

Integrated stratigraphy of the Guşteriţa clay pit: a key section for the early Pannonian (late Miocene) of the Transylvanian Basin (Romania)

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Abstract

The Neogene Transylvanian Basin (TB), enclosed between the eastern and southern Carpathians and the Apuseni Mountains in Romania, is a significant natural gas province with a long production history. In order to improve the (bio) stratigraphic resolution, correlations and dating in the several 100-m-thick upper Miocene (Pannonian) succession of the basin, the largest and most fossiliferous outcrop at Guşteriţa (northeastern part of Sibiu) was investigated and set as a reference section for the *Congeria banatica* zone in the entire TB. Grey, laminated and massive silty marl, deposited in the deep-water environment of Lake Pannon, was exposed in the ~55-m-high outcrop. The uppermost 25 m of the section was sampled in high resolution (sampling per metres) for macro- and microfossils, including palynology; for authigenic ¹⁰Be/⁹Be dating and for magnetostratigraphy; in addition, macrofossils and samples for authigenic ¹⁰Be/⁹Be isotopic measurements were collected from the lower part of the section as well. The studied sedimentary record belongs to the profundal *C. banatica* mollusc assemblage zone. The upper 25 m can be correlated to the *Hemicytheria tenuistriata* and *Propontoniella candeo* ostracod biozones, the uppermost part of the *Spiniferites oblongus*, the entire *Pontiadinium pecsvaradense* and the lowermost part of the *Spiniferites hennersdorfensis* organic-walled microplankton zones. All samples contained endemic Pannonian calcareous nannofossils, representing the *Noelaerhabdus bozinovicae* zone. Nine samples were analysed for authigenic ¹⁰Be/⁹Be isotopic measurements. The calculated age data of six samples provided a weighted mean value of 10.42 ± 0.39 Ma. However, three samples within the section exhibited higher isotopic ratios and yielded younger apparent ages. A nearly twofold change in the initial ¹⁰Be/⁹Be ratio is a possible reason for the higher measured isotopic ratios of these samples. Magnetostratigraphic samples showed normal polarity for the entire upper part of the outcrop and can be correlated with the C5n.2n polarity chron (11.056–9.984 Ma, ATNTS2012), which is in agreement with the biostratigraphic data. Based on these newly obtained data and correlation of the biozones with other parts of the Pannonian Basin System, the Guşteriţa section represents the ~11.0–10.5 Ma interval, and it is a key section for correlation of mollusc, ostracod, dinoflagellate and calcareous nannoplankton biostratigraphic records within this time interval.

1. Introduction

The Transylvanian Basin (TB) is one of the largest gas provinces of Eastern Europe with a long production record (Ștefănescu et al., 2006). The upper Miocene sedimentary sequence of the basin fill has an average thickness of ca. 300 m, but it can reach ca. 1400 m thickness in the central part of the basin, in the surroundings of Sighișoara (Ciulavu et al., 2000; Sanders et al., 2002; Krézsek and Filipescu, 2005; Krézsek and Bally, 2006; Til-îță et al., 2013). The upper Miocene deposits in the TB are present in a more or less contiguous area throughout the central, southwestern, and eastern part of the basin, in an area of ca. 7500 km² (representing about one-third of the total basin area) (Fig. 1c). Fossils from the upper Miocene sedimentary record of the TB are largely identical with the endemic molluscs, ostracods, and algae that once lived in Lake Pannon, an enormous and long-lived lake that covered most of the intra-Carpathian Pannonian Basin (PB) in the late Neogene. Therefore, it was inferred long ago that in the late Miocene, the TB was part of Lake Pannon, and the regional chronostratigraphic term “Pannonian” can be applied for these sediments (Lőrenthey, 1902).

Lake Pannon was a large, deep (more than 1000 m deep in some parts) lake with brackish-water conditions (salinity: 5–12‰). Like most long-lived lakes, a diverse endemic fauna and flora (molluscs, ostracods, fishes, dinoflagellates, acritarchs, diatoms and calcareous nannoplankton) evolved in the lake (Kázmér, 1990; Müller et al., 1999; Neubauer et al., 2016).

The biostratigraphic subdivision and chronostratigraphic framework of this several hundred-meter-thick sequence in the TB, representing ~2.5 Ma, are still relatively poorly developed and imply much uncertainty. The mollusc and ostracod biozonations were largely based on the biostratigraphy of shallow-water deposits of the Vienna Basin developed many decades ago (Papp, 1951, 1953). The results of some recent magnetostratigraphic studies are available (Vasiliev et al., 2010; de Leeuw et al., 2013), but their interpretations are partly debatable (see the Discussion section). Radiometric age measurements have never been published from the Pannonian of the TB.

Our main objective was the development of a comprehensive Pannonian biochronostratigraphy in the TB; therefore, we conducted integrated stratigraphic research in the most fossiliferous Pannonian outcrop of the TB, the Gușterița clay pit, in Sibiu. We investigated various fossil groups; identified and correlated mollusc, ostracod, dinoflagellate cyst and calcareous nannoplankton biozones; performed magnetostratigraphic research and experimented with the authigenic ¹⁰Be/⁹Be dating method.

Our study has relevance not only in the TB but also in the PB, where surface distribution of the coeval deep-water sediments is confined to the eastern and southern margins of the basin, whereas they are usually deeply buried and comprise hydrocarbon source rocks and reservoirs in other parts of the PB.

2. Geographic and geological settings

The TB is surrounded by the chains of the eastern and southern Carpathians. It is separated from the PB by the Apuseni Mountains (Fig. 1a–b) and has a relatively high present-day altitude of 300–500 m above the mean sea level.

The Cenozoic evolution of the TB was controlled by the Carpathian orogeny. Synchronously with the uplift of the Carpathians, a more than 3500-m-thick middle to upper Miocene sedimentary sequence accumulated in the TB. Exhumation and erosion of the infilled basin started at the end of the Miocene (Krézsek and Bally, 2006), which resulted in the erosion of younger than 9–8 Ma deposits (Sanders et al., 1999, 2002). Lower Pannonian sands, marls and conglomerates are the youngest of the preserved sediments in the TB; however, Pliocene brackish-water deposits can be found in the small basins of the Eastern Carpathians (Brașov-Baraolt, Ciuc and Gheorghe- ni Depressions – Fielitz and Seghedi, 2005; László, 2005).

At the end of the middle Miocene (end of Sarmatian), connection with the Eastern Paratethys ceased due to the uplift of the Carpathians, and Lake Pannon was born. Brackish- and freshwater endemic faunas evolved in the lake (Lubenescu, 1981; Magyar et al., 1999a; Müller et al., 1999). Older theories suggested continental environment and erosion around the Sarmatian–Pannonian transition (Vancea, 1960; Marinescu, 1985; Magyar et al., 1999a). According to Marinescu (1985), the oldest Pannonian littoral mollusc biozone (*Congerina ornithopsis* zone) is totally missing from the TB. More recent studies, however, indicated that the sedimentation was continuous through the Sarmatian–Pannonian boundary, as witnessed by the deep-water facies of the Oarba de Mureș (ODM) sections located in the depocenter of the TB (Sztanó et al., 2005; Sütő and Szegő, 2008; Vasiliev et al., 2010; Filipescu et al., 2011).

At the beginning of the late Miocene (beginning of Pannonian), a deep-lacustrine environment formed in most parts of the basin. Unlike in the PB, deep-water sediments can be studied in surface exposures due to the subsequent erosion that uncovered them. Deep-water fans are preserved in the southwestern part, while in the southeastern part, some 100-m-thick shallow-water (delta), freshwater-paludal and continental (fluvial) formations can be found. In the latter region, Pliocene volcanics cover and protect the loose Pannonian rocks from erosion (Krézsek et al., 2010). In the eastern part of the basin, deep-water turbiditic successions are preserved (Bartha et al., 2016).

Deposition in the TB probably lasted until the end of the Miocene, but most of the shallow-lacustrine, continental-fluvial deposits were eroded during the Pliocene to Quaternary. According to apatite fission track thermochronological analyses on borehole samples and numerical flexural-isostatic 3-D modelling, it is likely that at least a 500-m-thick sedimentary succession was eroded (Sanders et al., 1999, 2002).

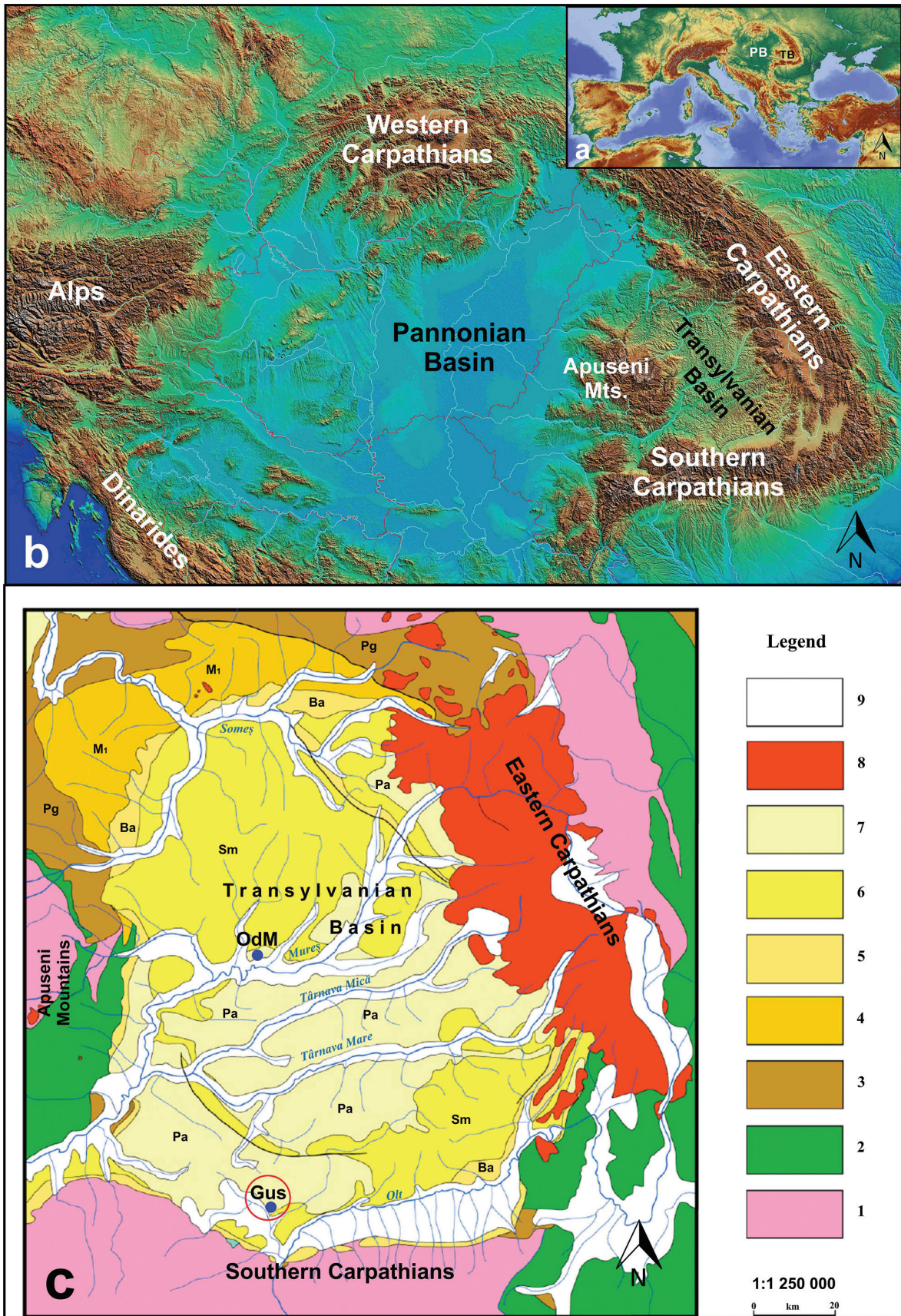


Figure 1: Geographic and geological maps of the Transylvanian Basin in the intra-Carpathian realm. **a:** Geographic map indicating the two basins in Europe (PB: Pannonian Basin and TB: Transylvanian Basin). **b:** DEM of the Pannonian Basin System. **c:** Geological map of the Transylvanian Basin and geographic situation of the discussed localities in this study (GUS: Guşteriţa, OdM: Oarba de Mureş). Legend: Pg: Paleogene, M₁: lower Miocene, Ba: Badenian, Sm: Sarmatian and Pa: Pannonian. 1–2: Units of the Carpathians and the Apuseni Mountains (1. Metamorphics, 2. Mesozoic sediments), 3. Paleogene, 4. lower Miocene, 5. middle Miocene (Badenian), 6. middle Miocene (Sarmatian), 7. upper Miocene (Pannonian), 8. Neogene volcanic and volcano-sedimentary rocks and 9. Quaternary (modified after Săndulescu et al., 1978). DEM: digital elevation model.

The Pannonian lithostratigraphy of the TB is not uniform. Beside formations, informal units are used as well, and due to the heterogeneity of lithofacies, different classifications are created for different parts of the basin. The Lopadea Formation (Lubenescu and Lubenescu, 1977) comprises sandy–clayey layers in the western basin margin. In the eastern part, the Ocland Formation (Rado et al., 1980) was erected for the deltaic, sandy-marly deposits. Sediments of the Guşteriţa and Vingard formations (Lubenescu, 1981), as well as the pebbly Săcădate Member, are located in the southern-southwestern part of the basin. The clayey-marly deposits and fauna of the Guşteriţa Formation provide evidence for a deep-water, profundal environment, while the sand and fauna of the Vingard Formation indicate shallow-water, littoral deposition. The conglomerate and sand of the Săcădate Member contain a mixed Sarmatian–Pannonian fossil fauna (Lubenescu, 1981; Chira et al., 2000). These formations can be paralleled with the Pannonian formations of the PB. Deep-water marls of the Guşteriţa Formation correspond to the Endrőd Marl Formation (Juhász, 1997). The turbiditic succession of the Lopadea Formation is similar to the Szolnok Sandstone Formation (Juhász et al., 1997). The Săcădate Member resembles the Békés Conglomerate Formation (Gajdos et al., 1997). In the case of the regressive sediments (Vingard Formation, Ocland Formation and the unassigned sequences in the eastern part of the basin), the correlation is less straightforward, because their fossil content is somewhat different from their PB relatives.

A sequence stratigraphic framework of the Pannonian of the TB was proposed by Krézsek and Filipescu (2005) and Krézsek et al. (2010), using the original three-system tract model of Vail et al. (1977). They divided the middle to late Miocene sedimentary succession of the basin into minimum eight different sequences based on seismic profiles and well logs. The Pannonian sediments included the following system tracts: TST7, HST7, LST8, TST8, HST8 and LST9 (Krézsek and Filipescu, 2005; Krézsek et al., 2010).

The Wienerberger clay pit and brickyard of Guşteriţa (German: Hammersdorf, Hungarian: Szenterzsébet) is located along the southern rim of the TB, in the north-eastern part of Sibiu (German: Hermannstadt, Hungarian: Nagyszeben) (45°48'20.23"N, 24°11'47.30"E) (Fig. 1c). The exposed thick (~55 m) Pannonian marl has been mined here for more than a century (Oebbecke and Blanckenhorn, 1901) (Fig. 2a–b). Light grey, laminated or massive, highly calcareous (~75%), silty marl layers and thin, very fine-grained, cross-laminated sand intercalations are observed in the mine (minor Bouma-type: Tc sandy turbidites) (Fig. 2c). Based on sedimentological investigations and surface gamma-ray logging, the marl can be a product of background sedimentation, with occasional low-density turbidites (sand intercalations), which is a characteristic of inner fan overbank deposits as well as outer fan lobes (Tókécs, 2013; Tókécs et al., 2015). Based on seismic interpretation, the locality can

represent the transgressive system tract of the early Pannonian (Krézsek et al., 2010).

Guşteriţa is one of the largest outcrops and perhaps the most fossiliferous site of the deep-water Pannonian formations in the TB. The Pannonian macrofauna of the locality was examined by some earlier authors, but their faunal lists contain a relatively low number of taxa (Ackner, 1852; Lörenthey, 1893; Koch, 1876, 1895; Bielz, 1894; Lubenescu, 1981). Plant remains from the outcrop were described by Givulescu (1969).

3. Material and methods

Samples were collected from four different section parts of the Guşteriţa clay pit. In October 2015, macrofossils and marl samples for authigenic ¹⁰Be/⁹Be isotopic measurements were collected from the lower, middle and upper parts of the mine (Guşteriţa 1, 2 and 3) (Fig. 2a). Later, in June 2017, the uppermost 25 m of the quarry (Guşteriţa 4) was sampled (Fig. 2b). Samples were collected for macro- and microfossils (ostracods, dinoflagellates and calcareous nannoplankton), for magnetic polarity measurements (per metre) and for authigenic ¹⁰Be/⁹Be dating (per 5 m). In addition, numerous trace fossils (Fig. 2d), thecamoebians, fish teeth, otoliths, some partial fish skeletons and fossil plant remains were found.

3.1 Biostratigraphy

Altogether 1295 mollusc specimens were determined. The bulk of the studied material was collected by the authors from various parts of the clay pit (Guşteriţa 1, 2, 3 and 4). The studied material also comprised the collections of the Brukenthal Museum, Sibiu, Romania, and the Paleontology-Stratigraphy Museum of the Babeş-Bolyai University, Cluj-Napoca, Romania. The collected molluscs were prepared in the laboratory of the Department of Palaeontology of Eötvös Loránd University, Budapest, Hungary. Polyvinyl butyral and polyvinyl acetate were used for solidifying the thin and fragile shells.

A total of 25 micropalaeontological samples were examined from the upper part of the outcrop (Guşteriţa 4). The microfossils with carbonate shells were processed with hydrogen peroxide (10%) from about 250 g of air-dried sediments. The scanning electron microscope (SEM) images were made with a Hitachi S-2600N Variable-Pressure Scanning Electron Microscope at the Botanical Department of the Hungarian Natural History Museum in Budapest. The ecological limits of the Pannonian ostracods are based on recent analogies with taxa that are still living; in the case of the extinct forms, the co-occurring faunal elements, sediment type and previous ostracod studies were referred to.

Palynological analysis was carried out on 25 samples collected from the uppermost 25 m of the quarry. Standard palynological processing techniques were used to extract the organic matter (e.g. Moore et al., 1991; Wood et al., 1996). The samples were treated with sodium pyrophosphate (Na₄P₂O₇), cold HCl (15%) and HF (40%), removing carbonates and silica. Heavy liquid

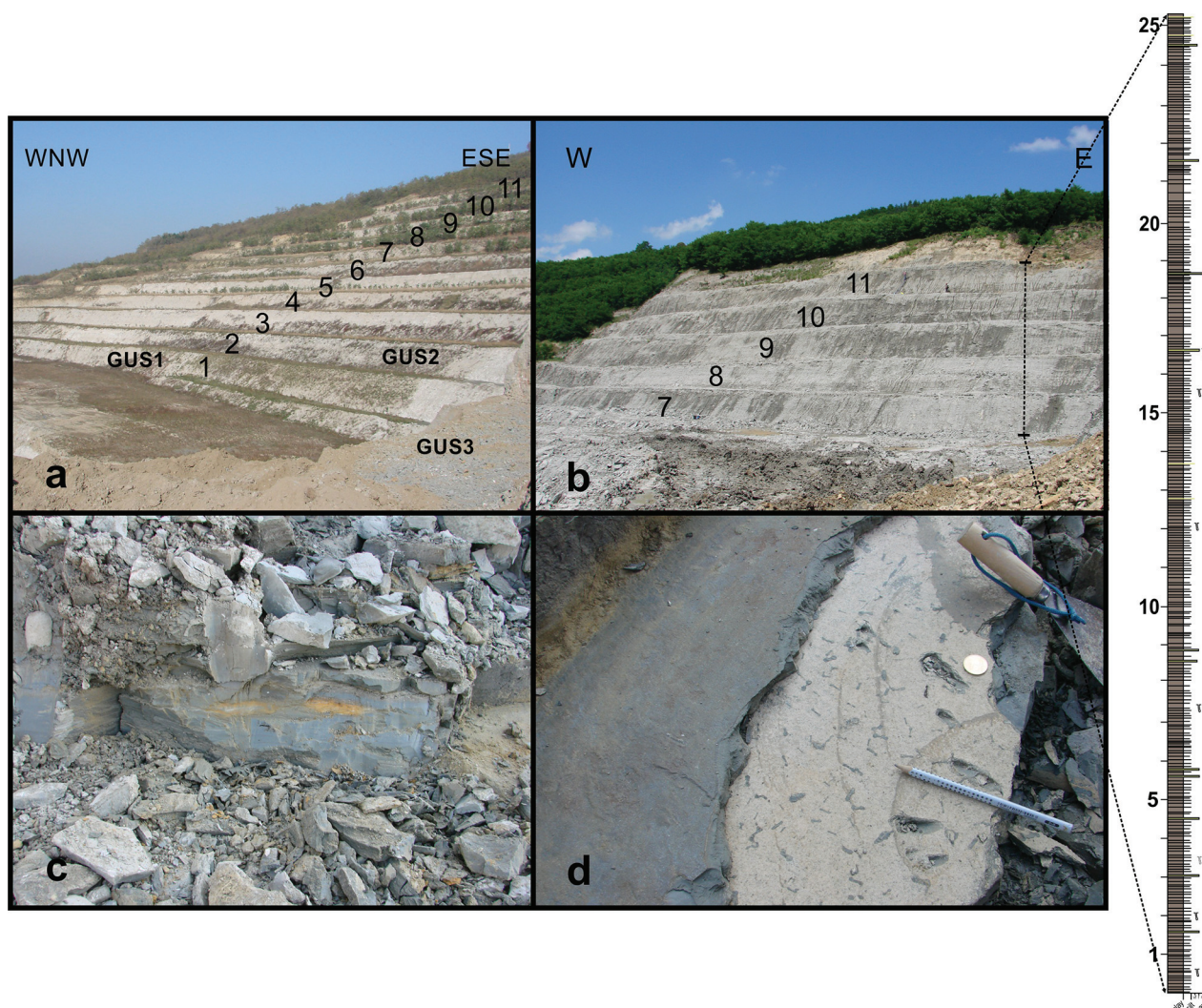


Figure 2: Clay pit of Gušterița. **a:** The mining site, with view from the upper part (GUS3). The three sampled levels are indicated by the captions. **b:** The 25-m-high Gušterița 4 section (uppermost part of the mine). Numbers indicate terraces; each one is ca. 5 m high. Its detailed sedimentary log can be seen on the right side. **c:** Very fine-grained, cross-laminated sand lenses cropped out in the upper part (GUS3). **d:** Light grey, carbonate- and *Diplocraterion* isp. trace fossil-bearing bedding plane in the upper part of the quarry.

($ZnCl_2$, density >2.1 kg/l) was used to separate the organic matter from the undissolved inorganic components. The organic residue was sieved through a $10\ \mu m$ mesh. Palynological slides were mounted in glycerin for palynofacies analysis and in silicon oil for palynomorph analysis. Microscopic analyses were performed using Olympus BH-2 and Leitz Aristoplan microscopes. Photomicrographs were taken using an AmScope™ camera adapter connected to the AmScope v.3.7 camera software and an Olympus DP25 camera connected to the Olympus Stream Motion software. The samples, organic residues and palynological slides were curated at the Department of Geology, Croatian Geological Survey, and at the Rock and Fluid Analysis, INA Oil Industry Plc., Zagreb, Croatia.

The calcareous nannoplankton distribution was studied in 25 samples from the Gušterița 4 section. Smear slides were prepared for all samples using standard procedures described by Perch-Nielsen (1985) and examined under a light microscope (cross and parallel nicols) with

1000× magnification at the Department of Sedimentary Geology, Geological Survey of Austria, Vienna, Austria. Quantitative data were obtained by counting at least 300 specimens from each smear slide.

3.2 Magnetostratigraphy

Gušterița 4 section was sampled for magnetostratigraphic purposes by drilling 26 marl samples from the quarry. Measurements were carried out in the Fort Hoofddijk Paleomagnetic Laboratory of the Utrecht University, Utrecht, the Netherlands. Magnetic susceptibility measurements were made on an AGICO MFK1-FA Multi-Function Kappabridge automatic device, using the Saphyr6 software. For the alternating field (AF) measurements, a laboratory-built automated AF-coil-interfaced measuring device with a 2G cryogenic magnetometer was used (Mullender et al., 2016). The following field steps were used: 0, 5, 10, 15, 20, 25, 27, 30, 32, 35, 40, 45, 50, 60 and 80 mT. The thermal (TH) measurements were carried out with a manually operated 2G Enterprises DC

SQUID cryogenic (He-cooling) magnetometer, operating using the Cryo2Go software. Heating of samples took place in a magnetically shielded cylindrical metal oven, controlled by the Oven2Go software. The following temperature steps were applied: 20, 80, 120, 170, 200, 220, 240, 260, 280, 300, 320, 340 and 370°C. During heating, a conservative heating profile, 25°C linger time and 7°C T-tolerance were used. In order to avoid coil drift, samples were always placed in the same line-up. Then, a calibration phase with two blank measurements was executed with the empty sample holder. Every measurement was performed in two positions. Zijderveld projections were interpreted to understand the magnetic behaviour and to determine the magnetic directions of the samples (Zijderveld, 1967). Principal component analysis was used to fit regression lines onto the measured values. All the samples showed strong magnetic characteristics; therefore, no quality groups were separated. All measured declination values were corrected for the present-day declination at the study location (MSL=450 m; day of sampling: 20 June 2017), with the help of the magnetic field calculator of the National Centers for Environmental Information, USA (<https://www.ngdc.noaa.gov>).

3.3 Authigenic ¹⁰Be/⁹Be dating

Authigenic ¹⁰Be/⁹Be isotopic dating method was applied on altogether eleven marl samples, nine from four sections of the Guşteriţa clay pit (Guşteriţa 1, 2, 3, and 4) and two from the ODM A section (ODM-15.2 and ODM-28). Samples were collected from the most clayey parts of the outcrops. Physical preparation of the samples was carried out in the laboratory of the Department of Palaeontology of the Eötvös Loránd University, Budapest, while chemical preparation was performed in the research institute of the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE), Aix-en-Provence, France (samples ODM and GUS1 to GUS3) and in the laboratory of the Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava, Slovakia (samples G01 to G25).

The method is based on the radioactive decay of the initial ¹⁰Be/⁹Be ratio after the sediment deposition. The stable ⁹Be is derived from chemical weathering of rock massifs, whereas the radionuclide ¹⁰Be is produced by spallation reactions induced by cosmic rays in the atmosphere (Bourlés et al., 1989). Since beryllium is strongly chemically reactive, it adsorbs abruptly to the surface of sediment particles in a water column, and after their deposition, the initial ¹⁰Be/⁹Be ratio is determined. Hence, if the system is chemically closed, the ratio decreases only by the decay of ¹⁰Be (with the half-life of 1.387 ± 0.012 Ma; Chmeleff et al., 2010; Korschinek et al., 2010). Then after the determination of the actual ¹⁰Be/⁹Be ratio, the depositional age of a sediment can be calculated using the equation of radioactive decay, which is given as follows:

$$R_{(t)} = R_0 \times e^{-\lambda t},$$

where $R_{(t)}$ is the measured ¹⁰Be/⁹Be isotopic ratio, R_0 the initial ¹⁰Be/⁹Be isotopic ratio, λ the decay constant of ¹⁰Be isotope ($\lambda = (4.997 \pm 0.043) \times 10^{-7} \text{ a}^{-1}$) and t the elapsed time.

The initial ¹⁰Be/⁹Be isotopic ratio (R_0) is usually determined from recent sediment representative of the former environment and assuming constant deposition processes and source areas through time.

For authigenic ¹⁰Be/⁹Be isotopic dating, ~40 g air-dried marl from each sample was grinded in an agate hand mortar and oven-dried. The sample preparation followed the procedure of Bourlés et al. (1989) and Carcaillet et al. (2004), adopted by Šujan et al. (2018). Approximately 1.5 g of each sample was leached in a solution of acetic acid and hydroxylammonium hydrochloride. After lixiviation, aliquots for ⁹Be measurements were taken and a beryllium carrier was added (~0.3 g of a 1000 ppm ICP standard beryllium solution). The beryllium was separated from other elements using ion chromatography (Merchel and Herpers, 1999). Purified samples were oxidised at 800°C and cathoded for accelerator mass spectrometry (AMS) measurements of their ¹⁰Be/⁹Be ratio. AMS measurements were performed at the French national facility ASTER (CEREGE, Aix-en-Provence, France). The concentrations of ⁹Be were determined by AAS in CEREGE (samples ODM and GUS1, 2, 3) and by ICP-MS in the laboratory of the Institute of Chemistry, Slovak Academy of Sciences, Bratislava, Slovakia (Šujan et al., 2018; samples G01–G25). The comparability of both ⁹Be measurement approaches was tested using replicated measurements. The ¹⁰Be concentrations were corrected according to chemical processing blank values (Table 1). The weighted mean ages were calculated using the KDX software by Spencer et al. (2017).

4. Results

4.1 Molluscs

Altogether 23 mollusc taxa were determined, representing 13 genera and 19 species (Suppl. S1). The assemblage consisted of brackish-water bivalves (*Congeria banatica*, *Lymnocardium undatum*, *Paradacna lenzi* and *Paradacna syrmienne*), pulmonate (*Gyraulus ponticus*, *Gyraulus tenuistriatus*, *Orygoceras levis*, *Undulotheca halavatsi*, *Undulotheca nobilis* and *Velutinopsis velutina*) and prosobranchiate snails (*Micromelania striata* and *Prosothenia sundecici*) (Fig. 3). They represented seven families (Dreissenidae, Cardiidae, Sphaeriidae, Planorbidae, Hydrobiidae, Lymnaeidae and Valvatidae). The most frequent bivalve species of the deep-water fossil fauna was the dreissenid *C. banatica*, which sometimes formed coquina-like monospecific accumulations on bedding planes (Fig. 3k). Pulmonate snails were strongly dominant amongst gastropods (Fig. 3e–j and l).

The mollusc biostratigraphy of the offshore deposits of Lake Pannon is poorly developed. For the time being, only three biozones are distinguished: the *Lymnocardium*

Sample ID	Depth (m)	⁹ Be (at.g ⁻¹) × 10 ¹⁶	¹⁰ Be (at.g ⁻¹) × 10 ⁵	Natural ¹⁰ Be/ ⁹ Be × 10 ⁻¹¹	Age - R _{0-lacus} (Ma)	Age - R _{0-ODM-28} (Ma)	Age - R _{0-ODM-15.2} (Ma)
ODM-28	28	3.41 ± 0.04	5.76 ± 0.41	1.69 ± 0.12	12.05 ± 0.9	11.62 ± 1.18	10.7 ± 1.11
ODM-15.2	15.2	3.41 ± 0.04	3.63 ± 0.26	1.07 ± 0.08	12.97 ± 0.99	12.54 ± 1.29	11.62 ± 1.22
GUS1	52.7 ± 2.5	5.99 ± 0.03	11.59 ± 0.76	1.93 ± 0.13	11.78 ± 0.82	11.35 ± 1.11	10.43 ± 1.04
GUS2	47.7 ± 2.5	4.11 ± 0.03	13.02 ± 0.69	3.17 ± 0.17	10.79 ± 0.62	10.36 ± 0.94	9.44 ± 0.87
GUS3	32.7 ± 2.5	3.98 ± 0.05	9.83 ± 0.58	2.47 ± 0.15	11.29 ± 0.72	10.86 ± 1.02	9.94 ± 0.95
G01	25	2.26 ± 0.03	7.56 ± 0.31	3.34 ± 0.14	10.69 ± 0.51	10.25 ± 0.87	9.34 ± 0.8
G06	19.8	1.95 ± 0.03	15.53 ± 0.57	7.98 ± 0.32	8.94 ± 0.4	8.51 ± 0.70	7.59 ± 0.63
G10	15	1.92 ± 0.02	11.01 ± 0.37	5.73 ± 0.2	9.61 ± 0.39	9.17 ± 0.74	8.26 ± 0.66
G14	11	2.56 ± 0.03	16.96 ± 0.65	6.64 ± 0.27	9.31 ± 0.42	8.88 ± 0.74	7.96 ± 0.66
G20	5	2.05 ± 0.05	5.81 ± 0.27	2.83 ± 0.15	11.02 ± 0.62	10.59 ± 0.95	9.67 ± 0.87
G25	0	2.25 ± 0.07	10.69 ± 0.55	4.76 ± 0.28	9.98 ± 0.63	9.55 ± 0.90	8.63 ± 0.81

Table 1: Authigenic ¹⁰Be/⁹Be isotopic data from the Orba de Mureş A outcrop and from the Guşteriţa quarry. ODM-15.2 and ODM-28 indicate the samples taken from the ODM "A" outcrop. Guşteriţa 1, 2 and 3 represent the lower, middle and upper part of the mine. G01 to G25 samples are from the Guşteriţa 4 section. R_{0-lacus}: (6.97 ± 0.14) × 10⁻⁹, R_{0-ODM-28}: (5.61 ± 0.41) × 10⁻⁹ and R_{0-ODM-15.2}: (3.55 ± 0.26) × 10⁻⁹. Blank sample for ODM and GUS samples: 2.32 × 10⁻¹⁵. Blank sample for G01 to G25 samples: 1.18 × 10⁻¹⁴. Abbreviations: GUS: Guşteriţa and ODM: Orba de Mureş.

praeponticum or *Radix croatica* zone, the *C. banatica* zone and the "*Dreissenomya*" *digitifera* zone (for a summary, see Magyar et al., 1999b). In the mollusc biostratigraphic system developed for the TB by Lubenescu (1981), the deep-water sediments were subdivided into the older *C. banatica* and the younger *C. prezujuvici* zones. In both stratigraphic schemes, the molluscan record from Guşteriţa 1 to 4 belonged to the *C. banatica* zone, based on the presence of *C. banatica* throughout the entire section.

The stratigraphic distributions of other species from Guşteriţa were either not known or not narrow enough to be used for further subdivision of the *C. banatica* zone. The only exception was the *Radix*–*Velutinopsis*–*Undulotheca*–*Provalenciennesia*–*Valenciennius* evolutionary lineage of lymnaeid snails, which was characterised by progressively larger shell size, widening of the aperture, reduction of whorl number and appearance and strengthening of transversal ribs (e.g. Gorjanovič-Kramberger, 1901, 1923; Moos, 1944). The morphotypes of this lineage are good candidates for high-resolution biostratigraphic markers, but only after their taxonomy, nomenclature and stratigraphic range of individual taxa are revised.

In the Guşteriţa material, we recognised that the names *Velutinopsis nobilis* (Reuss, 1868) and *Undulotheca pancici* (Brusina, 1893) refer to the same species (Fig. 3h–i). The difference between the two types is probably due to the different direction of compaction that affected the shells after burial. The type specimen of *V. nobilis* is laterally compacted, while the name *U. pancici* is used for dorsoventrally compacted specimens. According to our observations and opinion, these two forms belong to one species, because otherwise they are characterised by the same morphological traits (large aperture, reduction in number of whorls and strong rounded ribs) (Fig. 3h–i). Applying the priority rule, the valid species name would be *V. nobilis*, but because of the rounded ribs characteristic for the genus *Undulotheca*, we propose to use

the species name *U. nobilis* instead. *V. velutina* (usually smooth, more whorled form) is also a common form in the Pannonian of the TB. In Guşteriţa, we found specimens slightly different from the type. The shell surface of this species is usually completely smooth, while in the case of some specimens, slightly bulged growth lines are observed, which are not strong enough to call them ribs. These specimens may represent a transitional form between *V. velutina* and *U. nobilis*. Similar specimens from Beočin, Serbia, were described by Gorjanovič-Kramberger (1901) as *Velutinopsis rugosa*.

4.2 Ostracods

Samples from the Guşteriţa 4 section produced a relatively diverse benthic ostracod material. The preservation is moderate and sometimes poor (with a lot of broken valves and carapaces). There are more adult specimens than juvenile ones. Altogether 18 euryhaline benthic ostracod taxa were identified belonging to eight species, eleven genera, five families and one order (Podocopida) (Fig. 4 and Suppl. S2).

Older strata of the section Guşteriţa 4 (samples G1 to G9) are characterised by the specimens of *Candona* sp., *Candona (Propontoniella)* sp., *Candona (Thaminocypris)* sp., *Candona (Thaminocypris) aspera*, *Candona (Thaminocypris) transylvanica*, *Candona (Thyphlocypris)* sp., *Hemicytheria* sp. and *Hungarocypris* sp. (Fig. 4c–d and f–h). The dominance of the thin-shelled Candoninae suggests a sublittoral to profundal depositional environment.

The fauna of the younger layers (samples G10 to G25) contains the specimens of *Bakunella* sp., *Candona (Propontoniella) candeo*, *C. (T.) aspera*, *C. (Thaminocypris) transylvanica*, *Euxinocythere naca*, *Hemicytheria croatica*, *Leptocythere* sp., *Leptocythere (Amnicythere) stanchevae*, *Loxoconcha granifera*, *Loxoconcha rhombovalis* and *Pseudocandona* sp. (Fig. 4a–e, g and i–j).

Modern *Bakunella* lives at salinities of 11.5 to 13.5‰ in sublittoral to profundal depths of the central and



Figure 3: Dominant mollusc species of the Guşteriţa clay pit. **a:** *Congeria banatica* R. Hörnes, 1875, Guşteriţa 3. **b:** *Lymnocardium undatum* (Reuss, 1868), Guşteriţa 3. **c:** *Paradacna syrmiese* (R. Hörnes, 1874), Guşteriţa 3. **d:** *Paradacna lenzi* (R. Hörnes, 1874), collection of the Brukenthal Museum, Sibiu, inventory number: 49.383–49.384. **e:** *Gyraulus ponticus* (Lörenthey, 1893), Guşteriţa 3. **f:** *Gyraulus tenuistriatus* (Gorjanović-Kramberger, 1899), Guşteriţa 3. **g:** *Orygoceras levis* Gorjanović-Kramberger, 1890, Guşteriţa 3. **h:** *Undulotheca nobilis* (Reuss, 1868), Guşteriţa 2, dorsal view. **i:** *U. nobilis* (Reuss, 1868), Guşteriţa 3, lateral view. **j:** *Undulotheca halavatsi* Gorjanović-Kramberger, 1901, Guşteriţa 3, dorsal view. **k:** *C. banatica*-dominated coquina-like accumulations on a bedding plane, note the orientation of the specimens, collection of the Brukenthal Museum, Sibiu, inventory number: 48.892. **l:** *Velutinopsis velutina* (Deshayes, 1838), collection of the Brukenthal Museum, Sibiu, inventory number: 48.919, dorsal view.

southern Caspian Basin (Gofman, 1966; Boomer et al., 2005). *Euxinocythere* is not only known from brackish environment but also tolerates freshwater littoral to deep limnic conditions (e.g. Pipík and Bodergat, 2004; Czicz

et al. 2008). Recent *Hemicytheria* and *Loxoconcha* live mainly on algae in the littoral zone (Puri et al., 1969), and their fossil representatives are known from mesohaline lacustrine environments (Gross, 2002; Witt, 2010). The

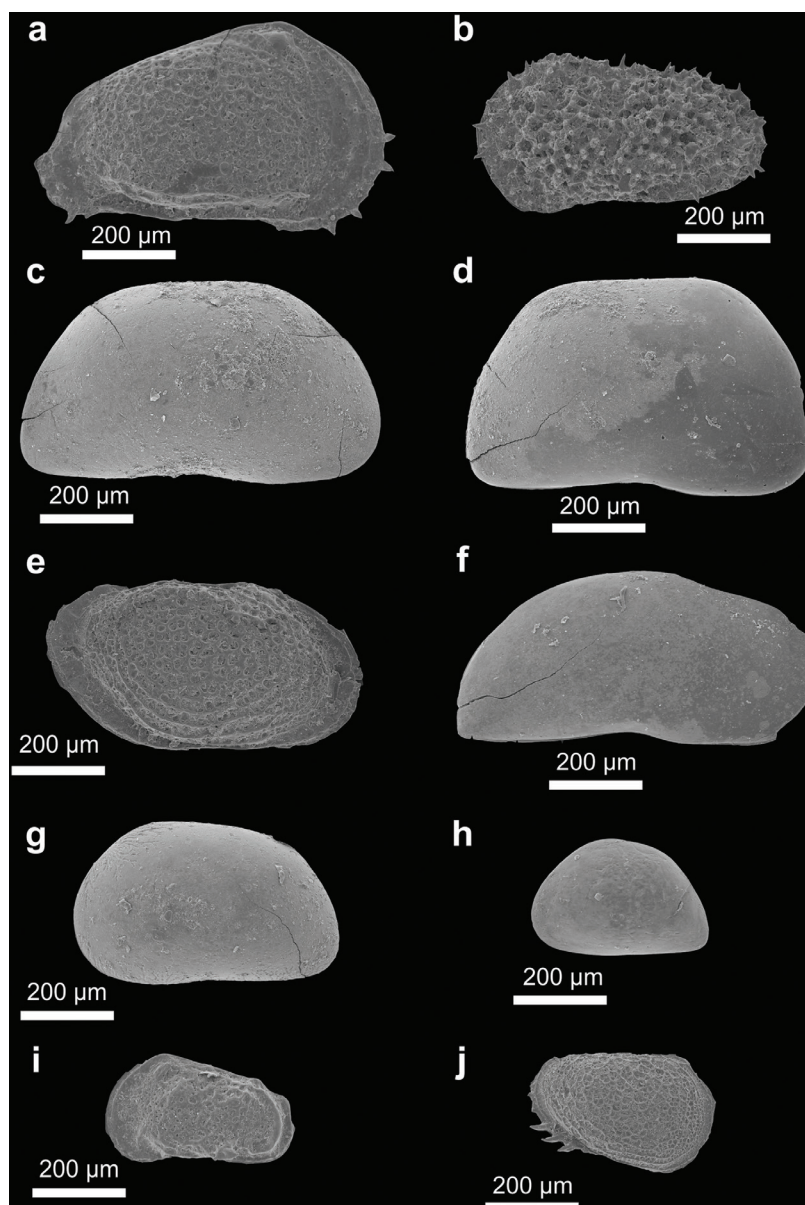


Figure 4: Pannonian ostracods from the Gušterița quarry. Abbreviations: LV = left valve and RV = right valve. **a:** *Hemicytheria croatica* Sokač, 1972, RV in lateral view, sample G25. **b:** *Euxinocythere naca* (Méhes, 1908), LV in lateral view, sample G12. **c:** *Candona (Thaminocypris) aspera* (Héjjas, 1894), RV in lateral view, sample G06. **d:** *Candona (Thaminocypris) transylvanica* (Héjjas, 1894), RV in lateral view, sample G06. **e:** *Loxoconcha rhombovalis* (Pokorný, 1952), RV in lateral view, sample G25. **f:** *Candona (Propontoniella) sp.*, RV in lateral view, sample G11. **g:** *C. (T.) aspera* juv. (Héjjas, 1894), LV in lateral view, sample G06. **h:** *Candona (Thyphlocypris) sp. juv.*, LV in lateral view, sample G18. **i:** *Leptocythere (Amnicythere) stanchevae* (Krstić, 1973), LV in lateral view, sample G25. **j:** *Loxoconcha granifera* (Reuss, 1850), RV in lateral view, sample G25.

ostracod assemblages of the younger strata indicate meso- to pliohaline (5–16 ‰) sublittoral depositional environment with a few littoral elements transported from the margins. In the uppermost layer (sample G25), nearshore faunal elements become dominant beside the common sublittoral forms.

Two successive ostracod biozones were identified in the studied Gušterița 4 section, based on the system of Krstić (1985): the *Hemicytheria tenuistriata* (samples G1 to G9) and *P. candeo* zones (samples G10 to G25). According to Krstić (1985), the older *E. naca* and *L. rhombovalis* overlap in their stratigraphic ranges with the younger *L. granifera* exclusively within the *H. tenuistriata* and *P. candeo* zones. Within this interval, the first appearance of the species

P. candeo marks the bottom of the *P. candeo* zone (sample G10 in our section). Krstić (1985) also claimed that *C. (Thaminocypris) transylvanica* is restricted to zones older than the *P. candeo* zone. In our material, there is a slight overlap between the stratigraphic ranges of the older *C. transylvanica* and the younger *P. candeo* (samples G10–G14). Nevertheless, we mark the boundary between the older *H. tenuistriata* and the younger *P. candeo* zones between the samples G9 and G10, with the first occurrence of *P. candeo*.

In the system of Krstić (1985), both zones belong to the lower Pannonian Slavonian Substage. The appearance of *H. croatica* was unexpected in the uppermost sample (G25), because this form is the index fossil of the younger

H. croatica zone (Serbian Substage of the Pannonian). This phenomenon requires further discussion, because *H. croatica* was also found by Rundić in ter Borgh et al. (2013) in older “Slavonian” strata in Beočin. The stratigraphic range of *H. croatica* thus seems to be wider than supposed by Krstić (1985), so its stratigraphic marker role should be reconsidered.

4.3 Palynology

The Guşteriţa samples yielded a moderately diverse but excellently preserved dinocyst assemblage and several other aquatic (prasinophytes, acritarchs and green algae) and terrestrial palynomorph groups (spores and pollen) (Fig. 5 and Suppl. S3). The majority of the dinocysts are endemic Pannonian taxa belonging to the genera *Spiniferites*, *Impagidinium* and *Virgodinium* (Fig. 5a–e, j–l and o). The common occurrence of the Badenian–Sarmatian taxa (e.g. *Polysphaeridium zoharyi*, *Cleistosphaeridium placacanthum*, *Melitasphaeridium choanophorum*, *Nematosphaeropsis* sp., *Homotryblium* sp.) indicates the reworking of older Miocene sediments into the lake.

The dinocyst assemblages through the Guşteriţa 4 section have allowed three biozones to be identified. Samples G1–G9 reveal a rich assemblage with *Spiniferites pannonicus* and *Spiniferites oblongus* and are assigned to the *S. oblongus* zone. The zone is characterised by the high abundance of *S. pannonicus* and *S. oblongus* in the Hungarian part of the Pannonian Basin System (PBS), while the zone is defined as ranging from the first appearance date of *S. oblongus* to the first appearance date of *Pontiadinium pecsvaradense* in Croatia (Bakrač et al., 2012). Similar associations are known from the entire PBS and have been recorded from Serbia (Rundić et al., 2011) and Austria (e.g. Kern et al., 2013) as well.

The first occurrence of *P. pecsvaradense* is recorded in sample G10, and it remains common throughout the section with higher abundance ratios in the uppermost samples (G21–G24). The *P. pecsvaradense* biozone is characterised by the common occurrence of the species *P. pecsvaradense* and *P. obesum* together with various proximate cysts, such as *Impagidinium* spp. and *Virgodinium* spp. in Hungary (Sütő-Szentai, 1988, 2000). Bakrač et al. (2012) defined this zone as an interval from the first occurrence of *P. pecsvaradense* to the first occurrence of *Spiniferites bentorii coniunctus* in distal and/or *Spiniferites validus* in proximal settings. In the Guşteriţa 4 section, samples G10–G21 are assigned to the *P. pecsvaradense* zone.

The dinocyst composition of samples G22–G25 is similar to the dinocyst assemblage of the lower part of the *Spiniferites hennersdorfensis* zone (Sütő-Szentai, 1988, 2000; Soliman and Riding, 2017) in Hungary and the distal association of the *S. validus* zone (Sve) in Croatia (Bakrač et al., 2012) by the common occurrence of *Spiniferites* specimens with membranous crests, especially *S. hennersdorfensis*. *S. validus* is not recorded in Guşteriţa, although its absence is explained by the more distal depositional setting in the TB. The Sve zone has a rich and

diverse dinocyst assemblage in distal settings, including membranous *Spiniferites* types, *Spiniferites maisensis*, *S. oblongus*, *P. pecsvaradense* and various *Virgodinium* species (Bakrač et al., 2012), which is a good match for the association in samples G22–G25. It has to be noted though that the differences in dinocyst species composition might be also related to changes in environmental parameters, e.g. salinity variation from incoming river runoff, nutrients and/or hydrodynamic conditions suggesting slightly different environmental conditions for the uppermost part of the section.

4.4 Calcareous nannoplankton

All samples from the Guşteriţa section contain very well-preserved and common calcareous nannoplankton assemblages (Fig. 6). Endemic calcareous nannofossils are represented by the species *Isolithus semenenko*, *Isolithus pavelici*, *Noelaerhabdus jerkovici*, *Noelaerhabdus bozinovicae* and *Praenoelaerhabdus banatensis*. The genus *Isolithus* dominates the assemblages in the lower part of the section, in samples G1–G2, G6–G8, G10–11 and G14 (Fig. 6j, o and q). In contrast, the upper part of the section (samples G14–G25) is characterised by the dominance of *Noelaerhabdus*, which occurs in increasing number from G4 to the top of the section (Fig. 7), reaching the highest values in samples G21 (97.8%) and G24 (86.3%). Species of genus *Noelaerhabdus* are characterised by possession of a central spine placed vertical on the basal plate. The shape ending of the central spine is a crucial feature for distinguishing various species within the genus. Upon this criterion, all *Noelaerhabdus* specimens from the Guşteriţa 4 section can be assigned to *N. bozinovicae* and *N. jerkovici*. During preparation, the central spine was usually broken, and the original shape of fossils could not be always reconstructed. Therefore, coccoliths without spine were counted separately (*Noelaerhabdus* spp.) from coccoliths with spine. This group also included endemic nannofossils described as *P. banatensis*. Coccoliths with spine in the central field (*N. bozinovicae* and *N. jerkovici*) were grouped in *Noelaerhabdus* spp. and subdivided into three morphotypes according to the length of the spine: 3–7 µm, 7–15 µm and >15 µm (Suppl. S4). In assemblages from the middle and upper parts of the section, *Noelaerhabdus* spp. with longer spine (7–15 µm and >15 µm) dominated. These changes in the length of the spine can be caused by changes in the palaeoecological conditions. Blooms of ascidian spicules (*Perforocalcinella fusiformis*) in samples G2–G5 and G13 and in high amounts in samples G13, G16 and G20–G21 may point to periods when sediment transport was more effective.

Non-endemic Miocene calcareous nannofossils are represented by taxa, which have their first occurrence in the early/middle Miocene and the last occurrence in the upper Miocene/Pliocene. Among them, *Coccolithus pelagicus* and *Reticulofenestra pseudoumbilicus* are common, and they are accompanied by *Calcidiscus leptoporus*, *Helicosphaera carteri*, *Helicosphaera wallichi*, *Sphenolithus heteromorphus*, *Umbilicosphaera jafari*, *Umbilicosphaera*

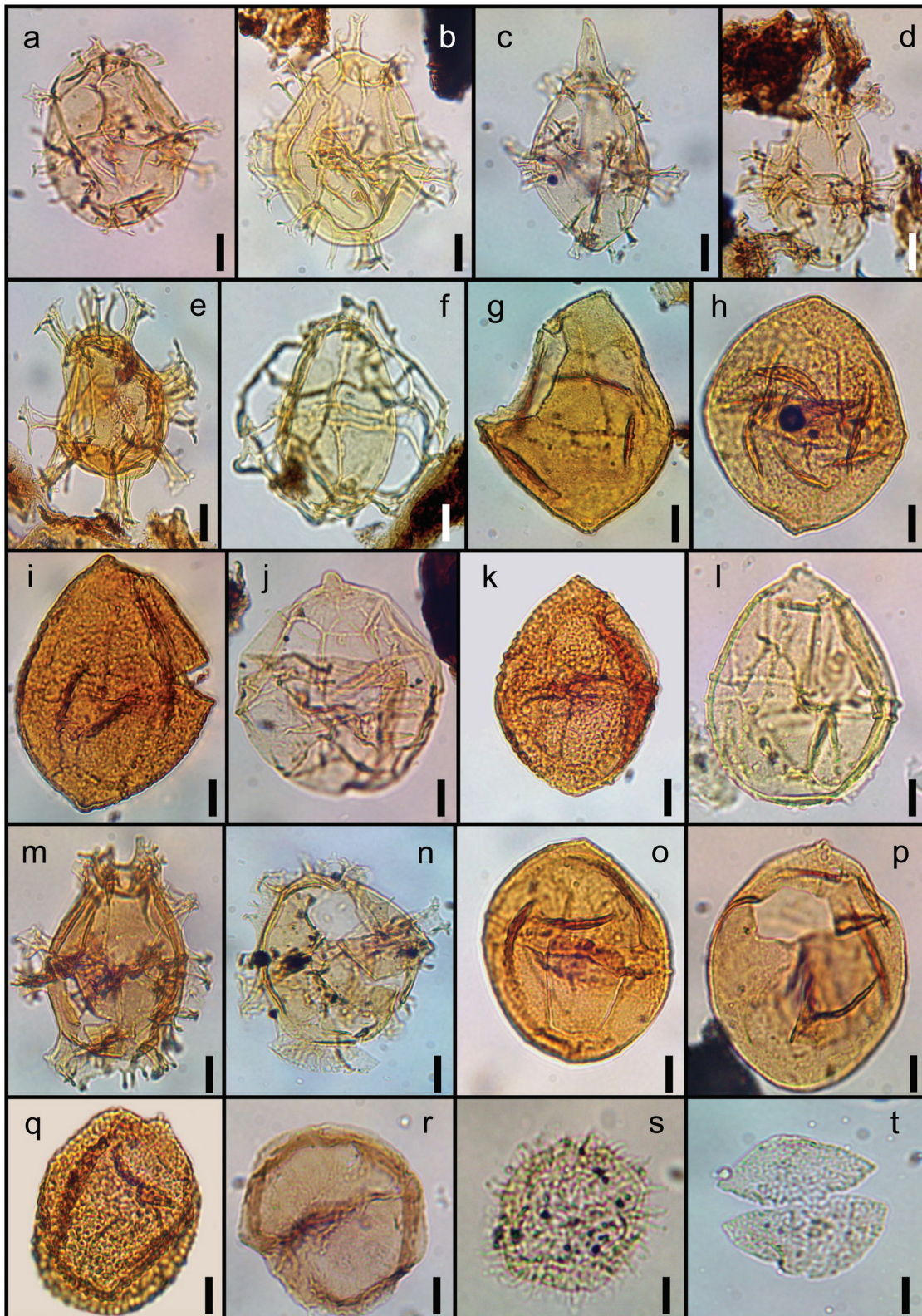


Figure 5: Photomicrographs of selected organic-walled microplankton from the Guşteriţa 4 section. Each scale bar represents 10 μ m. Sample and slide numbers are indicated in the brackets. **a:** *Spiniferites pannonicus* (Sütőné Szentai, 1986; Soliman and Riding, 2017), lateral view (G1/1). **b:** *S. pannonicus*, lateral view (G4/1). **c:** *Spiniferites oblongus* (Sütőné Szentai, 1986; Soliman and Riding, 2017), right lateral view (G24/2). **d:** *S. oblongus*, right lateral view (G10/1). **e:** *Spiniferites maisensis* (Sütő Zoltánné, 1994), right lateral view (G14/2). **f:** *Nematosphaeropsis bicorporis* (Sütő-Szentai, 1990), right lateral view (G14/1). **g:** *Pontiadinium pecsvaradense* (Sütőné Szentai, 1982), right lateral view (G10/1). **h:** *Pontiadinium obesum* (Sütőné Szentai, 1982), lateral view (G25/2). **i:** *P. pecsvaradense*, lateral view (G17/2). **j:** *Virgodinium asymmetricum primus* (Sütő-Szentai, 1988; Sütőné Szentai, 2010), lateral view (G1/1). **k:** *Virgodinium pelagicum* (Sütőné Szentai, 1982; Sütőné Szentai, 2010), lateral view (G10/1). **l:** *V. asymmetricum primus*, lateral view (G6/1). **m:** *Spiniferites hennersdorfensis* (Soliman and Riding, 2017), lateral view (G17/2). **n:** *S. hennersdorfensis*, lateral view (G21/1). **o:** *Impagidinium spongianum* (Sütő-Szentai, 1985), lateral view (G15/1). **p:** *Bitectatodinium tepikiense* (Wilson, 1973) (G20/1). **q:** *Chytroeisphaeridia tuberosa* (Sütőné Szentai, 1982) (G2/1). **r:** *Selenopemphix* sp. (G5/1). **s:** Indeterminate palynomorph (HdV type 128 van Geel) (G2/1). **t:** *Mendicodinium mataschenensis* (Soliman and Feist-Burkhardt, 2012), dorsal view (G2/1).

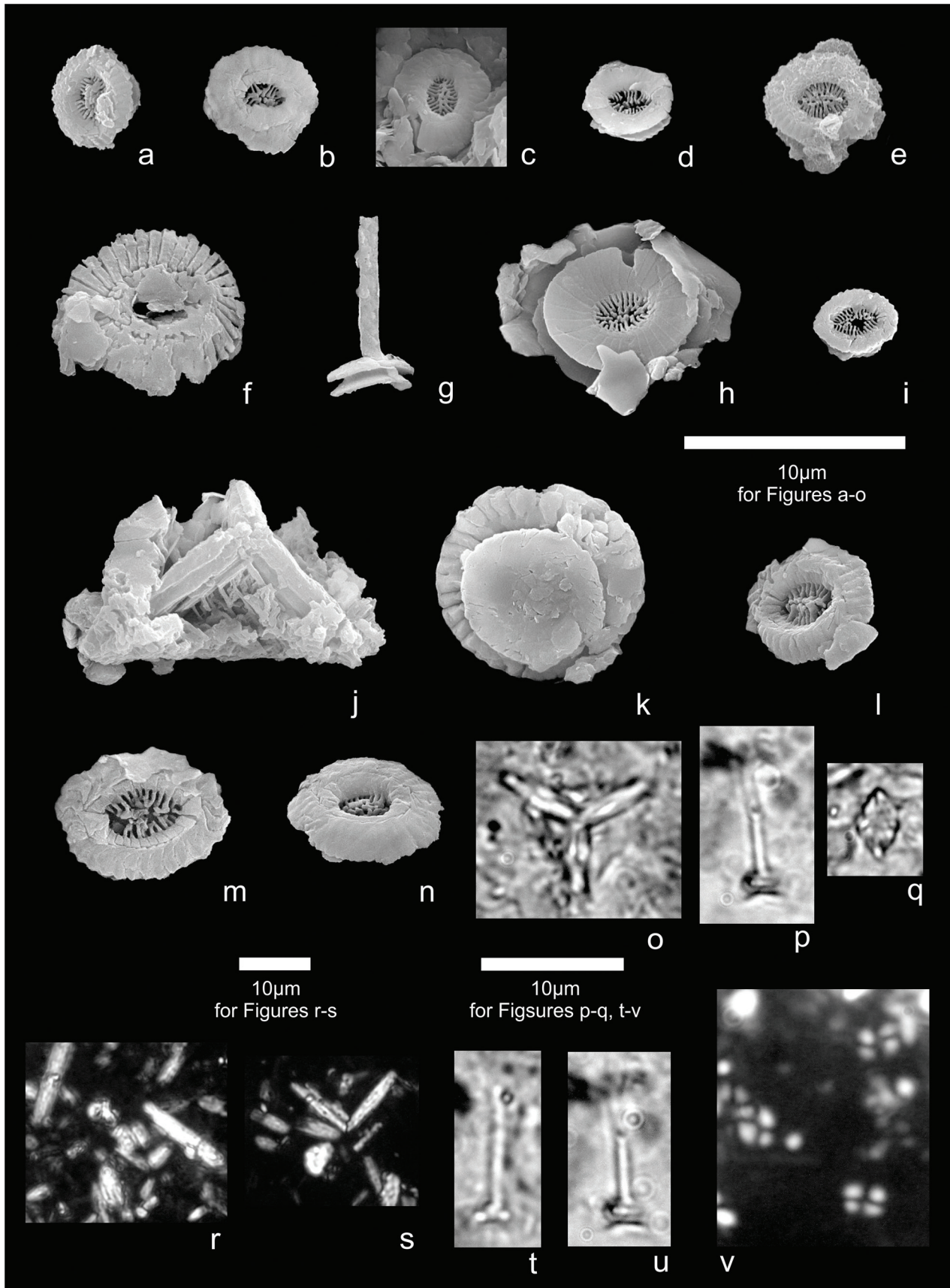


Figure 6: Calcareous nannoplankton from the Gușterița 4 section. **a–e, h–i, l–n** and **v**: *Praenoelaerhabdus banatensis* (Mihajlovic, 1993) (1–5 and 8–9: sample G23; 12–14 and 22: sample G25). **f**: *Coccolithus pelagicus* (Wallich, 1877; Schiller, 1930), sample G12. **g** and **t**: *Noelaerhabdus bozinovicae* (Jerkovic, 1970), sample G25. **j** and **o**: *Isolithus semenenko* (Ljul'eva, 1989), sample G10. **k**: *Calcidiscus leptoporus* (Murray and Blackman, 1898; Loeblich and Tappan, 1978), sample G20. **p** and **u**: *Noelaerhabdus jerkovici* (Bóna and Gál, 1985), sample G23. **q**: *Isolithus pavelici* (Čorić, 2006), sample G10. **r–s**: *Perforocalcinella fusiformis* (Bóna, 1964) (18: sample G4 and 19: sample G5).

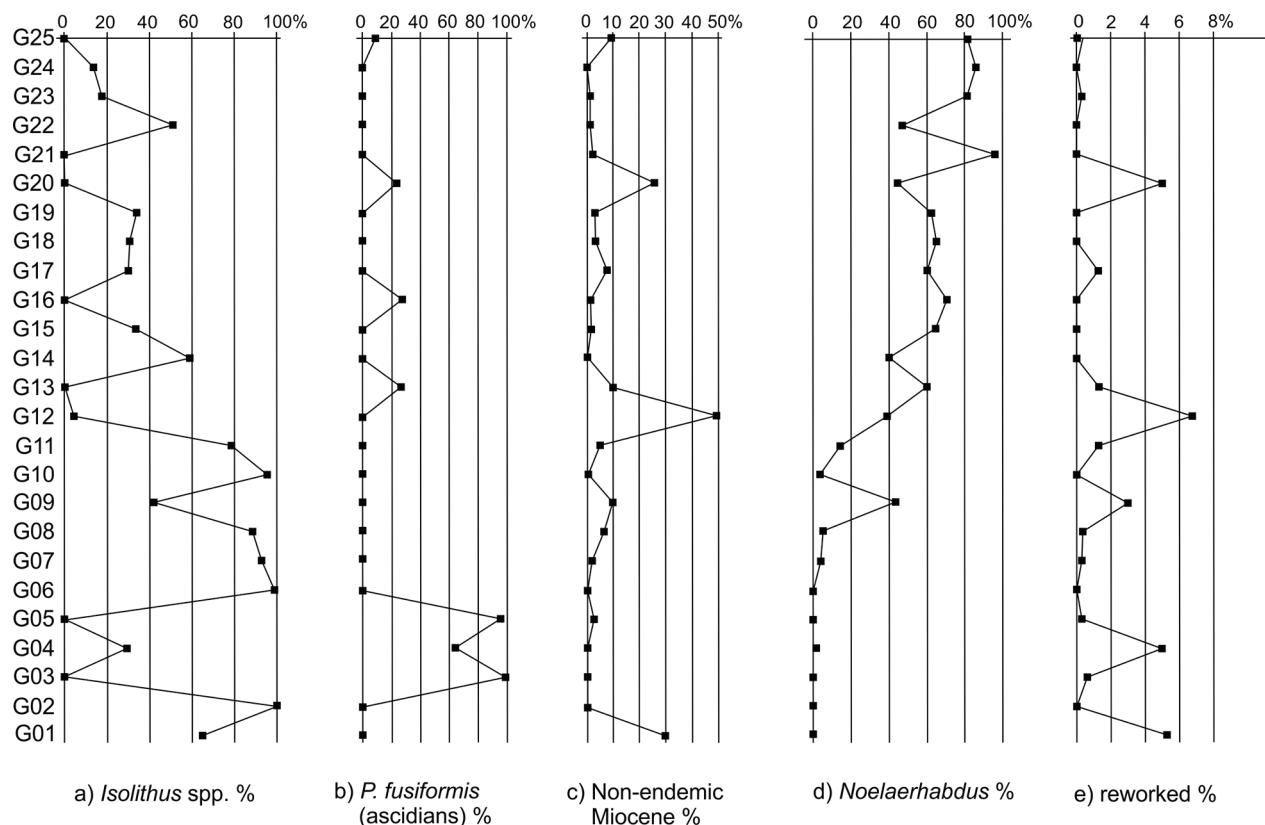


Figure 7: Distribution and ratio of calcareous nannoplankton taxa within the Gușterița 4 section. Numbers indicate the sampling levels (G01 to G25).

rotula, etc. Non-endemic (normal marine) Miocene nannofossils are common in sample G1 (30.7%), but then absent in the lower part of the section (samples G2–G4), reaching a maximum in sample G12 with 49.8%. The occurrence of these species is varying throughout the section (Fig. 7). Most of the clearly redeposited nannofossils are from the Cretaceous (*Micula stauropora*, *Watznaueria barnesiae*, etc.), Eocene/Oligocene (*Reticulofenestra umbilicus*, *Cribocentrum reticulatum*, etc.) and lower/middle Miocene (*S. heteromorphus*, *Helicosphaera ampliaperata*, etc.) with a maximum in sample G1 (5.4%) (Fig. 7). As all samples contain also plant remains, it seems that all normal marine long-range taxa are reworked too. In addition, there is a correlation between the amount of normal marine long-range forms and the amount of reworked Badenian (NN5) specimens, suggesting that these long-range (non-endemic) nannofossils are also redeposited (Fig. 6f and k).

The correlation between endemic calcareous nannofossils and standard nannofossil zones is still not clear (see Mărușțeanu, 1997; Chira, 2006; Chira and Malacu, 2008). Mărușțeanu (1997) investigated the evolution trends in Pannonian endemic calcareous nannofossils and erected three biozones: *P. banatensis*, *N. bozinovicae* and *Noelaerhadus bonagali* zones. Sediments from the Gușterița clay pit can be attributed to the *N. bozinovicae* zone, based on the presence of *N. bozinovicae*, *N. jerkovici* and the absence of *N. bonagali* in the investigated samples.

4.5 Trace fossils and other remains

During the collection and preparation of molluscs, several remains of other fossil groups were unearthed (Suppl. S2). Two types of trace fossils were frequent. One of them was a few centimeter long residence tube of probably annelid worms, such as *Pectinaria*. This tube was lined (agglutinated) with calcareous shell fragments of tiny animals (ostracods and/or bivalve embryos, shell fragments) or with mineral grains during the life activity of the worm. This trace fossil can be easily recognised by the regular and tight positions of the tiny shells. Jámbor and Radócz (1970) distinguished and described several morphotypes based on the composition of the tubes from drill cores in the PB. We were able to distinguish and identify two of them, *Pectinaria ostracopannonicus* and *Pectinaria gigantea*. The first one was made of almost exclusively carapaces of ostracods (Fig. 8c), and the latter consisted of bivalve embryos and shell fragments (Fig. 8e). Another frequent trace fossil was *Diplocraterion* isp. These appeared as dumbbell-like forms on the bedding planes, but in fact they were U-shaped burrows (Fig. 8d). Their creators were probably crustaceans (Fürsich, 1974).

Fishes are represented by a relatively large number of teeth, a few otoliths and further unidentifiable elements. Teeth of Morphotype 1 are the most characteristic among all. The high, curved base is circular in cross-section, bearing a fine apicobasal striation. The slightly reclined tip is lanceolate and usually translucent. Morphologically identical teeth were published by Brzobohatý and Paně

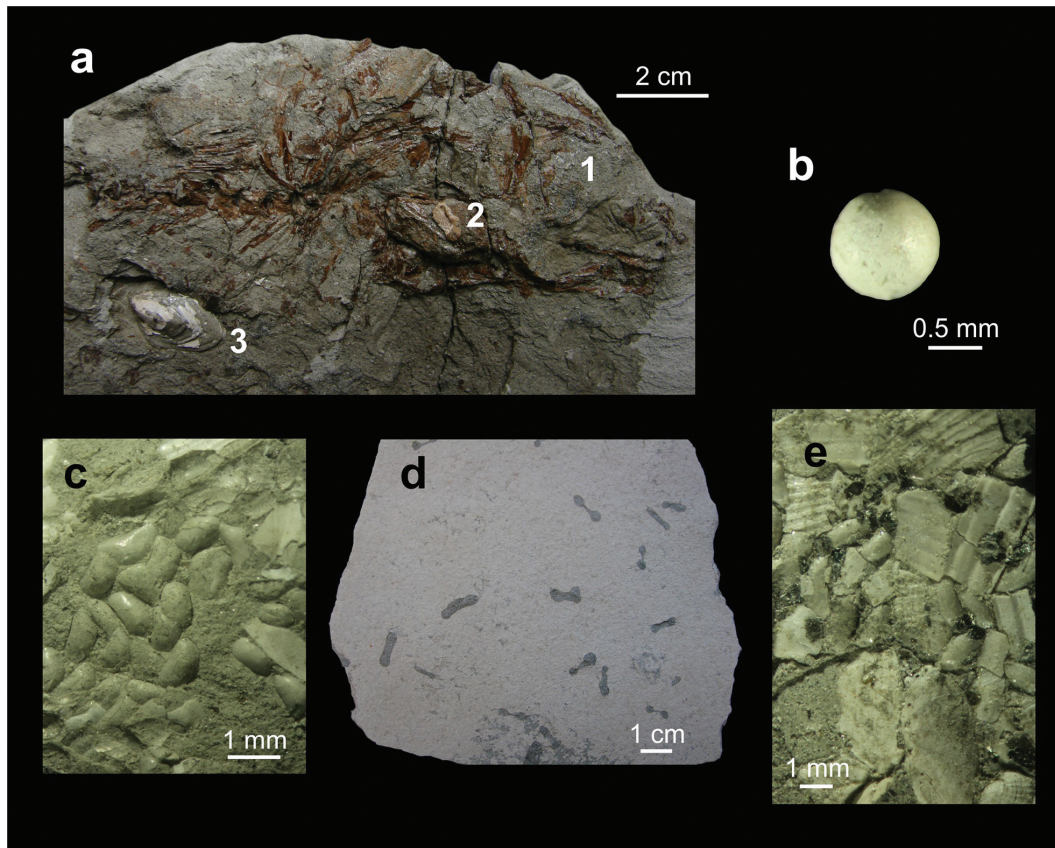


Figure 8: Other fossil remains from the Guşteriţa quarry. **a1:** Partial fish skeleton, **a2:** otolith and **a3:** *Congerina banatica* (R. Hörnes, 1875), Guşteriţa 3. **b:** *Silicoplacentina* cf. *majzoni* Kóváry, 1956, Guşteriţa 2. **c:** *Pectinaria ostracopannonicus* (Jámbor and Radócz, 1970), Guşteriţa 3. **d:** *Diplocraterion* isp., Guşteriţa 3. **e:** *Pectinaria gigantea* (Jámbor and Radócz, 1970), Guşteriţa 2.

(1985) as teeth of indeterminate gadid fishes (Figs. 9a–d). Teeth of Morphotype 2 include simple recurved teeth, circular in cross-section. The small, shiny and smooth cap is separated from the apicobasally striated base (Fig. 9e). Teeth of Morphotype 3 are of simplest morphology. The teeth are minute, narrow and shiny, tapering to the tip, bearing no surface striations. They are also weakly bent to the supposed lingual direction. The taxonomic identification of these isolated teeth is very problematic due to their simple, almost featureless morphology; however, here we tentatively attribute them to family Gadidae or Gobiidae (Fig. 9) (see Brzobohatý and Paná, 1985; Kramer et al., 2009; Berkovitz and Shellis, 2017). These forms frequently occur in late Miocene deposits of the PB. Two generally poorly preserved otoliths were also unearthed, both representing the family Sciaenidae (after Schwarzhans, 1993; Bosnakoff, 2008).

Since the collected fish material is isolated and only hardly identifiable (only at the family level), it is less important regarding the paleoenvironmental reconstructions. Families Gadidae, Gobiidae and Sciaenidae occur in fresh-water, brackish-water and normal marine conditions as well (see Froese and Pauly, 2019). Modern members of Gadidae are found in circumpolar water and temperate water. Most gadid species are demersal or benthopelagic, feeding mainly on fish and invertebrates. Extant gobiids are distributed mostly in tropical water

and subtropical water (Froese and Pauly, 2019). Recent Sciaenidae members are generally bottom-dwelling fish, living in the neritic zone of temperate and warm shallow seas and estuaries, playing a key role in estuarine ecosystems (Carnevale et al., 2006).

In the micropalaeontological samples, plant remains, bone fragments, fish scales, fish vertebra and thecamoebians were common together with some reworked older Miocene fossils (foraminifers and bryozoans). During the preparation process, a specimen of a regular, oval thecamoebian, similar to *Silicoplacentina majzoni* (Kóváry, 1956; Fig. 8b), and a partial fish skeleton (Fig. 8a) were found in the Guşteriţa 2 section.

4.6 Magnetostratigraphy

From the Guşteriţa 4 section, two types of palaeomagnetic measurements (TH demagnetisation and AF demagnetisation) were performed on 26 samples. Suppl. S5 contains the results of TH measurements, while Suppl. S6 includes the outcomes of AF measurements.

The investigated samples had good magnetic characters; thus, only one quality group was created. We chose four TH samples to figure them on Zijdeveld diagrams. Two different T-sessions were separated (T1: orange and T2: black) based on the measured values (Fig. 10a–d).

A total of 24 samples were chosen for AF measurements. We chose four AF samples to figure them on Zijdeveld

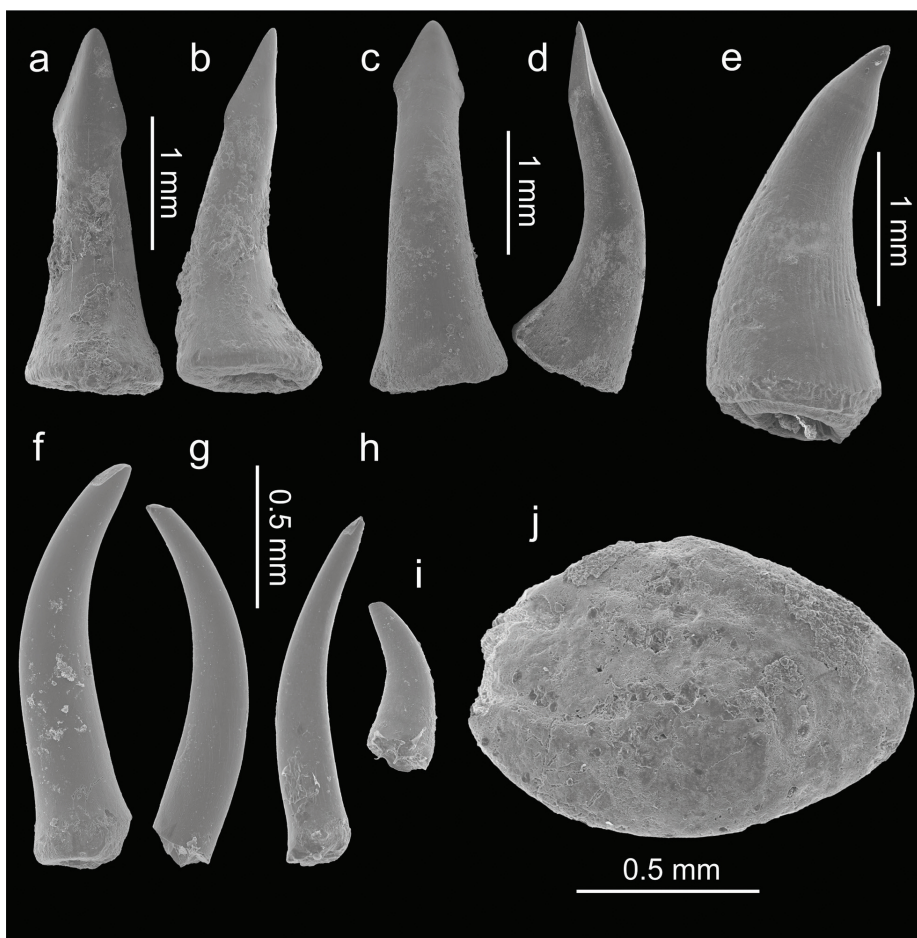


Figure 9: Fish teeth and otolith from the Gušterița quarry. **a–d:** Fish tooth morphotype 1 (Gadidae). **e:** Fish tooth morphotype 2 (Gadidae or Gobiidae). **f–h:** Fish tooth morphotype 3 (Gadidae or Gobiidae). **i:** Sciaenidae otolith (inner face).

diagrams. Two different F-sessions were separated (F1: orange and F2: black) based on the measured values (Fig. 10e–h). In the case of some samples, gyroremanent magnetisation was observed, which means the effect of increased random direction that can happen above 35 mT (Fig. 10e and g). Owing to this phenomenon, the given sample could not be properly demagnetised. It usually predicted the presence of greigite (Fe_3S_4) in the sample (Babinszki et al., 2007); however, no rock thermomagnetic analyses were carried out.

All the results show normal polarity for the entire section, i.e. all the samples gave positive inclination and declination values above 270° (Suppl. S5–S6). It must be tested whether this normal polarity is in the primary or near-primary direction and may be used for correlation to the global time scale. To check if they represent a present-day overprint, the mean inclination and declination of the samples were compared to the present-day magnetic field in the study area. Present-day magnetic field values were the following on the day of sampling at the locality: declination 5.467° and inclination 63.004° . The mean inclination of the samples was clearly different from the present-day field direction, and thus interpreted as a sub-recent viscous component; however, the mean declination was similar to the present-day value.

The palaeomagnetic signal was interpreted as primary or penecontemporaneous with deposition.

4.7 Authigenic $^{10}\text{Be}/^9\text{Be}$ dating

The initial ratio, which is essential for the age calculation, could be determined either by the analysis of recent equivalents of the studied depositional environment or by independent dating of a sample taken from the same basin and depositional environment. In first calculations of this study, the lacustrine initial ratio $(6.97 \pm 0.14) \times 10^{-9}$ ($R_{0-\text{lacus}}$) from Šujan et al. (2016) was applied providing ages apparently slightly older compared to the biostratigraphic age proxies (Table 1). Hence, to test the validity of the lacustrine initial $^{10}\text{Be}/^9\text{Be}$ ratio, it was decided to calculate independently the initial ratio relevant to the eastern part of Lake Pannon. The ODM “A” outcrop, which is located in the central TB and represents an equivalent of the Gušterița locality in terms of depositional environment, contained a tuff layer dated at 11.62 ± 0.12 Ma by the $^{40}\text{Ar}/^{39}\text{Ar}$ method (Vasiliev et al., 2010). Two samples (ODM) were taken from a horizon above the tuff layer. The sample ODM-28 was chosen for the calculation of the initial ratio due to its proximity to the tuff horizon. Its estimated age was 12.05 ± 0.9 Ma based on the $R_{0-\text{lacus}}$. The resulting initial $^{10}\text{Be}/^9\text{Be}$ ratio ($R_{0-\text{ODM}}$) of $(5.61 \pm 0.41) \times$

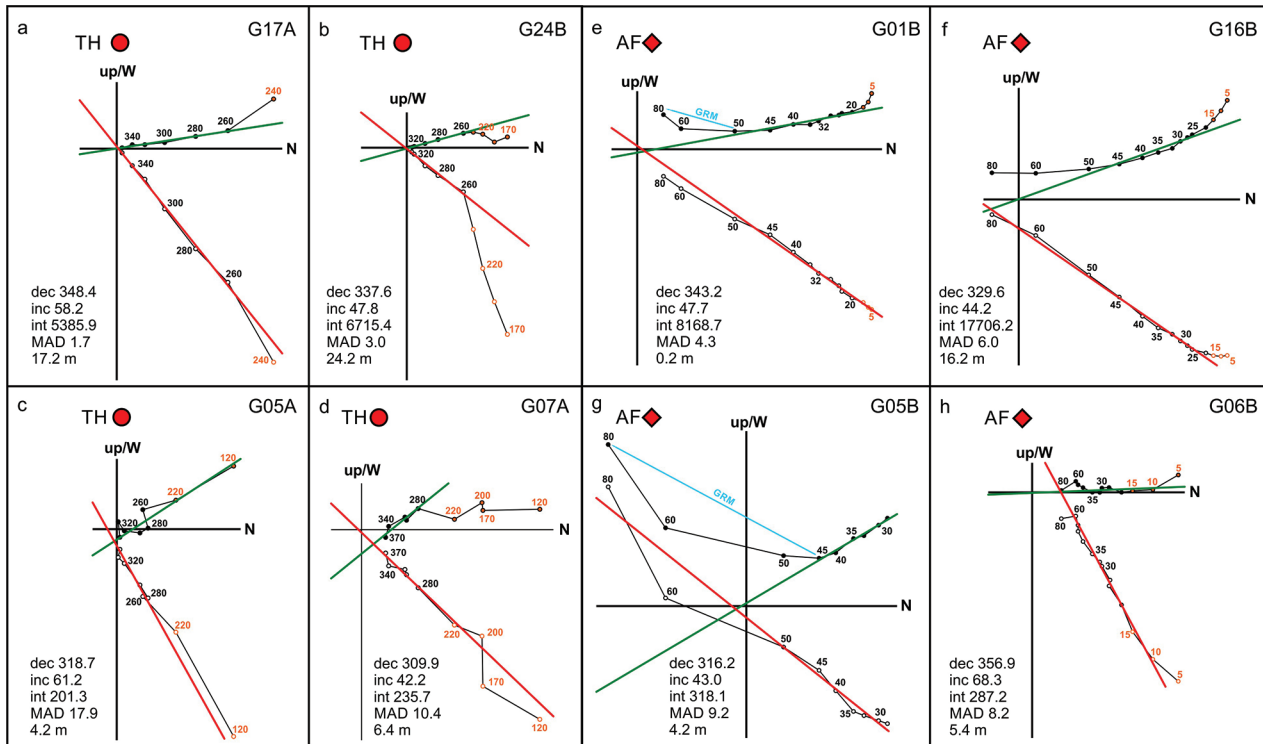


Figure 10: Zijderveld diagrams of the TH and AF demagnetisation results from the Guşteriţa 4 section. Orange numbers and points mark the T1 (F1) phase. Black numbers and points indicate the T2 (F2) phase. Sample numbers are indicated in the right upper corners. Filled dots are declination values. Empty dots are inclination values. Lowermost numbers mean stratigraphic levels. Green lines are regression lines fitted to the T2 (F2) declination values. Red lines are regression lines fitted to the T2 (F2) inclination values. Abbreviations: TH: thermal, AF: alternating field, N: north, W: west, dec: declination, inc: inclination, int: intensity, MAD: maximal angular deviation and GRM: gyroremanent magnetisation.

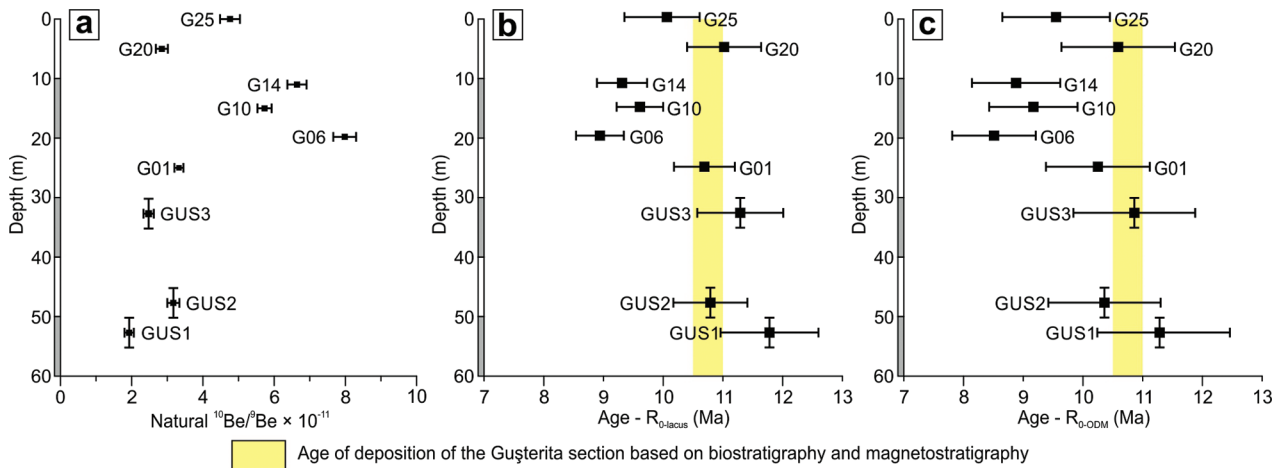


Figure 11: Results of the authigenic $^{10}\text{Be}/^{9}\text{Be}$ isotopic measurements of the Guşteriţa clay pit. **a:** Depth chart of the natural $^{10}\text{Be}/^{9}\text{Be}$ ratios of the measured samples. **b:** Depth chart of the age R_0 -lacus data (Ma), estimated with the help of an initial lacustrine isotopic ratio. **c:** Depth chart of the age R_0 -ODM data (Ma), estimated with the help of the $^{40}\text{Ar}/^{39}\text{Ar}$ age of the Oarba de Mureş tuff. Age of deposition based on biostratigraphy and magnetostratigraphy of the Guşteriţa section is marked with yellow stripes.

10^{-9} was then used for the age calculations of all samples taken from the Guşteriţa locality.

The authigenic $^{10}\text{Be}/^{9}\text{Be}$ ages of the samples from the Guşteriţa outcrop were calculated using both the initial ratio determined by Šujan et al. (2016) for lacustrine facies ($R_{0\text{-lacus}}$) and the new initial ratio based on the ODM sample ODM-28 ($R_{0\text{-ODM}}$) (Table 1 and Fig. 11). Two groups of samples could be distinguished. Six samples (GUS1,

GUS2 and GUS3 from Guşteriţa 1, 2 and 3 sections and samples G01, G20 and G25 from the Guşteriţa 4 section) attained ages in agreement with other geochronological proxies with a weighted mean age of 10.83 ± 0.26 Ma using $R_{0\text{-lacus}}$ and 10.42 ± 0.39 Ma using $R_{0\text{-ODM}}$. These two ages are statistically identical within uncertainties. We consider the ages calculated by the local initial ratio ($R_{0\text{-ODM}}$) to be the best estimates of the deposition age of

the sediment succession at Guşteriţa; thus, these are discussed in the following.

The remaining three samples (G06 to G14 from the Guşteriţa 4 section), however, exhibited higher isotopic ratios and yielded ages between 9.17 ± 0.74 Ma and 8.51 ± 0.70 Ma (R_{0-ODM}). The estimated age of these samples overlapped within uncertainties with a weighted mean of 8.84 ± 0.42 Ma (N_{0-ODM}), considerably younger than the mean age calculated using the other six samples.

5. Discussion

5.1 Depositional environment

The abundant and diverse benthic life, represented by the body and trace fossils of the Guşteriţa outcrop, indicates oxygen-rich bottom conditions. Sand intercalations and the silt grain size suggest weak, but continuous flows, probably events of low-density turbidity currents, which maintained the permanent dissolved oxygen level. The occurrence of partial fish skeletons may indicate short periods of dysoxia, but there seems to be no disturbance in the permanent benthic life.

The recovered fossil fish fauna refers to a warm to temperate water. It is composed of euryhaline taxa (tolerating a wide range of salinities) with variable habitat preferences.

The mollusc and ostracod fauna consist of mostly deep-water or offshore species that live well below the storm wave base as suggested by their very thin shells. Extant relatives of some of the ostracod taxa live at salinities of 11.5–13.5‰ in sublittoral to profundal depths of the central and southern Caspian Basin. Based on the available and observed sedimentological and faunal characteristics, the depositional environment of the locality could be around the toe of slope (Kr zsek et al., 2010).

5.2 Biostratigraphy

In general, the early Pannonian mollusc fauna is quite uniform across the PBS, suggesting that a large lake existed in the intra-Carpathian region at the beginning of the Pannonian (late Miocene). The overall appearance of the TB fauna shows great similarity to the early Pannonian mollusc fauna of northern Croatian and northern Serbian outcrops, e.g. Vrap e (Gorjanovi -Kramberger, 1890), Lond ica (Gorjanovi -Kramberger, 1899), Kostanjek/Podsused (Vrsaljko, 1999), Beo in (Stevanovi  and Papp, 1985; ter Borgh et al., 2013) and drilling cores from Hungary, e.g. Lajoskom rom-1 (J mbor et al., 1985).

In the early Pannonian offshore sediments of the TB, two clearly different mollusc assemblages occur. The older one is the *L. praeponticum* assemblage, which contains small-sized pioneer mollusc species, such as *L. praeponticum*, *Gyraulus vrapceanus*, *G. tenuistriatus*, *Gyraulus praeponticus*, *O. levis* and *Orygoceras fuchsi brusinaei*. A similar association is present in the entire PBS, probably representing a short time interval and a relatively deep- (sublittoral or profundal) and brackish-water

stressed environment. This assemblage is only found at some localities in the central and eastern parts of the TB (Sztan  et al., 2005; Magyar, 2010). The younger assemblage is the *C. banatica* association, which indicates profundal water depth and a stable environment, and it can be found in the entire PBS as well. Characteristic species of the *C. banatica* biozone are the dominant *C. banatica*; thin-shelled cardiids, such as *P. lenzi* and *P. syrmiense*; *L. undatum*; pulmonate gastropods, such as *G. tenuistriatus* and *G. praeponticus*; the tiny scaphopod-like *Orygoceras*; *Micromelania* and lymnaeid snails. The index fossil of the youngest profundal Pannonian mollusc zone in the PBS, "*Dreissenomya*" *digitifera*, has not been recovered from the TB so far (Fig. 12).

The age of the *C. banatica* zone was assessed by correlation with dinoflagellate and polarity zones in various locations (Magyar et al., 1999b; ter Borgh et al., 2013). Lying directly above the very thin, basal Pannonian (i.e. basal upper Miocene, <11.6 Ma) *L. praeponticum* or *R. croatica* zone, the bottom of the *C. banatica* zone can be dated as ca. 11.4 Ma, whereas its top is younger than the top of C5n chron (9.7 Ma), so it is ca. 9.6 Ma (Fig. 12).

Pannonian ostracods have been poorly documented from the TB. The published data were mainly taxon lists with a brief biostratigraphic evaluation (Chint uan, 1971; Clichici et al., 1980; Popescu et al., 1995; Filipescu, 1996; Filipescu et al., 2011; de Leeuw et al., 2013). The first Pannonian ostracod assemblages, however, were described as early as in the 19th century (H jjas, 1894). The most comprehensive work was published by Kov cs et al. (2016) from the western margin of the TB (G rbova de Jos, G rbovi a, Mihal , T u, Cun a, and ODM) with a detailed study of biostratigraphic and palaeoecological distributions.

The biostratigraphic subdivisions based on ostracods are different within the territory of Lake Pannon, depending on the local character of the depositional environment (e.g. Pokorn y, 1944; Kollmann, 1960; Soka , 1972; Krsti , 1985; Ji i ek, 1985; Szuromi-Korecz, 1992; Olteanu, 2011; Rundi  et al., 2011). In the TB, no comprehensive ostracod zonation has been established yet; therefore, various biostratigraphic schemes were applied at different localities (cf. Filipescu, 1996; de Leeuw et al., 2013; Kov cs et al., 2016). In this study, we tentatively use the most detailed Pannonian biozonation, erected by Krsti  (1985) in the southern part of the PB, which takes into consideration some basic differences in the depositional environment. Data on the numerical ages of these zones, however, are not available in the literature.

Organic-walled microplankton assemblages, in particular dinocysts, are extensively used for the biostratigraphic subdivision of late Miocene sediments in the PBS. Dinocysts are the hypnozygotic resting cysts of the dinoflagellates representing a eukaryotic plankton group (Fensome et al., 1996). The majority of the late Miocene dinocysts from the PBS are endemic taxa that originate from marine dinocysts (e.g. Soliman and Riding, 2017). The brackish-water conditions of Lake Pannon initiated

Age (Ma)	Stage	Magnetic polarity	Magnetic chron	Mammal biozones	Biozones of Lake Pannon deposits			
					Organic-walled microplankton	Molluscs	Ostracods	Calcareous nannoplankton
6	Messinian		C3r	MN13	<i>Galeacysta etrusca</i>	„ <i>Dreissenomya digitifera</i> ”	?	?
7			C3An					
7			C3Ar	MN12				
8			C3B					
8	Tortonian		C4n	MN11	<i>Spiniferites validus</i>			
9			C4r					
9			C4An	MN10	<i>Spiniferites hennersdorfensis</i>		<i>Typhlocyprella lineocypriformis</i>	<i>Noelaerhabdus bonagali</i>
10			C4Ar					
10			C5n	MN9	<i>Pontiadinium pecsvaradense</i>	<i>Congeria banatica</i>	<i>Propontoniella candeo</i>	<i>Noelaerhabdus bozinoviciae</i>
11			C5r					
11			C5r	MN7-8	<i>Spiniferites oblongus</i>		<i>Hemicytheria tenuistriata</i>	<i>Praenoelaerhabdus banatensis</i>
					<i>Spiniferites pannonicus</i>			
					<i>Mecsekia ultima</i>			
						<i>Lymnocardium praeponticum</i>		
							<i>Hemicytheria loerentheyi</i> & <i>H. hungarica</i>	

Figure 12: State-of-the-art stratigraphic chart of Lake Pannon deposits, with magneto-, mammal, organic-walled microplankton, mollusc, ostracod and calcareous nannoplankton stratigraphy. Some organic-walled microplankton zone names are changed based on the revision of Soliman and Riding (2017). Biozone boundaries indicated by dashed lines are uncertain. Highlighted zones are recognised in the fossil assemblages of the Guşteriţa clay pit (modified after Magyar and Geary, 2012).

a remarkable radiation among organic-walled dinoflagellates after the connection to the Eastern Paratethys and the Mediterranean region ceased around 11.6 Ma ago. Most of the newly emerged Pannonian taxa are exclusively known from the Central Paratethyan areas, the late Miocene sedimentary successions of the PBS and the Pliocene of the Dacian Basin in Romania, but some of them (e.g. *Spiniferites cruciformis*) are closely related to dinocysts occurring in the Pliocene–Pleistocene of the Black Sea and the Caspian Sea (e.g. Richards et al., 2018). The rapid morphological changes formed the basis of several regional biozonation schemes developed for the Hungarian and Croatian parts of the PBS (e.g. Sütő-Szentai, 1988, 2000; Bakrač et al., 2012). The biozonation is primarily based on the different morphological variants of the *Spiniferites* Mantell, 1850 complex. The endemic nature of these dinocyst assemblages prohibits correlation to the Miocene–Pliocene dinocyst zones of the Mediterranean region or beyond (Magyar and Geary, 2012). Similarly, the taxonomy of Lake Pannon dinocysts is not without its problems due to the varied morphology of the cysts and is currently under revision (e.g. Soliman and Riding, 2017; Mudie et al., 2018). Here, the nomenclature of Sütő-Szentai (1988, 2000) updated with the most recent taxonomical developments from Soliman and Riding (2017) is applied. In particular, the term *Spiniferites paradoxus* zone of Sütő-Szentai (1988, 2000) is eliminated and changed to *S. hennersdorfensis* zone since *S. paradoxus* was renamed (Soliman and Riding, 2017).

The *S. oblongus* zone is correlated to the upper part of C5r polarity zone and the lower part of C5n polarity zone indicating an age of ca. 11.3–10.8 Ma for the entire biozone from the Hungarian part of the PBS (Magyar et al., 1999b; Magyar and Geary, 2012). The overlying *P. pecsvaradense* zone is magnetostratigraphically correlated to C5n chron (Magyar et al., 1999b). This zone is usually thin, representing a relatively short time interval in the Hungarian and Croatian parts of the PBS; therefore, it was tentatively dated between 10.8 and 10.6 Ma (Magyar and Geary, 2012). The base of the *S. hennersdorfensis* zone (former *S. paradoxus* zone) cannot be younger than the Pannonian sequence of the name-giving Hennersdorf outcrop. The age of the latter was estimated by Harzhauser et al. (2004) as 10.3–10.4 Ma based on the vertebrate fauna of Hennersdorf, Vösendorf and Inzersdorf (Daxner-Höck in Harzhauser et al., 2004) and cyclostratigraphic considerations (Harzhauser et al., 2008). Data on the numerical ages of endemic nannoplankton biozones have not been published yet.

5.3 Dating and integrated stratigraphy

In the TB, the age of both the oldest and the youngest Pannonian sediments is debated. Based on magnetostratigraphic correlations, Vasiliev et al. (2010) dated the Sarmatian–Pannonian boundary at 11.3 Ma, and de Leeuw et al. (2013) suggested an age of 8.4 Ma for the youngest erosional top of the Pannonian.

In the central part of the TB, however, where the Sarmatian–Pannonian boundary is characterised by continuous

sedimentation in deep water (Sztanó et al., 2005; Sütő and Szegő, 2008; Filipescu et al., 2011), the 11.62 and 11.65 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age data gained from an andesitic tuff from the uppermost part of the more than 1-km-thick Sarmatian at ODM (Vasiliev et al., 2010) is a very solid argument in favour of a ca. 11.6-Ma-old boundary (similar to other parts of the PBS established by e.g. Paulissen et al., 2011 and ter Borgh et al., 2013). The 8.4 Ma age is based on the combination of palaeomagnetic measurements from Viforoasa and Țoimușu Mic and seismic stratigraphy (de Leeuw et al., 2013), but for the time being, no fossil remains younger than 9.0 Ma and no deep-water fauna younger than 9.6 Ma are known from the TB to confirm this hypothesis.

Although we are aware that the chronostratigraphic value of Lake Pannon biozones requires further testing and confirmation in the future, here we use them as biochronozones with supposedly synchronous boundaries across the entire PBS. The mollusc record of the Gușterița outcrop indicates the *C. banatica* zone (11.4–9.6 Ma, according to Magyar and Geary, 2012). The presence of the *S. hennersdorfensis* zone in the uppermost layers of the Gușterița outcrop indicates that the top of the Gușterița sequence cannot be younger than 10.5 Ma, because the long-known and well-studied Pannonian sublittoral clays representing the *S. hennersdorfensis* zone at Vienna (Soliman and Riding, 2017) have recently been dated between 10.5 and 10.3 Ma (Harzhauser et al., 2004, 2008).

All magnetostratigraphic samples from the Gușterița 4 section show normal polarity, i.e. positive inclination values and declination values more than 270° . This signal may be the primary palaeomagnetic component according to the inclination values. Based on the biostratigraphic data mentioned earlier, the section can be correlated with the C5n.2n normal polarity magnetic chron (11.056–9.984 Ma; ATNTS2012 – Hilgen et al., 2012) (Fig. 13).

The authigenic $^{10}\text{Be}/^9\text{Be}$ dating of the GUS1-3, G01, G20 and G25 samples gave a weighted mean age of 10.42 ± 0.39 Ma (N_{0-ODM}), indicating that the outcrop is younger than 11 Ma. The considerable scatter (0.61 Ma) of the ages did not enable to identify a trend of increasing age with depth. This is indicative of sedimentation rates at which the age difference between the bottom and top of the studied succession remains within the uncertainties of the authigenic $^{10}\text{Be}/^9\text{Be}$ method.

Authigenic $^{10}\text{Be}/^9\text{Be}$ ratios of the three samples from Gușterița 4 (G06 to G14) differ from the remaining samples (Fig. 11). This discrepancy might be explained by a change in the initial isotopic ratio within the depositional environment or by a post-depositional transport of beryllium isotopes. The basin floor environment with turbidite flows is prone to mixing of various sources of sediment, depending on the depositional system proximity and river drainage basin pattern. The continuous growth of the authigenic rims around the clay particles causes that the duration of a particle transport (sediment-source

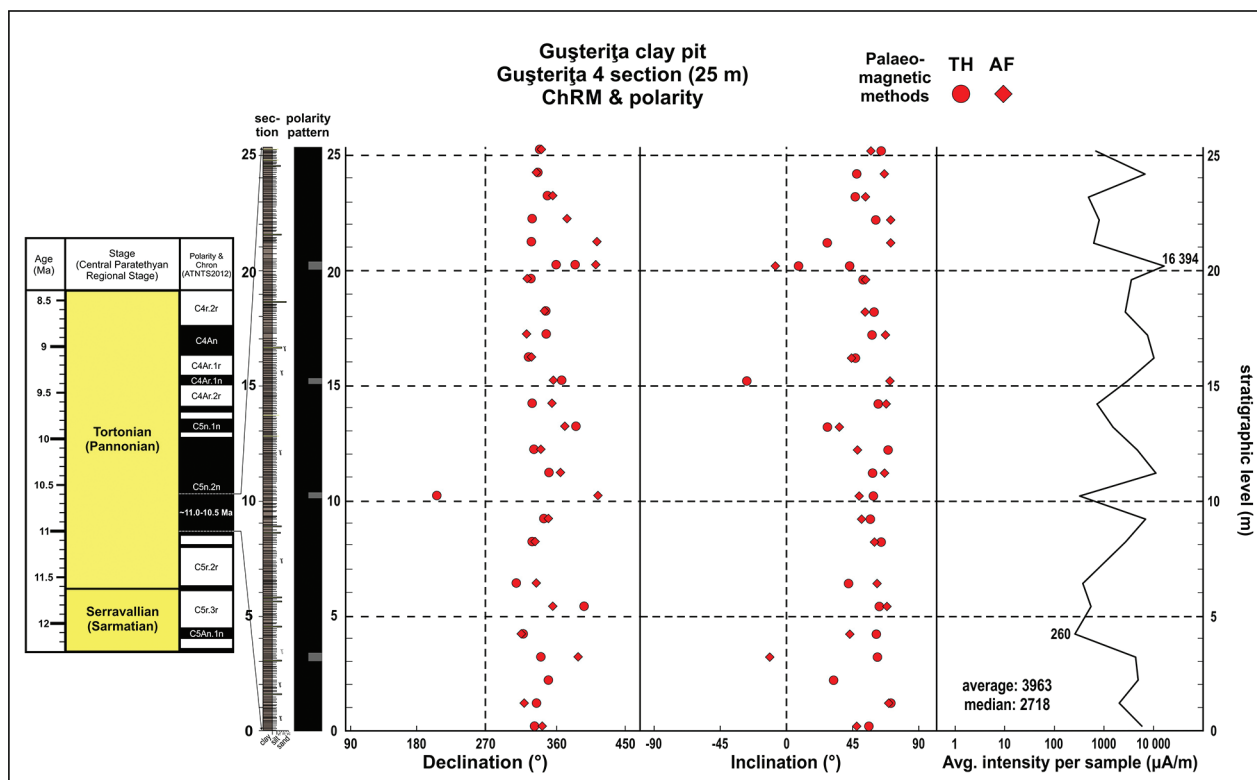


Figure 13: Magnetostratigraphic summary chart of the Gușterița 4 section (uppermost 25 m of the quarry). Declination, inclination, and average intensity per sample values, with polarity pattern, sedimentary log, and Central Paratethyan stratigraphic chart. All the samples showed normal polarity, i.e. positive inclination values and declination values above 270° . The section can be placed into the C5n.2n long normal polarity magnetic chron, and based on biostratigraphic considerations, its age is ~11.0–10.5 Ma (ChRM: Characteristic remanent magnetization, TH: Thermal demagnetization results, and AF: Alternating field demagnetization results).

proximity) also affects the resulting isotopic ratio (Wittmann et al., 2017). The gained results indicate that a change in beryllium isotopic input might appear within the studied sedimentary section.

A backward calculation of the initial ratio of the samples G06 to G14 assuming their age to be in agreement with the weighted mean of the rest of the samples of the same set (10.42 ± 0.39 Ma) yielded initial ratios between $(14.6 \pm 0.80) \times 10^{-9}$ and $(10.05 \pm 0.53) \times 10^{-9}$, with a mean value of $(12.39 \pm 2.07) \times 10^{-9}$, what differs from both applied initial ratios by a factor of ~ 2 . Although the fossils and the sedimentary facies do not indicate any major change, a study of sediment provenance may prove the hypothesis of change in sediment source as the cause of observed discrepancy in $^{10}\text{Be}/^{9}\text{Be}$ concentrations.

Another possible explanation for the change in the initial ratio in a water column during sedimentation could be an overall rise of the water level of Lake Pannon, which attained its largest extent at ~ 10 Ma (Magyar et al., 1999a). This transgression was probably related to flooding and retrogradation of a depositional system, causing increase in distality of the sediment source and decrease in the ^{9}Be input. A significant change in precipitation, which would affect the delivery of ^{10}Be , is not expected in the studied time period.

The calculated mean initial ratio of samples G06 to G14 provides an important insight into the variability of the initial isotopic ratios within the depositional environment of sediment gravity flows on a basin floor. Nevertheless, the changes observed in the studied depositional record could be considered as not significant in the light of the high variability of $^{10}\text{Be}/^{9}\text{Be}$ ratios in recent continental environments reaching the value of 3.5×10^{-8} to 1.55×10^{-10} (e.g. Brown et al., 1992; Graham et al., 2001; Wittmann et al., 2012; von Blanckenburg et al., 2012). The $^{10}\text{Be}/^{9}\text{Be}$ record of the Guşteriţa section implies that analysing of higher number of samples might be useful to effectively determine fluctuations of isotopic ratios, which should be expected in comparable depositional settings.

The approach of independent calculation of the initial isotopic ratio could substitute its determination from the recent samples, which would be problematic in sedimentary successions similar to those of Lake Pannon in the TB. The circumstances that call for using the above-mentioned approach are as follows: (1) there is no recent equivalent of turbiditic depositional environment and (2) major changes appeared in the petrology of the drainage basins since the late Miocene, mostly because of the latest Miocene to Quaternary volcanism (Fielitz and Seghedi, 2005) in the catchment areas of the incoming rivers.

Although ages calculated using the $R_{0-\text{lacus}}$ determined by Šujan et al. (2016) in Holocene lakes in the western PB provided statistically similar results, the ages calculated by the local, $^{40}\text{Ar}/^{39}\text{Ar}$ -based initial ratio ($R_{0-\text{ODM}}$) are suggested to be the best estimate authigenic $^{10}\text{Be}/^{9}\text{Be}$ age of the studied sediments.

The 55-m-high Guşteriţa section thus represents a time interval of 500 kys at most (between 11.0 and 10.5 Ma).

Based on this age model and supposing that the ~ 0.11 m/kyr average sedimentation rate was more or less constant during deposition of the sequence, we have the opportunity to estimate, for the first time, the age of the boundaries between the *S. oblongus* and *P. pecsvaradense* dinoflagellate zones, the *H. tenuistriata* and *P. candeo* ostracod zones (both ~ 10.75 Ma) and the *P. pecsvaradense* and *S. hennersdorfensis* dinoflagellate zones (~ 10.65 Ma).

6. Conclusions

The 55-m-thick, highly fossiliferous sedimentary sequence exposed in the clay pit of Guşteriţa (Sibiu, Romania) was deposited in the deep-water zone of Lake Pannon during the late Miocene. It can be considered as a reference section for the “*C. banatica* beds”, widely distributed in the TB as well as in the neighbouring PB.

The upper 25 m of the profile displays normal magnetic polarity. As the authigenic $^{10}\text{Be}/^{9}\text{Be}$ dating of six samples gave a weighted mean age of 10.42 ± 0.39 Ma (initial ratio based on independent $^{40}\text{Ar}/^{39}\text{Ar}$ dating of an analogous profile at ODM), the outcropping sequence can be correlated most probably with the C5n.2n normal polarity chron (~ 11.1 – 10.0 Ma). While the entire sequence represents the *C. banatica* profundal mollusc biozone, the upper 25 m belongs to three dinoflagellate zones, two ostracod zones and one regional calcareous nannoplankton zone. Because the *S. hennersdorfensis* dinoflagellate zone, dated elsewhere as 10.5–10.3 Ma, occurs only in the topmost layers of the outcrop, the age of the Guşteriţa sequence can be constrained between 11.0 and 10.5 Ma; the section thus represents a time interval of maximum 500 kys. Supposing that the (at least) ~ 0.11 m/kyr average sedimentation rate was more or less constant during deposition of the sequence, the age of the boundaries between the *H. tenuistriata* and *P. candeo* ostracod zones, the *S. oblongus* and *P. pecsvaradense* dinoflagellate zones (both ~ 10.75 Ma) and the *P. pecsvaradense* and *S. hennersdorfensis* dinoflagellate zones (~ 10.65 Ma) can be substantiated for the first time. These new data are valuable contributions to the high-resolution biochronostratigraphy of the PBS.

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