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The Late Badenian shallow-water marine deposits of the southwestern Dacian Basin, Serbia

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Abstract

This study presents late Badenian (= early Serravallian) shallow-water marine environments in the Veliki Izvor and Nikoličevo areas in eastern Serbia. Biostratigraphically, the Upper Badenian *Bulimina-Bolivina* Zone and *Ammonia/Elphidium* impoverishment Ecozone are documented and correlated with the M6 zone, characterized by the presence of *Orbulina suturalis*. The Upper Badenian coarse- to medium-grained marine clastics transgressively overlie older Cretaceous flysch, carbonates, and volcanoclastics as well as early Miocene continental deposits. Comparative sedimentological and palaeontological analyses of the two outcrops reveal different depositional environments, water level fluctuation, and redepositional processes. The Veliki Izvor area represents a shallow-marine, tidally influenced system, whereas Nikoličevo is characterized by a more proximal, fluviodeltaic setting with evidence of episodic carbonate influx. Numerous well-preserved fossils of corals, bivalves, and gastropods, along with poorly preserved foraminifera and ostracods, indicate a marginal marine, well- oxygenated environment of normal salinity. Benthic foraminiferal assemblages (dominated by *Elphidium–Biasterigerina–Ammonia* specimens) suggest deposition in a well-oxygenated inner to middle shelf setting. A higher proportion of euryhaline genera such as *Elphidium* and *Ammonia* points to episodic freshwater inflows into the marine environment. Rare occurrences of *Bolivina* and *Heterolepa* specimens indicate brief periods of low oxygen conditions, while the *Elphidium–Biasterigerina* assemblage reflects recovery phases with renewed vertical water circulation and bottom water oxygenation. Low-diversity ostracod assemblages further support the shallow marine environments. These findings contribute to a better understanding of marginal Miocene basins in southeastern Europe and highlight the complexity of shallow-water marine depositional systems.

Keywords: Late Badenian, shallow-water, paleoecology, Paratethys, eastern Serbia

1. INTRODUCTION

During the early Miocene, eastern Serbia and northwestern Bulgaria were predominantly continental areas, characterized by small lacustrine basins (VESELINOVIĆ et al., 1967, 1975; IVANOV & WOROBIEC, 2017; RUNDIĆ et al., 2019). However, at the beginning of the middle Miocene, a significant marine transgression from the outer Carpathian area (Dacian Basin) extended over much of northwestern Bulgaria, forming the so-called Dacian Gulf of the Fore-Carpathian Basin (KOJUMDGIEVA & POPOV, 1989; IVANOV & WOROBIEC, 2017). This transgression also affected areas of eastern Serbia, establishing a marine connection between the Dacian domain to the east and the Pannonian domain to the west via the so-called the Carpathian (Đerdap Gorge) corridor. As a result, the sedimentary facies and fossil assemblages of both marine basins show considerable similarities (RÖGL, 1998). Accordingly, the older stratigraphic framework of the Pannonian Basin (including the Badenian Stage) can also be applied to the outer Carpathians (IVANOV & WOROBIEC, 2017; RUNDIĆ et al., 2019; SANT et al., 2019; POPOV et al., 2024).

During the middle Miocene, the area of eastern Serbia (referred to as the Timok Krajina), belonged to the westernmost part of the Dacian Basin, which bordered the Carpathian foothills and the southern branches of the Carpathians (MAROVIĆ et al., 1998; GANIĆ, 2005; TER BORGH et al., 2014; ĐAJIĆ et al., 2018; RUNDIĆ et al., 2019). In this region, Miocene clastic formations predominantly and unconformably overlie Lower and Upper Cretaceous carbonate and clastic rocks, as well as andesites and associated volcanoclastics (e.g., VESELINOVIĆ et al., 1967, 1975; RUNDIĆ et al., 2015; BANJEŠEVIĆ et al., 2018). Within the middle Miocene coarse- to fine-grained clastic succession, marine Badenian and restricted marine Sarmatian deposits are widely distributed (e.g., LASKAREV, 1934; PETROVIĆ, 1961, 1969, 1988; POPOVIĆ, 1968; POPOVIĆ & GAGIĆ, 1969; STEVANOVIĆ, 1958, 1964, 1967, 1977; DŽODŽO-TOMIĆ, 1979).

The middle-late Miocene to early Pliocene sedimentary facies of the Dacian Basin display a predominantly regressive pattern, marked by basin infill through large-scale progradation of nearshore facies and deltaic systems (e.g., OLTEANU & JIPA, 2006; VASILIEV, 2006; JIPA & OLARIU, 2009; TER BORGH et al., 2014; JIPA, 2015). Seismic profiles and drilling data indicate that the total thickness of the Neogene sediments can reach several thousand metres (MARINOVIĆ et al., 2025 and references therein).

In the vicinity of the city of Zaječar, marine Badenian deposits have been confirmed by numerous mollusc fossils and, later, foraminifera recovered from small outcrops in the village of Veliki Izvor. The coarse-grained clastic series are assigned to the Upper Badenian (PETROVIĆ, 1961; POPOVIĆ,

1968; POPOVIĆ & GAGIĆ, 1969; DOLIĆ, 1977; DŽODŽO-TOMIĆ, 1979; GANIĆ, 2005). Similarly, Badenian-aged molluscs and foraminifera have also been observed in the nearby villages of Nikoličevo and Rgotina, north of Zaječar. These middle Miocene marine formations transgressively overlie various Cretaceous units or a lower-middle Miocene continental-lacustrine series with coal seams (e.g., ŽUJOVIĆ, 1889; RADOVANOVIĆ & PAVLOVIĆ, 1891; ŽIVKOVIĆ, 1893; PAVLOVIĆ, 1898, 1900, 1908, 1911, 1923; BRUSINA, 1902; PAVLOVIĆ & PETKOVIĆ, 1903). Recent radiometric dating of the aforementioned lacustrine series with tuffs places them in the Karpatian age (RUNDIĆ et al., 2019).

Over the past decades, the first author has conducted extensive fieldwork in the study area, assembling a comprehensive collection of macrofossils (including molluscs, corals, scaphopods, echinoderms, and others) as well as microfossils (foraminifera and ostracods). This fossil assemblage holds significant potential for palaeoecological and stratigraphic research. In this study, we present an integrated sedimentological and biostratigraphic analysis of late Badenian shallow-marine environments located in the southwestern terminal gulf of the Dacian domain.

2. GEOLOGICAL SETTING

Eastern Serbia is part of the Carpatho – Balkanides, a major orogenic unit (e.g., KRÄUTNER & KRSTIĆ, 2003; SCHMID et al., 2008; RUNDIĆ et al., 2019 and references therein). This region also encompasses parts of the Serbo-Macedonian Massif and, to the west, borders the eastern margin of the East Vardar ophiolites (DIMITRIJEVIĆ, 1997). Inside this belt, the Timok Fault is one of the main strike-slip structures which displace the Cretaceous nappe units along the contact between the Dacia Mega-Unit and the Moesian Platform (SCHMID et al., 2008). This fault accommodated dextral strike-slip movement from the Oligocene to early Miocene, with total displacement exceeding a hundred kilometres (SCHMID et al., 2008). From the end of the early Miocene up to the older part of the middle Miocene, the Serbian segment of the Carpatho – Balkanides was subjected to extensional processes (MAROVIĆ et al., 1998, 2002; KRSTEKANIĆ et al., 2022). This extensional regime was primarily driven by tectonic activity associated with the Pannonian Basin and led to the formation of numerous basin structures in the area (MAROVIĆ et al., 1998, 2002). The current disposition of the Carpatho-Balkan orogen was influenced by a long-lasting uplift phase that began in the Sarmatian and continues to the present day (MAROVIĆ et al., 2002, 2007).

During the middle Miocene, the Paratethys Sea transgressed into the westernmost part of the outer Carpathians and extended into Serbian territory (ANĐELKOVIĆ & ANĐELKOVIĆ, 1997). Depending on the palaeorelief, this transgression flooded different Mesozoic and older Palaeogene – Miocene sub-basinal basement rocks (GANIĆ, 2005; ĐAJIĆ

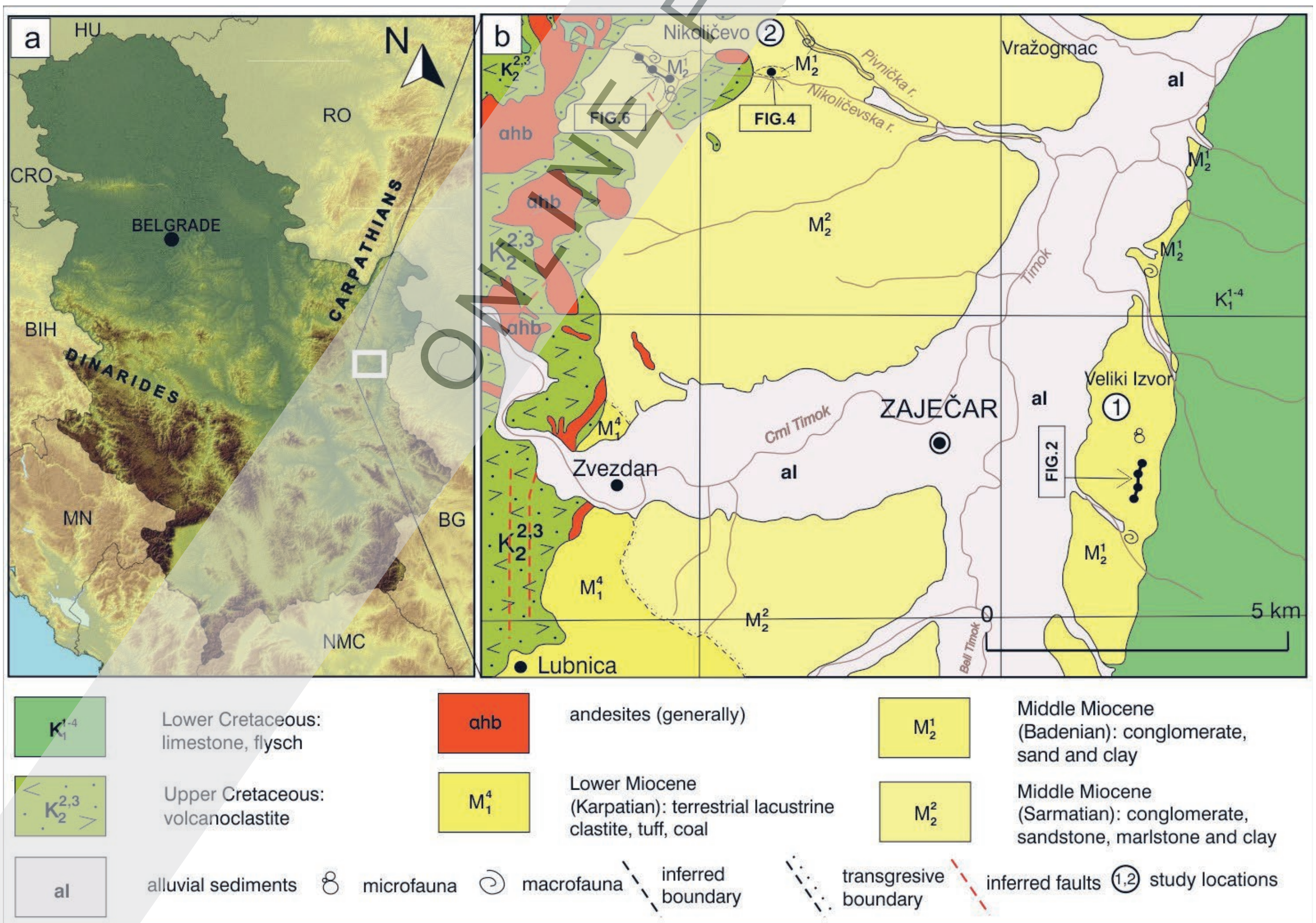

Figure 1. a Geographical position of the studied area (white square); **b** Geological map of the Zaječar area with the position of Veliki Izvor (1) and Nikoličevo (2) (according to VESELINOVIĆ et al., 1967 – modified). The lines with full black points indicate the position of the main lithological sections given in the text (Figs. 2, 4, 6). Note: The position of the Lower Miocene boundary is very approximative and based on a few data taken from the references.

et al., 2018; RUNDIĆ et al., 2019), including Lower and Upper Cretaceous flysch, clastics, volcanoclastics and carbonates as well as older Oligocene – Miocene continental – lacustrine successions. Notably, Upper Cretaceous magmatic formations in the region are known for hosting economically important metallic mineral resources (e.g., VELOJIĆ et al., 2020 and references therein).

In the study area, the oldest Cenozoic deposits are undivided late Oligocene to early Miocene continental – lacustrine freshwater clastic series with coal seams (RUNDIĆ et al., 2019; MARINOVIĆ et al., 2025; Fig. 1). These deposits occur near Zaječar (Zvezdan, Lubnica), where brown coal mining has a long tradition (the Lubnica coal mine remains active today). Middle Miocene (Badenian) marine deposits comprising coarse-grained sand, gravel, conglomerates and breccias represent the earliest marine transgressive – regressive sequence in the area. These Badenian sedimentary rocks on the surface are exposed in steep bays, outcrops, and stream banks extending from the large Danube River meander in the north (STEVANOVIĆ, 1958), through the so-called "zones of exhumed palaeorelief" in the central part (STEVANOVIĆ, 1964), to the widely distributed exposures in the Zaječar area (Rgotina, Nikoličevo, and Veliki Izvor) in the south (POPOVIĆ & GAGIĆ, 1969) (Fig. 1).

The older part of the Badenian sequence has been identified in the Timok – Štubik Trough (near Malajnica village). There, thick blue clays ("fat clays") contain foraminiferal assemblages corresponding to the lowermost part of the Lagenidae Zone (PETROVIĆ, 1967). The upper part of the Badenian succession corresponds to the *Orbulina suturalis* and *Trilobatus (=Globigerinoides) trilobus* Zone (PETROVIĆ, 1967, 1969), which are equivalent to the M5 or CPN7 zones (CICHA et al., 1998; WADE et al., 2011). Upper Badenian clastic sediments have been recorded at several localities. Lithologically, they consist of gray-green clays, yellowish sands and gravels containing abundant molluscs and well-preserved corals such as *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME), *T. conoidea* (REUSS), *Siderastrea crenulata* (GOLDFUSS), etc. Foraminiferal assemblages from these deposits correspond to the *Bulimina-Bolivina* Zone (STEVANOVIĆ & DOLIĆ, 1981).

Sarmatian rocks in the areas around Kladovo, Negotin, and Zaječar represent the most extensive Neogene stratigraphic unit exposed at the surface. These marine-restricted deposits consist of sandy clays, gravels, sands, siltstones, and carbonates of varying origins. The Volhynian, Bessarabian and Khersonian substages have been distinguished within the Sarmatian succession. These units either conformably overlie the marine Badenian or transgressively lie on the pre-Neogene palaeorelief (GANIĆ, 2005; RUNDIĆ et al., 2019; MARINOVIĆ et al., 2025). Quaternary sediments of various origins cover the lowland areas and occur along many slopes at the base of the Carpathian foothills.

3. MATERIALS AND METHODS

The studied sections are located in the villages of Veliki Izvor and Nikoličevo (Figs. 1, 2, 4, 6). All samples were collected during field investigations conducted in 1994 and 2024. At Veliki Izvor, four closely spaced outcrops were studied, ranging from 2.5 to 5 metres in thickness and varying in lithology and elevation. A composite stratigraphic column was constructed to represent the section (coordinates: N 43.922944°– 43.937916°; E 22.333941° – 22.346840°; Fig. 2). In Nikoličevo, a newly discovered, extensive section was investigated in 2024 (N 43.958101°; E 22.249460°; Fig. 4). Additionally, three smaller outcrops previously explored in 1994 are combined in a composite column shown in Figure 6 (N 43.955190° – 43.962823°; E 22.236245° – 22.223806°).

At Veliki Izvor, the collected samples were divided into two groups. The first consists of new samples collected in 2024 (VI-1, VI-2, VI-3, VI-4, and VI-5), which are integrated with samples collected in 1994 (10.1/94, 10.2/94, 10.3/94, 10.4/94, 11.1/94, 11.2/94, 11.3/94, 11.4/94, 11.5/94, 12.1/94, 12.2/94, 13.1/94, and 13.2/94) (Fig. 2). From Nikoličevo, five new samples (NK-1, NK-2, NK-3, NK-4, and NK-5) were collected from the newly discovered large section and are shown in Figure 4. The remaining samples (17.1/94, 17.2/94, 18.1/94, 18.2/94, 18.3/94, 18.4/94, 19.1/94, 19.2/94, 19.3/94, 19.4/94, 20.1/94, 20.2/94. 20.3/94, 20.4/94, and 20.5/94), obtained from the smaller outcrops during 1994, are presented in Figure 6. Each bulk sample weighed up to 1 kg. All samples were processed in the Laboratory of Sedimentology and the Laboratory of Palaeontology and Historical Geology at the Faculty of Mining and Geology, University of Belgrade.

A total of seven sedimentological samples (VI-4, VI-5, NK-1, NK-2, NK-3, NK-4, and NK-5) were analyzed both macroscopically and microscopically to determine grain size, mineral composition, and textural features. Grain-size analysis was performed using standard dry sieving techniques. Petrographic thin sections of selected sandstones, sandy marls and marls were examined under a Zeiss polarizing microscope equipped with integrated Axiom 208 colour camera. Additional inspection of loose, uncemented sands was conducted using a binocular stereomicroscope to assess grain morphology and roundness. Carbonate content was determined by rapid calcimetry following the standard volumetric SCHEIBLER method, which measures the volume of CO_2 released after treatment of powdered samples with 10% HCl, allowing estimation of total $CaCO_3$ content and allowing the distinction between carbonate-rich and siliciclastic lithologies.

The entire collection of thirty-eight samples were processed for micropaleontological analysis by standard micropalaeontological methods: soaking in water, washing over a 63 µm mesh sieve, and drying (ARMSTRONG & BRASIER, 2005). Due to poor preservation and taxonomic uncertainty, statistical analyses of the foraminiferal assemblages were not applied. Based on the number of specimens in ca. 500 g of treated sediment, the relative abundances of the taxa are expressed as follows: r = rare (<5), f = frequent (5 – 20) and a = abundant (>20) (Suppl. 2). Foraminiferal identification followed PAPP & SCHMID (1985), CICHA et al. (1998) using binocular microscopes Citoval 2 (Carl Zeiss) and Olympus SZX16 and updated according to the current World Register of Marine Species (WORMS) database (HAYWARD et al., 2025). Ecological and palaeoecological interpretations were based on BÁLDI (2006), MURRAY (2006), KOVÁČOVÁ & HUDÁČKOVÁ (2009), PEZELJ et al. (2007, 2013, 2016). Ostracod taxonomy and palaeoecology were interpreted according to VAN MORKHOVEN (1963), ZORN (2003, 2004), GROSS (2006), HAJEK-TADESSE

& PRTOLJAN (2011), with updated taxonomy also verified via WORMS (BRANDÃO et al., 2025). The same abundance classification used for foraminifera was applied to ostracods (Suppl. 3).

The taxonomy of corals, gastropods, and bivalves was based on the works of KOJUMDGIEVA & STRACHIMIROV (1960), NEVESSKAJA et al. (1993), BAŁUK (1997), RUS & POPA (2008), MIKUŽ (2009), KOVÁCS & VICIÁN (2013), GÓRKA (2018), KOVÁCS (2018), and HARZHAUSER & LANDAU (2016, 2019, 2023). In addition, all determinations were updated according to the current WORM database and the MolluscaBase particularly.

4. RESULTS

4.1. Sedimentology

4.1.1. Veliki Izvor

Middle Miocene sediments at the Veliki Izvor locality are exposed in several small outcrops in the central part of the

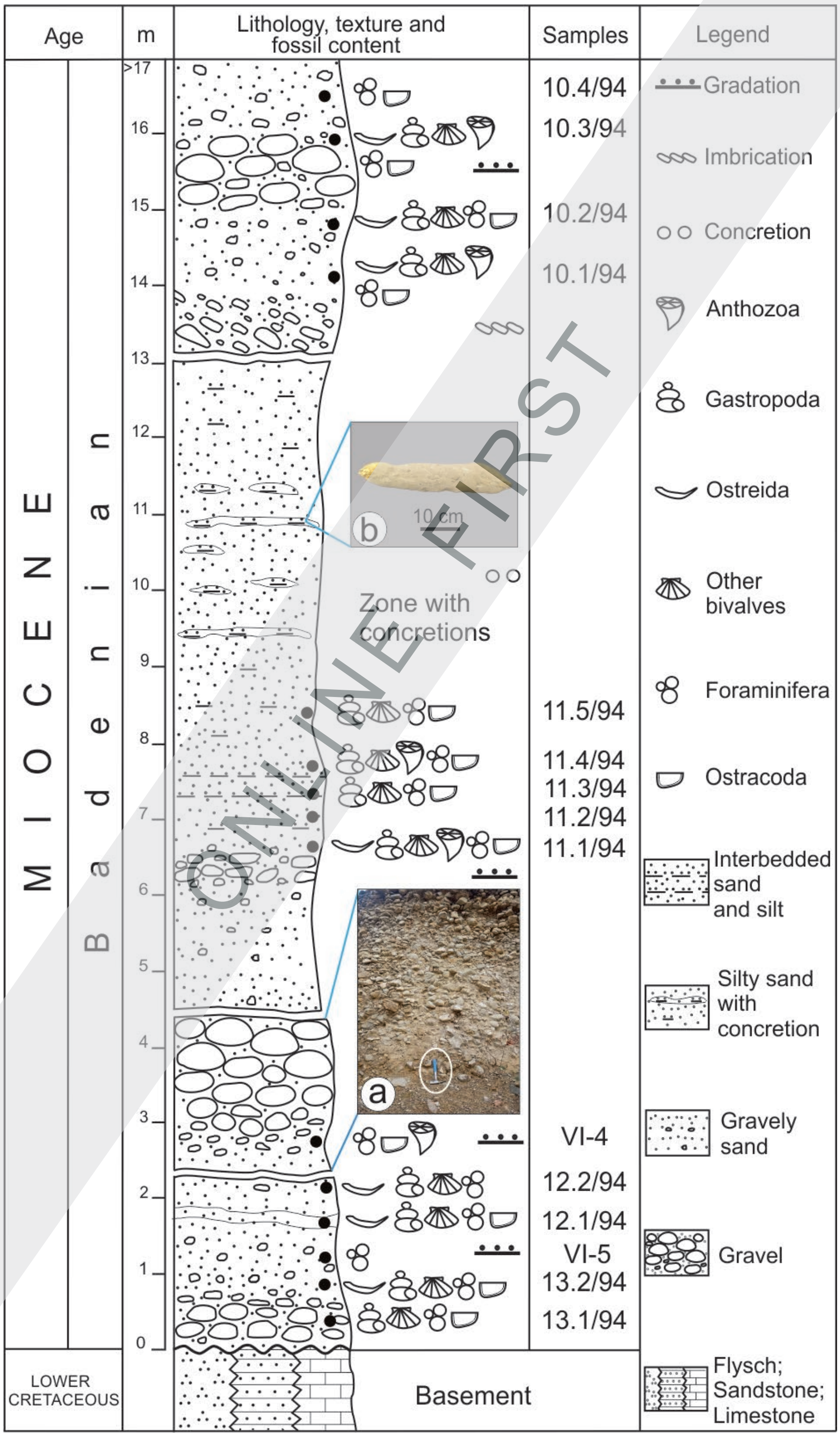

Figure 2. A composite lithostratigraphic column of the Badenian clastites in Veliki Izvor. The inserted photos mark: **a** A part of basal sand (VI-4) and gravel; **b** a large, elongated carbonate concretion in the middle sequence (one shown ca. 40 cm). The photos may show thicker segments than are drawn on the column; lenticular geometry and grain-size gradation are visible.

settlement. These sediments are unconsolidated, although cementation is visible in the gravel layers and in the upper parts of the sequence, where the deposits become semi-consolidated to lithified.

Based on multiple measured sections and collected samples, a composite lithological column was constructed to illustrate the typical vertical sedimentary succession in the area (Fig. 2). The most common sequences are two-member (gravel–sand) or three-member (gravel–sand–silt) lithofacies associations, i.e., rock units defined by their characteristic lithology, texture, and depositional features. Thinner intervals consist only of sands and fine- grained clastics, while thicker successions (of several metres) include interbedded conglomeratic and sandy layers with silts. Coarse- and medium-grained clastics typically appear red-yellow to yellow in colour, whereas finer clastics are grey-yellow to gray. The sedimentary bodies generally show lenticular geometries. Grain-size gradation is common within the coarse-grained units (Fig. 2a).

The basal part of the column consists of coarse sand and medium- to coarse-grained gravels. Samples VI-4 and VI-5, taken from this interval, represent typical poorly cemented sandy and gravelly sediments (Fig. 2). These basal layers exhibit poorly sorted, subangular to rounded clasts, with clast-supported fabric and occasional thin sandy lenses (Fig. 2a).

In the middle part of the section, from 4.5 to 13 m, an approximately 8 metre thick section contains large carbonate concretions. These are irregularly ellipsoidal, over 10 cm in diameter, and are embedded in a sandy-silty matrix (Fig. 2b). Petrographic analysis reveals that the concretions are composed entirely of calcite, primarily in the form of orthochemical microsparite cement. The allochemical components include fully micritized bioclasts and peloids, with several grains identifiable as cortoids (Fig. 3a).

The upper part of the column (13 – 17 m) comprises intervals of gravel and conglomerates. The lower horizons include large clasts with well-developed imbrication (Fig. 2), followed upward by medium-grained, poorly sorted gravels/conglomerates. Calcite cementation is sporadic. Sands in this interval are locally lithified into weakly cemented sandstones, and gravels into weakly cemented conglomerates. The sequence ends with fine-grained, limonitic sands, interpreted as Quaternary deposits.

The gravels are polymictic, with a notable presence of metamorphic pebbles, along with clasts derived from older sedimentary rocks (limestones, sandstones, marls) and from the andesitic volcanic complex. Pebbles are well-rounded and moderately sorted (Fig. 3b). Intraformational clasts derived from erosion of poorly consolidated fine-grained deposits, occur in the top of the column.

Grain sizes range from fine to coarse, with clasts either tightly packed or floating within a sandy to silty-clay matrix. Calcite cementation results in weakly lithified conglomerates.

Sandy fractions display heterogeneous grain-size distributions, including gravelly sands and silty sands. Petrographically, they contain lithic fragments, quartz, feldspars, and accessory minerals (Fig. 3c, d), forming both discrete layers and matrix material in gravels. Lithic fragments are subangular to subrounded. Phyllosilicates (muscovite, chlorite, biotite) occur as minor components, especially in finer-grained layers (Fig. 3d).

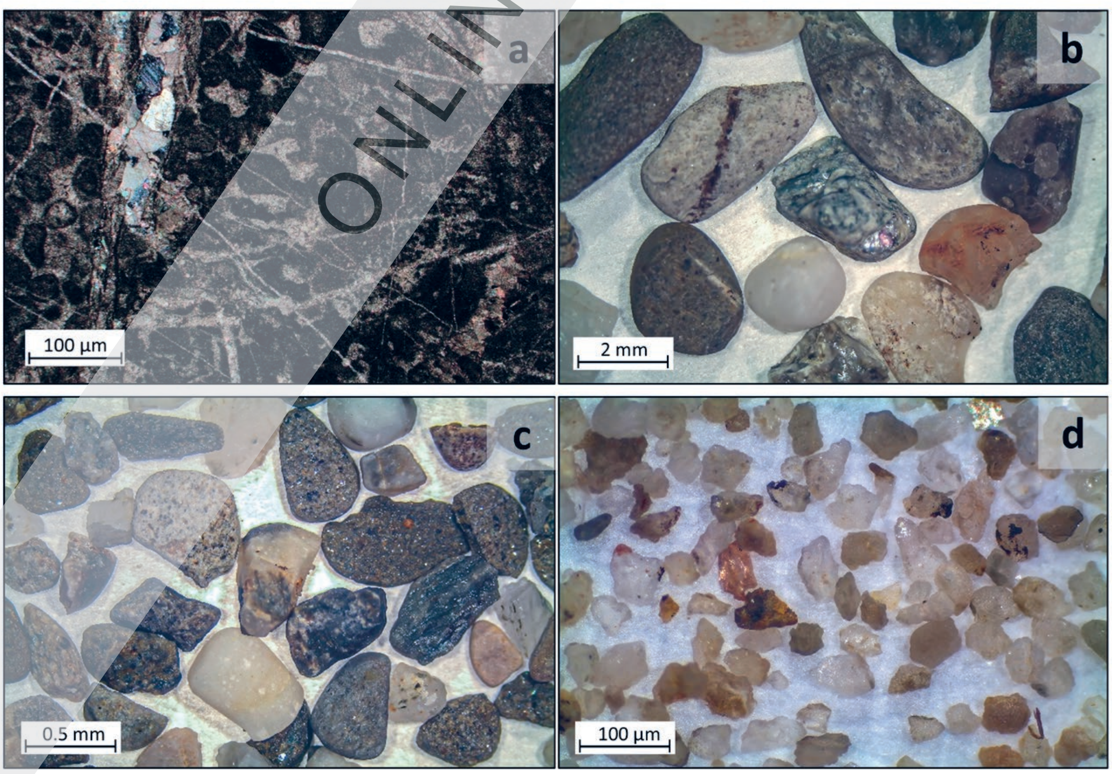

Figure 3. Microscopic and binocular images of characteristic components from the Veliki Izvor locality; **a** Microscopic view of a carbonate concretion: micritized bioclasts, peloids, and cortoids within microsparite cement; **b** Binocular images of the well-rounded and moderately sorted polymictic pebbles; **c** Sandy fraction: lithic fragments, quartz, major and accessory minerals; **d** The fine-grained sands with quartz and flakes of muscovite and chlorite.

4.1.2. Nikoličevo

A newly discovered large section, up to 13 metres thick and well exposed both vertically and laterally, displays a rhythmic alternation of coarse- and fine-grained sediments deposited in a complex fluviodeltaic environment. The setting includes incised channels, shallow ponds, and marginal bays (Fig. 4). Sedimentation patterns indicate dynamic fluctuations in flow regimes and energy levels, resulting in varied depositional processes. Several layers show wedge- shaped geometries with tabular and tangential cross-bedding of low dip, reflecting lateral channel migration or progradational infill of shallow channels. These features demonstrate gradual transitions between sandy, marly, and clay-rich beds. Notably, no pure clay layers were observed; instead, clay components are incorporated within sandy and marly matrices, contributing to overall lithological heterogeneity and subtle facies transitions (Fig. 5).

The basal portion of the section comprises prominent channel-fill structures, made up of gravelly sediments forming

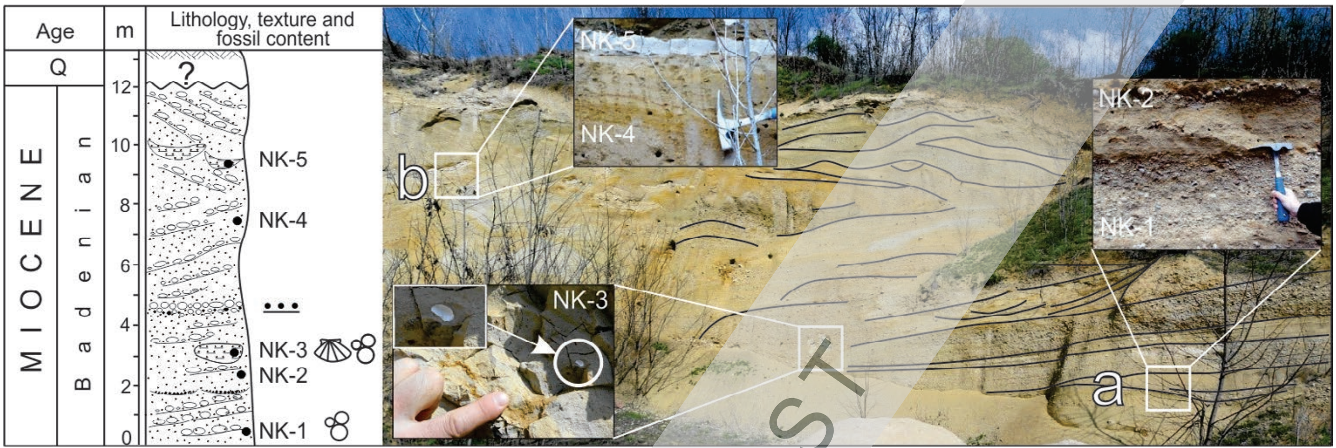

Figure 4. The well-exposed vertical succession of Badenian clastites in Nikoličevo. Signs NK-1 to NK-5 mark the positions of the samples; **a** The basal part of the profile shows wedge- shaped bodies of coarse sand and gravel with erosional lower contacts and poorly sorted subangular to rounded clasts. Channelized bedding downcuts the underlying lithology; **b** Higher in the sequence, lens-shaped and intercalated sand, silt, and gravel bodies reflect superimposed or laterally migrating depositional units, indicating dynamic fluviodeltaic processes. Note: The white circle within NK-3, marks the occurrence of the bivalve *Anadara turonica*.

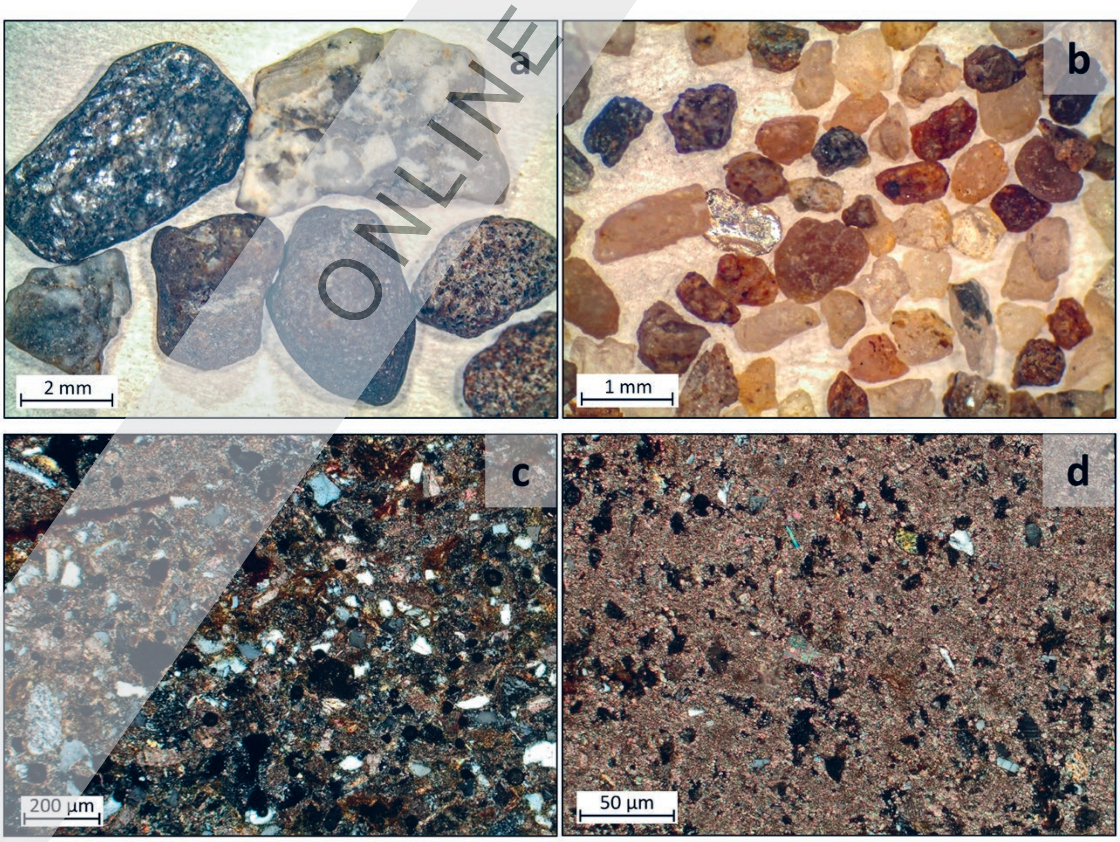

Figure 5. Binocular (a, b) and microscopic (c, d) images of characteristic components from the Nikoličevo. **a** Conglomerate from the basal channel lag deposit composed of sub-angular to rounded clasts of quartzite, andesites, cherts, and metamorphic rocks (sample NK-1); **b** Quartz- rich sands (sample NK-2) with sub-angular grains and moderate sorting, typical for mid-energy channel fills; **c** Fine-grained sandy-silty material with increased carbonate and clay content (sample NK-3); **d** Marl with a carbonate-clay matrix embedding quartz grains and minor heavy minerals (sample NK-5).

lag deposits and wedge-shaped bodies with concave basal contacts. These gravels, preserved as poorly cemented conglomerates, contain subangular to well-rounded clasts mostly 2 – 4 mm in size (Fig. 5a). Clasts show diverse petrographic origins, including Mesozoic limestones, sandstones, cherts, andesites, and metamorphic rocks such as quartzites and schists, indicating mixed provenance and varied transport distances.

Overlying this basal unit is a coarse-grained sandy layer with cross-bedding, occasionally containing quartz pebbles and marl fragments, indicative of reduced flow energy and channel progradation. Granulometric analyses of samples NK-1 and NK-2 show medium- to fine-grained quartz-rich sands (Fig. 5b), with mean grain diameters of 0.355 mm (NK-1) and 0.558 mm (NK-2). Grains are subangular and accompanied by feldspar, mica, and lithic fragments. Sorting values (≈1.5) suggest deposition in moderately stable, mid-energy environments.

The middle part of the section is dominated by laminated sandstones with wavy and horizontal lamination, transitioning into fine-grained sandy-silty and marly beds. These reflect deposition in lower-energy sub-environments such as abandoned channels and marginal ponds. Sample NK-3, taken from this interval, exhibits higher calcite, silt, and clay content (Fig. 5c), consistent with reduced hydrodynamic conditions and potential redeposition or "mudflushing" events, indicating a shift towards quieter depositional settings within the channel.

In the upper part of section, partially cemented fine-grained sandstones (NK-4) and marls (NK-5) predominate, with horizontal lamination and transitions into massive marl layers. Sample NK-5 contains a carbonate-clay matrix binding primarily quartz grains, along with trace amounts of feldspar, micas, and heavy minerals (Fig. 5d). Cementation is weak to moderate, with localized carbonate nodules suggesting early diagenesis and a transition toward a shallow marine setting.

In addition, during the 1994 field investigation, three smaller outcrops (0.5 – 1.7 m thick) were examined in a small stream valley opposite the large Nikoličevo section (Fig. 1). These outcrops are combined into a composite column (Fig. 6). The basal part of the column (up to 0.5 m thick) consists of poorly cemented conglomeratic gravels and sandy deposits, gravels and sands — mixtures of gravel-sized clasts and sandy matrices — containing only very rare foraminifera. Above this is a ≈ 1 m thick unit of yellow, coarse- to medium-grained sands with silt layers (up to 20 cm thick) interspersed with conglomerate lenses. A lumachel bed (up to 5 cm thick; sample 18.1/94) rich in ostreid shells is interbedded within silty sands and sandy gravels. At 110 cm above the base, a second ostreid-rich layer (sample 18.3/94) occurs within a 40 cm thick silty sandstone (Fig. 6). The ostreids assemblage shows low taxonomic diversity (three well-defined species) but high abundance, with numerous small, disarticulated valves. The middle portion of the column (≈ 170 cm thick) comprises yellowish to gray loosely consolidated sands and clayey sands with small carbonate concretions. No other distinct sedimentary structures were observed. Samples 19.1 – 19.3/94 yielded scarce fossil remains (gastropods and bivalves; see Suppl. 1). Rare poorly preserved foraminifera were found in all samples, while ostracods occur only in sample 19.4/94. The uppermost package, about 140 cm thick, consists of coarse-grained sands with gravel interbeds (Fig. 6). Within these interbeds, clasts display well-developed preferred orientation (imbrication). Except for sample 20.4/94, which contains scarce foraminifera and ostracods, all other samples do not contain fossil remains.

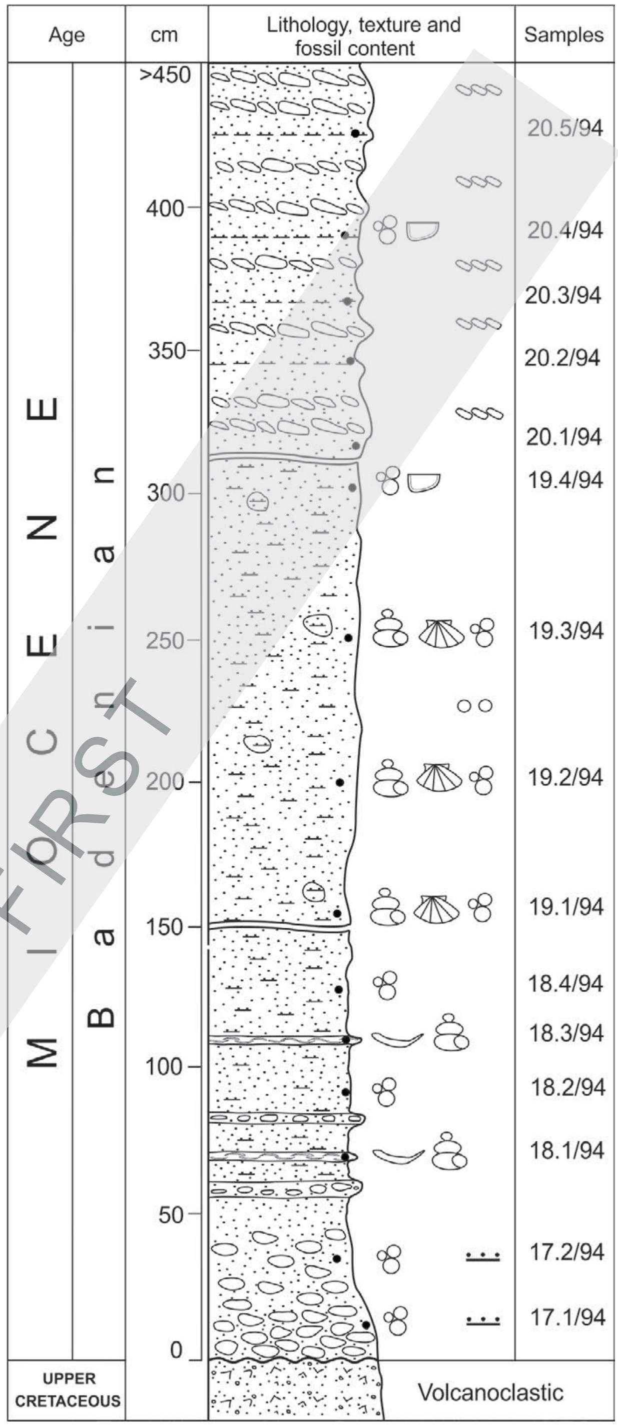

Figure 6. A composite lithological column of the Badenian clastites in the Nikoličevo area. For the key, see Figure 2.

4.2. Fossils

4.2.1. Veliki Izvor

4.2.1.1. Anthozoa

Colonial anthozoans were identified from samples 10.1/94, 10.3/94, 11.1/94, 11.4/94, and VI-4. The specimens are generally well-preserved, though some are broken into smaller fragments, mostly up to 5 cm in size, with two larger examples (Pl. 1). They were irregularly scattered throughout the sediments (conglomerates and coarse-grained sands), often associated with other macrofaunal remains. The most abundant forms belong to the family Merulinidae, with less frequent occurrences of representatives from the Faviidae and the Pocilloporidae. The following species were identified: *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME), *T. conoidea* (REUSS), *Echinopora defrancei* (MILNE EDWARDS & HAIME), *Favites neglecta* (MICHELOTTI), *Favia gotschevi* KOJUMDGIEVA, *Stylophora subreticulata* REUSS, *Favia s*p. (Pl. 1).

4.2.1.2. Gastropoda

Gastropods were collected from eleven samples (10.1/94, 10.2/94, 10.3/94, 11.1/94, 11.3/94, 11.4/94, 11.5/94, 12.1/94, 12.2/94, 13.1/94, and 13.2/94), and are represented by numerous well-preserved specimens. The most abundant are from the family Conidae, followed by the Cerithidae, Nassariidae, Naticidae, and Terebridae. Microscopic gastropod assemblages from samples 11.4/94 and 13.2/94 are also well-preserved, dominated by juvenile forms of Terebridae and Cerithidae, which provide insight into population structure. Traces of predation were observed on almost all individuals except one broken specimen. The following species were identified: *Thericium crenatum* (BROCCHI), *T. europaeum* MAYER, *Pithocerithium turonicum* (MAYER), *Cerithium* sp., *Tiaracerithium pictum* (BASTEROT*), Conilithes exaltatus* (EICHWALD), *Conus ponderosus* BROCCHI, *C. tietzei* R. HOERNES & AUINGER, *Nassarius striatulus* (EICHWALD), *Naticarius stercusmuscarum* (GMELIN), *Natica tigrina* (DEFRANCE), *Neverita josefinia* RISSO, *Archimediella abundans* (HANDMANN), *Oligodia spirata* (BROCCHI), *Ptychidia* cf. *vindobonensis* (HANDMANN), *Alvania oceani* (D'ORBIGNY), *Mohrensternia angulata* juv. EICHWALD, *Hastula sublaevigata* (GRATELOUP), *Subula* (*Oxymeris*) cf. *plicaria* (BASTEROT), *Terebralia lignitarum* (EICHWALD*), Terebralia* sp., *Clavatula* cf. *granulatocincta* (MÜNSTER), *Trigonostoma schroeckingeri* (R. HOERNES & AUINGER) et al. (see Suppl. 1; Pl. 2).

4.2.1.3. Bivalvia

Bivalves were collected from the same eleven samples as the gastropods. Most shells are cracked, brittle and broken. The best-preserved specimens belong to the genus *Ostrea*. Shell-cracking traces were observed on larger individuals. Microscopic examination revealed numerous juvenile forms, some showing signs of predation. Other bivalves occur individually and are generally poorly preserved, complicating identification. In samples 11/94 and 12/94, the appearance of "cementation" was observed, which made the process of preparation of the samples even more difficult. Identified species include: *Pecten besseri* ANDRZEJOWSKY, *Oppenheimopecten aduncus* (EICHWALD), *Pecten* sp., *Pycnodonte gigantica* (SOLANDER), *Neopycnodonte cochlear* (POLI), *Cubitostrea digitata* (EICHWALD), *Ostrea edulis* LINNAEUS, *O. fondrosa* de SERRES, *Ostrea* sp., *Clausinella* cf. *fasciata* (DA COSTA), *Microloripes dentatus* (DEFRANCE), *Spondylus crassicosta* LAMARCK, *Spondylus* sp., *Cardiolucina agassizii* (MICHELOTTI), *Lucina* sp., *Myrtea* cf. *spinifera* (MONTAGU), *Cardium* sp., *Anadara turonica* (DUJARDIN) and *Anadara* sp. (Suppl. 1; Pl. 3).

In addition to the above-mentioned macrofauna, skeletal remains of bryozoans, echinoids, scaphopods (*Dentalium* sp.), Vermetidae (*Vermetus* sp.) and coralline algae were identified in some samples, but they are not specifically treated in this paper.

4.2.1.4. Foraminifera

Fourteen samples from Veliki Izvor (10.1/94, 10.2/94, 10.3/94, 10.4/94, 11.1/94, 11.3/94, 11.4/94, 11.5/94, 12.1/94, 12.2/94, 13.1/94, 13.2/94, VI-4, and VI-5) yielded foraminifera; four samples (11.2/94, VI-1, VI-2, VI-3) were barren. A total of 48 species were identified (see Suppl. 2). Dominant benthic taxa include: *Ammonia* ex gr. *beccarii* (LINNE*), A. viennensis* (D'ORBIGNY*), Biasterigerina planorbis* (D'ORBIGNY*), Amphistegina* cf. *mammilla* (D'ORBIGNY*), Bolivina antiqua* (D'ORBIGNY*), Nonion commune* (D'ORBIGNY*), Cibicidoides ungerianus* (D'ORBIGNY*), Coryphostoma digitale* (D'ORBIGNY*), Laevidentalina badenensis* (D'ORBIGNY*), Dentalina acuta* (D'ORBIGNY*), Elphidium fichtelianum* (D'ORBIGNY), *E. crispum* (LINNE), *E. macellum* (FICHTEL & MOLL), *E. flexuosum grilli* PAPP, *E. hauerinum* (D'ORBIGNY), *Heterolepa dutemplei* (D'ORBIGNY*), Lagena striata* (D'ORBIGNY*), Lenticulina inornata* (D'ORBIGNY*), Lobatula lobatula* (WALKER & JACOB), etc. Planktonic foraminifera were rare, with only sporadic occurrences of *Globigerina bullolides* (D'ORBIGNY*), Orbulina suturalis* BROENNIMANN *Trilobatus trilobus* REUSS and *T. quadrilobatus* (D'ORBIGNY) (Pl. 4).

In general, the foraminiferal assemblages were poor in both diversity and abundance. Only a few samples (e.g., 10.1/94, 10.2/94, 10.4/94) contained richer assemblages (up to 15 species) (Suppl. 2). Most taxa were eroded and poorly preserved. *Biasterigerina planorbis* and *Ammonia* ex gr. *beccarii* were dominant and showed continuous distribution across the section. Notably, *Elphidium* species were frequent in sample 10.1/94. Despite the low abundance, these foraminifera provided important biostratigraphic data, indicating a late Badenian age based on the presence of *O. suturalis* and *Trilobatus quadrilobatus*.

4.2.1.5. Ostracoda

Out of eighteen samples from Veliki Izvor, twelve yielded ostracods (10.1/94, 10.2/94, 10.3/94, 10.4/94, 11.1/94, 11.3/94, 11.4/94, 11.5/94, 12.1/94, 13.1/94, 13.2/94, and VI-4; see Suppl. 3).

Assemblages were generally poor, both qualitatively and quantitatively, with most samples containing fewer than five species. Exceptions include samples 10.1/94, 10.2/94, and 11.1/94, which had 9 – 11 species each. Twenty-one species were identified (alphabetically listed in Suppl. 3). The most abundant taxa include: *Aurila cicatricosa* (REUSS), *A. haueri* (REUSS), *Aurila* sp., *Callistocythere* sp., *Cnestocythere truncata* (REUSS), *Cytheretta ornata* (HEJJAS), *Eucytherura* cf. *pygmea* (REUSS), *Loxoconcha punctatella* (REUSS), and *Loxoconcha* sp. Less frequent taxa include *Tenedocythere sulcatopunctata* (REUSS), *Cletocythereis haidingeri* (REUSS), *Cytheridea* cf. *acuminata* BOSQUET, *Costa* cf. *edwardsii* (ROEMER), *Eucytherura* cf. pygmea (REUSS), *Leptocythere* sp., *Loxocorniculum hastatum* (REUSS), *Pokornyella deformis* (REUSS) (Pl. 4).

Genera such as *Bythocypris*, *Buntonia*, and *Senesia* were extremely rare. Both valves and adult carapaces were found; juvenile forms were absent. Most ostracods have eroded, "washed" and poorly visible species characteristics. Taxa with strong and thick carapace such as *Aurila*, *Pokornyella*, *Tenedocythere*, and *Cletocythereis* have a wider distribution per samples. Similar trends were observed in *Loxoconcha* and *Cnestocythere*. Only *Aurila* species were recorded in notable abundance (Suppl. 3).

4.2.2. Nikoličevo

4.2.2.1. Gastropoda

The gastropod fauna was collected from five samples (18.1/94, 18.3/94, 19.1/94, 19.2/94 and 19.3/94). It is represented by rare forms, both macro- and microscopic in size. The largest number of individuals belong to the family Cerithidae. The following species are recognized: *Tritia schoenni* (R. HOERNES & AUINGER), *Trigonostoma schroeckingeri* (R. HOERNES & AUINGER), *Alvania oceani* (D'ORBIGNY), *Chicoreus aquitanicus* (GRATELOUP), *Thericium europaeum* (MAYER), *Tiaracerithium pictum* (BASTEROT), *Asthenotoma ornata* (DEFRANCE), and *Pirenella* sp.

4.2.2.2. Bivalvia

Bivalves were collected from the same five samples near Nikoličevo. Assemblages are dominated by *Ostreidae*, which form shell accumulations. These oysters have thin shells and are relatively small (up to 10 cm). Other bivalves are rare, small, and often broken. Microscopic fractions of samples 19.1/94 – 19.3/94 are dominated by juvenile forms from the lucinid group. The following bivalvia species were identified: *Ostrea frondosa* (DE SERRES), *Ostrea* sp., *Cubitostrea digitata* (EICHWALD), *Crassostrea* cf. *gryphoides* (SCHLOTHEIM), *Anadara turonica* (DUJARDIN), *Anadara* sp., *Microloripes* cf. *dentatus* (DEFRANCE), *Varicorbula* cf. *gibba* (OLIVI), *Caryocorbula* cf. *carinata* (DUJARDIN), and *Lucina* sp. (Pl. 3).

Samples also contain remains of *Vermetus* sp., scaphopods, echinoid spines, fish bones, and small coral fragments which were not studied in detail.

4.2.2.3. Foraminifera

A total eleven samples from Nikoličevo contain foraminifera (17.1/94, 17.2/94, 18.2/94, 18.4/94, 19.1/94, 19.2/94, 19.3/94, 19.4/94, 20.4/94, NK-1, and NK-3 – see Suppl. 2).

Assemblages were generally poor in both diversity and abundance. *Ammonia* ex gr. *beccarii* occurred in most samples, with frequent occurrence in 18.2/94. Other samples contained only rare, indeterminate *Elphidium* species. Two samples (18.2/94 and 19.4/94) had slightly more diverse assemblages (7 – 8 species, each with <5 specimens). No planktonic species were recorded.

4.2.2.4. Ostracoda

Only two older samples (19.4/94 and 20.4/94) yielded ostracods, represented by the poorly preserved carapaces of *Aurila* sp. and fragments of ?*Pokornyella* sp. (Suppl. 3). All five new samples (NK-1 to NK-5) were barren.

5. DISCUSSION AND INTERPRETATION

5.1. Palaeoecological remarks

The sedimentary sequences from Veliki Izvor and Nikoličevo represent complex lithofacies architectures that reflect dynamic depositional conditions. Although both sites show features typical of deltaic and fluvial systems, they differ significantly in terms of environmental settings and sedimentary processes. These differences are evident in their lithology, petrography, and microstructures. In summary, both locations represent transitional zones between fluvial and marine environments. The Veliki Izvor section (Fig. 2) reflects a shallow- marine depositional system with strong tidal and wave influences, while the large Nikoličevo section (Fig. 4) represents a proximal deltaic system with episodic carbonate influx. Nevertheless, some correlation between composite sections on Figures 2 and 6 can be observed. These distinctions highlight the palaeogeographic complexity of marginal Miocene basins in southeastern Europe (POPOV et al., 2004).

5.1.1. Veliki Izvor

The sedimentary succession shows features typical of Middle Miocene shallow-marine to lagoonal systems. The lithofacies are composed of alternating layers of gravel, sand, and silt organized in two- and three-membered cycles (MIALL, 1985; NICHOLS, 2009). This indicates dynamic conditions in a nearshore marine environment, influenced by fluvial input, tidal currents, and wave activity. The presence of normal grading, poor sorting, and laterally extensive bodies indicates deposition on a low-gradient coastal plain, affected by storm surges and tidal redistribution (BRIDGE, 2003).

Carbonate concretions are locally developed within sandy-silty intervals, particularly in the middle part of the section. Their internal structure — microsparitic cement and micritized allochems including cortoids, peloids, and bioclasts — suggests early diagenetic formation under oxidizing conditions, in shallow, low-energy marine settings with limited pore water circulation (MORAD et al., 2000; FLÜGEL, 2004).

The sedimentological-petrological characteristics and faunal association indicate deposition in a shallow marine bay, close to the coastline. High-energy conditions in this setting led to the deposition of thick conglomerate and coarse sand layers, with only rare occurrences of finer material. The presence of relatively large coral species suggests a nearby reef, although no such structure has yet been confirmed in the study area.

Corals, bivalves, and gastropods were collected from conglomeratic sandstones. The genus *Tarbellastraea* is dominant, while others occur as small, isolated fragments. The occurrences of epibiosis and perforations that indicate the adaptation of corals and other molluscs to life in the reef zone are significant (TAYLOR & WILSON, 2002, 2003; WALKER & MILLER, 1992). Epibiosis was observed on the *Spondylus* shell, on the valve which a coral colony began to form (Fig. 7a). An example of biotic injuries to a colony of coral *Tarbellastraea* sp. was also observed, which occurred as a result of formation of the *Lithophaga* sp. shell.

The occurrences of *Scleractinia* are also characteristic of the Early Badenian period, coinciding with the Middle

Figure 7. A few examples of mutual relationships among various faunal groups (Veliki Izvor). **a** The epibiosis of the Spondylus valve and a colony of Scleractinia sp.; **b** Perforations on an *Ostrea* sp. shell by the action of the sponge Entobia; **c** Ostrea shell attached to conglomerate pebbles as an example of xenomorphism; **d** predation on a gastropod *Oligodia* sp. shell. Scale bar – 1 cm.

Miocene Climate Optimum (e.g., BOSELLINI & PERRIN, 2008). A high diversity of corals from Veliki Izvor aligns with similar findings from the Central Paratethys during the Lower Badenian (e.g., RUS & POPA, 2008; JOVANOVIĆ et al., 2021). The fragments suggest short transport distances from a biohermal reef, potentially located between Veliki Izvor and Nikoličevo to the east. The lack of borehole data limits the ability to confirm this, but the presence of coral remains at both sites suggests a possible WNW – ESE reef trend.

The bivalve assemblage from both sites indicates a shallow, warm marine environment with mostly normal salinity, evidenced by the presence of stenohaline forms such as *Pecten* and *Flabellipecten*. However, the occurrence of euryhaline species from the families Lucinidae, Ostreidae, and Potamididae, suggests periodic freshwater influx from nearby land (e.g., STUDENCKA & JASIONOWSKI, 2011).

The Ostrea group is most abundant. Larger, thicker-shelled forms (e.g., at Veliki Izvor) likely thrived in warm, high-energy waters (JOVANOVIĆ, 2018). *Entobia* borings from clinoid sponges were observed on some Ostrea valves, a common feature on Miocene shells from rocky, shallow environments (NAIMI et al., 2021; BOŠNJAK et al., 2024). *Entobia* borings are occasional, and given the sessile nature of these bivalves, diverse forms of xenomorphism are observed (JOVANOVIĆ, 2018). In a coastal habitat with the higher hydrodynamic regime, the Ostrea attached to conglomerate pebbles (Fig. 7c). Bioerosion was detected on the various gastropod and bivalve shells. In the area of southern Central Paratethys, the most common bioerosion is predation by Naticidae and Muricidae (GANIĆ et al., 2016; BOŠNJAK et al., 2021). The largest number of predations was observed on gastropods (Fig. 7d). No injuries of this type were observed on bivalves due to the broken shells in most samples.

The presence of relatively diverse (forty-eight species in Veliki Izvor) and small number of shallow-water benthic foraminifera (except of *Ammonia* and *Biasterigerina*), alongside rare occurrences of planktonic taxa such as *Orbulina*, *Globigerina*, and *Trilobatus*, provides robust evidence for a shallow, warm marine environment. The rare occurrence of planktonic species such as *Orbulina suturalis* and *Trilobatus trilobus* further supports a habitat ranging from tropical to warm-temperate conditions as well as redeposition processes (PEZELJ et al., 2013, 2016; FILIPESCU & SILYE, 2008; MANDIC et al., 2019; FILIPESCU et al., 2020). The modern *Biasterigerina* is a trochospiral form that lives as free-living epifauna in an oligotrophic environment with seagrass meadows evidenced by the predominance of *B. planorbis* and cibicidoids (JAMRICH et al., 2024). These taxa are herbivorous and thrive in warm waters. Genera such as *Elphidium* and *Cibicidoides* prefer shallow, algae- or seagrass- covered substrates (KOVÁČOVÁ & HUDÁČKOVÁ, 2009; PEZELJ et al., 2013, 2016; PEZELJ & DROBNJAK, 2019; PERYT et al., 2021; BRZOBOHATÝ et al., 2022). Modern *Ammonia beccarii* is known from subtidal, nearshore habitats (13 – 21 m depth) in the Adriatic Sea (SCHÖNFELD et al., 2021). Frequent finds of *Amphistegina* ex gr. *mammilla* further support a shallow-water marine habitat. Modern *Amphistegina* species range from 0 to >150 m (PILLER et al., 2022) with *A. radiata* and *A. lessonii* (morphologically similar to *A. mammilla*) typically abundant at 20 – 30 m depth in the NW Pacific, southern Tunisia, and the Central Mediterranean (HOHENEGGER et al., 1999; EL KATEB et al., 2018; COSENTINO et al., 2024). Other large benthic foraminifera such as *Planostegina* sp. have rare occurrence per samples but high abundance in samples 10.1/94 and 13.1/94. It suggests some temporary influence from the deeper photic zone (HOHENEGGER, 2004; PILLER et al., 2022). In that sense, the rare occurrence of *Laevidentalina*, *Martionella* and *Siphonodosaria* species as deep waters dwellers (> 1,000 m) could indicate a process of redeposition. Therefore, the quality of the foraminiferal assemblages, preservation of tests as well as their position in the sedimentary column suggest a high dynamic process, water fluctuation and redeposition.

In total, 21 ostracod species were identified at Veliki Izvor. This is a poor assemblage, especially based on the number of specimens. The preservation of the valve/carapace and missing juvenile forms demonstrate that ostracods do not represent an autochthonous assemblage. The distinct domination of two genera in the assemblages (*Aurila*, *Loxoconcha*) as well as their generally low frequency suggests unfavourable life conditions. Isolated adult valves and carapaces are dominant, probably because of the strong selective size sorting due to the high energy currents, and/or rapid sedimentation (VAN HARTEN, 1986).

The assemblage reflects a shallow, warm, pericoastal (inner-neritic) setting, supported by taxa such as *Aurila*, *Callistocythere*, *Cnestocythere*, *Cytheridea*, *Loxoconcha*, *Pokornyella*, *Semicytherura*, *Senesia*, *Tenedocythere*, etc.

Based on similar findings from the Mediterranean Sea (VAN MORKHOVEN, 1963), these assemblages are characteristic of the upper infralittoral zone (up to 40 m depth). Representatives of the genus *Callistocythere* are recorded from shallow water and warm environments (VAN MORKHOVEN, 1963; RUNDIĆ, 1992; RUNDIĆ et al., 2024).

In the Adriatic Sea, *Callistocythere flavidofusca* is found at depths of up to 120 m and is particularly abundant around 70 m (ZORN, 2003). Also, the recent *Aurila convexa* (BAIRD) is most abundant at depths of 50 – 70 m in the Adriatic Sea (ZORN, 2003, 2004). The recent *Cytheridea neapolitana* KOLLMANN, lives in the Mediterranean Sea in range depth between 10 and 90 m (ZORN, 2004). Other recorded genera show comparable depth ranges, with *Loxoconcha* exhibiting a broader bathymetric tolerance (SZCZECHURA, 2006; HAJEK-TADESSE & PRTOLJAN, 2011; MANDIC et al., 2019). Comparable shallow-water littoral communities from the various Badenian-aged deposits across the western, northern, and southern parts of the Central Paratethys have been previously reported (RUNDIĆ, 1992; RUNDIĆ et al., 2000; ZORN, 2003, 2004; AIELLO & SZCZECHURA, 2004; GROSS, 2006; SZCZECHURA, 2006; HAJEK-TADESSE & PRTOLJAN, 2011; DUMITRIU et al., 2017; MANDIC et al., 2019; JOVANOVIĆ et al., 2021; RUNDIĆ et al., 2024). Sporadic findings of *Bythocypris* and *Buntonia* are considered to have been relocated and likely represent the allochthonous part of the ostracod assemblage.

5.1.2. Nikoličevo

From a palaeoecological perspective, the sedimentological and petrographic characteristics of the Nikoličevo area provide important clues about the sedimentary environment, despite the low diversity and rarity of fossils, which nonetheless help refine the interpretation of depositional settings.

The large Nikoličevo section (Fig. 4) shows lithofacies features typical of fluviodeltaic environments (MIALL, 1985; NICHOLS, 2009). Alternating beds of sand, gravel, and clay are present, but with greater lithological variability. The occurrence of andesitic clasts implies a volcanic source from the nearby volcanic complex of eastern Serbia, while limestone fragments suggest reworking of the pre-Miocene carbonate basement. The poor sorting and moderate rounding indicate high sedimentation rates and short transport distances, consistent with proximal delta plain deposition (BOGGS, 2011).

Some sandy units contain irregular, decimetre-scale carbonate-rich bodies, interpreted as reworked layers originating from nearby shallow- or marginal-marine environments. These lens-shaped bodies, rich in micritized components and carbonate detritus, indicate episodic carbonate influxes during brief transgressions or sediment supply events (SCHLAGER, 2005). At the top of the large Nikoličevo profile (Fig. 4), sedimentation transitions into distal, clayey-marly units, interpreted as shallow-marine deposits formed during the final stage of delta progradation into a quieter basin setting (COLEMAN & WRIGHT, 1975). These fine- grained, carbonate-rich deposits mark the terminal phase of sedimentation. The presence of fine-grained clast fragments within sandy-silty intervals is interpreted as reworked material, mobilized during dynamic processes, such as channel migration or transitions in energy conditions (READING, 1996). Their presence suggests dynamic reorganization of sediments and formation of new sedimentary structures. In that sense, a sandy-silt clast (NK-3) with a specimen of marine species *Anadara turonica* supports this concept (Fig. 4).

Microstructural features, including imbricated grains and "floating" grains within a sandy matrix, indicate high-energy fluvial conditions. The presence of muscovite, biotite, and chlorite points to short transport distances and the working of older sediments — typical characteristics of deltaic to floodplain systems (BOGGS, 2011).

In contrast, smaller outcrops in the dry stream valley at Nikoličevo, presented as a composite lithological column (Fig. 6), show different sedimentary features. The succession is composed mainly of coarse-grained sands, partly gravelly and partly clayey, with several shell- rich layers indicating deposition under low-energy, shallow-water conditions, with minor water depth fluctuations. Lenticular and wedge-shaped bodies in the basal part, together with alternating coarser and finer layers, and locally developed carbonate nodules and intraformational clasts, suggest episodic variations in depositional energy. The poorly to moderately sorted clasts and the preserved internal structures demonstrate dynamic sediment reworking typical of a nearshore or marginal marine setting. Overall, these features resemble aspects of the Veliki Izvor succession, where fluvial influences are limited, and provide a basis for comparison with the larger Nikoličevo profile (Fig. 4).

The bivalve assemblage indicates a shallow-water marine environment. The most numerous bivalves belong to the genus *Ostrea*. Compared to Veliki Izvor, specimens from Nikoličevo are smaller but more numerous (Fig. 6; Suppl. 1), consistent with deposition in very shallow waters (up to 10 m depth) (MANDIC & HARZHAUSER, 2003). *Entobia* borings are more common in Nikoličevo specimens than in those from Veliki Izvor (Fig. 7b, rounded). Oysters are often preserved in lumachelle form (Fig. 6) and typically have thinner, smaller shells, suggesting a calmer environment or potential freshwater influence. Although xenomorphism is more prevalent at Veliki Izvor, valve-to-valve attachment is more frequent in Nikoličevo specimens (Fig. 7b, arrow), possibly reflecting a colony living on soft, silty-sand substrates. Rare occurrences of small euryhaline gastropods (*Pirenella* sp.) and frequent *Thericium europaeum* further support a shallow-water setting.

Foraminifera are rare in the Nikoličevo area, except for *Ammonia* ex gr. *beccarii*, which occurs sporadically to frequently across both sections. In addition, *Elphidium crispum* and *Elphidium* sp. appear in most samples, while other *Elphidium* species occur sporadically. *Amphistegina*, *Biasterigerina*, and *Lenticulina* are exceedingly rare in individual samples (Suppl. 2). The shallow-water marginal marine Ammonia – Elphidium assemblage, probably lived closer to land than the Veliki Izvor assemblages, with a possible freshwater inflow. Only a few badly preserved carapaces of *Auril*a sp. and fragments of ?*Pokornyiella* sp. could suggest a shallow, warm water (inner-neritic) and pericoastal environment.

5.2. Biostratigraphic remarks

Based on foraminifera, as well as molluscs and ostracods, certain conclusions can be drawn regarding the biostratigraphic position of the studied sections. In addition to the palaeontological material collected during fieldwork, literature data on biostratigraphic analyses from a broader area were also considered, along with correlations to previously published data from neighboring countries (Fig. 8).

Biostratigraphic analysis of foraminifera is based on standard biozonations for Central Paratethys (PAPP & SCHMID, 1985; CICHA et al., 1998). The Upper Badenian *Bulimina– Bolivina* Zone and *Ammonia beccarii* Ecozone are standard bio/eco zone of small benthic foraminifera for this part of Middle Miocene (Fig. 8) and can be recognized as an equivalent of M6 Zone. The predominance of ammonias, elphidia, and some other more euryhaline taxa in some samples, initiated the determination of the Ammonia/Elphidium impoverishment Ecozone (PETROVIĆ, 1961, 1969, 1988; GANIĆ, 2005; RUNDIĆ et al., 2024).

Regarding the biostratigraphic position of the studied sections, determination is nearly impossible for Nikoličevo, primarily due to the rarity and poor preservation state of the foraminifera. However, the occasional presence of *Ammonia* in all samples (notably frequent in sample 18.2/94), along with *Elphidium*, supports assignment to the aforementioned impoverishment ecozone.

Foraminiferal assemblages from Veliki Izvor show greater potential for biostratigraphic analysis, particularly in certain samples (Suppl. 2). The rare occurrence of *Bolivina* species and the more abundant presence of several typically marine taxa — such as *Biasterigerina planorbis*, *Amphistegina* cf. *mammilla*, *Elphidium crispum*, *Nonion commune*, *Bolivina antiqua*, *Bolivina* sp., *Conyphostoma digitale*, *Heterolepa dutemplei* and *Hanzawaia boueana* indicate a marine development during the Upper Badenian. However, throughout the composite Veliki Izvor outcrop, this association is interspersed with intervals dominated by *Ammonia* and small *Elphidium* species, consistent with the *Ammonia/Elphidium* impoverishment Ecozone. Supporting these findings, previous studies of foraminiferal records from the Zaječar region report similar assemblages. For instance, the FMTC-1109 borehole (282 – 375.50 m) at nearby Borska Slatina, northwest of Nikoličevo (see RUNDIĆ et al., 2015) yielded species including *Ammonia* ex gr. *beccarri* LINNE, *A*. cf. *viennensis* (D'ORBIGNY), *Nonion commune* (D'ORBIGNY), *Biasterigerina planorbis* (D'ORBIGNY), *Caveastomella adolphina* (D'ORBIGNY), *Bolivina dilatata* REUSS, *Bolivina* cf. *antiqua* D'ORBIGNY, *Bolivina* sp., *Bulimina striata* D'ORBIGNY, *B*. cf. *elongata* D'ORBIGNY, *Lagena striata* (D'ORBIGNY), *Lenticulina*

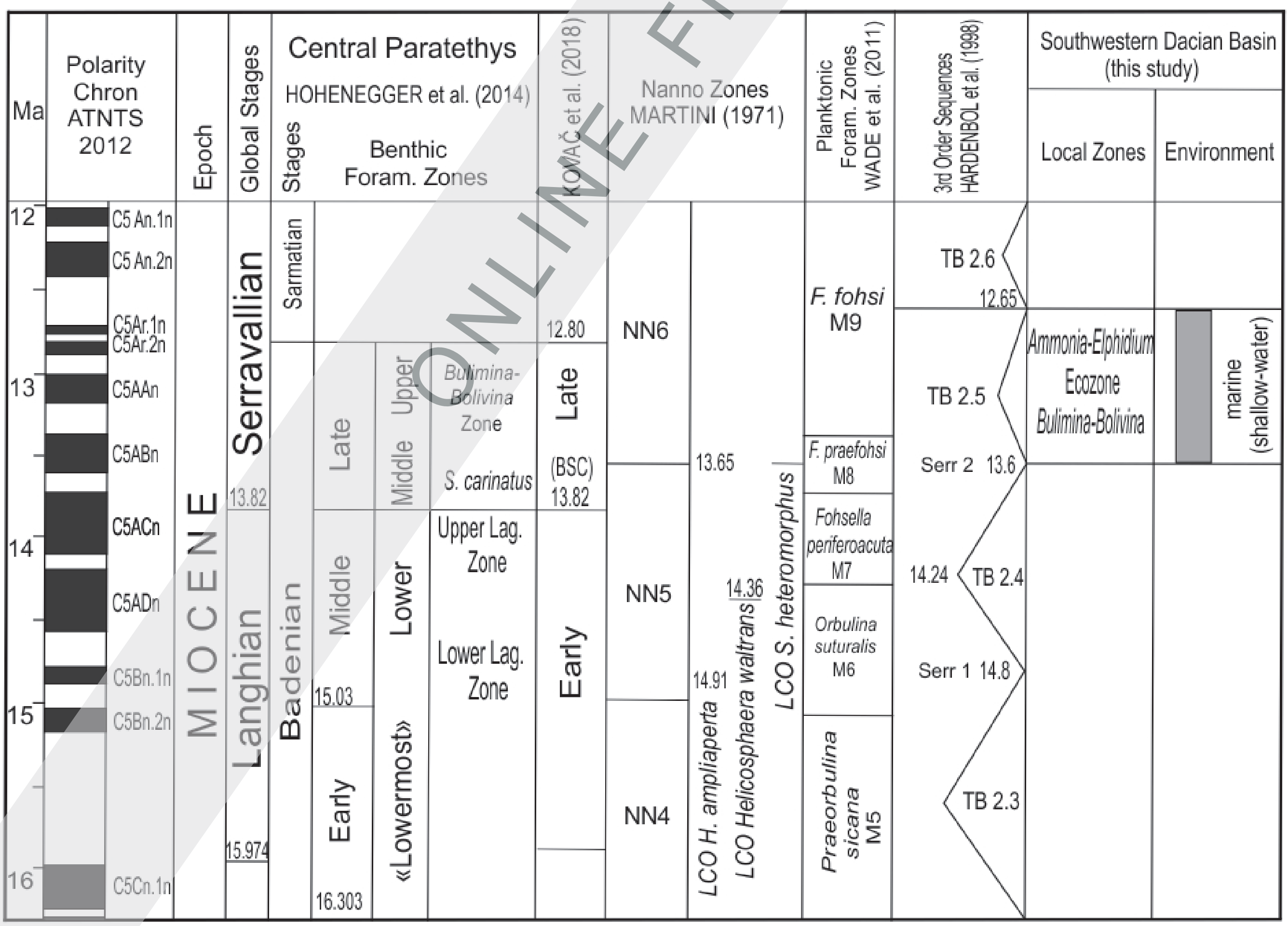

Figure 8. Part of the chronostratigraphic scheme of the Middle Miocene of Paratethys (after PEZELJ et al., 2016; LIRER et al., 2019; RAFFI et al., 2020; POPOV et al., 2024; RUNDIĆ et al., 2024). The biostratigraphic position of the studied sites marked by grey rectangles. Badenian/Sarmatian boundary marked according to PALCU et al. (2015).

calcar (LINNE) and *L. inornata* D'ORBIGNY. These assemblages place the studied interval firmly within the Upper Badenian *Bulimina-Bolivina* Zone, i.e. and *Ammonia/ Elphidium* impoverishment Ecozone (RUNDIĆ et al., 2015). Stratigraphically, this interval underlies Lower Sarmatian clastics. Additionally, several boreholes (e.g., RTK-1501, RTK-1502A) east of Lubnica near Zaječar (Fig. 1) record a late Badenian marine transgression in the area (RUNDIĆ et al., 2019). This aligns well with previous biostratigraphic studies confirming late Badenian marine and marine-brackish conditions near the Badenian/Sarmatian boundary (POPOVIĆ, 1968; POPOVIĆ & GAGIĆ, 1969; PETROVIĆ, 1961, 1969, 1988; GANIĆ, 2005). Similar shallow-water environments during the late Badenian (early Serravallian) and a regressive trend characterized by extensive clastics and dominance of more restricted marine foraminifera (TB2.5 3rd order sequence) have been documented in other marginal marine basins of the Paratethys (e.g., PEZELJ et al., 2007, 2013, 2016; DUMITRIU et al., 2017; KOVÁČ et al., 2017, 2018; PAVELIĆ & KOVAČIĆ, 2018; FILIPESCU et al., 2020; PERYT et al., 2014, 2021, 2024; JAMRICH et al., 2024; RUNDIĆ et al., 2024).

Considering the exceedingly rare and low-diversified ostracods (Suppl. 3), the standard biozonation of Badenian based on ostracods (BRESTENSKÁ & JIŘÍČEK, 1978; HAJEK- TADESSE & PRTOLJAN, 2011; PEZELJ et al., 2016) could not be applied. Nonetheless, the presence of taxa such as *Cnestocythere lamellicostata*, *Aurila haueri*, and *Loxoconcha punctatella* suggests an Upper Badenian age.

6. CONCLUSION

– The Upper Badenian shallow-water marine sediments at the southwestern margin of the Dacian Basin (Veliki Izvor and Nikoličevo, eastern Serbia) were deposited transgressively over various Cretaceous deposits including flysch, carbonates, volcanoclastics, and Early Miocene continental deposits.

– The comparative sedimentological analysis of the Veliki Izvor and Nikoličevo sections reveals contrasting depositional environments within the same Miocene palaeogeographic framework. Veliki Izvor is characterized by a shallow-marine, tidally influenced system, while Nikoličevo represents a more proximal, fluviodeltaic setting with evidence of episodic carbonate influx. Both sections exhibit dynamic lithofacies architectures and early diagenetic features, reflecting the interplay of fluvial, marine, and volcanic influences during sedimentation.

– The marginal marine highly oxygenated setting with normal salinity is documented by well-preserved corals as well as bivalves and gastropods (e.g., Ostreidae, Conidae, etc.).

– Generally, benthic foraminifera have poorly preserved tests and occur along sections with small numbers of individuals and low-diversity assemblages. At Veliki Izvor, a shallow-water *Biasterigerina–Ammonia* assemblage typical of a well-oxygenated, normal marine inner shelf environment was identified. The shallow-water marginal marine *Ammonia* and *Elphidium* assemblage at Nikoličevo likely lived closer to land, with possible freshwater influence.

– Rare planktonic foraminifera (*Trilobatus*, *Orbulina*) suggest an open-marine influence, while some deep-water benthic foraminifera (*Laevidentalina*, *Martionella*, *Siphonodosaria*) indicate redeposition.

– Ostracod assemblages include taxa which are typical for shallow marine environments. Sporadic findings of *Bythocypris* and *Buntonia* indicate the allochthonous part of the ostracod assemblage.

– The studied marine shallow-water deposits and its sedimentologic and stratigraphic characteristics, indicates an emersion process near the Badenian/ Sarmatian transition.

– The obtained results contribute to a better understanding of marginal Miocene basins in southeastern Europe and underscore the complexity of transitional depositional systems.

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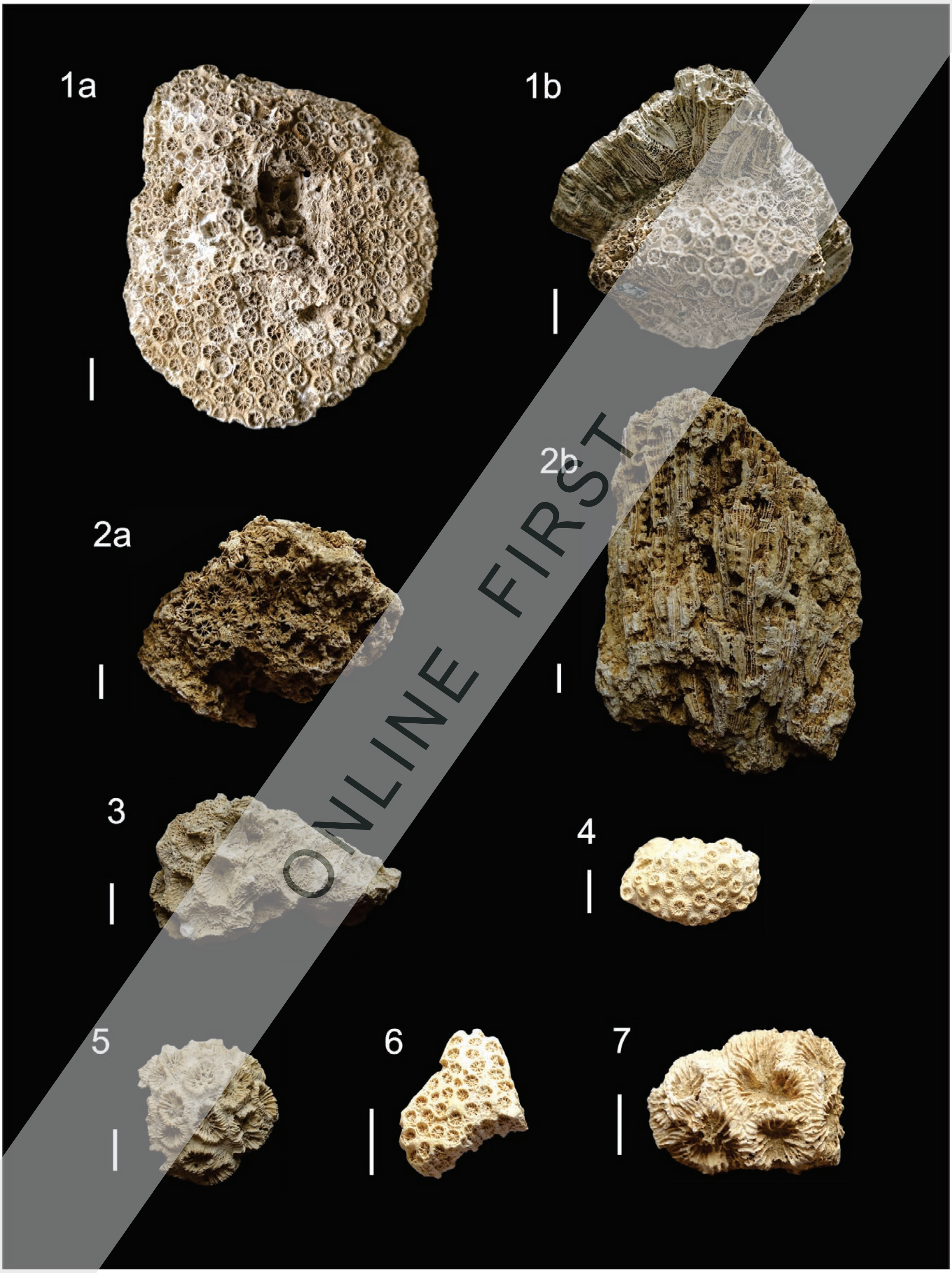

Plate 1. Badenian corals from Veliki Izvor. **1a, b** – *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME); **2a, b** – *Echinopora defrancei* (MILNE EDWARDS & HAIME); **3** – *Favites neglecta* (MICHELOTTI); **4** – *Tarbellastraea conoidea* (REUSS); **5** – *Favia gotschevi* KOJUMDGIEVA; **6** – *Stylopora subreticulata* REUSS; **7** – *Favia* sp. Scale bar – 1 cm.

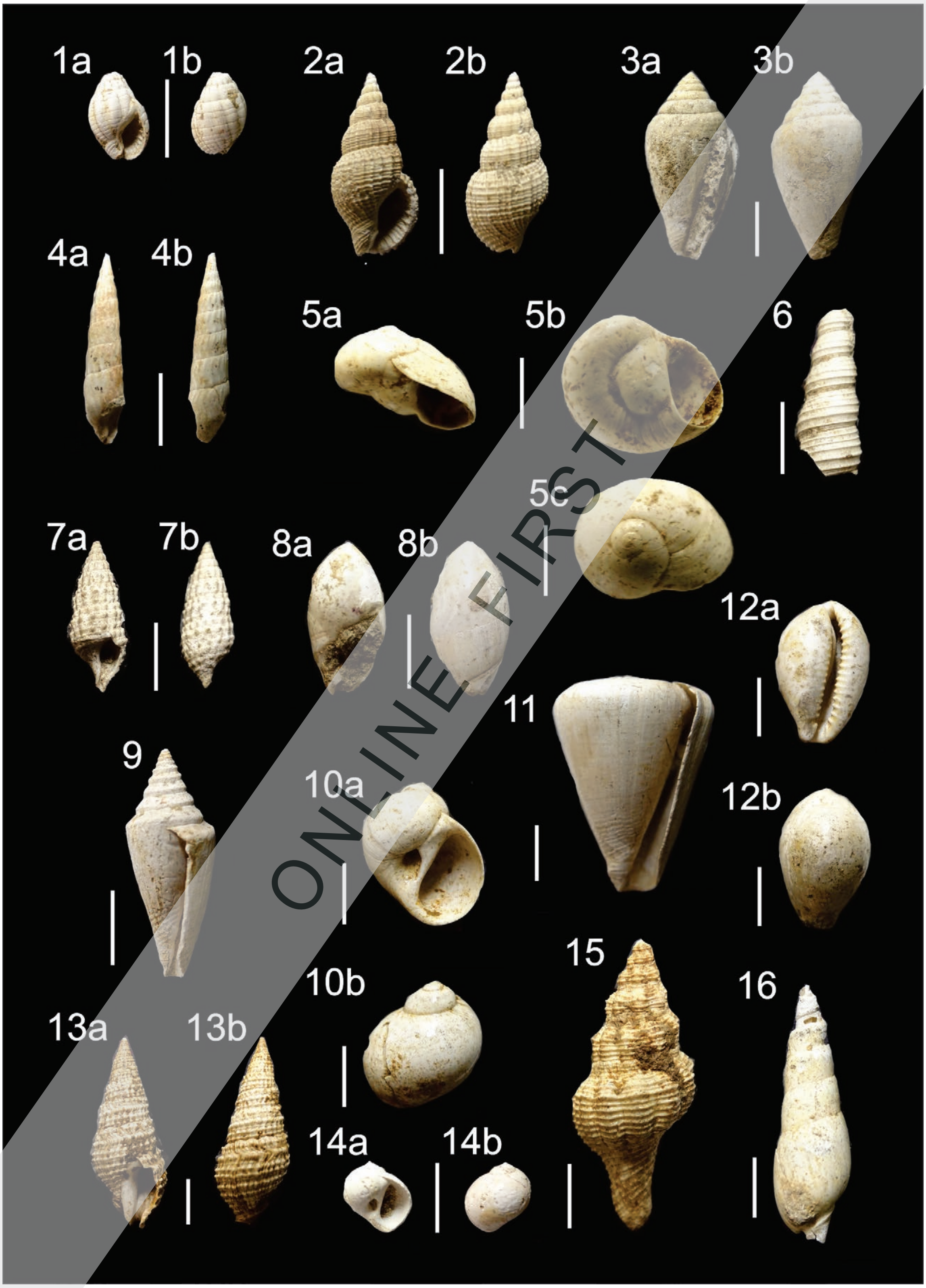

Plate 2. Badenian gastropods from Veliki Izvor. **1a, b** – *Nassarius* cf. *pupaeformis* R. HOERNES & AUINGER; **2a, b** – *Eosipho hoernesi* BELLARDI; **3a, b** – *Conus tietzei* R. HOERNES & AUINGER; **4a, b** – *Hastula sublaevigata* (GRATELOUP); **5a, b, c** – *Neverita josefinia* RISSO; **6** – *Ptychidia* cf. *vindobonensis* (HANDMANN); **7a, b** – *Pythocerithium turonicum* (MAYER); **8a, b** – *Amalda glandiformis* (LAMARCK); **9** – *Conolithes exaltatus* (EICHWALD); **10a, b** – *Natica tigrina* (DEFRANCE); **11** – *Conus daciae* (R. HOERNES & AUINGER); **12a, b** – *Zonaria columbaria* (LAMARCK); **13a, b** – *Clavatula* cf. *granulatocincta* (MÜNSTER); **14a, b** – *Naticarius stercusmuscarum* (GMELIN); **15** – *Phyllocheilus* cf. *speciousus* (A. D'ORBIGNY); **16** – *Oxymeris* cf. *plicaria* (BASTEROT). Scale bar – 1 cm.

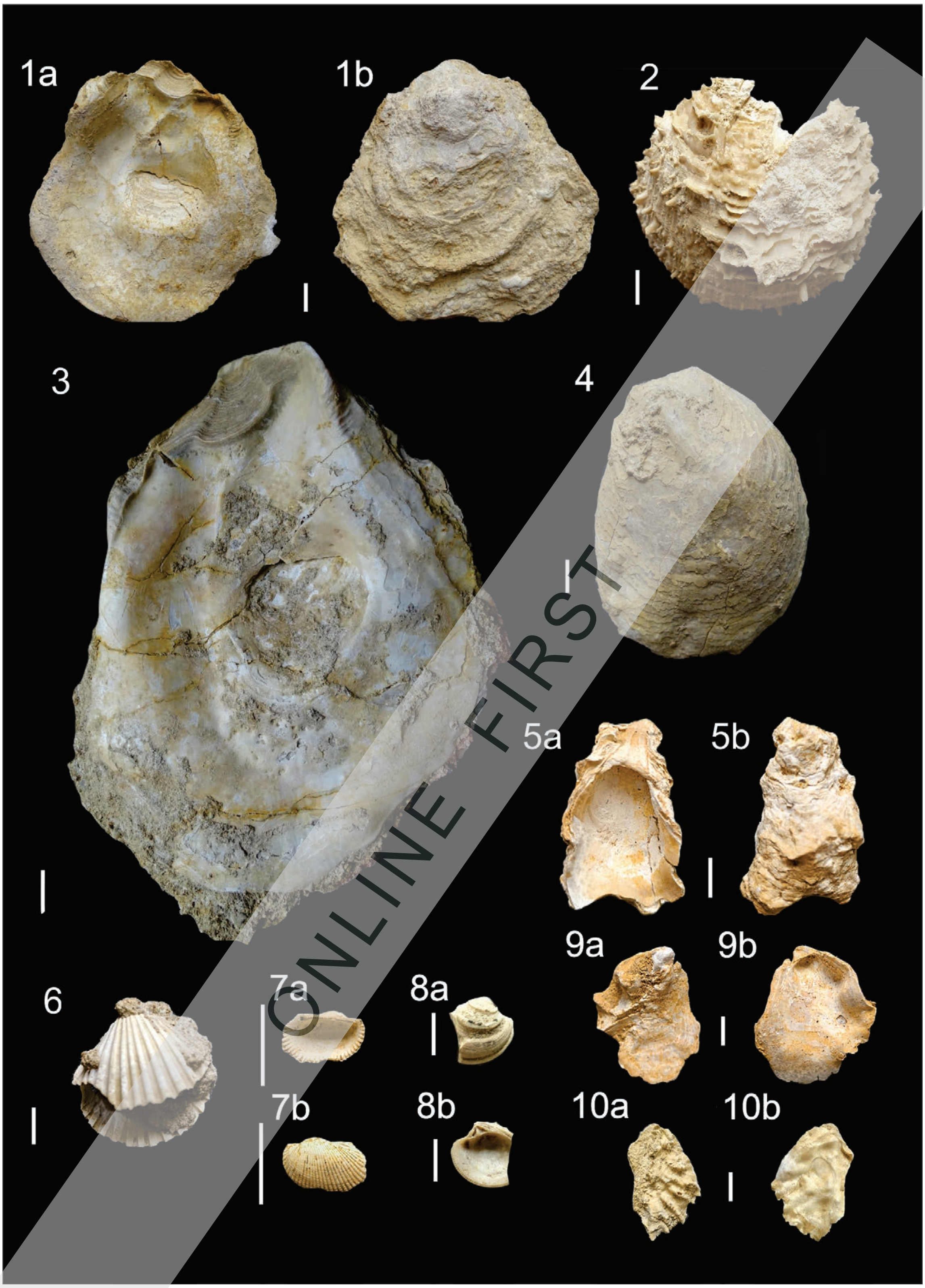

Plate 3. Badenian bivalves from Veliki Izvor (1 – 4, 6, 8) and Nikoličevo (5, 7, 9, 10). **1a, b** – *Pycnodonte gigantica* (SOLANDER); **2** – *Spondylus crassicosta* LAMARCK; **3** – *Ostrea edulis* LINNAEUS; **4, 9a, b, 10a, b** – *Cubitostrea digitata* (EICHWALD); **5a, b** – *Crassostrea* cf. *gryphoides* (SCHLOTHEIM); **6** – *Pecten besseri* ANDRZEJOWSKI; **7a, b** – *Anadara turonica* (DUJARDIN); **8a, b** – *Clausinella* cf. *fasciata* (DA COSTA). Scale bar – 1 cm.

Plate 4. Badenian foraminifera (1 – 30) and ostracoda (31 – 36) from Veliki Izvor. Foraminifera specimens from Nikoličevo (37 – 39). Scale bar – 200 µm. **1** – *Bolivina antiqua* D'ORBIGNY (10.2/94); **2, 3** – *Coryphostoma digitale* (D'ORBIGNY) 2 – 10.2/94, 3 – 11.4/94; **4** – *Bolivina* sp. (11.4/94); **5** – *Quinqueloculina* sp. (11.4/94); **6 – 11** – *Biasterigerina planorbis* (D'ORBIGNY), **6** – spiral view, **7** – umbilical view (10.2/94), **8** – spiral view, **9** – umbilical view (11.4/94), **10** – spiral view, **11** – umbilical view (13.1/94); **12** – **15** – *Ammonia ex gr. beccarii* (LINNE), **12** – spiral view, **13** – umbilical view (10.2/94), **14** – spiral view, **15** – umbilical view (11.1/94); **16** – *Elphidium macellum* (FICTHEL & MOLL) (13.2/94); **17** – *Elphidium flexuosum* (D'ORBIGNY) (VI-4); **18, 19** – *Cibicidoides ungerianus* (D'ORBIGNY), **18** – umbilical view, **19** – spiral view (10.2/94); **20, 21** – *Lobatula lobatula* (WALKER & JACOB), **20** – umbilical view, **21** – spiral view (11.4/94); **22, 23** – *Nonion commune* (D'ORBIGNY), **22** – umbilical view, **23** – spiral view (13.1/94); **24** – *Amphistegina* ex gr. *mammilla* (FICTHEL & MOLL) (VI-4); **25** – *Lenticulina inornata* (D'ORBIGNY) (10.1/94); **26, 27** – *Trilobatus trilobus* (REUSS) (10.1/94); **28** – *Orbulina suturalis* BRÖNNIMANN (11.1/94); **29** – *Globulina gibba* (D'ORBIGNY IN DESHAYES) (11.1/94); **30** – *Guttulina* sp. (13.2/94); **31, 32** – *Loxoconiculum hastatum* (REUSS), **31** – right valve, outside, **32** – same, inside (11.1/94); **33, 34** – *Pokornyella deformis* (REUSS), **33** – left valve, outside, **34** – same, inside (11.1/94); **35, 36** – *Aurila haueri* (REUSS), **35** – left valve, outside, **36** – same, inside (11.1/94); **37, 38** – *Ammonia* ex gr. *beccarii* (LINNE), **37** – spiral view, **38** – umbilical view (18.2/94); **39** – *Lenticulina* sp. (NK-1).