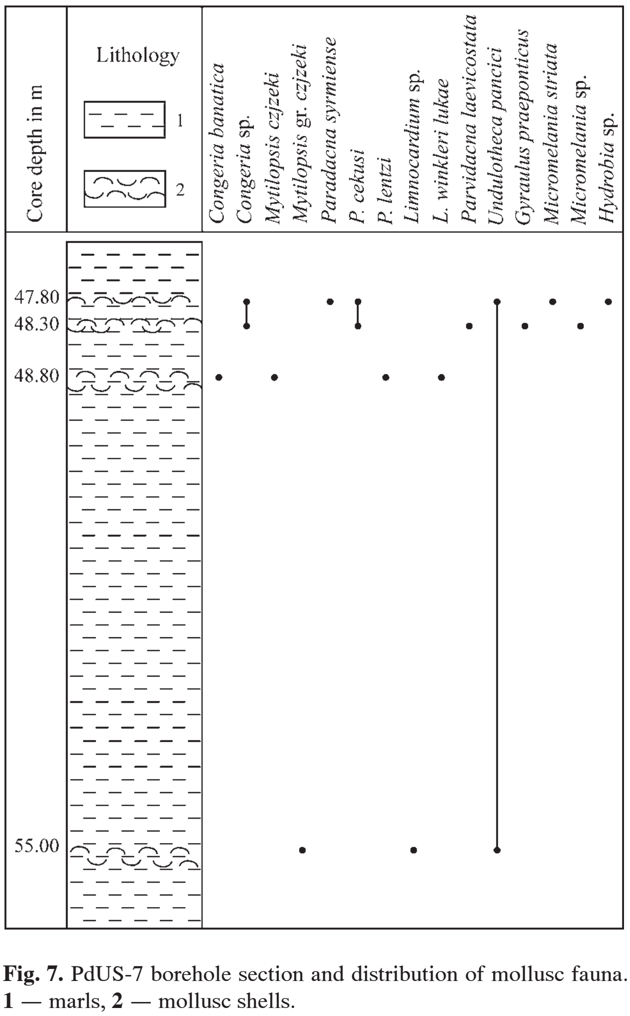

Fig. 7. PdUS-7 borehole section and distribution of mollusc fauna. **1** — marls, **2** — mollusc shells.

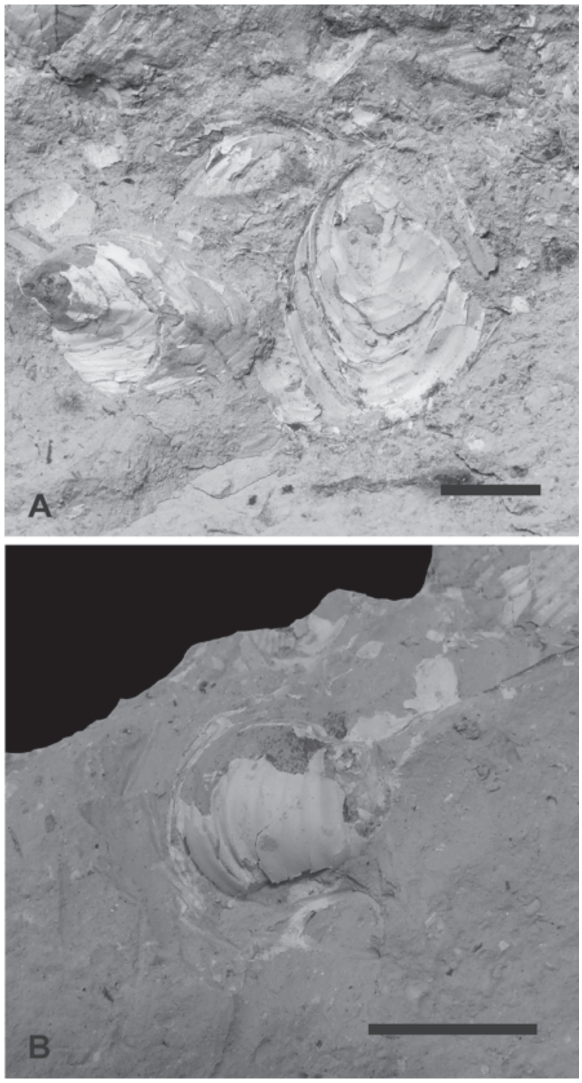

Fig. 8. Molluscs from the borehole PdUS-7: **A** — *Congeria banatica*, **B** — *Undulotheca pancici*. Scale bar: 1 cm.

are numerous and strongly calcified in the upper core samples. Different *Typhlocyprella* species are recorded in the uppermost sample. In general, preservation of valve/carapace is good. There are more adult specimens than juvenile ones. The above-mentioned candonids are the most diversified ostracod group and represent more than 50 % of the total number of species found. Biostratigraphically, the determined ostracods suggest the *Amplocypris abscissa* and *Hemicytheria croatica* Zones (Krstić, 1985) or older part of the Middle Pannonian (Serbian, *sensu* Stevanović 1985). Some of these Pannonian ostracods are shown in Fig. 9.

Dinoflagellates

The four investigated samples are very rich in dinoflagellate cysts, however, the diversity is low and the encountered assemblage is quite similar in all samples. *Spiniferites*, *Impagidinium*, and *Pyxidinopsis* were the dominant dinoflagellate cysts with considerable occurrences of heterotrophic taxa (e.g.

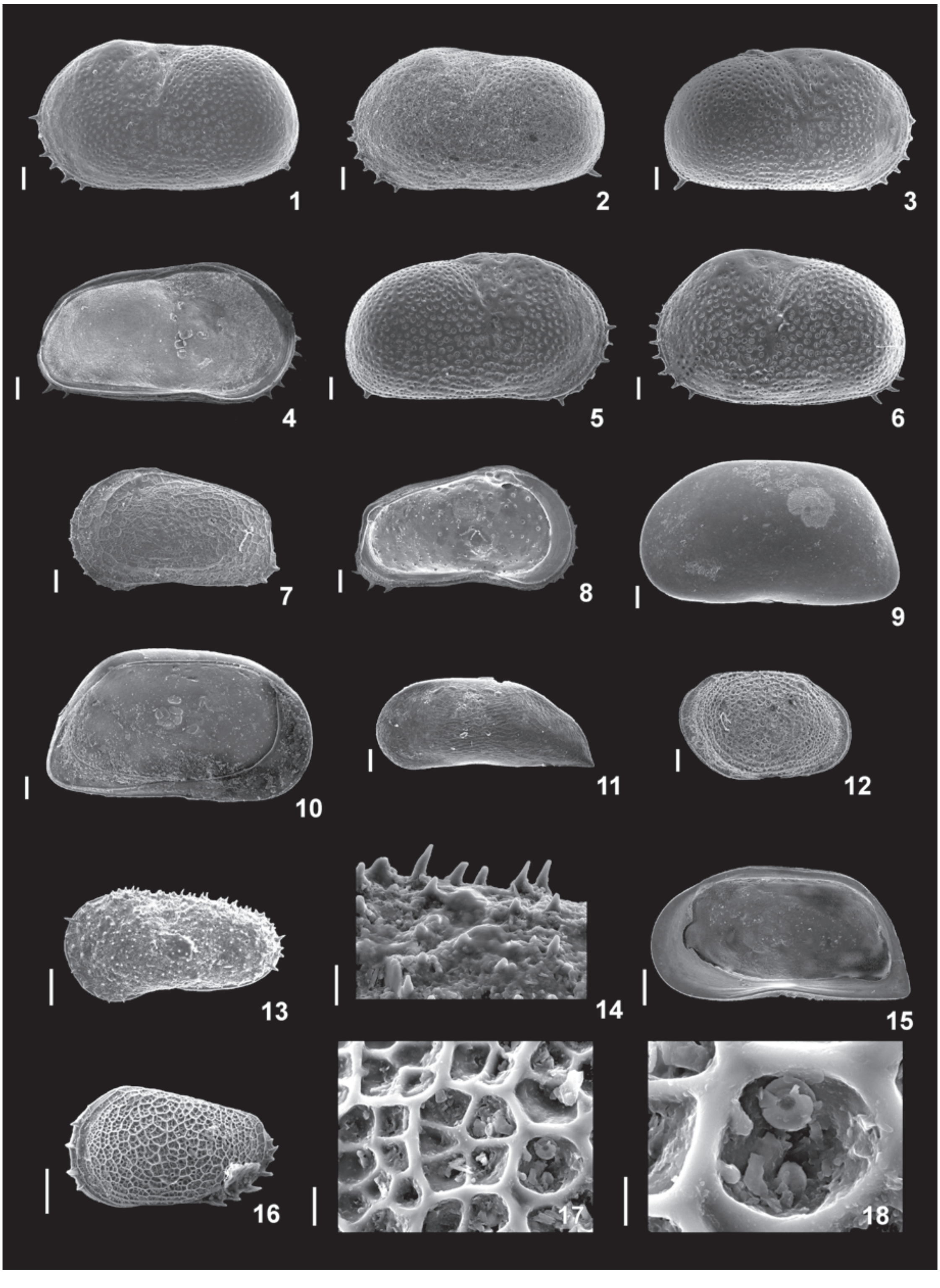

Fig. 9. Pannonian ostracods from the borehole ZV-3. Scale bar: Figs. 1–13, 16 — 100 μm; Fig. 14 — 20 μm; Figs. 15 — 200 μm; Fig. 17 — 10 μm and Fig. 18 — 5 μm. **RV** — right valve, **LV** — left valve. The depth of specimen is shown at the end of each explanation. **1–5** — *Cyprideis longa* Krstić, 1968; 1, 2 — LV, external view, 4 — LV, internal view/21.60 m; 3, 5 — RV, external view/20.60 m. **6** — *Cyprideis* cf. *brevis* Krstić, 1968; LV, external view/20.60 m. **7, 8** — *Hemicytheria marginata* Sokač, 1972; 7 — LV, external view and 8 — LV, internal view/20.60 m. **9, 10** — *Reticulocandona reticulata* (Méhes, 1908); 9 — LV, external view and, 10 — LV, internal view/20.10 m. **11** — *Serbiella* cf. *unguiculus* (Reuss, 1850); LV, external view/20.60 m. **12** — *Loxoconcha rhombovalis* Pokorny, 1952; RV, external view/21.60 m. **13, 14** — *Amnicythere naca* (Méhes, 1908); 13 — LV, external view and 14 — Detail of surface spines/20.60 m. **15** — *Amplocypris* cf. *abscissa* (Reuss, 1850); RV, internal view/17.50 m. **16–18** — *Loxoconcha granifera* (Reuss, 1850), /20.60 m; 16 — LV, external view, 17 — Detail of reticulated ornamentation and 18 — The single fossae infilled by nannoplankton grain.

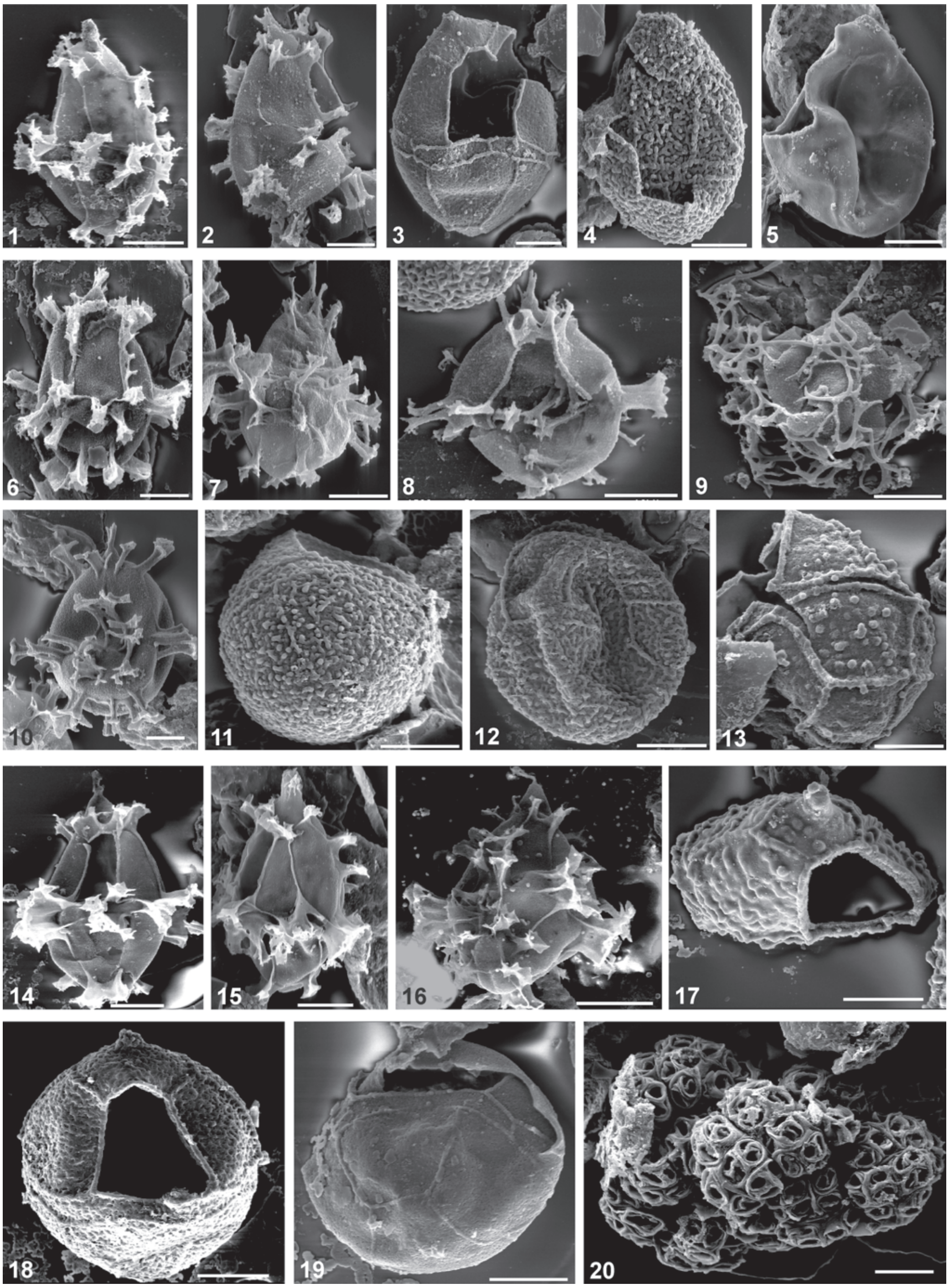

Fig. 10. Pannonian dinoflagellates from the borehole ZV-3. All microphotographs are from the borehole ZV-3 (depth 20.60 m). The scale is 20 μm. **1, 2, 8** — *Spiniferites bentorii* subsp. *pannonicus* Sütőné Szentai, 1986; right-lateral view. 2 — *Spiniferites bentorii* subsp. *pannonicus* Sütőné Szentai, 1986; left-lateral view, note the weak parastures. **3** — *Impagidinium sphaericum* (Wall) Lentin & Williams, 1981; dorsal view, a specimen with fine surface ornamentation. **4** — *Impagidinium* sp.; later view, note the coarse reticulate surface. **5** — *Pyxidinopsis psilata* (Wall & Dale) Head, 1994; lateral view. **6** — *Spiniferites* sp.; dorsal view, a specimen with robust processes. **7** — *Spiniferites bentorii* subsp. *budajenoensis* Sütő-Szentai, 1986; ventral view. **8** — *Spiniferites bentorii* subsp. *pannonicus* Sütőné Szentai, 1986; dorsal view. **9** — *Nematosphaeropsis* sp., uncertain orientation. **10** — *Achomosphaera argesensis* Demetrescu, 1989; ventral view. **11** — *Impagidinium* sp.; oblique antapical view. **12** — *Impagidinium spongianum* Sütő-Szentai, 1985; crumpled specimen in ventral view. **13** — *Impagidinium* sp.; oblique antapical view, note the coarse gammae on the surface. **14** — *Spiniferites tengelicensis* Sütő-Szentai, 1982; dorsal view. **15** — *Spiniferites bentorii* subsp. *oblongus* Sütőné Szentai, 1986; dorsal view. **16** — *Spiniferites bentorii* subsp. *oblongus* Sütőné Szentai, 1986; ventral view. **17** — *Impagidinium* sp.; apical view, note the prominent apical boss. **18** — *Impagidinium sphaericum* (Wall) Lentin & Williams, 1981; dorsal view, a specimen with coarse surface ornamentation and apical boss. **19** — *Impagidinium sphaericum* (Wall) Lentin & Williams, 1981; oblique antapical view, a specimen with a smooth surface. **20** — *Botryococcus* colony.

Selenopemphix spp. and "small brown round cysts" (*Brigantedinium* spp.)), *Achomosphaera* spp., *Protoperidinium* sp., *Nematosphaeropsis* sp., and *Komewuia* sp. (see Appendix). Sporadic occurrences of the freshwater green algae, *Pediastrum*, *Botryococcus* and fungal spores are recorded. On the other hand, saccate and non-saccate pollen were common but no attempt has been made to identify them. No marker taxa for the Upper Miocene similar to those contemporaneously recovered from the circum-Mediterranean and other regions have been recorded. This could go back to the Upper Miocene (Pannonian), however, the Central Paratethys is highly endemic in both fauna and flora and there was no seaway connection with the adjacent basins (Magyar et al. 1999; Piller et al. 2007; Harzhauser & Mandic 2008). The encountered assemblage is quite similar to the recorded dinoflagellate cyst assemblages from many sections and drill-holes in Hungary (e.g. Sütőné-Szentai 2000), and the Vienna Basin (Harzhauser et al. 2008). Thus, a Early Pannonian age could be suggested for the investigated samples (Fig. 10). Additionally, the absence of *Spiniferites paradoxus* could confirm the suggested age (Magyar et al. 1999).

Discussion

The whole area near the Sava–Danube confluence represents the marginal zone between two different geographical and morphostructural entities: 1) The Great Pannonian Plain that is located on the left bank of the Sava River and, 2) the Balkan Peninsula terrain on the right bank of the Sava River (Marović & Knežević 1985). It is generally accepted that the structural setting and morphological features of the investigated area were consequences of younger phases of Alpine tectogenesis (the so-called Rodanian and the Vlaška phases, Marović & Knežević 1985). Radial deformations (faults and differential fault block movements) were more significant than the plicative structures. As a result, during the Pliocene and Pleistocene, a great area of relatively depressed blocks was established in the Pannonian Plain, opposite relatively elevated terrains with more morphostructural forms — the Šumadija Hills (Marović et al. 2002). The studied area belongs to the complex horst of the Vardar Zone with a SSE–NNW direction (Marović et al. 2007). On the eastern and western sides of this structure, there are two graben-like structures, which are recognized as subsiding zones during the Miocene: 1) the Velika Morava Graben in the east and 2) the Kolubara-Tamnava Graben in the west (Marović & Knežević 1985; Marović et al. 2007). This very complex structure was separated by faults into numerous local grabens and small horsts during its evolution through the Miocene. Uplifted horst structures were affected by erosion (Marović et al. 2002).

During the Pannonian age, the water level of Lake Pannon increased due to regional isolation and the Belgrade City area was a zone of maximal flooding (Magyar et al. 1999). According to the new interpretations, the early stage of Lake Pannon (ca. 11.6 Ma) was still influenced by the latest Middle Miocene dry climate (e.g. Harzhauser et al. 2004). This phase coincided with a pronounced radiation of melanopsid gastropods (Magyar et al. 1999; Harzhauser & Mandic 2008). During the warm early Late Miocene (ca. 10 Ma) humidity increased and culminated in a phase with high summer precipitation (Bruch et al. 2007; Utescher et al. 2007). This caused a reorganization of the coastal-deltaic faunas, suppressing the radiation of melanopsids (Harzhauser & Mandic 2008). On the other hand, high nutrient loads favoured the dispersion of filter-feeding dreissenids (Harzhauser et al. 2007; Harzhauser & Mandic 2010). Despite continually declining salinity, Lake Pannon remained an alkaline lake (Harzhauser et al. 2007). Similar sedimentological data from the Kolubara Basin (ph and Eh values) indicate a slightly alkaline environment (Rundić 2006).

More than 60 mollusc species from the different Pannonian levels inside the Belgrade City's centre have been recorded by our study and previously published data. According to the overall biostratigraphical range of the investigated species as well as comparison with the magnetostratigraphic data (Magyar et al. 1999, 2007), the total estimated time span for all the investigated samples from 9.8 to 11.4 Ma includes the Early and Middle Pannonian ("Serbian"). Small limnocardids (*Paradacna cekusi*, *Parvidacna laevicostata*, *Limnocardium praeponticum*) and snails (*Radix croatica* and *Gyraulus* cf. *praeponticus*) form the basis of the Early Pannonian molluscs (Magyar et al. 2007). They were found in the marly limestone and marl (borehole B-1). The occurrence of limestone suggests a shallow lake environment without considerable influence of the land area whilst marl was deposited from suspension in a sublittoral zone. The appearance of numerous pulmonate gastropods and small limnocardids, which live on water grasses as epibionts, suggest a high degree of aeration and desalinization of the lake. This association have a very high endemicity (>86 %, Harzhauser & Mandic 2004). It is correlative with the evolution, species number and the size of gastropod shells within the Lake Pannon Phase I (Harzhauser & Mandic 2008). Stevanović (1957) gave the evolution of the small limnocardids (recently accepted as a separate genus *Lymnocardium*) and concluded that they originated from the Sarmatian cardids (genus *Cerastoderma*). Later, Vrsaljko (1999) showed their phylogenetic lineage based on the number and type of ribs (however, Mandic et al. (2008) assigned these forms as endemic genera, such as *Obsoletiforma*, *Plicatiforma*, etc.). According to Stevanović (1977), occurrence of *Mytilopsis zujovici*, *Limnocardium lukae* and *Radix croatica* indicate a sublittoral lake deposition of water depth between 15 and 80 meters. Similarly, Tarasov (1997) estimated the lower limit of the sublittoral zone in the Caspian Sea at 80–100 m. The presence of *Congeria banatica*, *Paradacna syrmiense*, *Paradacna lenzi* and *Undulotheca pancici*, as well as *Gyraulus praeponticus* can suggest a quiet and stable regime in generally sublittoral condition. Additionally, absence of prevailing orientation of shells excludes a dynamic water system. Similar salinity conditions were reported by Korpás-Hódi (1983) who designated the Late Miocene assemblage with *Mytilopsis czjzeki–Paradacna abichi* as pliohaline environment (9–16 ‰).

Relatively diversified and abundant ostracods correspond to the Middle Pannonian — Serbian (Krstić 1972, 1973; Rundić 1998, 2006). This period was assigned as the "bloom time" for many ostracods, both in terms of diversity and abundance. It corresponds to the first appearance of some genera such as *Zalanyiella*, *Camptocypria*, *Sinegubiella*, etc. (Krstić 1985; Rundić 2006) which radiated during the Late Pannonian. Ostracods might settle the environment of high nutrient productivity (e.g. estuaries along the southern Baltic Sea coast, Frenzel & Boomer 2005). The elongated forms of candonids with thin carapace can indicate quiet and relatively stable water conditions (Rundić 2006). The brackish species (*Hemicytheria*, *Loxoconcha*) as well as more freshwater and river-marsh genera with a strong massive carapace (*Herpetocyprella*, *Amplocypris*) also suggest a mesohaline, infralittoral/sublittoral environment (Rundić 2002). According to Meisch (2000), the recent *Cyprideis torosa* (Jones, 1850) suggests a wide range of salinities, from 2–16.5 ‰. It is a typical euryhaline species (Boomer & Eisenhauer 2002; Rostovtseva & Tesakova 2009). Similar observations and discussion about environmental changes and diversification of Late Miocene *Cyprideis* from the Lower Pannonian of the Styrian Basin have been reported by Gross (2008) and Gross et al. (2008). Analogous forms of *Amnicythere* species are living in the sublittoral zones of the Black Sea and the Caspian Sea in brackish environments as well as in more freshwater bays (Cziczer et al. 2009). Similar to this, recent *Cypria* species are generally freshwater forms but can tolerate mesohaline conditions (Meisch 2000; Starek et al. 2010). There is other evidence that confirms this model (see the occurrence of different molluscs). There are no ostracod species that would indicate an oligohaline environment, such as *Ilyocypris*, *Cyprinotus*, and *Vestalenulla* (Gross 2008) which are well known in the Late Pannonian from other parts of the southern margin of the Pannonian Basin (Sokač 1972; Krstić 1972; Rundić 2006).

The development of the flora within the lake was controlled by its (bio)geographic restriction as well as by the gradual freshening of the water body (Harzhauser et al. 2007). These environmental conditions led to the evolution of endemic species of gonyaulacoid dinoflagellate cysts, such as *Spiniferites* and *Impagidinium*. Both are well recorded in the Upper Badenian (Jiménez-Moreno et al. 2006), however, they exhibit a much higher morphological variability in the Pannonian. This variability has been used to introduce several endemic species/subspecies (e.g. Sütő-Szentai 1985). The dominance of *Spiniferites* and *Impagidinium* taxa with their characteristic/endemic morphotypes, characterized by the presence of a well-developed apical boss and variable surface ornamentation, could indicate a change in the water chemistry of the Pannon Lake (Harzhauser et al. 2007). In addition, the abundance of heterotrophic taxa, especially of *Selenopemphix* and "small round brown cysts" (cf. *Brigantedinium*), indicates nutrients-rich surface waters. Besides, the presence of *Pyxidinopsis psilata*, the green algae, *Pediastrum*, and *Botryococcus* indicates a freshwater input to the basin as well as a brackish water environment (Marret et al. 2007).

Conclusion

The investigated Pannonian sediments from the Belgrade City area represent a sublittoral environment of the early Lake Pannon (estimated time interval: 9.8–11.4 Ma). They are blue-grey, sandy and silty marls belonging to the *Limnocardium praeponticum* and *Mytilopsis czjzeki* mollusc Zones (Magyar et al. 1999) that correspond to the Lower Pannonian and the Middle Pannonian (Serbian, sensu Stevanović 1985). On the basis of the ostracod biozonation, the investigated sediments belong to the *Amplocypris abscissa* and *Hemicytheria croatica* Zones (Middle Pannonian). The endemic dinoflagellate associations suggest the Lower Pannonian.

All the analysed fossil assemblages indicate a mesohaline (8–16 ‰) sublittoral environment within Lake Pannon (< 90 m) that was very similar to the recent sublittoral zones of the Black Sea and the Caspian Sea. Most of the encountered species from studied boreholes and outcrops are considered endemic. Brackish cardids and dreissenids (species found here) are typical representatives of the sublittoral assemblages. Common findings of the basinal form *Congeria banatica* suggest a calm, stable water regime rather than a deeper, basinal influence. Among the ostracods, the dominant forms are candonids. Their diversity and the numerous presences in the uppermost parts of some boreholes (ZV-3) indicate a more stable brackish environment during the early phase of the maximum extent of Lake Pannon.

All the collected data suggest that the investigated Pannonian sediments of the Belgrade City area represent the older phase in the deposition of the long-lived Lake Pannon (parts of phases I and II, Harzhauser & Mandic 2008).

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Appendix

List of the identified dinoflagellate cysts (for taxonomic references see, Fensome et al. 2008)

Achomosphaera ramulifera (Deflandre) Evitt, 1963
Achomosphaera argesensis Demetrescu, 1989
Achomosphaera cf. *A. fenestra* Kirsch, 1991
Batiacasphaera hirsuta Stover, 1977
Impagidinium sphaericum (Wall) Lentin & Williams, 1981
Impagidinium spongianum Sütő-Szentai, 1985
Impagidinium spp.
Komewuia spp.
Lejeunecysta communis Biffi & Grignani, 1983
Nematosphaeropsis sp.
Pyxidinopsis psilata (Wall & Dale) Head, 1994
Selenopemphix brevispinosa Head, Norris & Mudie, 1989
Selenopemphix sp.
Selenopemphix nephroides Benedek emend. Bujak in Bujak et al., 1980
Spiniferites bentorii (Rossignol) Wall & Dale, 1970
Spiniferites bentorii subsp. *budajenoensis* Sütő-Szentai, 1986
Spiniferites bentorii subsp. *oblongus* Sütőné Szentai, 1986
Spiniferites bentorii subsp. *pannonicus* Sütőné Szentai, 1986
Spiniferites galeaformis Sütő-Szentai, 1994
Spiniferites tengelicensis Sütő-Szentai, 1982
Spiniferites virgulaeformis Sütő-Szentai, 1994