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Upper Miocene ostracods from the Krško Basin, SE Slovenia

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Abstract

The purpose of this study was to identify the ostracod assemblage from a 43 m thick section of the Bizeljsko Formation, which constitutes the middle part of the Upper Miocene Posavje Group. The succession comprises sandstone, siltstone, and marlstone, deposited in a delta front environment. The determined ostracods belong to the families Cyprididae, Cytheridae, Darwinulidae, and Loxoconchidae. In total, 30 species were identified. Additionally, 8 morphotypes were determined at the genus level. The most common genera are *Candona, Hemicytheria*, and *Cyprideis*. The assemblage belongs to the *Caspiocypris labiata* subzone from the upper Pannonian. The ostracod assemblage from the Krško Basin is similar in species composition to Pannonian ostracod assemblages from Croatia and Serbia.

1. INTRODUCTION

The Central Paratethys disintegrated towards the end of the middle Miocene, leaving in its wake the Late Miocene Lake Pannon (MAGYAR et al., 1999; PILLER et al., 2007). The brackish Lake Pannon lost its marine life, and the largely endemic ostracod and molluscan fauna of the lake is well-known from its fossil record. Research on the ostracod fauna is thus extremely important in determining the relative age, the palaeoecological conditions, and the palaeogeographic connections between individual sub-basins of Lake Pannon (KRSTIĆ, 1972, 1973; SOKAČ, 1981, 1989; JIŘIČEK & RIHA, 1991; RUNDIĆ, 1997; TER BORGH et al., 2013).

This paper presents the ostracod assemblage recovered from a 43 m thick succession of the Upper Miocene Bizeljsko Formation near the village of Bizeljsko, situated on the NE hilly rim of the Krško Basin in SE Slovenia (Figs. 1, 2). The succession is well exposed along a forest road, starting at coordinates Lat: 45°59'49.10'', Lon: 15°41'01.23'' (Figs. 3, 4).

The relative age of the studied section and palaeosalinity were determined, based on ostracods. Finally, the determined ostracod assemblage was compared to assemblages of the same age from the Paratethys area. Data presented here serve as an important contribution to the understanding of the distribution of ostracods in Lake Pannon as the last known scientific paper on Miocene ostracods from Slovenia was published in 1989 (STEVANOVIĆ & ŠKERLJ, 1989). A short

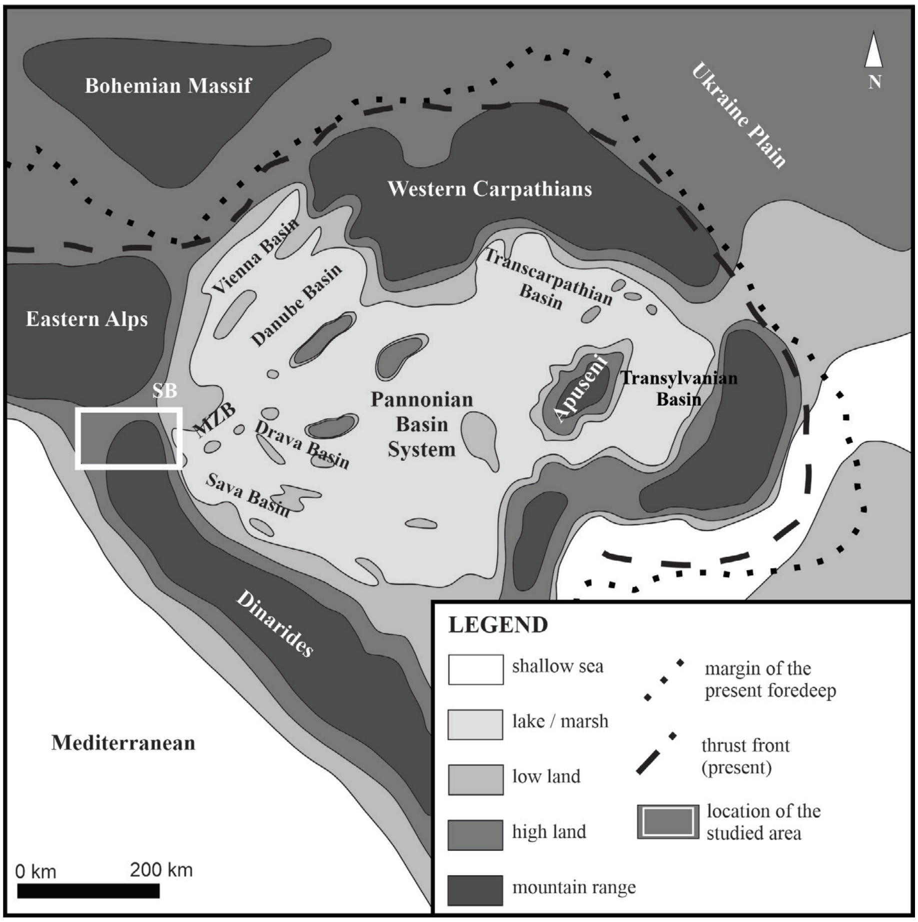

Figure 1. Palaeogeographic map of the Central Paratethys (Pannonian age) with the approximate location of Slovenia (SB: Styrian Basin; MZB: Mura-Zala Basin) modified after KOVAC et al., 2017).

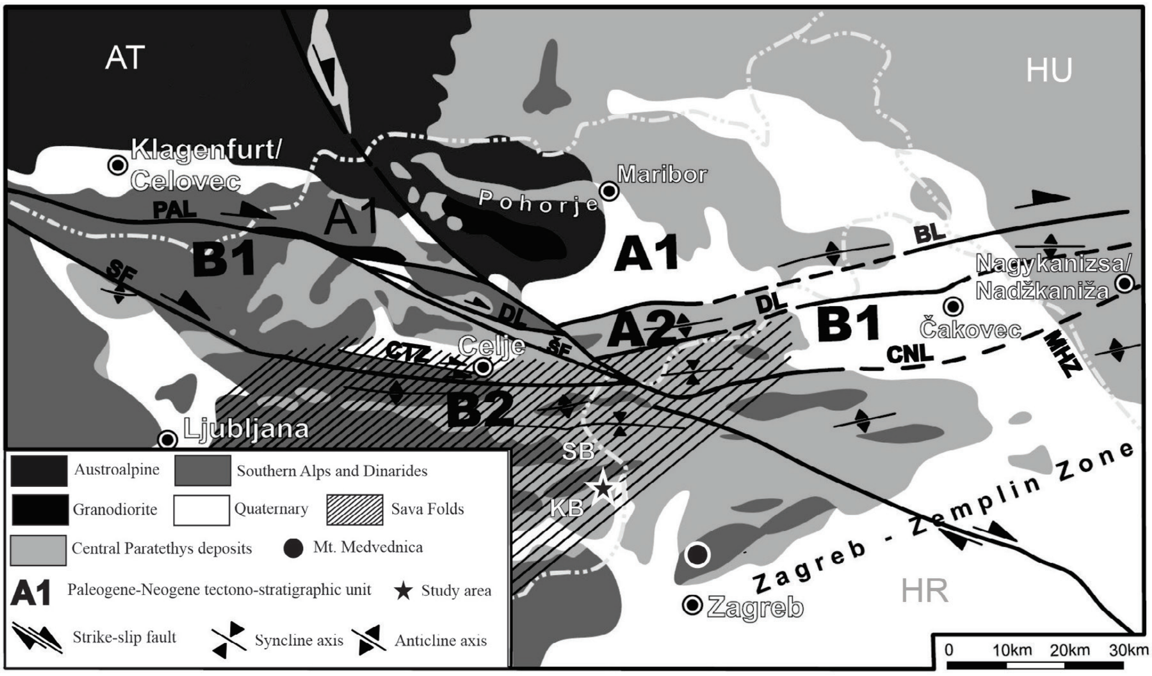

Figure 2. The present-day distribution of sediments and sedimentary rocks of the tectono-stratigraphic units of the Central Paratethys in eastern Slovenia. BL Balaton Line, CNL Celje-Nadžkaniža Line, CTZ Celje Tectonic Zone, DL Donat Line, MHZ Middle Hungarian Tectonic Zone, PAL Periadriatic Line, SF Sava Fault, ŠF, Šoštanj Fault, SB Senovo Basin, KB Krško Basin. For an explanation of the tectonostratigraphic units (A1, A2, B1, B2) see text. The star symbol marks the position of the sampled section. Modified after JELEN & RIFELJ (2002).

description of ostracods from the Krško Basin and the Bizeljsko section are given by VESEL-LUKIĆ (2012) and VESEL-LUKIĆ et al., (2013, 2014). There was also a Masters thesis done on the studied section by MARINŠEK (2020).

2. GEOLOGICAL AND STRATIGRAPHIC SETTING

Slovenia is located in the western part of Central Paratethys, where the Transtethyan corridor was theorised to be located in the Badenian (BARTOL, 2009). Sediments of the Central Paratethys in Slovenia are predominantly found in the eastern part of the country and extend westwards towards central Slovenia in a series of synclines that once formed interconnected basins (Fig. 2). The NE part of Slovenia was connected to the "Styrian" and Mura-Zala basins (JELEN & RIFELJ, 2002) and most of the SE part was connected to the North Croatian Basin (JELEN et al., 1992; PAVELIĆ, 2005). The structural development of eastern Slovenia resulted in four tectono-stratigraphic units (TTU) (JELEN et al., 1992). From north to south, these are: TTU A1, TTU A2, TTU B1, and TTU B2 (Fig. 2).

Unit A1 covers the area north of the Periadriatic fault zone, namely the Northern Karavanke, Pohorje, and the Pannonian Plain of northeastern Slovenia. Unit A2 is a narrow area between

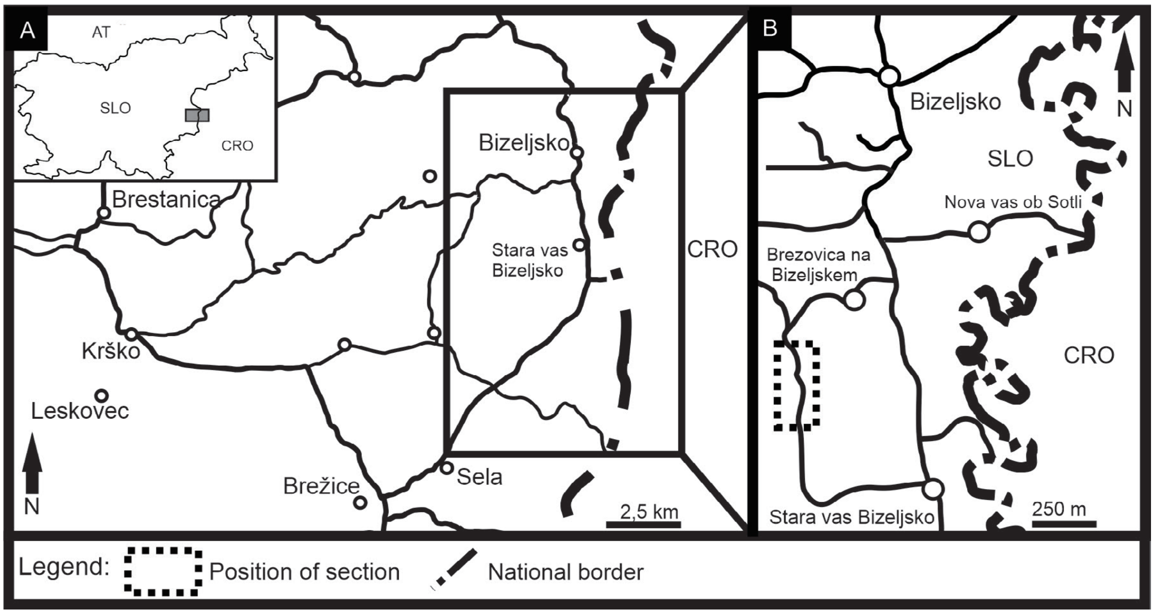

Figure 3. Position of the studied area. The exact position of the section is shown by a dashed rectangle in Figure 2B. The section starts at coordinates Lat: 45°59'49.10", Lon: 15°41'01.23".

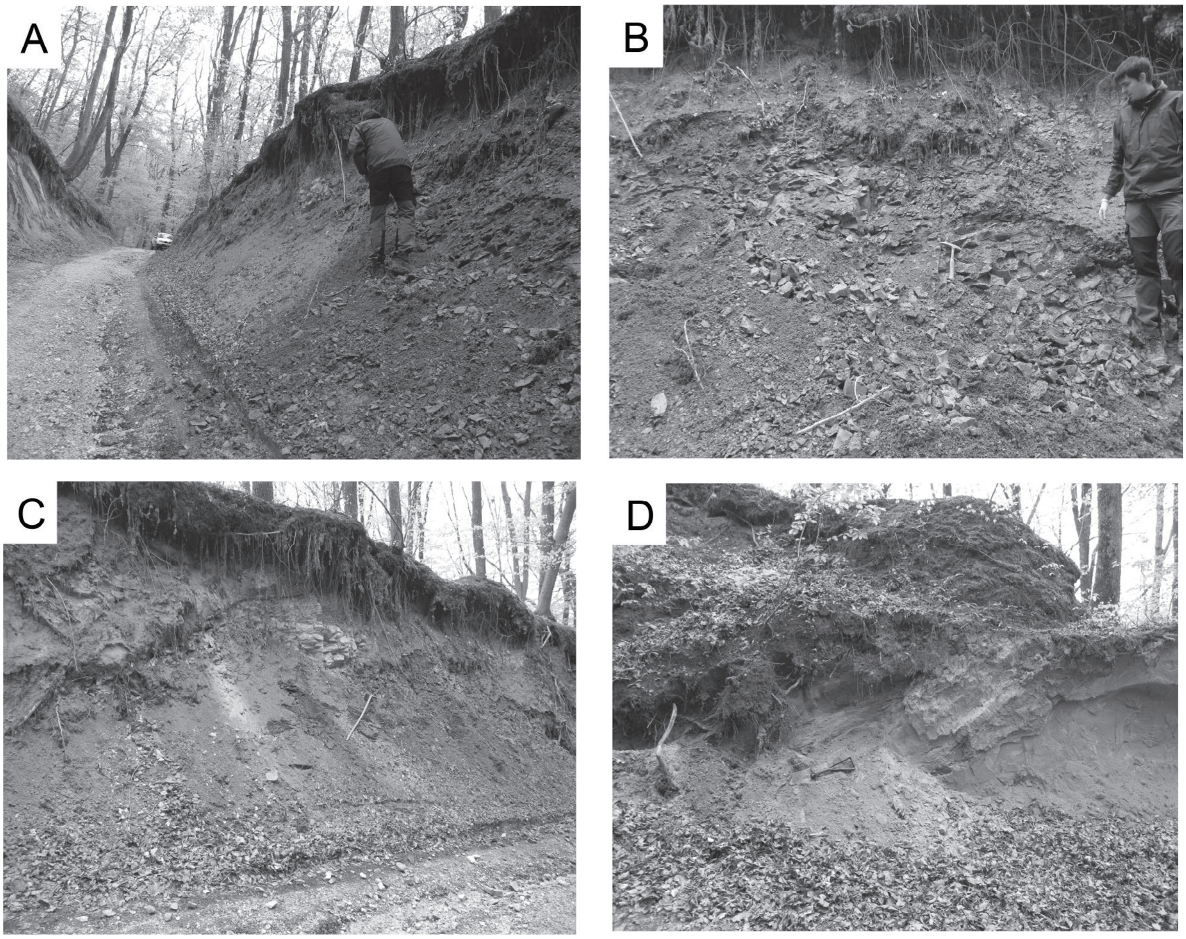

Figure 4. Field pictures of the studied section. A – bottom of the marl in the middle of the section (view towards the south).; B – a detailed picture of the marl section; C – transition from the marl to sand; D – sand section in the upper part of the outcrop (Author: Marina Vesel-Lukić, 2012)

the Periadriatic Fault Zone and the Don Tectonic Zone, which includes the Southern Karavanke and Haloze areas. Unit B1 stretches from the Julian Alps to the Sava Tectonic Zone and continues to the area of Varaždin in Croatia. Unit B2 covers the entire south-eastern part of Slovenia, including the Krško basin and thus also the area of Bizeljsko. After deposition of the Neogene sediments, the area underwent compression, resulting in the formation of the Sava Folds, a W-E extending series of antiforms and synforms (PLACER, 1999a). The general facies succession of the Miocene sediments in Slovenia is composed of alternating marl/marlstone, sand/sandstone with cobblestone, and in some places, there are beds of lignite (PLENIČAR, 1954; CIGIT, 1958; VONČINA, 1966; PLENIČAR, 1968; PREMRU & MARINČIĆ, 1971; KUŠČER, 1973; ARSOVSKI et al., 1975; MIOČ & ŽNIDARČIČ, 1978; KALOPER 1984; ANIČIĆ & JURIŠA 1985a, b; ŽNIDARČIČ & MIOČ, 1987; MARKOVIĆ & MIOČ, 1988; MIOČ & ŽNIDARČIČ, 1989; DJURASEK, 1995; PLACER, 1999b; ŠRAM et al., 2015). In Slovenia, the evolution of Lake Pannon is best recorded in the Krško and Senovo basins (Fig. 2). Panonnian calcareous marls conformably overlie Sarmatian beds; which are overlain by "ostracod marls". In some parts of the Krško Basin the Pannonian lies unconformably on the Sarmatian beds (POLJAK et al., 2016) The Pannonian succession ends with quartz sand and marly-clayey intercalations with lignite on top. The entire Neogene succession can be interpreted as a transition from marine to brackish and finally freshwater conditions (PAVŠIČ & HORVAT, 2009; IVANČIČ, 2021). Important fossil groups that have been investigated in the Upper Miocene sediments of eastern Slovenia are ostracods (PIERAU, 1958; SOKAČ, 1981; STEVANOVIĆ & ŠKERLJ, 1985, 1989; HAJEK-TADESSE, 2007; VESEL-LUKIĆ, 2012; VESEL-LUKIĆ et al., 2013, 2014; MARINŠEK, 2020), and molluscs (MIKUŽ, 2005, 2014; MIKUŽ et al., 2015).

The Bizeljsko area corresponds to the northern limb of the Krško synclinorium and is a part of the B2 TTU (PLACER, 1999a, b; POLJAK, 2017). The geological maps of the study area were produced by ANIČIĆ & JURIŠA (1985a, b), and more recently by POLJAK et al. (2017). A simplified geological map is shown in Figure 5. The stratigraphic succession in the study area is summarized after POLJAK (2017) (Fig. 6). The oldest deposits of the Central Paratethys in the research area belong to the Badenian–Sarmatian Laško Formation. It comprises shallow marine coralline algal-rich limestone, the "Lithothamnium limestone", and the deeper marine "Laško marl". The Laško Formation is, after another prominent unconformity, followed by marls and sands of the deltaic Pannonian Drnovo Formation, which in its upper part passes into the Bizeljsko Formation. The latter comprises quartz sand, marl, and subordinate sandstone and gravel, deposited within a delta front environment. The uppermost Pannonian Raka Formation almost entirely consists of quartz sand, which was also deposited in a deltaic environment. The Drnovo, Bizeljsko, and Raka Formations together comprise the Posavje Group, which represents the final remnants of the Central Paratethys. The youngest sediments in the area are represented by Quaternary gravel (POLJAK, 2017).

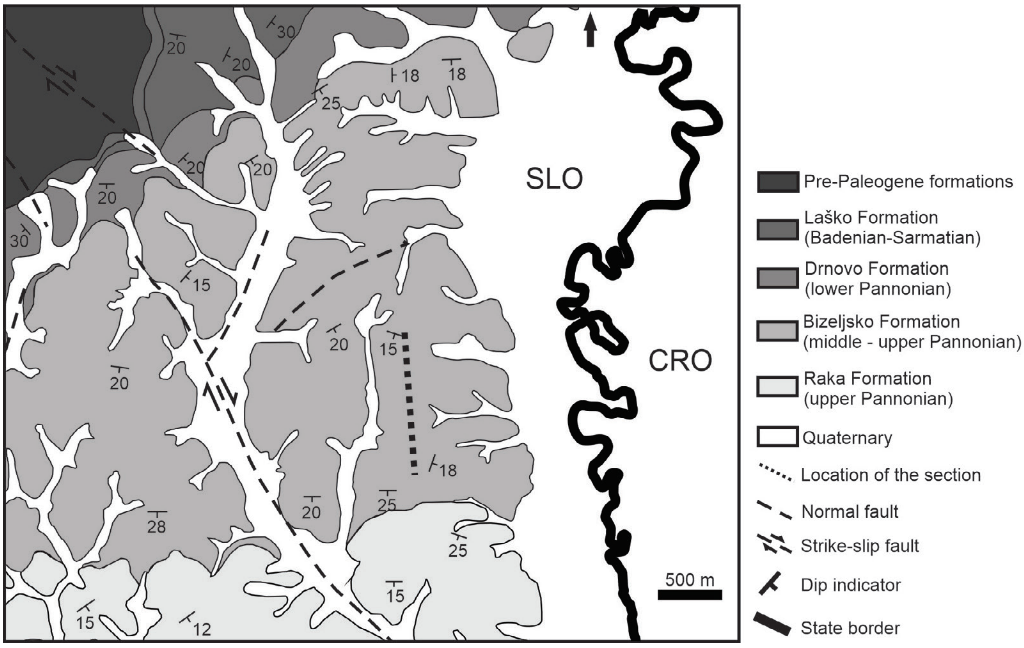

Figure 5. A simplified geological map by POLJAK et al. 2017, slightly modified.

The Bizeljsko Formation is best exposed in the eastern Krško Basin, especially in the Bizeljsko area. The formation was defined by POLJAK (2017). It was previously also researched by LAPAJNE (1976), ŠIKIĆ et al. (1979), SKABERNE (1990), ŠKERLJ (1990), TRAJANOVA (2006), HAJEK-TADESSE (2007), VESEL-LUKIĆ et al. (2013, 2014); MARINŠEK (2020) and POLJAK (2017). The formation consists mainly of marls and sands, which alternate over short distances. Beds of sand locally show traces of slumping and/or contain rip-up clasts of marl. It reaches its thickest point (up to 800 m) in the wider Bizeljsko area. The age was first determined based on bivalves (*Congeria croatica*, *C. rhomboidea*, *C. zagrabiensis*, *Lymnocardium majeri*, *L. riegeli, Paradacna abichi* and *Paradacna okrugici*, as well as ostracods (ŠIKIĆ et al., 1979; HAJEK-TADESSE, 2007; POLJAK, 2017). POLJAK (2017) interpreted the succession as a delta front deposit based on individual layers of sand showing signs of synsedimentary slumping with frequent layers containing rip-up marl clasts. It represents the part of the Lake Pannon evolution where it began to shrink and transitioned locally from brackish to freshwater conditions. The Bizeljsko Formation is completely missing in the western part of the Krško Basin. Instead, the upper Pannonian deposits are represented there by a much thinner succession of marls and sandy marls of the Drnovo Formation (POLJAK, 2017).

3. MATERIAL AND METHODS

The section of the Bizeljsko Formation was logged and sampled with a total stratigraphic length of 43 m (Fig. 7). In total, 38 samples were collected and subsequently processed in the laboratory. Individual samples weighed between 1 and 2 kg. Each sample was quartered to a weight of 250g – 500g. Samples were dissolved in a 5% hydrogen peroxide solution; samples that contained a large number of ostracod valves filled with sediment were put in an ultrasonic bath for 30 seconds. The dissolved material was then wet sieved using mesh sizes of 0.500 mm, 0.250 mm, 0.125 mm, and 0.063 mm. The specimens were hand-picked under a ZEISS Stemi 2000-C binocular magnifier with a magnification of × 50. Approximately 100 adult ostracod valves were collected from each sample. Picking was nonselective to preserve the original proportions of the species within the assemblage. This was done by collecting valves either until we reached 100 valves or until the sample was looked through fully. Selected specimens were photographed on the JEOL JSM 6490LV scanning electron microscope at the Geological Survey of Slovenia. For determining the families of ostracods, the suprageneric classification scheme proposed by MOORE (1961) and HORNE et al. (2002) was used, as they are widely used classification schemes for ostracods. Samples are stored at the Geological Survey of Slovenia under field numbers GeoZS B-019 – B-057. The diversity was calculated using the Shannon-Wiener index (H) for each sample (SHANNON & WEAVER, 1949).

4. RESULTS

The total stratigraphic thickness of the section is 43 m (Fig. 7). A thin gravel layer at the base of the section is overlain by alternating sands and marls in 3 m thickness, with each sand and marl layer being approximately 20 to 30 cm thick (with a 1-meter-thick unlogged interval). The following 8-metre-thick sand has a sharp erosional base and clay intraclasts at the bottom part. The sand grades upward into marl, again overlain by a 10-metre-thick, dominantly sandy unit with an erosional base at 13 m. This unit contains thin clay and marl layers and even pebbly intervals at 17 m and between 20 and 21 m (Fig. 7). The sand is overlain by a 7-metre-thick clay with sand intercalations. The top of the clay is eroded by a channel sandstone at 30 metres, with pebbles above the erosion surface. This sandstone is 7 metres thick and contains a few thin marl layers. Marl predominates in the uppermost 6 m of the outcrop (Fig. 7). A total of 30 ostracod species were determined (Figs. 8-10 + Supplement 1). In addition, 8 morphotypes were determined to the genus level. Approximately 70 % of the collected valves were intact, and the rest were fragmented. Only adult specimens were included in the palaeontological determination. Diversity is strongly controlled by lithology: higher in marlstone, and lower in more sandy facies and claystone. The maximum value of diversity is 2.29 in sample B-024 at the 4 metre point of the section (taken from clay lithoclasts), but on aver-

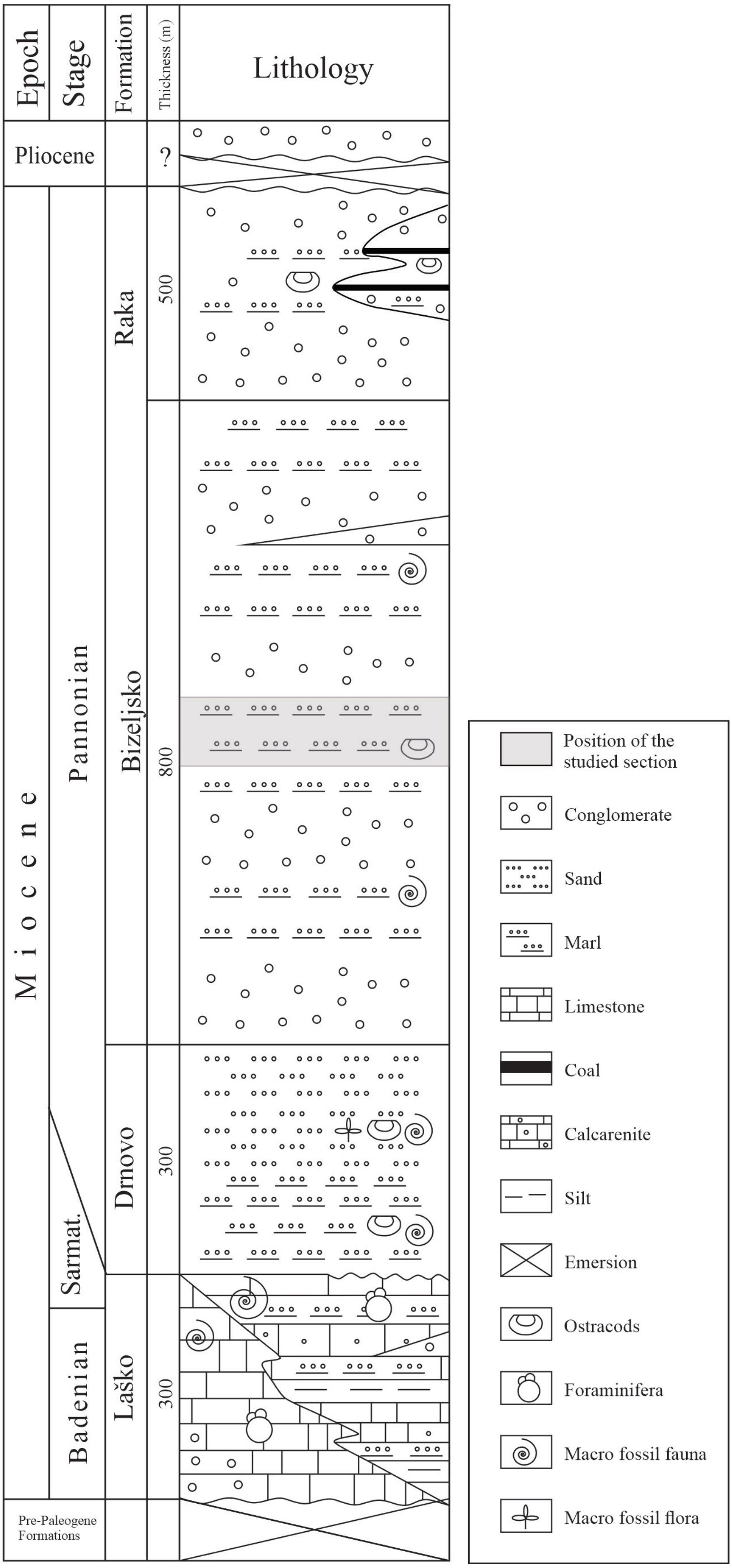

Figure 6. A general stratigraphic column of the Miocene deposits within the Krško Basin (Modified after POLJAK et al., 2017).

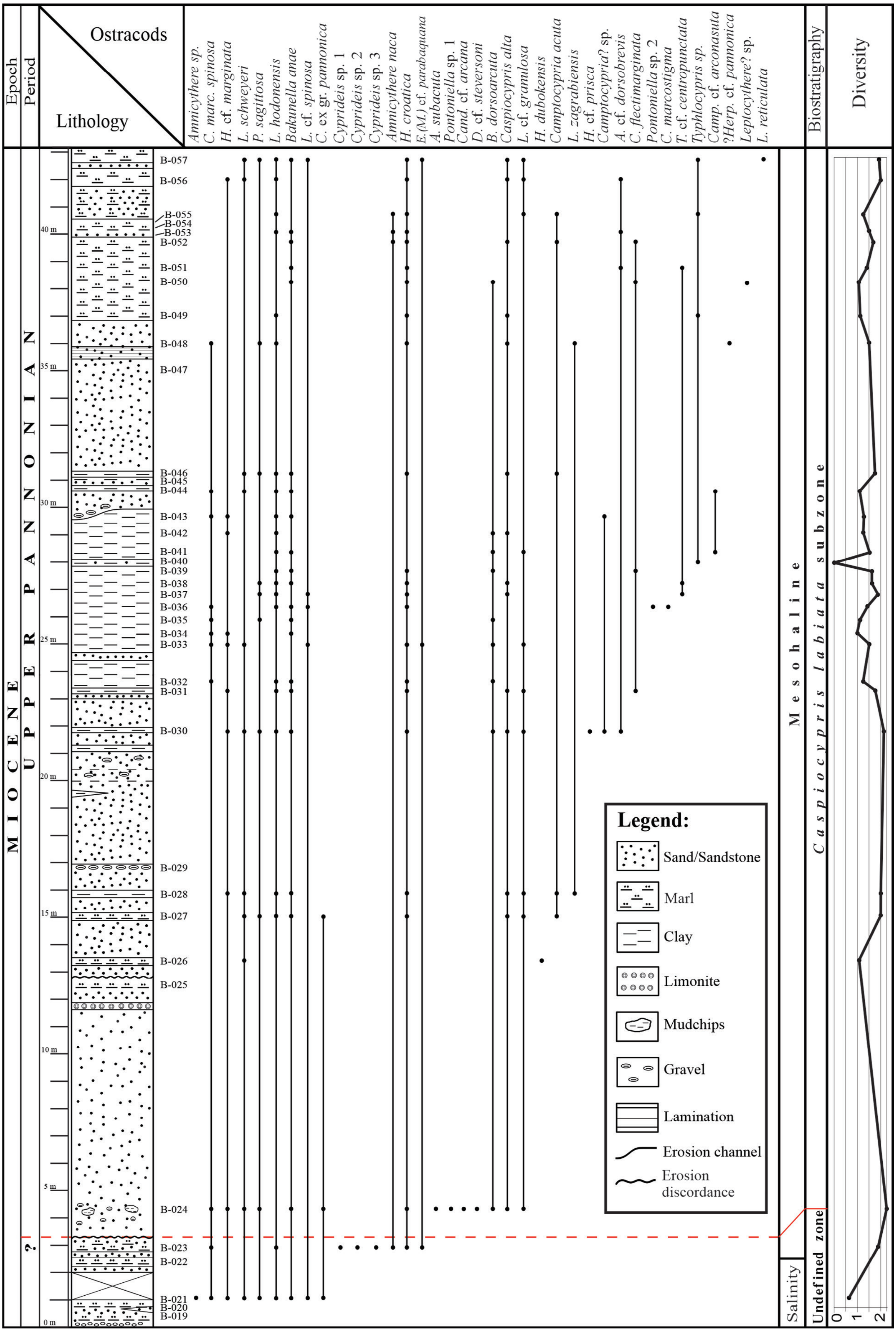

Figure 7. Sedimentary log and stratigraphic distribution of ostracod species in the section. The "diversity" column shows values of the Shannon-Wiener index as a measure of species richness and evenness.

age the Shannon-Wiener diversity index values are between 1.0 and 1.5 (Fig. 7).

The most abundant specimens are from the genera *Cyprideis* and *Hemicytheria*. *Loxoconcha* is present in most of the section but represents only a small percentage of the total assemblage.

Of the species observed here, the most important ones for determining the age were: *Amplocypris dorsobrevis* SOKAČ, *Caspiocypris alta* (ZALÁNYI) and *Camptocypria* aff. *acronasuta* (LIVENTAL).

5. DISCUSSION

5.1. Depositional environment

The studied section begins with sandy facies which suggests a higher energy environment. Indicators for this are mud chips and interbedded gravel. The environment changes at 22 metres from the beginning of the succession where we see a thick sequence of clay with thin layers of sand. At the 30 metre mark, the facies change again, with a rise in energy with an erosional channel in the clay, in which sand was deposited. The section ends with a lower energy environment indicated by marl deposition. These shifts in diversity and lithological changes correspond to rapidly changing conditions and lateral migration of the delta (DALRYMPLE et al., 1992).

The ostracod genera *Cyprideis, Hemicytheria, Leptocythere* and *Loxoconcha* in the lowermost sand layer (0-2 m) indicate brackish conditions. Ostracod diversity is low in this sandy part. Moving upwards through the succession the ostracod diversity fluctuates significantly. Diversity is highest in the marl-dominated part of the section, which can be explained by low-energy sedimentation and the reduced influence of fresh water. The diversity of the ostracod community reaches its highest value in sample B-024, which was taken from clay lithoclasts (Fig. 6). The species *Cyprideis* ex. gr. *pannonica* from that sample is considered by the authors to be reworked from older beds. Further along the section, the diversity of the ostracod assemblage decreases drastically. The low values of diversity between samples B-035 and B-043 are due to the sudden intake of sand. The presence of *Cyprideis, Hemicytheria,* and *Loxoconcha* indicates that beds from the upper part of the sequence were deposited under brackish conditions.

Previous research of the Bizeljsko Formation suggested deposition in a delta-front environment (POLJAK, 2017), and this interpretation is accepted here. It is to be noted that POLJAK (2017) does not describe any progradation and/or cyclic deposition, which would be typical for deltaic deposition as described and studied in SZTANÓ et al. (2016), SEBE et al. (2020) and ŠPELIĆ et al. (2023). This studied outcrop is too short to log any cyclic deposition apart from alternating marl and sand. According to HAJEK-TADESSE (2007), the composition of the ostracod community of the Bizeljsko profile, the preservation and abundance of ostracod shells depend on the change in the salinity of the lake water and the sedimentation. In general, the same author (HAJEK-TADESSE, 2007) concluded that several changes in lake water salinity and ostracod fauna can be distinguished on the Bizeljsko profile. At the beginning of the late Pannonian, water salinity increases to mesohaline values, while in the uppermost samples of the late Pannonian, the ostracod fauna of the Bizeljsko profile takes on a more freshwater character and indicates deposition near fresh-water input and a near-shore environment as stated in POLJAK (2017). We agree with the paleoenvironmental interpretation of both HAJEK-TADESSE (2007) and POLJAK (2017).

5.2. Biostratigraphy

There are quite a few ostracod biostratigraphic zonal schemes available for the Pannonian stage (e.g., POKORNÝ, 1944; BRESTENSKÁ, 1961; KRSTIĆ, 1973, 1985; JIŘIČEK, 1975, 1985; SOKAČ 1972, 1989; JIŘIČEK & RIHA 1991; and RUNDIĆ, 1998, 2006). According to OLTEANU (2011), the ostracod assemblages are well-differentiated only between two units, the Lower Pannonian and the »Portaferrian« (with *Congeria rhomboidea*), and most of the known species cannot be considered reliable index fossils. The same author concludes that the biostratigraphy of the brackish-water facies, generally and especially of the Pannonian Basin, is also difficult to dtermine. A similar view was expressed by KOVÁCS et al. (2016). The same authors conclude that different ostracod biostratigraphic schemes have been erected in different parts of the Pannonian Basin System, but they usually reflect local characteristics and differ significantly from each other.

The four most commonly used schemes for biozonation are presented in Fig. 8. Here, the biozonation by SOKAČ (1989) was used. The great majority of the investigated section can be placed within the *Caspiocypris labiata* subzone (Fig. 8), which is the oldest subzone in the Upper Pannonian (previously known as upper Pontian) *Bakunella dorsoarcuta* zone (SOKAČ, 1972; KRSTIĆ 1973; SOKAČ, 1989). The subzone is defined by *Caspiocypris labiata* (Zalányi), *Caspiocypris alta* (Zalányi) and C. *Caspiocypris pontica* Sokač. Although the species *Caspiocypris labiata* itself is absent, the defined subzone contains the typical *Caspiocypris* form, such as *Caspiocypris alta*. In addition, *Amplocypris* aff. *dorsobrevis* SOKAČ, *Camptocypria* aff. *acronasuta*, *Typhlocypris* cf. *centropunctata*, *Loxoconcha schweyeri* are relatively abundant in this zone which is characteristic for this subzone. The *Camptocypria flectimarginata*, which reaches its acme in the *Camptocypria flectimarginata* subzone, rarely occurs in the studied section. However, the younger *Pontoniella truncata* subzone is excluded due to the absence of the index species, as well as the lack of the usual accompanying species e.g., *Pontoniella paracuminata* and *Hastacandona loczyi* (JIŘIČEK, 1983; SOKAČ, 1989). The subzone was chosen out of all the others in the literature, due to the proximity of the localities where the subzone was defined, in agreement with the results of previous research undertaken around the studied area (SOKAČ, 1981; HAJEK-TADESSE, 2007). Ostracods determined here only correspond to the described ostracod assemblages of the *Caspiocypris labiata* subzone.

The lowermost 3.5 m of the section does not contain species diagnostic of the *Caspiocypris labiata* subzone, nor are there any species that would indicate the presence of the preceding, lower level of upper Pannonian *Hemicytheria prisca* SOKAČ biozone. The latter ostracod zone was defined by KRSTIĆ (1973) based on the nominate species, and the presence of the species *Pontoniella ilica* KRSTIĆ, *Zalanyiella longissima* KRSTIĆ, *Camptocypria acuta* SOKAČ, *Bakunella anae* SPADI (SPADI et al., 2019), *Cyprideis salopeki* SOKAČ, and *C. parallela* KRSTIĆ. In the investigated section, the species *Camptocypria acuta* SOKAČ and *B. anae* SPADI occur in the lower part. The stratigraphic ranges of these species, however, extend to the upper Pannonian. The lowermost 3.5 m of the section is therefore not defined in age.

The species *Bakunella anae*, characteristic of the upper Pannonian (previously known as the lower and upper Pontian) (SOKAČ, 1972), was also observed in the sample B-024. The sample was collected from a marl lens within a sandstone bed, which is, as mentioned before, was interpreted as a clast eroded

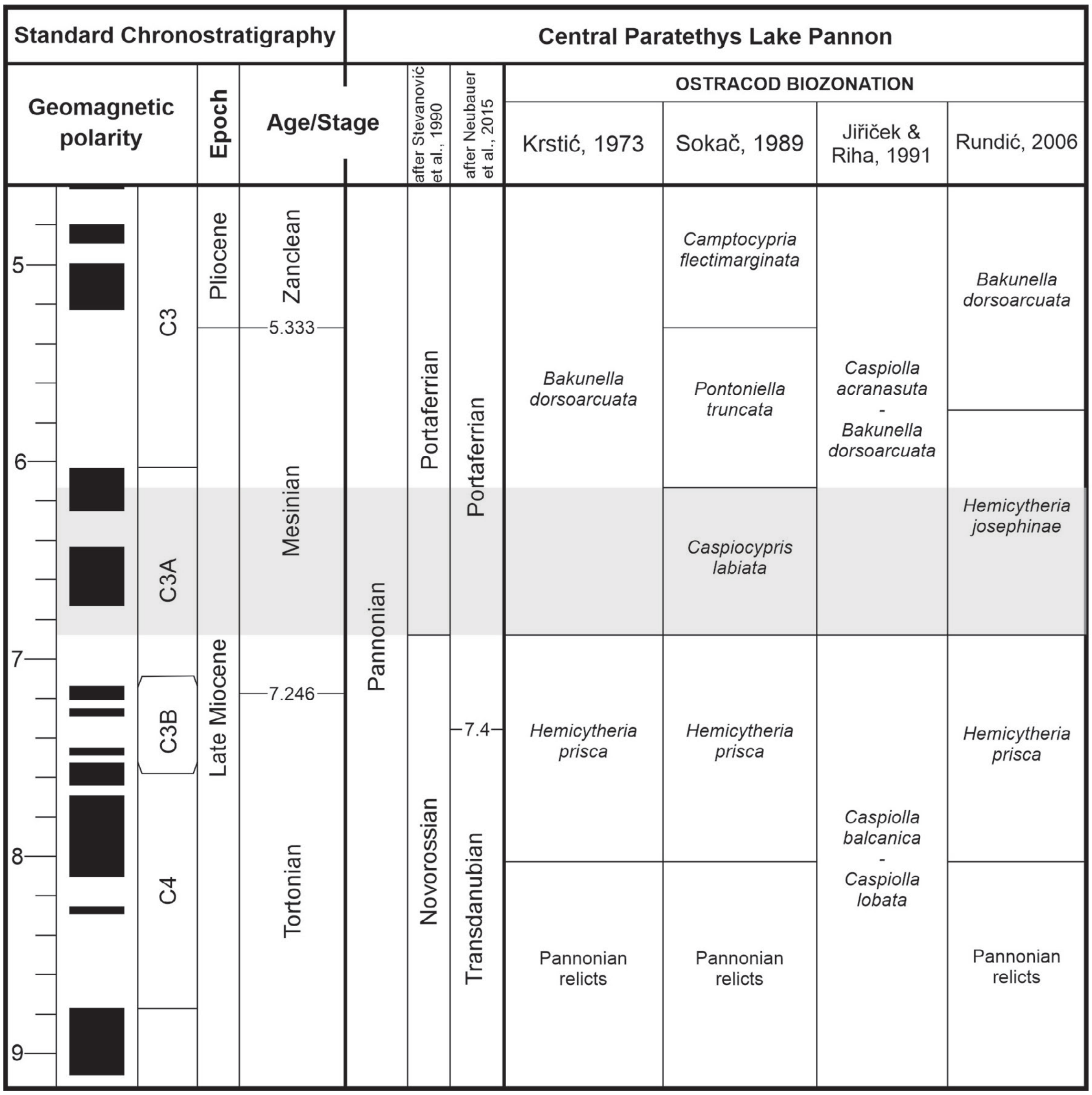

Figure 8. Four selected biozonation schemes proposed by different authors (KRSTIĆ, 1973; SOKAČ, 1989; JIŘIČEK & RIHA, 1991; RUNDIĆ, 2006) with the stratigraphic position of the study site.

from the underlying beds. Resedimentation of the fossils is also possible for samples B-035, B-037, and B-048 (see Fig. 7).

According to JIŘIČEK & RIHA (1991), the equivalent ostracod zone for the *Caspiocypris labiata* subzone is the lower Pontian Ostracod Zone 20 "*Candona* (*C.*) *balcanica- Candona* (*C.*) *lobata*" in which there is the first occurrence of *Bakunella dorsoarcuata*. However, in the biozonation set by JIŘIČEK (1983), the species *Caspiocypris labiata* is placed in the upper Pannonian Zone E 1-2. The correlation of biozones is further complicated by the different compositions of ostracod assemblages in various parts of the Central Paratethys (see POKORNÝ, 1944; BRESTENSKÁ, 1961; KRSTIĆ, 1973, 1985; JIŘIČEK, 1975, 1985; RUNDIĆ, 1998, 2006). Also, there is much confusion related to the ostracod taxonomy, which needs a serious revision (see OLTEANU, 2011; SPADI et al., 2019).

5.3. Palaeosalinity levels

The Pannonian microfauna is dominated by brackish to freshwater ostracods which tolerate an increase in salinity (Figs. 8 and 10). This suggests that the composition of the Lake Pannon ostracod assemblages is strongly facies dependent, as was previously demonstrated for the Pannonian mollusc fauna (MAGYAR et al., 1999). Many of the detected ostracod species may tolerate a considerable range of salinity. The number of freshwater species diminishes when salinity surpasses 3‰, and the number of true brackish water species in the range from 3-10‰ is not numerous but the number of specimens is large (MORKHOVEN, 1962).

The important genera for determining palaeosalinity levels in the logged part of the Bizeljsko Formation are *Darwinula*, *Candonopsis*, *Pontoniella*, *Lineocypris*, *Camptocypria*, *Caspiocypris*, *Typhlocypris*, *Bakunella*, *Hemicytheria*, *Leptocythere*, *Amplocypris*, and *Loxoconcha* (TUNOĞLU, 2003). *Candonopsis* and *Darwinula* are specific to freshwater environments. According to Meisch (2000), recent *Darwinula* tolerates an increase in salinity up to a maximum of 15‰, and *Candonopsis* from a maximum salt content of 5 ‰. Considering the poor preservation of their valves in sample B-024 and their probable re-deposition they were excluded from the environmental interpretation. Paleosalinity was determined to be in the range of brackish conditions. The interpretation is based on the presence of the genus *Hemicytheria*, which was abundant in the section (MORKHOVEN,1962; MEISCH, 2000; FRENZEL & BOOMER, 2005).

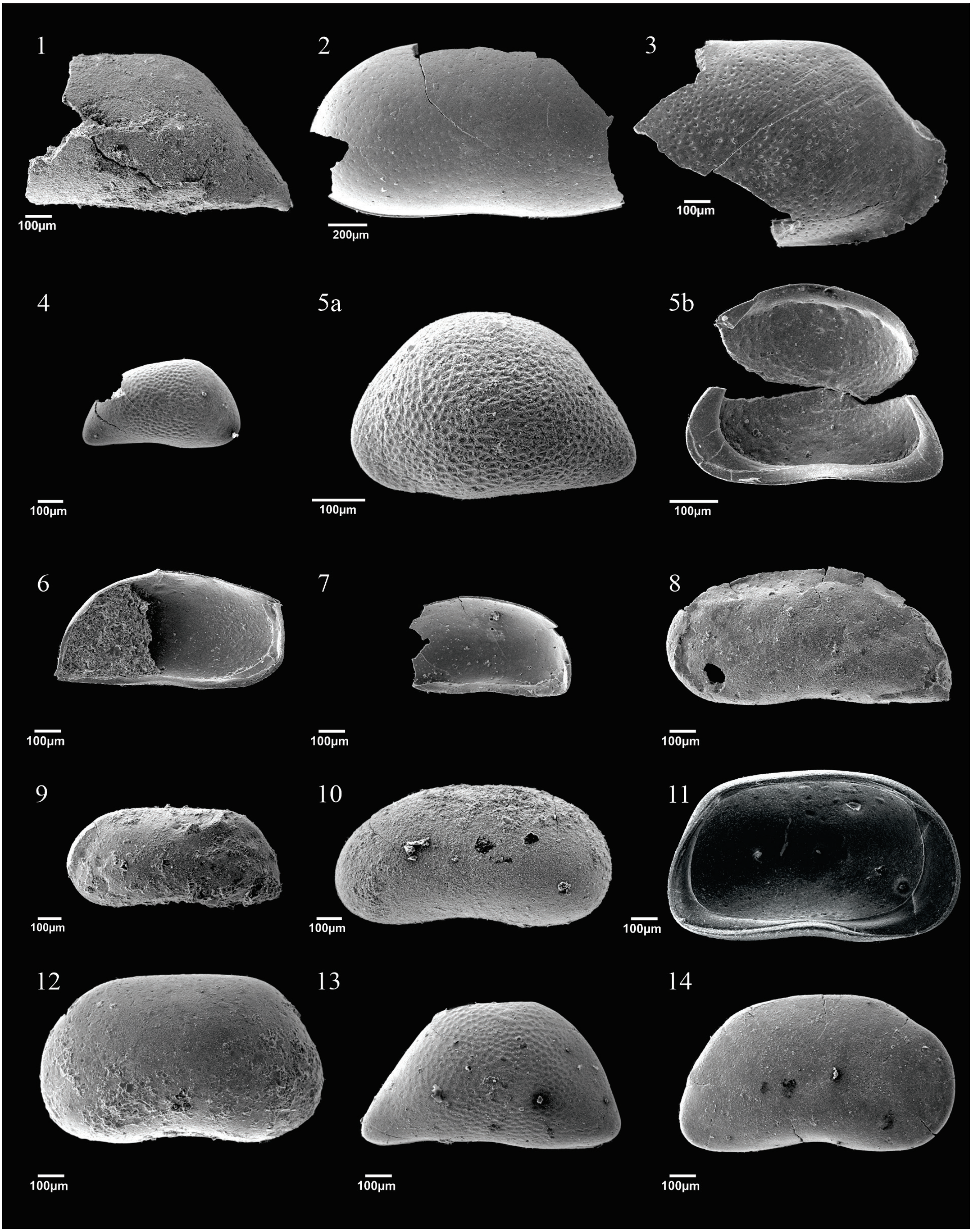

Figure 9. SEM pictures of Pannonian ostracods from the Bizeljsko section. 1. *Amplocypris subacuta* ZALÁNYI (LV, external view, sample B-024, fragmented valve); 2. *Amplocypris* cf. *dorsobrevis* SOKAČ (LV, external view, sample B-051, fragmented valve); 3. *Herpetocyprella* cf. *pannonica* ZALANYI (LV, external view, sample B-048, fragmented valve); 4. *Bakunella anae* (Vekua) SPADI (RV, external view, sample B-024), alternatively, possible juvenile of *B. dorsoarcuata*; 5a., 5b. *Bakunella dorsoarcuta* ZALÁNYI (a. LV, external view, sample B-024; b. RV, internal view, sample B-024); 6. *Camptocypria acuta* SOKAČ (LV, internal view, sample B-027); 7. *Camptocypria* cf. *acronasuta* LIVENTAL (RV, internal view, sample B-027); 8. *Camptocypria flectimarginata* SOKAČ (LV, external view, sample B-031); 9. *Camptocypria*? sp. (LV, external view, sample B-030); 10. *Candonopsis* cf. *arcana* KRSTIĆ (LV, external view, sample B-024); 11. *Caspiocypris alta* ZALÁNYI (LV, internal view, sample B-031); 12. *Lineocypris reticulata* (MÉHES) (LV, external view, sample B-057); 13. *Lineocypris hodonensis* POKORNÝ (RV, external view, sample B-027);14. *Lineocypris zagrabiensis* SOKAČ (RV, external view, sample B-041).

5.4. Comparison between the ostracod fauna from the Pannonian deposits of the Krško Basin and other parts of the Paratethys

The ostracod fauna from the Upper Pannonian deposits of the Krško Basin, which includes taxa that were determined both here and in previously published papers (SOKAČ, 1981; STEVANOVIĆ & ŠKERLJ, 1989; HAJEK-TADESSE, 2007), was compared to the ostracod faunas of the same age reported from similar localities in the Central Paratethys. The results are presented in Supplement 2.

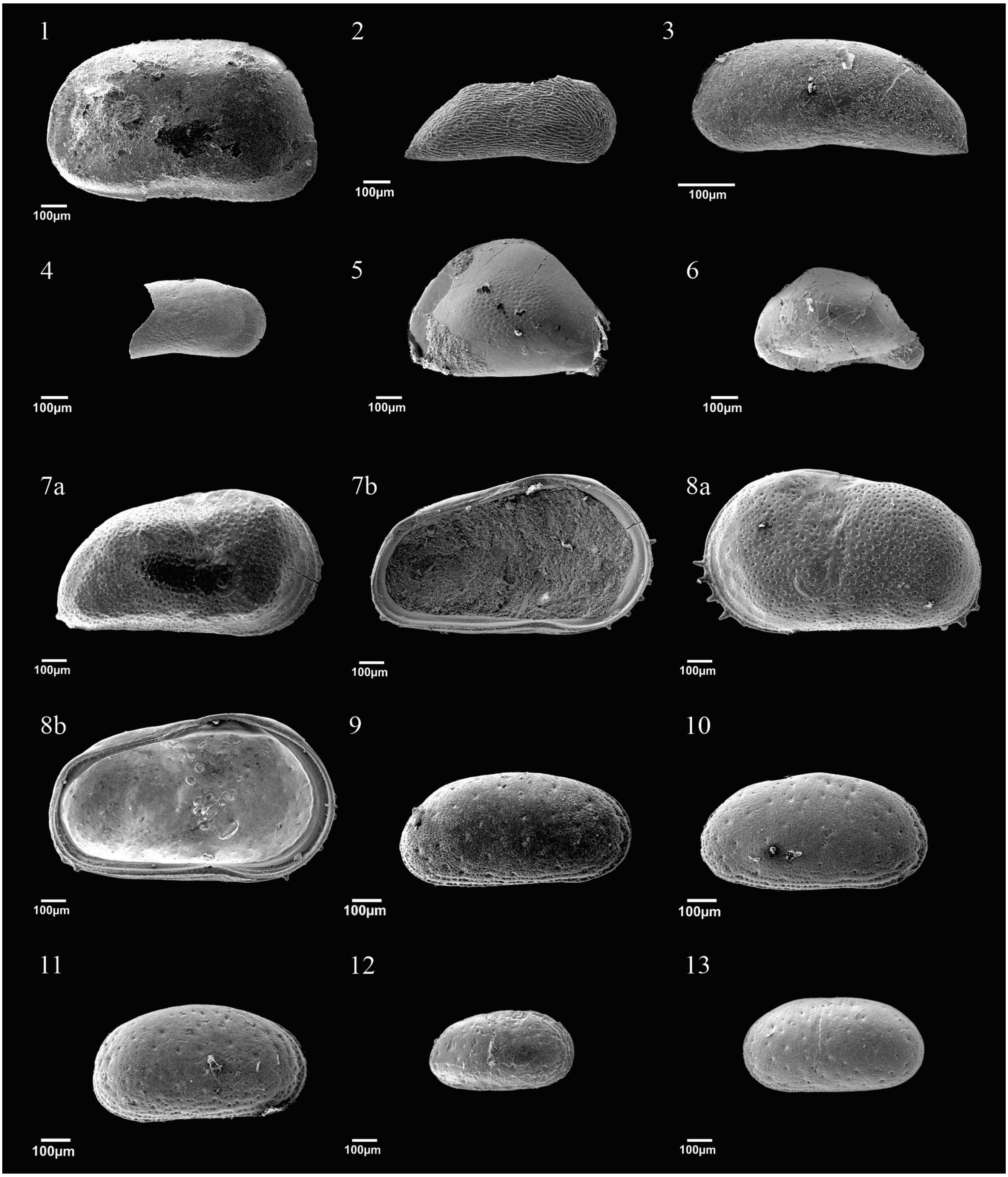

Figure 10. SEM pictures of Pannonian ostracods from the Bizeljsko section. 1. *Lineocypris* cf. *granulosa* ZALÁNYI (LV, external view, sample B-024); 2. *Pontoniella sagittosa* KRSTIĆ (RV, external view, sample B-024); 3. *Pontoniella* sp. 1 MANDELSTAM (LV, external view, sample B-024); 4. *Pontoniella* sp. 2 (LV, sample B-036); 5. *Typhlocypris* cf. *centropunctata* SUZIN (LV, external view, sample B-038); 6. *Typhlocypris* sp. (HÉJJAS) (LV, external view, sample B-040); 7. *Cyprideis macrostigma* KOLLMANN (a. RV, external view, b. LV, internal view, sample B-036); 8. *Cyprideis macrostigma spinosa* SOKAČ (a. LV, external view, b. LV, internal view, sample B-032); 9. *Cyprideis* ex gr. *pannonica* MÉHES (RV, external view, sample B-024); 10. *Cyprideis* ex gr. *pannonica* MÉHES (RV, external view, sample B-027); 11. *Cyprideis* ex gr. *pannonica* MÉHES (RV, external view, sample B-020); 12. *Cyprideis* sp. 1 (RV, external view, sample B-023); 13. *Cyprideis* sp. 2 (LV, external view, sample B-023).

In the comparison, from the literature, we only included Upper Pannonian ostracod species. The ostracod assemblage from the Krško Basin is most similar to that from Mt. Medvednica as the locality is very close by. Out of 73 species found in the Krško Basin, in total, Croatia has 43 of the same species from similar deposits. The resemblance with Croatia was expected as it belongs to the same system of supposed basins and the location of the outcrop and samples are only a few kilometres away from the comparison locations studied on Mt. Medvednica and reported in the literature. Ostracod assemblages from Romania and Serbia have, respectively, 29 and 33 species in common with Krško Basin. The Vienna Basin only has 13 species similar to those recorded at Bizeljsko. Regarding Serbia and Romania, the number of similar species indicates a good connection with the Central Paratethys.

Papers involving the older Pannonian ostracods (e.g., VRSALJKO, 1999; KOVÁCS et al., 2016; CSOMA et al., 2021), as well as Pannonian ostracods from Austria /Vienna Basin (GROSS, 2004; GROSS et al., 2008; STAREK et al., 2010) are not included in Supplement 2. Apart from these localities, some ostracods are the same species as the ones that migrated from Paratethys to the Palaeo-Mediterranean. These are *Caspiocypris alta* and *Euxinocythere* (*M.*) cf. p*raebaquana* (GLIOZZI et al., 2012).

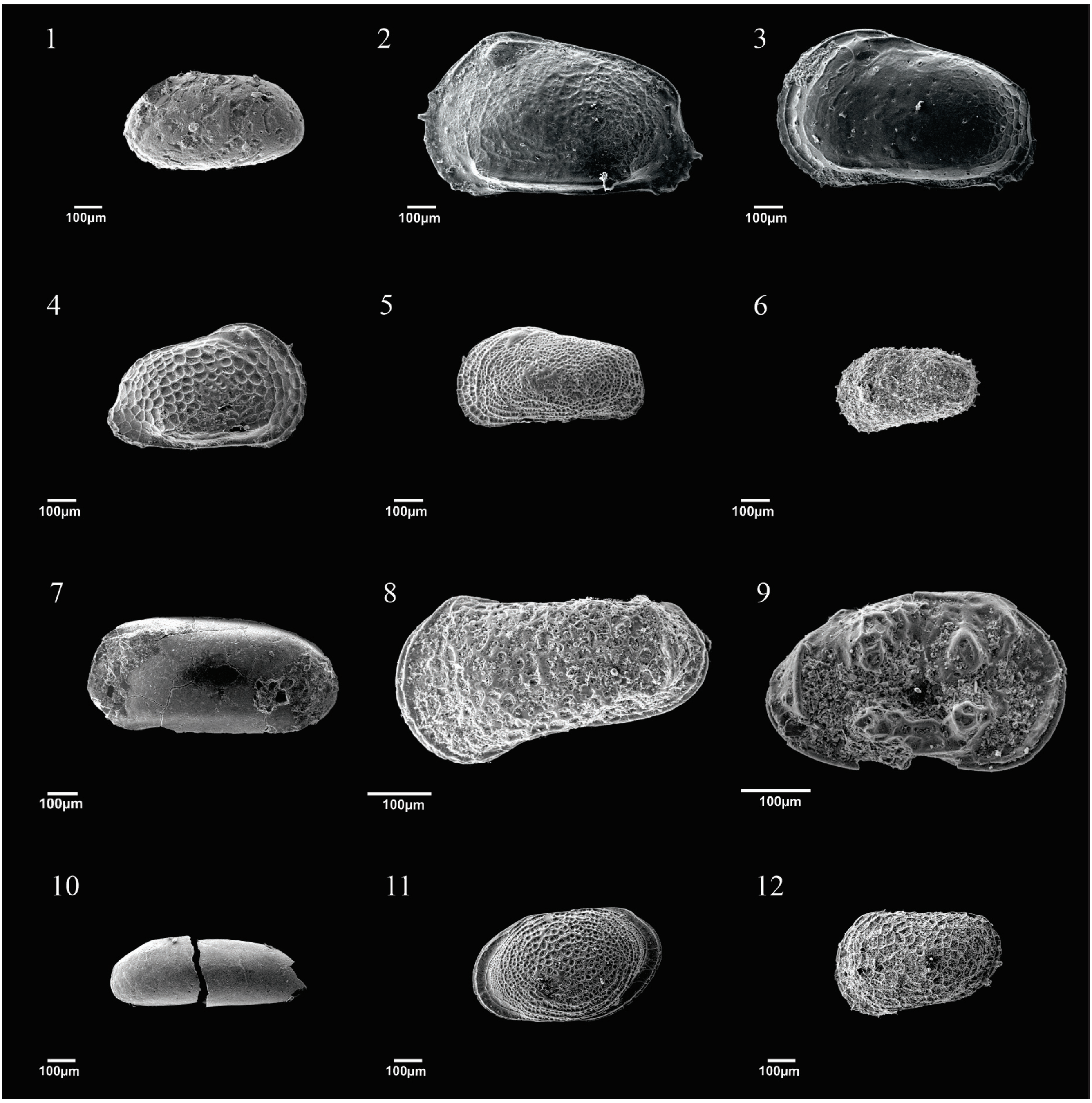

Figure 11. SEM pictures of Pannonian ostracods from the Bizeljsko section. 1. *Cyprideis* sp. 3 (LV, external view, sample B-023); 2. *Hemicytheria croatica* SOKAČ (LV, external view, sample B-024); 3. *Hemicytheria* cf. *marginata* SOKAČ (LV, external view, sample B-024); 4. *Hemicytheria* cf. *prisca* SOKAČ (RV, external view, sample B-030); 5. *Hemicytheria dubokensis* KRSTIĆ (LV, juvenile, external view, sample B-026); 6. *Amnicythere naca* (MÉHES) (LV, external view, sample B-052); 7. *Amnicythere* sp. (LV, external view, sample B-020); 8. *Leptocythere*? sp. (LV, external view, sample B-051); 9. *Euxinocythere (Maeotocythere)* cf. *praebaquana* (LIVENTAL) (RV, external view, sample B-033); 10. *Darwinula* cf. *stevensoni* BRADY & ROBERTSON (LV, external view, sample B-024) fragmented due to handling of the specimen; 11. *Loxoconcha schweyeri* SUZIN (LV, external view, sample B-024); 12. *Loxoconcha* cf. *spinosa* SOKAČ (LV, external view, sample B-024).

6. CONCLUSIONS

The Pannonian ostracods studied from the 43 m thick lithological succession (Bizeljsko Fm., Krško basin) are relatively well preserved and diverse. The determined species delineate the late Pannonian *Caspiocypris labiata* subzone. Palaeosalinity levels, as indicated by the ostracods, show brackish water conditions. Comparison with the ostracod assemblages from the region shows the highest similarity in species composition to the fauna from Croatia, less so with faunas from Serbia and Romania. Within the Bizeljsko ostracod assemblage, two species are recognised that migrated from Paratethys to the Palaeo-Mediterranean during the Lago-Mare event of the Messinian Salinity Crisis.

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Appendix:

Supplement 1. Systematic list of determined ostracod species in this study.

Class Ostracoda LATREILLE, 1802
Subclass Podocopa SARS, 1866
Order Podocopida SARS, 1866
Suborder Cypridocopina BAIRD, 1845
Superfamily Cypridoidea BAIRD, 1845
Family Cyprididae BAIRD, 1845
Amplocypris ZALÁNYI, 1944
Amplocypris subacuta ZALÁNYI, 1944
Amplocypris cf. *dorsobrevis* SOKAČ, 1972
Subfamily Herpetocyprellinae BRONSTEIN, 1947
Herpetocyprella DADAY, 1909
Herpetocyprella cf. *pannonica* ZALÁNYI, 1959
Family Candonidae KAUFMANN, 1900
Subfamily Candoninae KAUFMANN, 1900
Bakunella SCHNEIDER, 1958
Bakunella anae (VEKUA) SPADI, 2019
Bakunella dorsoarcuta ZALÁNYI, 1929
Camptocypria ZALÁNYI, 1959
Camptocypria acuta SOKAČ, 1972
Camptocypria cf. *acronasuta* (LIVENTAL, 1929)
Camptocypria flectimarginata SOKAČ, 1967
Camptocypria? sp.
Candonopsis VAVRA, 1891
Candonopsis cf. *arcana* KRSTIĆ, 1968
Caspiocypris MANDELSTAM in SCHNEIDER et al., 1956
Caspiocypris alta (ZALÁNYI, 1929)
Lineocypris ZALÁNYI, 1929
Lineocypris reticulata (MÉHES, 1907)
Lineocypris hodonensis POKORNÝ, 1952
Lineocypris zagrabiensis SOKAČ, 1972
Lineocypris cf. *granulosa* ZALÁNYI, 1959
Pontoniella MANDELSTAM in LUEBIMOVA et al., 1960
Pontoniella sagittosa KRSTIĆ, 1968
Pontoniella spp.
Typhlocypris VEJDOVSKÝ, 1882 (sensu NAMIOTKO et al. 2014)
Typhlocypris cf. *centropunctata* (SUZIN, 1956)
Typhlocypris sp.
Superfamily Cytheroidea BAIRD, 1850
Family Cytherideidae SARS, 1925
Subfamily Cytherideinae SARS, 1925
Cyprideis JONES, 1857
Cyprideis macrostigma KOLLMANN, 1958
Cyprideis macrostigma spinosa SOKAČ, 1972
Cyprideis ex. gr. *pannonica* (MÉHES, 1908)
Cyprideis spp.
Family Hemicytheridae PURI, 1953
Subfamily Hemicytherinae PURI, 1953
Hemicytheria POKORNÝ, 1955
Hemicytheria croatica SOKAČ, 1963
Hemicytheria cf. *marginata* SOKAČ, 1972
Hemicytheria cf. *prisca* SOKAČ, 1972
Hemicytheria dubokensis KRSTIĆ, 1963
Family Leptocytheridae SARS, 1925
Amnicythere DEVOTO, 1965
Amnicythere naca (MÉHES, 1909)
Amnicythere sp.
Leptocythere SARS, 1925
Leptocythere sp.
Euxinocythere (Maeotocythere) STANCHEVA, 1968
Euxinocythere (M.) cf. *praebaquana* (LIVENTAL, 1956)
Family Loxoconchidae SARS, 1925
Loxoconcha SARS, 1866
Loxoconcha schweyeri SUZIN, 1956
Loxoconcha cf. *spinosa* SOKAČ, 1972
Superfamily Darwinuloidea BRADY & ROBERTSON, 1885
Family Darwinulidae BRADY & ROBERTSON, 1885
Darwinula BRADY & ROBERTSON, 1885
Darwinula cf. *stevensoni* BRADY & ROBERTSON, 1870

Localities / Species	Slovenia	Croatia								Serbia				Hungary			Romania			
	Bizeljsko This study	Medvednica Mt. Sokač, 1972	Croatian Zagorje Sokač, 1989	Drava Depression Sokač, 1989	Sava Depression Sokač, 1989	Karlovac Subdepression Sokač, 1989	Ilova Subdepression Sokač, 1989	Eastern Slavonia Sokač, 1989	Požeška Mt. Avanić et al., 2022b; Basch et al., 2022	Beograd Region Krstić, 1973	Beograd Region Rundić et al., 2011	Beočin section Ter Borgh et al., 2013	Beli Potok Rundić et al., 2019	Makó Trough Szuromi-Korecz et al., 2004	Kisalföld Basin Cziczer et al., 2009	Paks Magyar et al., 2019	Badislava & Topolog Valleys Floroiu et al., 2011	Dacia Basin Olteanu, 2011	Slănicul de Buzău Lazarev et al., 2020	Şimleu Basin Bartha et al., 2021
Amplocypris cf. *abscissa*		+							+		+							+		+
Amplocypris cf. *reticulata*		+	+	+	+		+													
Amplocypris nonreticulata									+							+				
Amplocypris aff. *odessiensis*																				
Amplocypris subacuta		+										+						+		
Amplocypris cf. *dorsobrevis*	+	+			+												+			
Amplocypris major		+																		
Herpetocyprella cf. *pannonica*	+	+					+		+	+										
Paracandona kochanskae		+																		
Bakunella dorsoarcuta	+	+	+	+	+		+	+		+			+	+	+	+	+	+		
Bakunella anae	+	+			+															
Cypria sibovici		+																		
Cypria tocorjescui		+			+		+		+	+			+		+	+	+			
Camptocypria acuta	+	+			+															
Camptocypria cf. *acronasuta*	+	+			+		+													
Camptocypria balcanica		+	+	+	+	+	+	+							+					
Camptocypria flectimarginata	+	+	+										+							
Camptocypria cf. *brusinai*		+			+		+								+					
Candonopsis arcana	+	+			+		+		+	+										
Caspiocypris alta	+	+	+	+	+	+	+		+	+					+	+	+		+	
Caspiocypris symmetrica		+																+		
Caspiocypris labiata		+		+	+		+	+	+	+										+
Caspiocypris pontica					+					+									+	
Caspiocypris venusta		+			+		+													
Hastacandona histerica																				
Hastacandona lotzyi		+			+		+	+		+									+	
Lineocypris reticulata	+	+							+			+								
Lineocypris hodonensis	+	+							+											
Lineocypris zagrabiensis	+	+							+											
Lineocypris cf. *granulosa*	+	+			+															
Lineocypris trapezoidea		+		+	+	+	+	+	+							+		+		
Lineocypris inflexa		+																		
Pontoniella aff. *maximunguiculata*																				
Pontoniella sagittosa	+	+							+			+				+				
Pontoniella paracuminata			+	+	+	+	+	+	+	+								+		
Pontoniella truncata		+			+										+			+		
Reticulocandona elongata		+																		
Reticulocandona cf. *orientalis*																				
Typhlocypris* cf. *centropunctata	+	+		+	+		+		+	+										
Zalanyiella longissima																				
Zalanyiella venusta		+					+	+		+		+			+				+	
Cyprideis longitesta																				
Cyprideis heterostigma sublittoralis																				
Cyprideis heterostigma obessa		+																		
Cyprideis macrostigma	+	+		+		+			+	+					+					
Cyprideis macrostigma spinosa	+	+																		
Cyprideis macrostigma ventricosa																				
Cyprideis ex gr. *pannonica*	+																			+
Cyprideis triangulata		+			+					+			+							
Cyprideis aff. *parallela*										+										
Cyprideis tuzlae																				
Cyprideis pontica																				
Hemicytheria pannonica		+																+		
Hemicytheria croatica	+	+							+			+			+					
Hemicytheria marginata	+	+							+				+					+		
Hemicytheria cf. *prisca*	+				+					+								+		
Hemicytheria dubokensis	+	+							+				+					+		
Hemicytheria reticulata		+																+		
Hemicytheria cf. *josephinae*									+	+			+			+				
Hemicytheria pejinovicensis		+	+	+		+	+	+	+									+		
Amnicythere naca	+	+			+						+	+			+			+		
Amnicythere multituberculata		+								+					+			+		
Euxinocythere (M.) bosqueti		+															+	+		
Euxinocythere (M.) cf. *praebaquana*	+									+		+			+				+	
Darwinula stevensoni	+	+																		
Loxoconcha schweyeri	+	+			+		+			+			+		+		+			
Loxoconcha cf. *spinosa*	+	+			+													+		
Loxoconcha ex gr. *subrugosa*		+								+								+		
Loxoconcha rhombovalis		+							+		+							+		
Loxoconcha cf. *diaffarovi*																				
Loxoconcha cf. *petkovici*																		+		
Loxoconcha petasus		+																		
Pontoleberis pontica		+			+		+		+	+		+								

Supplement 2. Table showing the regional distribution of Upper Pannonian ostracod species found in the Krško Basin (SOKAČ, 1972; KRSTIĆ, 1973; SOKAČ, 1981, 1989; STEVANOVIĆ & ŠKERLJ, 1989; SZUROMI-KORECz et al., 2004; HAJEK-TADESSE, 2007; CZICZER et al., 2009; FLOROIU et al., 2011; OLTEANU, 2011; RUNDIĆ et al., 2011; TER BORGH et al., 2013; MAGYAR et al., 2019; RUNDIĆ et al., 2019; LAZAREV et al., 2020; BARTHA et al., 2021; AVANIĆ et al., 2022b; BASCH et al., 2022).