Palaeoecological and sedimentological characterisation of Middle Miocene sediments from the Hrvatska Kostajnica area (Croatia)

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1. INTRODUCTION

The studied area is located in the middle part of Croatia (Fig. 1a), in the south-western part of the Pannonian Basin System (PBS) (HORVÁTH & ROYDEN, 1981; ROYDEN, 1988) and belongs to the North Croatian Basin (NCB) (PAVELIĆ & KOVAČIĆ, 2018). The investigated lithostratigraphical column of Hrvatska Kostajnica (KOS-I) (45.22833° N, 16.55905° E) represents the main scarp of the landslide located in the Hrvatska Kostajnica area on the eastern slopes of the Kubarnovo brdo hill, north of the Una River and west of the Kostajnica stream.

Soil breakdown and sliding formed 30 m outcrop of the Badenian–Sarmatian marly deposits on which sedimentological, mineralogical, geochemical and palaeontological investigations were performed. The simplified Basic Geological Map of the SFRY, 1: 100 000, Kostajnica (Fig. 1b) represents the latest complete geological investigation of the area of Hrvatska Kostajnica. According to JOVANOVIĆ & MAGAŠ (1986a, 1986b), a broader landslide area is composed of Neogene and Quaternary deposits. Badenian deposits conformably overlie early Miocene sediments and conformably/ transgressively cover Eocene sediments and volcanic-sedimentary sequences. The Lower Sarmatian deposits conformably overlie Badenian deposits and contain marls and clayey limestones.

According to recent research, the NCB during the Early Miocene was predominantly characterised by a fresh-water depositional environment. Marine sedimentation began in the Middle Badenian (ČORIĆ et al., 2009; BRLEK et al., 2016; PAVELIĆ & KOVAČIĆ, 2018 and MANDIC et al., 2019a) when this basin was connected to the Hrvatsko Zagorje Basin (HZB). The Badenian marine sedimentation was presented by the deposition of marls in the offshore environment (Vejnovna formation) and coarse-grained material in the shoreface depositional environment (Trstenik member and Vrâpče formation) (AVANIĆ et al., 2018). During the Sarmatian, reduced salinity occurred, while sediments were represented by shallow-water conglomerates, calcarenites and limestones (the Pećinka member) as well as horizontally laminated pelitic sediments (the Dolje formation) deposited in a deeper marine environment (AVANIĆ et al., 2018; PAVELIĆ & KOVAČIĆ, 2018 and references therein). Studies of the provenance of the Middle Miocene sedimentary rocks of the SW margin of NCB are deficient. The only reliable data about the provenance of these sedimentary rocks are from areas N and NE of Hrvatska Kostajnica investigated by KOVAČIĆ et al. (2011) and GRIZELJ et al. (2017). According to these investigations in the area of Medvednica Mt. and the Slavonian Mts., the sources of material for the Middle Miocene elastic sedimentary rocks were located to the south of the investigated area, in the area of the northern Inner Dinarides, while some of the material was also supplied from locally uplifted blocks in the SW part of the PBS.

The aim of this paper is to reconstruct the Badenian/Sarmatian transition in the area of the SW marginal part of the NCB and PBS based on a multiproxy approach: mineralogical, geochemical, sedimentological and integrated palaeontological analyses (calcareous nannofossil, foraminifers, ostracodes, palynomorphs determination) and palaeoecological reconstruction putting the results in the frame of new chronostratigraphic divisions within the Middle Miocene. Furthermore, the aim of the present study is also to make a contribution to the discussion about the evolution, palaeogeography and climate history of the marine succession in the south-western PBS.
2. GEOLOGICAL SETTINGS
The PBS represents one of the Mediterranean back-arc basins, which is surrounded by mountain chains comprising the Alps, Carpathians, and Dinarides. Furthermore, it includes several different-sized, deep depressions (sub-basins) separated by a comparatively shallow complex of basement rocks (HORVÁTH & ROYDEN, 1981; ROYDEN, 1988), which influenced the distribution of marine organisms and the development of stress-tolerant species (STEININGER et al., 1988; GALOVIĆ & YOUNG, 2012). Palaeogeographically, it belongs to the Central Paratethys...
realm, a sedimentation area that, during the Miocene lost and re-established connections with the Mediterranean and the Indo-Pacific Ocean on several occasions (HARZHAUSER & PILER, 2007; KOVAC et al., 2017, 2018). Thus, the Early/Late Badenian boundary was marked by a gradual weakening in the connection with the Mediterranean Sea, leading to the interruption of the water exchange between the western and eastern Central Paratethys (Kovac et al., 2017). This event is called the Badenian Salinity Crisis (BSC) which began at 13.81 ± 0.08 Ma (De Leeuw et al., 2010). Moreover, Gradstein et al. (2012) observed a causal relationship between cooling during the glacial event Mi-3b (13.81 Ma) and evaporite formation. Formation of the PBS back-arc basin began in the Early Miocene with continental collision and subduction of the European Plate beneath the Apulian Plate. In the area of North Croatia during the Early Miocene two basins with different depositional histories evolved: the Hrvatsko Zagorje Basin (HZB), which occupied a small area in north-western Croatia, and the North Croatian Basin (NCB), that covered almost the entire area of north Croatia (Pavelic & Kovacic, 2018). The syn-rift phase of basin development was characterized by tectonic thinning of the crust and isostatic subsidence, while the post-rift phase was marked by subsidence caused by cooling of the lithosphere (Hovath & Royden, 1981; Royden et al., 1983; Royden, 1988). In the south-western part of the PBS, the syn-rift phase lasted from the Ottanian to the Middle Badenian, while the post-rift phase extended from the Late Badenian to the end of the Quaternary (Pavelic & Kovacic, 2018).

The oldest deposits of the NCB are Early Miocene fresh-water, alluvial deposits (Avanic et al., 2003; 2018; Pavelic, 2001, Pavelic & Kovacic, 1999). These deposits were covered by Lower Badenian marls and sandstones deposited in a hydrologically open lake (Pavelic et al., 1998, Pavelic & Kovacic, 2018 and references therein). The lacustrine environment was replaced by marine environments with a transitional brackish-inland sea (Pavelic et al., 1998, Pavelic & Kovacic, 2018). At the beginning of the Middle Badenian, due to the marine connection, lithothamnium limestones, sandstones and marls intercalated with pyroclastic rocks (caused by occasional volcanic activity) were deposited (Avanic et al., 2003, Pavelic, 1998). The Badenian/Sarmatian transition is correlated with the top of polarity Chron CSzAr2n at 12.829 Ma (Hohenegger et al., 2014 and references therein). In the Sarmatian, the connections of the PBS with marine areas were significantly reduced which caused changes in depositional environments from marine to marine with reduced salinity and stratification. Sarmatian marls and sandstones were deposited mostly conformable on the Badenian deposits (Pavelic, 2001; Pavelic & Kovacic, 2018 and references therein).

3. METHODS
3.1. Fieldwork
Fieldwork included the following: outcrop rigging and sampling via Single rope technique, in situ determination of sediment type, observation of the type of contacts between intervals, measurement of the dimensions of the sedimentary bodies, sampling for various analyses and finally construction of a lithostratigraphic column.

3.2. Mineralogical and geochemical analysis
Mineralogical and geochemical analysis included the following: X-ray powder diffraction (XRPD) analyses (6 samples), chemical analysis of major and trace elements (7 samples) and measurement of CaCO$_3$ using Scheiblers calcimeter (15 samples).

Preparation for XRPD analyses included: sieving of the samples through the 63 µm sieve, carbonate fraction dissolution by acetate solution containing ammonium acetate (1 mol dm$^{-3}$) buffer of pH 5 (Jackson, 1956) and separation of the < 2 µm fraction from the insoluble residue of the sample. XRPD patterns were recorded on random mounts of bulk samples, fraction < 63 µm and oriented mounts of the < 2 µm fraction using the Philips vertical goniometer (type X’Pert) equipped with a Cu-tube (HGI-CGS), and using the following experimental conditions: 45 kV, 40 mA, PW 3080/00 PXIcel detector, primary beam divergence 14° and continuous scan (step 0.02 °2θ/s). Oriented mounts of the < 2 µm fraction were recorded after the following treatments: a) air drying, b) ethylene-glycol solvation, c) heating to 400°C and 550°C. The X-ray interpretation was performed using the HIGH SCORE PLUS (2016) calculation and PDF-4 / MINERALS 4.5 (2020) databases. Quantitative analysis was performed according to Schultz (1964).

Chemical analyses of samples were undertaken by the Bureau Veritas Commodities Canada Ltd., (www.acmelab.com) in Vancouver (Canada). After lithium borate (LiBO$_2$) fusion, the major elements content was determined by inductively coupled plasma emission spectroscopy (ICP-ES), while trace elements were measured on an inductively coupled plasma mass spectrometer (ICP-MS).

Provenance analyses were performed following the results of chemical analysis of major and trace elements using oxide or elemental ratios, ternary diagrams and diagrams based on the elemental ratios.

Reconstruction of provenance based on the major elements was performed by SiO$_2$/Al$_2$O$_3$, K$_2$O/Al$_2$O$_3$ and Na$_2$O/K$_2$O ratios.

For the analysis of provenance based on trace element content, elemental ratios dependant on provenance including La/Co, Th/Cr, Th/Sc, Th/Cr, Eu/Eu* [Eu*/Tb(Sm/Tb)1/2], LREE/HREE and diagrams La-Th-Sr, Th-Sc-Zr, Nb/Y – Zr/TiO$_2$ proposed by Bhattacharya & Crook (1986), Cullers (1994, 2000) and Winchester & Floyd (1977) were used.

The degree of chemical weathering of the source rocks was constrained by calculating the chemical index of alteration (CIA=[Al$_2$O$_3$/(Al$_2$O$_3$+CaO*)+Na$_2$O+K$_2$O]100 (Nesbitt & Young, 1982). Oxides are expressed in molar proportions and CaO* is the amount of CaO in siliciclastic minerals only, i.e. excluding carbonates and apatite. The data for CaO* have been corrected according to the procedure described by McLennan (1993). Because all the analysed samples contained significant amounts of carbonate component, it was assumed that the correction of CaO is equal to that of Na$_2$O.

3.3. Palaeontological analysis
3.3.1. Calcareous nannofossil analyses
The preparation method of Shamrock et al. (2015) was followed for TLM (transmitted light microscope) analyses of calcareous nannofossils, while for SEM (scanning electron microscope) analyses, calcareous nannofossils were coated with gold. Slides were examined using an Olympus BH-2 TLM (HGI-CGS) and JEOL JSM-6510 LV SEM (INA – Industrija nafte d.d.). The relative abundance of the calcareous nannoplankton was estimated after randomly counting more than 200 coccoliths along transects at 750x magnification (using a 60 x objective) according to Schmidt (1978).
Figure 2. Lithostratigraphic column of the Hrvatska Kostajnica showing sample position, CaCO₃ content, fossil distribution and sedimentological history with a palaeoenvironmental interpretation.
3.3.2. Palynological analyses
Palynological analyses were carried out on four samples collected from the lower 10 m of the column. 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 (NaP2O5), cold HCl (15%) and HF (40%), to remove carbonates and silica. Heavy liquid (ZnCl2, 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 µm mesh. For palynofacies analysis slides were mounted in glycerine and for palynomorphs analysis in silicon oil. Microscopic analyses were performed using an Olympus BH-2 and Leica DM2500 microscopes (HGI-CGS). Photomicrographs were taken using an AmScope v.3.7 camera software and a Leica MC190 HD camera connected to the Leica LAS EZ software. The palynofacies analyses represent qualitative examinations of the organic matter component groups according to the classifications proposed by TYSON (1995). Samples are plotted in the AOM-phytoclast-palynomorph (APP) ternary diagram to characterize the palaeoenvironment according to TYSON (1995).

3.3.3. Foraminiferal and ostracod analyses
Altogether 12 samples along the column were prepared for ostracod and foraminiferal analyses, both benthic and planktonic species. Approximately 200 g of sediment per sample was disaggregated by soaking in diluted hydrogen peroxide for 48 h, then washed through sieves (0.25; 0.125; 0.09 and 0.063 mm) and dried at room temperature. All fossil remains (ostracods, foraminifera, bryozoa, gastropods, pteropods, bivalves fragments, otoliths, and fish remains) were hand-picked from each dried residue and observed under a binocular microscope (WILD M32) and Zeiss stereomicroscope. All picked specimens were classified and counted but not statistically analyzed.

Planktic and benthic foraminifers are mainly classified based on CICHA et al. (1998); POPESCU & CRIHAN (2004; 2005 a,b; 2008; 2011); FILIPESCU & SILYE (2008); GEDL et al. (2016); PERYT et al. (2014); SCHÜTZ et al. (2007); DUMITRIU et al. (2017) and TÓTH et al. (2010).

Ostracod species identifications were based on Van MORKHOVEN (1963), HARTMANN & PURI (1974) and HORNE et al. (2002).

To interpret palaeoenvironmental conditions, calcareous benthic foraminifera are divided into different morphgroups based on their test morphology and mode of coiling. This widely used approach shows the relationship between the test morphology and ecological life preference of modern benthic taxa (SILYE, 2015 and references therein.). Ecological conditions required for each foraminiferal species are mainly accepted from TYSON (1995). Quantitative tests are made to characterize the palaeoenvironment according to TYSON (1995).

4. RESULTS

4.1. Sedimentology
The Hrvatska Kostajnica (KOS-I) lithostratigraphic column has a total thickness of 25.6 m, which consists of upper Badenian and Sarmatian pelitic sedimentary rocks (Figs. 1b, 2). Field research and measurement of CaCO3 has shown that the column consists of marls, and clayey limestones, while calcareous marls and silty marls are rare.

Marls contain 48-60% CaCO3, silty marls 29-49% CaCO3, calcareous marls 77% CaCO3 and clayey limestones 81-88% CaCO3 (Fig. 2). There is visible bedding dipping toward the north (N-NW) at a 10° angle, although the internal structure in individual layers is rarely visible. Lithological boundaries between the described intervals are mostly sharp and planar or gradational, except at 1.3 m and 6.6 m from the base of the outcrop, where the boundary is described as sharp and irregular. Horizontally stratification is present in the lower part of the outcrop and rarely in the upper part. At the top of the outcrop (from 22.6 to 25.6 m) there are bioturbation marks. Finally, there is no clearly visible discordance between the lower (Badenian) and upper (Sarmatian) parts of the lithostratigraphical column.

4.2. Mineralogy and geochemistry
The mineralogical composition and chemical composition of the marl samples are given in Tab. 1.

Table 1 shows the results of the quantitative mineral composition of the bulk marl samples and semi-quantitative results of the fraction < 63 µm and < 2 µm of the insoluble residue obtained by XPRTD. The main mineral components are calcite and clay minerals while quartz and aragonite are present in a lesser quantity. In the fraction < 63 µm of insoluble residue, besides clay minerals and quartz, all samples contain a small amount of plagioclase. Zeolites from the clinoptilolite/heulandite series are present in a lesser quantity in all samples except sample 15 (Fig. 3 and Tab. 1). Sample 1 contains a small amount of pyrite. In the fraction < 2 µm of insoluble residue smectite/I-S and illite/musco-

Table 1. Quantitative mineral composition of bulk samples and the semi-quantitative mineral composition of the <63 µm fraction of insoluble rock residue obtained by XRPD according to the procedure described by SCHULTZ (1964). Clay mineral content was determined from the <2 µm fraction of insoluble rock residue. Qtz – quartz, Cal – calcite, Arg – aragonite, Cli/Hul – clinoptilolite/heulandite, Pl – plagioclase, Py – pyrite, Sme/I-S – smectite/illite-smectite, Ill/Ms – illite/muscovite, Vrm – vermilionite, Kln – kaolinite, Chl – chlorite, XXX – dominant (>50%), XX – abundant (20-50%), X – subordinate (1-20%), + – traces (<1%).

| SAMPLE | KOS-I | 1 | 4 | 5 | 9 | 11 | 15 |
|--------|-------|---|---|---|---|----|----|
| BULK SAMPLE (wt. %) | | | | | | | |
| Qtz | 7 | 8 | 11 | 11 | 8 | 7 |
| Cal | 41 | 38 | 33 | 16 | 59 | 58 |
| Arg | 18 | 18 | 16 | 13 | | |
| CLAY | 34 | 36 | 40 | 60 | 31 | 35 |
| <63 µm | | | | | | | |
| Cli/Hul | + | X | X | X | | |
| Pl | X | X | X | X | + | X |
| Py | | | | | | | |
| <2 µm | | | | | | | |
| Sme/I-S | XX | XX | XX | XX | XX | XX |
| Ill/Ms | XX | XX | XX | XX | XX | XX |
| Vrm | + | + | | | | |
| Kln | X | X | X | X | X | |
| Chl | + | + | + | + | + | + |
Covite are well represented in all samples, while kaolinite is present in all samples in a lesser quantity (Tab. 1 and Fig. 4). Quartz is present in trace amounts in all samples except sample 15. Vermiculite and chlorite were determined in only a few samples (Tab. 1).

In Tab. 2, besides the chemical composition of marl sediments, the major element oxide ratios, trace element ratios, and the CIA index are listed.

### 4.3. Micropalaeontology

#### 4.3.1. Calcareous nannofossil assemblages

Among 42 taxa of calcareous nannofossils based on the occurrence frequency, 13 taxa were identified in all samples: *Calcisphaera leptoporus, Ca. pataeaces, Coccolithus pelagicus, Cyclicar- golithus floridanus, Helicosphaera carteri, Pontosphaera longiforminis, Reticulofenestra haqii, R. minuta, R. minutula,* etc.
Table 2. Content of major (wt. %), trace elements (ppm) and some ratios and CIA weathering index.

| ELEMENTS | KOS-I |
|----------|-------|
|         | 1     | 4     | 5     | 6     | 9     | 11    | 15 |
| SiO₂     | 21.41 | 25.08 | 28.79 | 9.44  | 38.43 | 22.73 | 23.66 |
| Al₂O₃    | 6.73  | 7.34  | 8.77  | 3.00  | 12.29 | 6.53  | 6.77  |
| Fe₂O₃    | 2.40  | 3.13  | 3.12  | 1.42  | 5.17  | 2.58  | 2.29  |
| MgO      | 0.99  | 1.02  | 1.12  | 0.66  | 1.57  | 0.95  | 1.23  |
| CaO      | 34.02 | 32.07 | 27.69 | 45.96 | 17.33 | 33.69 | 32.97 |
| Na₂O     | 0.38  | 0.44  | 0.45  | 0.15  | 0.63  | 0.33  | 0.28  |
| K₂O      | 1.17  | 1.32  | 1.66  | 0.54  | 2.27  | 1.19  | 1.23  |
| TiO₂     | 0.33  | 0.39  | 0.45  | 0.15  | 0.70  | 0.33  | 0.36  |
| P₂O₅     | 0.15  | 0.13  | 0.12  | 0.06  | 0.08  | 0.21  | 0.23  |
| MnO      | 0.01  | 0.01  | 0.02  | 0.02  | 0.03  | 0.01  | 0.02  |
| Cr₂O₃    | 0.01  | 0.01  | 0.02  | 0.02  | 0.01  | 0.01  | 0.01  |
| Ba       | 225.00| 517.00| 629.00| 219.00| 535.00| 494.00| 165.00|
| Ni       | 91.00 | 54.00 | 72.00 | 38.00 | 102.00| 65.00 | 57.00 |
| Sc       | 7.00  | 8.00  | 9.00  | 4.00  | 13.00 | 7.00  | 7.00  |
| LOI      | 32.10 | 30.50 | 27.30 | 34.80 | 21.10 | 31.10 | 30.70 |
| SUM      | 99.71 | 99.69 | 99.71 | 99.83 | 99.76 | 99.80 |
| CIA      | 89.38 | 8.84  | 7.60  | 9.00  | 8.90  | 8.50  |
| TOT/S    | 1.18  | 1.02  | 0.94  | <0.02 | 2.14  | <0.02 |
| Eu/Eu*   | 0.49  | 0.50  | 0.51  | 0.32  | 0.53  | 0.46  |
| SUM      | 99.71 | 99.69 | 99.71 | 99.83 | 99.76 | 99.80 |

Rhabdosphaera sicca, Sphenolithus abies, Syracosphaera clathratae, Umbilicosphaera rotula. Two main biostratigraphic Zones NN6 and NN7 were identified (MARTINI, 1971) (Fig. 2). Species diversity is highest (36 taxa) in Zone NN7 in sample 9, while up to 32 taxa were determined in Zone NN6 in sample 1. The most equally dominant species in the record (up to 24%) are Coccolithus pelagicus and Umbilicosphaera jafari, followed by less abundant Reticulofoenestra producta (up to 17%), R. minuta (up to 16%), small Reticulosphaera sp. (up to 14%) and Reticulosphaera haqii (up to 12%). All scattered and rare taxa (≤ 9%) are omitted from the results because they did not affect the palaeoecological interpretations. On the other hand, two rare index species (Calcisdiscus pataeicus and Discoaster kugleri) contributed to the biostratigraphy.

Late Badenian NN6c Subzone (MĂRUNȚEANU, 1999; amended by GALOVIĆ, 2019) (0-5.7 m)

The first occurrence (FO) of Calcidiscus pataeicus is characteristic for the late Badenian where it marks Subzone NN6c of Paratethys (MĂRUNȚEANU, 1999).

Umbilicosphaera jafari (up to 24%) is the main component in the assemblage with equally abundant (up to 14%) small Reticulofoenestra (Reticulosphaera sp., R. minuta, R. producta) and less abundant small Coccolithus pelagicus (up to 12%) and Reticulosphaera haqii (up to 11%) (Figs. 2, 5).

Early Sarmatian NN6d?–NN7a Subzone (GALOVIĆ, 2019) (7.8-23.5 m)

The first occurrence (FO) of Discoaster kugleri is characteristic for the early Sarmatian Subzone NN7a of Paratethys (GALOVIĆ, 2019).

Small to medium-sized Coccolithus pelagicus (up to 24%) dominates in the assemblage with less abundant small Reticulofoenestra producta (up to 17%), R. minuta (up to 16%) and R. haqii (up to 12%) (Figs. 2, 5).

4.3.2. Palynology

All samples contain palynomorphs in various amounts. The preservation degree of the grains is medium to good, i.e. the structure and sculpture of several grains are partially destroyed, making more precise determination impossible.

In the lower part of the column (samples 1 and 4), gymnosperm species (mostly Pinus) prevailed (90%). The dinocyst assemblage is dominated by chorate gonyaulacoids (Cleistosphaeridium placacanthum) (Fig. 5/17), Lingulodinium machaerophorum, Polysphaeridium zoharyi, Spiniferites ramo­

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Figure 5. 1. *Calcidiscus pataecus* (sample 15) Scale bar = 1 µ; 2. *Umbilicosphaera jafari* (sample 5) Scale bar = 1 µ; 3. small *Reticulofenestra* species (sample 9) Scale bar = 2 µ; 4. *Calcidiscus pataecus* (sample 15) Scale bar = 1 µ; 5. Partially disintegrated coccosphaeres of *Coccolithus pelagicus* (sample 1) Scale bar = 5 µ; 6. Palynofacies; pal-palynomorph *Pinus* with pyrite grains; Ph-phytoclast; AOM- amorphous organic matter (sample 9); 7. *Lingulodinium machaerophorum* (sample 9); 8. *Operculodinium piaseckii* (sample 9); 9. *Baticasphaera sphaerica* (sample 9); 10. *Impagidinium patulum* (sample 6); 11. *Cerebrocysta poulserii* (sample 6); 12. *Titthodiscus mecekensis* (sample 6); 13. *Hystrichokolpoma rigaudiae* (sample 4); 14. *Achomosphaera andalousiensis* (sample 4); 15. *Melitasphaeridium choanophorum* (sample 1); 16. *Spiniferites ramosus* (sample 1); 17. *Cleistosphaeridium placacanthum* (sample 1); 18. *Nematosphaeropsis labyrinthus* (sample 1) Scale bar = 10 µ for figs. 6-18.
ment was a distal dysoxic-anoxic shelf according to the palynofacies (Fig. 6).

On land, zonal vegetation developed, represented by a warm-temperate mixed mesophytic forest, with a large contribution from extrazonal elements (mountain conifer-rich forest). Above the horizon there is one thin layer (sample 6). Dinocysts prevail (60 %), mostly chorate gonyaulacoids (Spinifellites spp., Cleistosphaeridium placacanthum, Lingulodinium machaerophorum, Operculodinium piaseckii). In addition, proximate gonyaulacoids (Ceratocyclus poulsonii, Fig. 5/10) are also present, as well as chlorophyte algae Botryococcus braunii, prasinophyte algae Crassosphaera sp., and Titthodiscus mesekensis (Fig. 5/12). The assemblage indicates the Cleistosphaeridium placacanthum Zone (Cpl), BAKRAČ et al. (2012) and Ceratocyclus poulsonii Assemblage Biozone (Cpo) JIMENEZ-MORENO et al. (2006). The amount of the organic residue is very low in the proportion and barely enough to allow palynofacies analysis. It is dominated by the palynomorph group (50%), whereas the phytoclast group was the second most dominant (40%). The amorphous group account for only ca. 10% of the organic particles. Some phytoclasts are gelified. Pyrite inclusions and charcoal are present.

This palynofacies suggests that deposition took place in a mud-dominated oxic shelf environment (Fig. 6).

In the middle part of the column (sample 9), the dinocyst proportion is somewhat higher than gymnosperm pollen (mostly Pinus). The dinocyst assemblage is dominated by chorate gonyaulacoids (Spinifellites spp., Cleistosphaeridium placacanthum, Lingulodinium machaerophorum, Operculodinium piaseckii). In addition, proximate gonyaulacoids (Ceratocyclus poulsonii, Batiacasphaera sphaerica (Fig. 5/9) are also common, as well as prasinophyte algae Titthodiscus mesekensis, Crassosphaera sp., Mesecasia spinosa and foraminifera linings. The terrestrial palynoflora is represented only by elements characteristic for extrazonal vegetation such as montane conifer-rich forests. This assemblage is assigned to the Polysphaeridium zoharyi – Lingulodinium machaerophorum Zone (Pzo-Lma) BAKRAČ et al. (2012) and the Cleistosphaeridium placacanthum Assemblage Biozone (Cpl) JIMENEZ-MORENO et al. (2006). The palynofacies (Fig. 5/6) is dominated by the phytoclast group (50%), whereas the amorphous group attains 40% of the particles, while the palynomorph group is the least abundant (10%) element. Some phytoclast particles are gelified. Pyrite inclusions and charcoal are present. According to the palynofacies from sample 9, the depositional environment was a proximal suboxic-anoxic shelf (Fig. 6).

Alongside the zonal vegetation (warm-temperate mixed mesophytic forest at a very low ratio), extrazonal mountain conifer-rich forests were developed.

4.3.3. Foraminifera

The distribution of foraminifera from the marl samples is given in Supplement Tab. 1 and Fig. 7.

Altogether, 81 benthic and 31 planktonic species of foraminifera are determined in the lithostratigraphic KOS-I column. Large amounts of reworked Badenian microfossils within the Sarmatian sediments, together with the rare occurrence of Sarmatian index fossils, is the main characteristic of the KOS-I column.

Planktonic species are mostly represented by specimens of the genus Globigerina, Globigerinoides, together with Orbitolina species, Globoturborotalita sp., and Turborotalita quinqueloba, with rare occurrences of Velapertina indigena, Paragloborotalia siakensis, and Globigerinita glutinata.

Benthic foraminifera are predominantly represented by calcareous species, miliolids are scarce, while agglutinated species are absent. An engaging feature of the benthic foraminiferal assemblage is the slightly higher occurrence of unicameral foraminifera. Favulina hexagona, Porosolenia tibiaensis, Fissurina severantoni, Palliolatella sp. are species determined in the lower part of the column (samples 1 – 4). A high amount of bolivinids and buliminids is determined the KOS-I column as a whole. Benthic species have ranges varying from the early Badenian (e.g. Planularia moravica, Lenticulina cf. clypeiformis, Bolivina fastigia, Amphirhombina hauera) to the late Badenian (Uvigerina brunnensis, Pappina neudorfensis) which, together with the scarce occurrence of Sarmatian index species (Nonion bogdanowiczi) point to a high rate of reworking along the column. The Sarmatian index fossil is identified in the upper part of the column (above sample 7). The lower part of the column due to the co-occurrence of Bolivina dilatata, Bulimina elongata longa, Uvigerina brunnens, U. semiornata together with Globigerina bulloidies, G. praelbuloidies, G. concinna, and Globigerinoides trilobus is attributed to the late Badenian (DUMITRIU et al., 2017).

Furthermore, index fossils including Nonion bogdanowiczi, Bolivina sagittula, B. nisponenca, B. pseudoplicata, B. moravica, B. moldavica granensis, Fursenkoina sarmatica, Elphidium perscuti, E. ex gr. pucharovski, E. macellum tumidocamerale, E. incertum, E. excavatum, Elphidiella artex, and Nonion tumidulus point to the Sarmatian age.

Benthic foraminiferal taxa, based on their test morphology and mode of coiling, were clustered into six morphogroups. Morphogroup M1 is composed of forms with a rounded planispiral test (Elphidiella, Nonion, non-keeled elphidids). They are present throughout the whole KOS-I column. We presume that species from this group belong to the autochthonous assemblage. Morphogroup M2 includes elphidids (Elphidium crispum, E.
Figure 7. SEM photomicrographs of selected foraminifers from the KOS-I succession. 1. Bolivina plicatella; 2. Bolivina plicatella mera; 3. Bolivina pseudoplicata; 4. Bolivina moldavica; 5. Bolivina moldavica granensis; 6. Bolivina nisporenica; 7. Bolivina moravica; 8. Bolivina papulata; 9. Bolivina sagittula; 10. Bolivina sarmatica; 11. Bolivina striatulla; 12. Favulina hexagona; 13. Fissurina severantoni; 14. Cursina porocostata; 15. Parosolenia tibiscens; 16. Nonion biporus; 17. Porosonion martkobi; 18. Elphidium excavatum; 19. Elphidium perscitum; 20. Elphidium ex gr puscharovski; 21. Elphidium reussi; 22. Elphidiella artifex; 23. Elphidiella vignaeu.
of the shallow-shelf environment. Morphogroup M3 is composed of the low trochospiral tests of Ammonia. In the KOS-I column, Ammonia species are more frequent in sample 7. Morphogroup M4 is composed of unilocular lagenids. This morphogroup characterizes the outer shelf to bathyal environments, suboxic marine environments with a low-moderate organic influx (SILYE, 2015 and references therein). In the KOS-I column, they only appear in the lower part. Morphogroup M5 is composed of two genera, Bolivina and Bulimina. Morphogroup M6 represents low-trochospiral rotalids, Cibicidoides and Lobatula species. In samples from the KOS-I column morphogroups with an infaunal mode of life prevail, while the epifaunal lifestyle is subordinate.

4.3.4. Ostracods
A total of 10 samples were used for ostracod analyses, taken successively from the KOS-I column. Twenty four ostracod taxa belonging to 15 genera were identified, of which eight species remained in open nomenclature. Distributions of ostracod species are summarised in Supplement Tab. 2, listed alphabetically. Some of the species are illustrated in Fig. 8.

The ostracod fauna within the KOS-I succession includes marine ostracod species that represent six families: Callistocythere cf. postvallata, Callistocythere canaliculata, Cnestocythere sp., Cnestocythere truncata within Cytheridae; Aurila cf. notata, Aurila cf. merita, Aurila sp., Bosquetina carinella, Tenedocythere sibrosa, Tenedocythere sp., Tenedocythere sulcatopunctata within the Hemicytheridae; Amnicythere ? sp. within the Leptocytheridae; Buntonia sp., Costa sp., Olimfalunia ? plicatula, Grinioneis haidingeri within the Trachyleberididae; Paracytheridea triquetra, Semicytherura filicata, Semicytherura cf. alata within Cytheridae; Loxoconcha sp., Loxocorniculum hastatum, Loxocorniculum cf. schmidtii within the Loxoconchiidae; and Xestoleberis glaberscens and Xestoleberis sp. within the Xestoleberidae.

Ostracods were discovered in small numbers in nine samples, and their species richness was low. Ostracods were absent in sample 6. Common species in samples from the KOS-I column are: Aurila sp. (8 records), Callistocythere cf. postvallata (6 records) and Xestoleberis glaberscens (4 records). The diversity varies throughout the column and is generally low. The maximum number of species (11) was reported in sample 11. Sample 4 contain 10 species. Other samples include relatively low numbers of species: samples 2 and 13; 7 species each, and samples 1 and 5 with 6 species each. In other samples, the number of species varies between 3 and 4, and one sample contains only 2 species.

4.3.5. Other microfossils
Rare bryozoans, probably Crisia sp. and Tubulipora sp. (samples 9 and 11), according to FILIPESCU et al. (2014), prefer unstable, shallow and high energy environments. They usually belong to pioneer assemblages.

Pteropods, probably Limacina valvatina, are recognized in samples 4 to 9. Their occurrence is documented from the early to late Badenian and even in the lower Sarmatian (BOŠNJAK et al., 2017 and references therein). According to BOHN-HAVAS & ZORN (2002), the species was widely distributed during the Badenian.

5. DISCUSSION
5.1. Sedimentology
The lithostratigraphic column in Fig. 2 shows continuous sedimentation from the late Badenian to the early Sarmatian. Such a situation is well known from the area of the NCB, where Sarmatian sediments overlie upper Badenian sediments in a continuous depositional succession (VRSALJKO et al., 2006; PAVELIĆ &
KOVAČIĆ, 2018). Structureless marls, that are represented in most of the lithostratigraphic profile (Fig. 2), suggest sedimentation of fine-grained siliciclastic material from suspension in an open marine environment. Similar conditions recorded on the NE part of Mt. Medvednica indicate sedimentation in the deeper part of the basin which was not significantly affected by the sea-level fall at the end of the Badenian (VRSALJKO et al., 2006). The analysed samples contain calcite and in a lesser quantity aragonite. Carbonates were predominantly deposited from seawater (discussed in section 4.2.). The small amount of carbonate content in the marls could be associated with carbonate detritus derived from fossil skeletons and bioerosion of older carbonate bedrock. The fragments of bryozoans, gastropods, pteropods, bivalves, otoliths, and fish remains, together with marine ostracods, foraminifera, calcareous nanofossils, and palynomorphs indicate a marine depositional environment. The absence of wave action indicators and the presence of palaeontological species from deeper marine environments suggests that sediments were deposited on the shelf or below the base of the wave action (offshore). In contrast, the Badenian/Sarmatian boundary is discontinuous in many cases within Central Paratethys (VRSALJKO et al., 2006; MANDIC et al., 2019b; MANDIC et al., 2019c). This discontinuity is the result of the sea-level fall during the latest Badenian, and the formation of archipelagoes which were affected by erosion resulting in the deposition of shallow-water sediments and reworked Badenian flora and fauna (PAVELIĆ & KOVAČIĆ, 2018).

Figure 9. shows the stratigraphic position of the KOS-I column correlated with the Ugljevik (MANDIC et al., 2019c) and Donje Orešje columns (GALOVIĆ, 2003; VRSALJKO et al., 2006). The depositional environment of KOS-I column is similar to the environment of the Donje Orešje. Nevertheless, during the Sarmatian deposition occurred in the Donje Orešje in a lagoon, while in the studied area it continues in the deeper sea. The Badenian/Sarmatian boundary at the Ugljevik column (Bosnia and Herzegovina) as in many other parts of PBS, is marked by a weakly expressed erosive omission and hiatus (MANDIC et al., 2019c). According to AVANIĆ et al. (2003), these differences were probably the result of local tectonics in the earliest post-rift phase that has a significant role controlling sedimentation in these part of the PBS.

5.2. Mineralogical composition of marls

The bulk analyses of marls show that the main mineral components are calcite and clay minerals, while quartz and aragonite are present in lesser quantities. The type of carbonate and its morphology depends on the temperature of the water in which it is generated, together with the concentration of Ca$^{2+}$ and Mg$^{2+}$ ions in the solution, salinity and pressure of CO$_2$ (RAO, 1996). Calcite may form when the Mg/Ca ratio is < 2, while aragonite occurs when the Mg/Ca ratio is between 2 and 12 (MÜLLER et al., 1972). Moreover, calcite may occur in different environments, while aragonite is usually formed in warm (20–30 °C), shallow marine environments by direct precipitation from seawater, or it forms skeletons of various organisms (LIPPMANN, 1973; RAO, 1996; CHANG et al., 1998, TIŠLJAR, 2001). Such marine and marine environments with reduced salinity existed during both the Badenian and the Sarmatian. Also, part of the aragonite, that is unstable in the subsurface and at standard temperature and pressure, could be altered to the more stable isomorph calcite. In the fraction < 63 µm of insoluble residue, besides clay minerals and quartz, all samples contain a small amount of plagioclase and zeolites from the clinoptilolite/heulandite series. Zeolites are present in almost all samples, indicating that they were probably transported from some local source of origin. Such a local source could be the upper Cretaceous deposits in the locality of Volinja near KOS-I column, in which MARKOVIĆ (2002) mentions the occurrence of zeolite minerals. The results of previous provenance studies suggest also that the neighbouring Inner Dinarides produced a significant amount of clastic detritus during the Middle Miocene (KOVAČIĆ

![Figure 9. Illustration showing the stratigraphic position of the investigated Hrvatska Kostajnica column (KOS-I) and its correlation with the Ugljevik (MANDIC et al., 2019c) and Donje Orešje columns (GALOVIĆ, 2003; VRSALJKO et al., 2006). Magnetostratigraphy is from HILGEN et al. (2012). The geological time scale is from GRADSTEIN et al. (2012) and HÖHNEGGER et al. (2014).](image-url)
et al., 2011, GRIZEJ et al., 2017). In the < 2 μm fraction of insoluble residue, the main components are smectite/I-S and illite/muscovite, while kaolinite is present in a lesser amount. In some samples, chlorite and vermiculite are also present. While illite/muscovite and chlorite are considered typical terrigenous mineral species, formed directly from disintegrating intrusive and metamorphic rocks, kaolinite and vermiculite are characteristic products of chemical weathering (CHAMLEY, 1989). It should also be noted that chlorite is poorly resistant to chemical weathering, which probably explains its presence in small amounts in the analysed marls. According to WEAVER (1989), most smectite occurs as interlayer I-S. Smectites may form from the alteration of volcanic rocks in subaerial and submarine environments and do not suffer from marine and river transportation, and are often carried in the marine environment farther than other minerals because of their high buoyancy (CHAMLEY, 1989). In the investigated profile there were no traces of volcanic activity in the sediment. The occurrence of smectite could be explained by re-deposition from volcanic material from older formations such as tuffs that were determined in the area of Banovina (MANDIC et al., 2012 and MARKOVIĆ, 2017) or alteration of volcanic material which was transported over long distances. Intensive volcanic activity was reported for the Middle Miocene in the wider area of the PBS (PAMIĆ et al., 1995; KOVÁČ et al., 2007; MANDIC et al., 2012; MARKOVIĆ, 2017; BRLEK et al., 2020).

5.3. Chemical composition and provenance of terrigenous material

5.3.1. Major elements

Variation in the chemical composition of major elements of the samples may be explained by the observed variation in the mineralogy of the samples. Al₂O₃ values range between 3.00–12.29 wt %, an amount related to clay minerals, zeolites and plagioclase. The amount of Al₂O₃ and other major elements is dictated to the amount of CaO, which is mainly related to the amount of calcite and/aragonite in the samples. This is illustrated in Fig 4, which shows good positive correlations of SiO₂, Fe₂O₃, MgO, Na₂O, K₂O and TiO₂ with Al₂O₃, while CaO is strongly negatively cor-

Figure 10. Cross-plots of major oxides (wt. %) against Al₂O₃ (wt. %) showing their correlations.
related. Except for clay minerals, zeolites and plagioclase, a certain amount of SiO$_2$ is also associated with the amount of quartz (Tab. 1).

The SiO$_2$/Al$_2$O$_3$ ratio proposed by CULLERS (2000) was used as an indicator of the maturity of the clastic sedimentary rocks, as well as for the presence of quartz in relation to the clay minerals and feldspars. This ratio in all samples ranges from 3–3.5 (Tab. 2), and is lower than the values characteristic for the Upper Continental Crust (TAYLOR & McLENNAN, 1985).

The Al$_2$O$_3$/TiO$_2$ ratio in clastic sedimentary rocks is used to distinguish the types of source rocks (GARCIA et al., 1994; ANDERSSON et al., 2004). This ratio < 14 is indicative of mafic source rocks, whereas a ratio ranging from 19–28 is characteristic for felsic source rocks. The Al$_2$O$_3$/TiO$_2$ ratio in the Badennian-Sarmatian marls of KOS-I column ranges from 17.56 to 20.39 (Tab. 2), suggesting that these sediments are derived from felsic source rocks.

The K$_2$O/Al$_2$O$_3$ ratio is used as an indicator of the source composition of pelitic sedimentary rocks and is significantly different for clay minerals and feldspars. The K$_2$O/Al$_2$O$_3$ ratio ranging from 0–0.3 is indicative of clay minerals, and for feldspars, it ranges from 0.3–0.9 (COX et al., 1995). A K$_2$O/Al$_2$O$_3$ ratio of sediments > 0.5 indicates a significant content of alkali feldspar relative to other minerals in the source rocks, while a K$_2$O/Al$_2$O$_3$ ratio < 0.4 suggests recycling of pelitic sedimentary rocks (COX et al., 1995). In the analysed samples, this ratio is less than 0.2 (Tab. 2) suggesting, therefore, they could have been derived from older pelitic sedimentary rocks. From the mineral composition of the analysed marls, it could be presumed that the potassium content in the samples originates from the presence of illite/muscovite. Such a conclusion is supported by the perfect correlation of K$_2$O and Al$_2$O$_3$ (Figure 10f) and the mineral composition of the samples (Tab. 1).

The Na$_2$O/K$_2$O ratio ranges from 0.20–0.33 in the analysed samples. Sodium in marls has been associated mainly with plagioclase, and in lesser amounts it could be related to the exchangeable interlayer cations of clay minerals. Na$_2$O has a perfect correlation with Al$_2$O$_3$ in the analysed samples (Fig. 10e).

The degree of chemical weathering of the source rocks can be constrained by calculating the chemical index of alteration (CIA) proposed by NESBITT & YOUNG (1982). According to NESBITT & YOUNG (1982), the CIA values for average shale range from 70–75, and for clay minerals, illite and montmorillonites from 75.00–85.00. For the analysed marls, the CIA values range from 71.81–75.01 (Tab. 2), and are higher than the UCC values (< 50; TAYLOR & McLENNAN, 1985). The intensity of weathering of the source rock was also deduced by the triangular Al$_2$O$_3$-(CaO+Na$_2$O)-K$_2$O plot (after NESBITT & YOUNG 1982; 1984) with the values of the Upper Continental Crust given by TAYLOR & McLENNAN (1985), and the idealized mineral compositions of plagioclase, K-feldspar, kaolinite, chlorite, muscovite, illite and smectite (from NESBITT & YOUNG, 1984).

The degree of chemical weathering of the source rocks can be constrained by calculating the chemical index of alteration (CIA) proposed by NESBITT & YOUNG (1982). According to NESBITT & YOUNG (1982), the CIA values for average shale range from 70–75, and for clay minerals, illite and montmorillonites from 75.00–85.00. For the analysed marls, the CIA values range from 71.81–75.01 (Tab. 2), and are higher than the UCC values (< 50; TAYLOR & McLENNAN, 1985). The intensity of weathering of the source rock was also deduced by the triangular Al$_2$O$_3$-(CaO+Na$_2$O)-K$_2$O plot (after NESBITT & YOUNG 1982; 1984) with the values of the Upper Continental Crust given by TAYLOR & McLENNAN (1985), and the idealized mineral compositions of plagioclase, K-feldspar, illite/muscovite, smectite and kaolinite/chlorite (NESBITT & YOUNG, 1984) (Fig. 11).
The marl samples were plotted between the idealized compositions of smectite and illite/muscovite, implying that the source rocks underwent an intermediate degree of weathering.

5.3.2. Trace elements
The chemical composition and element ratios of samples critical for understanding provenance, such as La/Co, Th/Co, Th/Sc, La/Sc, Th/Cr, Eu/Eu', LREE/HREE, ΣREE are given in Tab. 2. Values of the La/Co, Th/Co, Th/Sc, La/Sc, Th/Cr, and Eu/Eu' ratios correspond to the values for acid (Si-rich) rocks, according to CULLERS (1994, 2000). Figure 12. represents the REE plots of samples normalized to chondrite (TAYLOR & McLennan, 1985).

All samples show LREE > HREE and a negative Eu-anomaly, which is in accordance with the Eu/Eu' ratio as indicators of the size of Eu-anomalies (COX et al., 1995). The sum of REE, depending on the carbonate content, varies in the analysed samples from 36–123 ppm, while the LREE/HREE ratios are more uniform (LREE/HREE = 5.8–7.3 ppm). High LREE/HREE ratio indicate predominantly acid (Si-rich) source rocks. Figure 13. shows Nb/Y – Zr/TiO2 diagrams proposed by WINCHESTER & FLOYD (1977) and illustrates that all the analysed samples plot to the rhyolite field, further suggesting acid (Si-rich) source rocks.

5.3.3. Inferred tectonic setting
La-Th-Sc and Th-Sc-Zr/10 diagrams proposed by BHATIA & CROOK (1986) were used to determine tectonic settings (Fig. 14).

According to these diagrams, the Badennian and Sarmatian marls plot close to the average composition of the Upper Continental Crust (TAYLOR & McLennan, 1985), and within the field of the Continental Island Arc, representing inter-arc, fore-arc, or back-arc basin, adjacent to a volcanic-arc developed on a thick continental crust or thin continental margins (BHATIA & CROOK, 1986). The inferred tectonic position corresponds to the fact that the PBS was one of the Mediterranean basins that existed from the Miocene to the Pliocene (HORVATH & ROYDEN, 1981; ROYDEN, 1988).
5.4. Biostratigraphy, palaeobiogeography, palaeoecology

Lithologically and according to microfossil content, three different depositional environments can be distinguished (Fig. 2).

5.4.1. Late Badenian; lower part of the column

(0.0 – 5.2 m; samples 1 – 5)

Silty marls dominate, followed by marls with intercalations of sand. The depositional environment varies from the distal dysoxic-anoxic shelf through a mud-dominated oxic shelf without terrigenous input to the proximal suboxic-anoxic shelf. Such conditions, affected by a humid climate, caused the development of a stratified water column and low oxic conditions at the sea bed. Low oxic conditions and a stratified environment were also confirmed by the presence of pyrite inclusions. These conditions are confirmed by the domination of buliminids, bolivinids and uivgerinids and the mass occurrence of Globigerina bulloides and Turborotalita quinqueloba (KOVAC et al., 2017 and references therein). Based on the different genera identified, the ostracod fauna from the KOS-I column can be defined as a shallow-water marine fauna. Some species of the genera Loxoconcha, Aminocythere and Xestoleberis tolerate lower water salinity, ranging from meso to oligohaline values. A Late Badenian age is determined based on the calcareous nannofossil assemblages (samples 1 and 5, Fig. 2) that identifies Subzone NN6c (MÂRÜNȚEANU, 1999), as well as palynomorphs (samples 1 and 4, Fig. 2), foraminifera (samples 1-5, Fig. 2), and ostracods (sample 4, Supplement Tab. 2).

During the late Badenian, vegetation in the southernmost parts of the Central Paratethys was thermophilous, partly sub-humid under subtropical climatic conditions (KVÂČEK et al., 2006; UTESCHER et al., 2007). Nevertheless, coccolith Umbilicosphaera is typical for the warm water, oligotrophic marine environments of subtropical to temperate climate (INKEL et al., 2000; KRAMMER et al., 2006), while small Reticulofenestra are typical for oligotrophic, warm waters of lower latitudes (HAQ, 1980; RAHMAN & ROTH, 1990). Umbilicosphaera jafari in assemblage with small Reticulofenestra species, noticed in sample 1, implies warmer and saltier shelf waters. This interval (Fig. 2; samples 1-2) probably belongs to the beginning of the late Badenian period of climate change from subtropical to warm, temperate humid climate recorded from 13.5 Ma according to BÖHME (2003), known as the Middle Miocene Climatic Transition (MMCT). Occurrence of the dinocyst Achnosphera andaloussensis in sample 4 points to an age younger than 13.3 Ma – Seravallian (LOURENS et al., 2004). Cleistosphaeridium placacanthon and Cerebrocysta poulsonii together indicate an age no younger than the latest Serravallian or earliest Torontian (JIMENEZ-MORENO et al., 2006). The HO of Cerebrocysta poulsonii is calibrated against basal C5r (~11.7 Ma) in Italy (ZEVENBOOM, 1995). An assemblage from the lower part (sample 1) is very similar to an assemblage from the Cerebrocysta poulsonii Assemblage Biozone of JIMENEZ-MORENO et al. (2006). They stated that the Cpo Zone indicates a late early Serravallian age and lies within nannofossil Zone NN6, as we detected here, and the Bolivina–Bulimina Zone of the regional benthic eco-zonation of GRILL (1941). This zone is also a correlate of the Achnosphera andaloussensis (Aan) Interval Zone in the Mazzapiedi and Cassinasco sections of northwest Italy of Late Serravallian age (ZEVENBOOM, 1995). However, JIMENEZ-MORENO et al. (2006) assigned this zone to the latest Badenian (late early Serravallian) in the Central Paratethys based on other fossils. The absence of agglutinated species with a dominance of Bulimina spp. and Bolivina spp. in the foraminiferal assemblage suggests a late Badenian age as well (PAULIŠSEN et al., 2011). The oceanic to outer neritic Nematosphaeropsis labyrinthus suggests that relatively open-marine conditions existed, which is in accordance with palynofacies that indicate a dysoxic-oxic shelf environment (Fig. 6). Among the foraminifera (sample 1-6), morphogroups M4 and M5 dominate. The presence of the aforementioned unicameral foraminifera also indicates a late Badenian age (POPESCU & CRIHAN, 2004). The main characteristic of this assemblages is its infaunal lifestyle in the muddy sediments mostly restricted to a shelf and slope environment (LI & MCGOWRAN, 1994). They prefer high productivity or a cold water environment (LI & MCGOWRAN, 1994), which is probably a consequence of a periodic influx of the cold Mediterranean current that affected the climate as well as humid periods under the subtropical climate detected here. The proportions of juveniles/adults and valves/carapaces of ostracods in the sedimentary record provide an estimate of wave energy during deposition (WHATLEY, 1988 and BOOMER et al., 2003). Higher energy conditions lead to the removal of smaller juvenile valves and cause the disarticulation of carapaces. Previous research showed that this relationship is autoclonthonous and characterizes the environment in which it is found when most ontogenetic stages are present in samples (WHATLEY, 1988; BOOMER & EISENHAUER, 2002). In all samples of KOS-I column valves and a few fragments were found. In three samples (KOS-I 2, 4 and 5) juvenile valves are dominant. The population structure suggested that ostracods from the KOS-I column are allochthonous. Most of them are transported from a high-energy environment, and deposited in a low-energy environment. Resediment ostracods can be readily distinguished by examining adult to juvenile ratios. The ratio of adults and juveniles, as well as their general low frequency, suggests unfavourable conditions for the development of ostracods. Finer grained particles, such as juvenile valves, are more readily transported over greater distances such as transported assemblages have clearly skewed adult to the juvenile ratio (LORD et al., 2012). Besides, a small portion of foraminifera morphogroups M1 and M2 also suggests reworking from the shallower, well-oxygenated environment. 5.4.2. Thin layer of clayey limestone (5.70 – 6.05 m; sample 6)

Restricted marine conditions are inferred from the low species richness of the dinocyst assemblages, but some oceanic influence was present as indicated by the rare occurrence of Impagidinium species in sample 6. According to JIMENEZ-MORENO et al. (2006), the Cerebrocysta poulsonii Assemblage Biozone (Cpo) reflects shallowing of the sea, before the emergence and erosion that led to the unconformity between the Cpo and Cpl zones at the Badenian–Sarmatian boundary. A general cooling trend appears as reflected by an increasing role of deciduous elements. Sometimes it overlaps with the lowermost Sarmatian, which is floristically barely distinguishable (KVÂČEK et al., 2006). Based on calcareous nannofossils, a cooling event defines the Badenian/Sarmatian transition as recorded in Subzone NN6c, while max. regression at the base of NN6d, close to the base of the Sarmatian (GALOVIC, 2017; GALOVIC, 2020), which is in accordance with HOHENEGER et al. (2014). Sample 6 has not been adequate for calcareous nannofossils, but this interval could apply to Subzone NN6d, and stress developments recognised near the Badenian/Sarmatian boundary. A characteristic feature of the period is the predominance of Coniferae pointing to extrazonal mountain forests.
The stressed marine environment is confirmed by prasinophytes. Some prasinophytes are “disaster species” because of their ability to survive in a stressed environment. They have a short-lived population increase, and they are most often replaced by opportunists (HARRIES et al., 1996, VAN DE SCHOOTBRUGGE et al., 2007). The environment was probably stressful, and the assemblage was dominated by disaster species which explains the co-occurrence of prasinophyte phycocyanin and redeposited dinocysts. *Lingulodinium machaerophorum* is restricted to coastal regions and regions in the vicinity of continental margins. High relative abundances can be observed in sediments near upwelling cells or below river discharge plumes or in highly stratified waters (ZONNEVELD et al., 2013).

Domination of foraminifera morphgroups M3 and M6 also suggests stressful and unfavourable environmental conditions. Small-sized and fragile tests of *Cibicidoides* species and prevailing *Ammonia* species are considered to be pioneer specimens. Based on all the investigated palaeontological data the Badenian/Sarmatian boundary in the KOS-I column is in line with the proposed position of the boundary (Fig. 2).

5.4.3. Early Sarmatian; upper part of the column (6.05 – 23.50 m; samples 7 – 15).

Marls dominate, followed by silty marls with intercalations of clayey limestone in the lower part to calcitic marls in the upper part.

Small, microperforate planktonic foraminifera species of the genera *Tenuellinita* and *Tenuitella* (indicative of the uppermost Badenian – the lowermost Sarmatian, according to FILIPESCUE and SILEYE (2008)) point to the aforementioned stress conditions that occurred in Paratethys at 12.73 Ma (HOHENEGGER et al. 2014), but here probably reworked from the earlier interval during the beginning of the transgression. Adult Badenian redeposited valves of the ostracod species *Bosquetina carinella*, *Grinio­neis haidingeri*, *Costa* sp., *Semicytherura filicata*, *Olimfalumia ? filicatula*, *Tenedocythere sibrosa*, *Tenedocythere sulphopunctata*, occur in samples 7, 8, 11 and 13. These species are very common in the Badenian deposits of the North Croatia Basin (HAJEK-TADESSE & PRTOLJAN, 2011; VESEL LUKIĆ & HAJEK-TADESSE, 2017) and wider area (ZORN, 2003, 2004; (HAJEK-TADESSE & PRTOLJAN, 2011; VESEL LUKIĆ & HAJEK-TADESSE, 2011); identified in the samples of the KOS-I column, are known from Sarmatian deposits of the wider area (GROSS, 2006; TÓTH, 2008). Sample 7 has not been adequate for calcareous nannofossils nor for palynomorphs, which is supported by aforementioned intermediate weathering and reworked shallow water ostracods and forams (Fig. 2).

Following the lowstand in the early Sarmatian, sea level rose in Paratethys at ca. 12.5 Ma (KOVAČ et al., 2001) which influenced connections with the Mediterranean Sea and Indo-Pacific Ocean (GALOVIC, 2017 and references therein). Occurrence of the Sarmatian index species *Nonion bogdanowiczi* in sample 7 characterised the Sarmatian age. An early Sarmatian age is confirmed in sample 9 based on assemblages of calcareous nanno­fossils that identify Subzone NN7a (Fig. 2). The appearance of *Discocysta nigra* in the assemblage with rare *Calcidiscus pataucus*, *Helicosphaera walbersdorfsiensis*, *Rhodosphaera* spp. and *Pontosphaera* spp. characterises Subzone NN7a (GALOVIC, 2019). The base of Zone NN7 for Paratethys is close to the FO(global) *D. hexapleuros* at 12.186 Ma, De KAENEL et al. (2017) and possibly sets the sample 9 close to 12.18 Ma for Paratethys (GALOVIC, 2020 and references therein) (Fig. 2).

According to JIMENEZ-MORENO et al. (2006), the *Cleistosphaeridium placacanthum* Assemblage Biozone (Cpl), contains a low diversity assemblage indicating environmentally unfavourable conditions for most marine dinoflagellates. They correlate this event to the shallow depths and oscillating environmental conditions of the early Sarmatian. A similar assemblage is also found in sample 9 from the KOS-I column. *Impagidinium* spp. and *Nematosphaeropsis labynithus* disappeared there, indicating marginal marine environments also documented by the common occurrence of the genus *Baiacaspheara* (GEDL, 2005). High relative abundances of *Lingulodinium machaerophorum* indicate enhanced nutrient levels and hypersaline conditions with seasonal stratifications (JIMENEZ-MORENO et al., 2006), while increments of the coccolith *R. producta*, as in high latitudes (WEI & THIERSTEIN, 1991), indicates periods of weaker upwelling and warmer surface water. Enhanced species diversity in Zone NN7 implies a deeper and more stable environment.

The increase of *Coccolithus pelagicus* and small *Reticulofenestracostracods, palynomorphs) analyses that suggest marine, offshore sedimentation.

2. The mineral composition of pelitic sedimentary rocks is common for Middle Miocene deposits. However, the appearance of smectite indicates possible local volcanic activity in this period, while the presence of minerals from the clinoptilolite/heulandite series indicates a local source of material. Provenance analyses based on the chemical composition show that the Badenian-Sarmatian marls were predominantly formed by the weathering of acidic (Si-rich) source rocks in the Continental Island Arc area.

3. The investigated column was recorded from the subtropical late Badenian to a warm temperate climate of early Sarmatian. A high rate of reworked microfossil species, especially foraminifera, together with small changes in the sedimentological composition and lack of significant tectonic features make it difficult to precisely define the Badenian/Sarmatian boundary. The biostratigraphy based on the fossil assemblages shows that the Badenian/Sarmatian boundary could be located within the column at 6.05 m from the base.

4. The position of the Hrvatska Kostajnica column (KOS-I) at the edge of the NCB shows different attributes in depositional settings and ecological conditions than the rest of the area studied to date (the Slavonian Ms. and Mt. Medvednica). The main feature of the KOS-I column, concerning fossil assemblage, reworking, can also be explained due to its position mostly detected at the edge of the basin.
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**Supplement Table 1. Distribution of foraminifera in samples from the sedimentary KOS-I column.**

| FORAMINIFERA | KOS-I |
|--------------|-------|
|              | 1     | 2 | 4 | 5 | 6 | 7 | 8 | 9 | 11 | 13 | 15 |
| **BENTHIC**  |       |   |   |   |   |   |   |   |    |    |    |
| Amphimorphina hauerina (Neugeboren) | x | x | x | x | x |   |   |   |    |    |    |
| Ammonia viensis (d'Orbigny) |     |   |   |   |   | x | x |   |    |    |    |
| Ammonia pseudobecarai Putjja | x |   |   |   |   |   |   |   |    |    |    |
| Anomalinaeoides cf. badensis (d'Orbigny) |     |   |   |   |   |   |   |   |    |    | x |
| Asterignanata planorba (d'Orbigny) | x | x |   |   |   |   |   |   |    |    |    |
| Astronion perossum Clossius | x | x |   |   |   |   |   |   |    |    |    |
| Articulina sp. | x | x |   |   |   |   |   |   |    |    |    |
| Baggina arenaria (Karrer) | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina antiqua d'Orbigny | x |   |   |   |   |   |   |   |    |    |    |
| Bolivina dilatata Reuss | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina ex gr. pokorny Cicha & Zapletalova | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina moldavica Didkowski | x |   |   |   |   | x | x | x |    |    |    |
| Bolivina granensis Cicha & Zapletalova | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina fastigia Cushman | x |   |   |   |   |   |   |   |    |    |    |
| Bolivina moravica Cicha & Zapletalova | x | x |   |   |   |   |   |   |    |    |    |
| Bolivina papula Cushman | x | x |   |   |   |   |   |   |    |    |    |
| Bolivina pseudoplicata Heron-Allen & Earland | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina pokorny Cicha&Zapletalova | x | x | x | x | x |   |   |   |    |    |    |
| Bolivina sagittula Didkowski | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina sarmatica Didkowski | x |   |   |   |   |   |   |   |    |    |    |
| Bolivina plicatella Cushman | x |   |   |   |   |   |   |   |    |    |    |
| Bolivina striatula Cushman | x | x | x | x | x | x | x | x |    |    |    |
| Bolivina nisporensis Didkowski | x | x | x | x | x | x | x | x |    |    |    |
| Bulimina buchiana d'Orbigny | x | x | x | x | x | x | x | x |    |    |    |
| Bulimina elongata longa d'Orbigny | x | x | x | x | x | x | x | x |    |    |    |
| Bulimina subulata Cushman&Parker | x | x | x | x | x | x | x | x |    |    |    |
| Chilostomella ovodes Reuss | x | x | x | x | x | x | x | x |    |    |    |
| Cibicidoides ungerianus (d'Orbigny) | x | x | x | x | x | x | x | x |    |    |    |
| Cursina porocostata Popescu&Crihan | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium cf. excavatum (Terquem) | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium cf. subumbilicatum Czepak | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium crispum (Linne) | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium ex gr. hauenerinum (d'Orbigny) | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium reussi Marks | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium grilli Papp | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium fichtelianum d'Orbigny | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium persicatum Serova | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium macellum tumidocamerale Bogdanowicz | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium incertum Williamson | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium macellum (Fichtel & Moll) | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium jovcri Serova | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium signaei (Caralp&Julius) | x | x | x | x | x | x | x | x |    |    |    |
| Elphidium artfex (Serova) | x | x | x | x | x | x | x | x |    |    |    |
| Favulin hexagona (Williamson) | x | x | x | x | x | x | x | x |    |    |    |
| Fissurina marginata (Montagu) | x | x | x | x | x | x | x | x |    |    |    |
| Fissurina severanti Popescu | x | x | x | x | x | x | x | x |    |    |    |
| Oolina globosa (Montagu) | x | x | x | x | x | x | x | x |    |    |    |
| Fursenkoina sarmatica (Venglinski) | x | x | x | x | x | x | x | x |    |    |    |
| FORAMINIFERA       | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 11 | 13 | 15 |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|
| **BENTHIC**       |    |    |    |    |    |    |    |    |    |    |    |    |
| Furunkoina acuta  | x  |    |    |    |    |    |    |    |    |    |    |    |
| Globobulimina pupoides |    | x  |    | x  |    |    |    |    |    |    |    |    |
| Globobulimina pyrula |    |    |    |    |    |    |    |    |    |    |    | x  |
| Globulina gibba d'Orbigny |    | x  |    |    |    |    |    |    |    |    |    |    |
| Guttulina communis d'Orbigny |    |    |    |    |    |    |    |    |    |    |    |    |
| Hanawasia crassiseptata (Luczkowska) |    |    |    |    |    |    |    |    |    |    |    | x  |
| Heterolepa dutemplei (d'Orbigny) | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Laevidentalina elegans (d'Orbigny) | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Lenticulina austriaca (d'Orbigny) |    | x  |    |    | x  |    |    |    |    |    |    |    |
| Lenticulina inornata (d'Orbigny) |    |    |    |    | x  |    |    |    |    |    |    |    |
| Lenticulina calcar (Linne) |    |    |    |    |    |    |    |    | x  |    |    |    |
| Lobatula lobatula (Walter & Jacob) | x  | x  | x  | x  | x  |    |    |    |    |    |    |    |
| Loxostomina digitalis (d'Orbigny) |    |    |    |    |    |    |    |    |    |    |    | x  |
| Neugeberina longiscata (d'Orbigny) |    | x  |    |    |    |    |    |    |    |    |    |    |
| Nonion bogdanowicz/Valoshinova |    |    |    |    |    |    |    |    |    |    |    |    |
| Nonion bicornus Krshteninnikov |    |    |    |    |    |    |    |    |    |    |    | x  |
| Oolina globosa (Montagu) |    |    |    |    |    |    |    |    |    |    |    | x  |
| Palliolatella sp. |    |    |    |    |    |    |    |    |    |    |    |    |
| Pappina neudorferensis (Toula) | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Planularia moravica (Karrer) | x  | x  | x  | x  |    |    |    |    |    |    |    |    |
| Porosolenia tibiscens Popescu | x  |    |    |    |    |    |    |    |    |    |    |    |
| Porosonion martkobi (Bogdanowicz) |    |    |    |    | x  |    |    |    |    |    |    |    |
| Pseudotiloculina consobrina (d'Orbigny) | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Sigmavirgulina tortuosa (Brady) |    |    |    |    |    |    |    |    |    |    |    |    |
| Siphonodosaria consobrina (d'Orbigny) | x  | x  | x  | x  |    |    |    |    |    |    |    |    |
| Spirosignilimina tenuis (Czjzek) | x  |    |    |    |    |    |    |    |    |    |    |    |
| Spirorutilus carinatus (d'Orbigny) | x  |    |    |    |    |    |    |    |    |    |    |    |
| Uvigerina brunensis Karrer | x  | x  | x  |    |    |    |    |    |    |    |    |    |
| Uvigerina pygoeides Papp & Turnovsky | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Uvigerina seminatata (d'Orbigny) | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Uvigerina venusta Franzenau | x  |    |    |    |    |    |    |    |    |    |    |    |
| Valvulineria complanata (d'Orbigny) | x  |    |    |    |    |    |    |    |    |    |    |    |

| **PLANKTONIC**    |    |    |    |    |    |    |    |    |    |    |    |    |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|
| Globigerina bulloides (d'Orbigny) | x  | x  | x  | x  |    |    |    |    |    |    |    |    |
| Globigerina cf. subcretae Lomnicki | x  |    |    | x  |    |    |    |    |    |    |    |    |
| Globigerina concinna Reuss | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Globigerina diplastoma Reuss | x  | x  |    |    | x  |    |    |    |    |    |    |    |
| Globigerina praebulloides Blow | x  | x  | x  |    |    |    |    |    |    |    |    |    |
| Globigerina tarchanensis (Subbotina & Chutzieva) | x  | x  | x  |    |    |    |    |    |    |    |    |    |
| Globigerina cf. lentana Frogl | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Globigerinella regularis (d'Orbigny) | x  | x  | x  | x  |    |    |    |    |    |    |    |    |
| Globigerinita glutinata (Egger) | x  | x  | x  | x  |    |    |    |    |    |    |    |    |
| Globigerinoidea apertusatalis (Jenkins) | x  | x  |    |    |    |    |    |    |    |    |    |    |
| Globigerinoidea quadrilobatus (d'Orbigny) | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |    |    |
| Globigerinoidea socculifer (Brady) | x  |    |    |    |    |    |    |    |    |    |    |    |
| Globigerinoidea trilobus (Reuss) | x  | x  | x  | x  | x  | x  | x  | x  |    |    |    |    |
| Globoquadrina altispira (Cushman & Jarvis) | x  | x  | x  | x  |    |    |    |    |    |    |    |    |
| Globoquadrina cf. Scitula Brady | x  | x  | x  | x  | x  |    |    |    |    |    |    |    |
| Globoturbo rotula decarapta | x  |    |    |    |    |    |    |    |    |    |    |    |
| Globoturbo rotula druryi Akers | x  |    |    |    |    |    |    |    |    |    |    |    |
### Supplement Table 2. Distribution of the ostracod species within the samples of the KOS-I succession.

| OSTRACODS | KOS-I |
|-----------|-------|
|           | 1     | 2     | 4     | 5     | 6     | 7     | 8     | 9     | 11    | 13    | 15    |
| Aurila cf. notata (Reuss) | x     | x     |     |     |     |     |     |     |     |       |       |
| Aurila cf. merita Zalányi |     | x     |     |     |     |     |     |     |     |       |       |
| Aurila sp. | x     | x     | x     | x     | x     | x     | x     | x     |     |       |       |
| Amnicythere sp. |     | x     |     |     |     |     |     |     |     |       |       |
| Bosquetina carinella (Reuss) |     | x     |     |     |     |     |     |     |     |       |       |
| Butonia sp. |     | x     |     |     |     |     |     |     |     |       |       |
| Callistocythere cf. postvallata Pietrzyeniuk | x     | x     | x     | x     | x     | x     |     |     |     |       |       |
| Callistocythere canaliculata (Reuss) | x     | x     |     |     |     |     |     |     |     |       |       |
| Cnestocythere sp. |     | x     |     |     |     |     |     |     |     |       |       |
| Cnestocythere truncata (Reuss) | x     |     |     |     |     |     |     |     |     |       |       |
| Costa sp. |     |     |     |     |     |     |     |     | x     |       |       |
| Grinioneis haidingeri (Reuss) | x     |     |     |     |     |     |     |     |     |       |       |
| Loxococho sp. |     | x     |     |     |     |     |     |     |     |       |       |
| Loxocomiculum cf. schmiedi (Cernajek) |     |     | x     |     |     |     |     |     |     |       |       |
| Loxoconiculum hastatum (Reuss) | x     |     |     |     |     |     |     |     |     |       |       |
| Olmflania ? plicatula (Reuss) |     |     |     |     |     |     |     |     | x     |       |       |
| Paracytheridea triquetra (Reuss) |     |     |     |     |     |     |     |     | x     |       |       |
| Semicytherura filicata (Schneider) |     | x     |     |     |     |     |     |     |     |       |       |
| Semicytherura cf. alata (Linenklaus) | x     | x     | x     |     |     |     |     |     |     |       |       |
| Tenedocythere slesbosa (Uliczny) |     |     |     |     |     |     |     |     | x     |       |       |
| Tenedocythere sp. | x     | x     |     |     |     |     |     |     |     |       |       |
| Tenedocythere sulcatopunctata (Reuss) |     | x     |     |     |     |     |     |     |     |       |       |
| Xestoleberis globerscens (Reuss) | x     | x     | x     | x     |     |     |     |     |     |       |       |
| Xestoleberis sp. |     | x     | x     | x     | x     |     |     |     |     |       |       |