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The Pannonian Basin System northern margin paleogeography, climate, and depositional environments in the time range during MMCT (Central Paratethys, Novohrad-Nógrád Basin, Slovakia)

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ABSTRACT

The Miocene global climatic changes together with profound regional tectonic activity significantly influenced the Central Paratethys epicontinental sea. The aim of this study was to reveal relationships between regional and global changes during the beginning Middle Miocene Climatic Transition. The work focused on the northern margin of the Pannonian Basin System, on the key Burdigalian and Langhian sites from the Novohrad-Nógrád and Danube basins (Slovakia). The outcrops and wells reveal variegated facial architecture, environments and processes. The sedimentary record can be subdivided into four main stratigraphic intervals: (i) The late Burdigalian (Karpatian) NN4 Zone. (ii) The earliest Langhian (Karpatian? - earliest Badenian; 14.9 Ma and older), top of NN4/base NN5 Zone. (iii) The lower Langhian (lower Badenian) deposits of NN5 Zone estimated to be ~14.9–14.4 Ma old. (iv) The late Langhian (lower Badenian) sediments of NN5b-5c Zone with estimated age of 14.4 Ma or younger. Langhian (lower Badenian) rift related volcanism was responsible both for pronounced relief formation and for supply of nutrients and silica into the basin. The Burdigalian/earliest Langhian shelf break slope mudstone (after hiatus) have been replaced by the Langhian inner to outer shelf environment dominated by tidal and wave processes. These were dominated by infaunal foraminifer associations which changed to epiphytic ones. Occasionally the patchreef environment was recorded by miliolide forms. In general, on the southern edge of the Krupina volcanic field the shelf setting passed into deltaic and fluvial deposits. Foraminiferal and calcareous nannoplankton assemblages point more to the nutrient decrease and circulation system change around the Bur/Lan boundary than to warm water condition, followed by cooling during the MMCT. Pollen spectra documents a slight post-Burdigalian cooling and aridification trend.

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INTRODUCTION

The MMCO (Middle Miocene Climatic Optimum ca. 17–15 Ma) represents the last warm interval in the Earth history (Zachos et al., 2001) and is characterized by warm conditions, comparable to those of the late Oligocene (Pound et al., 2012). Important change associated with an Antarctic ice sheet expansion known as Middle Miocene Climate Transition (15 to 13 Ma – MMCT) representing global cooling is expressed in the increase of $\delta^{18}O$ in foraminiferal records (Holbourn et al., 2005; Shevenell et al., 2008). However, its influence on the specific environment of epicontinental seas, where global trends strongly interfere with local and regional process, is still poorly known. In the Central Paratethys area the climate change was evaluated based on the terrestrial pollen associations by Kováčová et al. (2011) and Kern et al. (2011), which shows a very mild (negligible) trend from Early to Middle Miocene vegetation still of subtropical climate. Mandič et al. (2011) concluded that the optimum climatic conditions triggered the formation of long-lived Gacko Lake (Dinaride Lake System) between ~ 15.8 and ~ 15.2 Ma. The effect of climate change on marine environment in Central Paratethys is evaluated by Piller et al. (1997), Harzhauser et al. (2003), Kováč et al. (2007), Kroh (2007) and confirming global trends. A shift in the global trend was documented in the Central Carpathian Foredeep (Holcová and Demeny, 2012; Holcová et al., 2015, 2018; Scheiner et al., 2018).

The Cenozoic convergence between the European and Adriatic (African) plates resulted in immense changes in the middle European paleogeography (literature summarized by Kováč et al., 2018a). During the Oligocene, these processes resulted in the origin of the semi-closed basin systems consisting of Western, Central and Eastern Paratethys (Popov et al., 2004). Closing and reactivation of seaways, especially during the Miocene (~23–10 Ma), resulted in environmental changes in the partial depocenters of the Paratethys. The Central Paratethys was one the most influenced (Kováč et al., 2017) and lasted up to the early Serravallian (late Badenian 13.6–12.7 Ma) stage, which represents the last period of marine connection with the Mediterranean Tethys (Báldi, 1980;

Harzhauser et al., 2002; Kováč et al., 2004, 2018b; Márton, 2006; Harzhauser and Piller, 2007). These processes have affected the terrestrial and marine environment, occasionally interfering with the Mediterranean and the Eastern Paratethys (Sant et al., 2017; Kováč et al., 2017, 2018). During the Burdigalian/Langhian (Karpatian–early Badenian; ca 17.2–15.9–13.6 Ma (Hohenegger et al., 2014; Kováč et al., 2018a, b) resp. 16.3–13.8 Ma (Piller et al., 2007)) the Central Paratethys Sea reached far out into the Central Western Carpathians (Kováč et al., 2017) and the associated sediments can today be found in the Vienna, Danube, Novohrad-Nógrad and in the East Slovakian basins. The depositional environments of the Vienna, Danube and East Slovakian basins (Kováč, 2000; Kováč et al., 2007, 2018b; Rybár et al., 2016) are relatively well known, but on the other hand only a little attention was given to the sediments of the Novohrad-Nógrad Basin, situated at the northern margin of the Pannonian Basin System. The lithofacial character, sediment distribution and paleocurrent patterns of the tidal sandy deposits in this area were originally studied by Čechovič and Seneš (1950), Seneš (1954) and Vass (1977). More details and paleogeographic implication were later added by Vass et al. (1979) and Konečný et al. (1983), and the last lithostratigraphic evaluation was published by Vass (2002).

This study aims to refine knowledge about stratigraphy, depositional systems and about the paleo-climate at the junction of the northern Central Paratethys Sea with the Central Western Carpathians during an interval between the MMCO and MMCT (Burdigalian/Langhian) by utilizing: facies analysis, nannofossils and foraminifer biomarkers together with palynomorphs and other micro-, meio- and macrofauna.

GEOLOGICAL SETTINGS

The lower Badenian (Langhian) strata *sensu* Vass (2002) of the Novohrad-Nógrad Basin (Ipeľ depression) and Krupina plain (southern part of Central Slovak Volcanic Field) is represented by the volcano sedimentary Vinice Formation onlapping discordantly onto the late Burdigalian (Karpatian) Modrý Kameň Formation. This formation includes two members: (1) the Príbelce Member (40-60 m thick) dominated by fine to coarse, tuffaceous, cross-bedded sands with occasional algal bioherms; and (2) the Hrušov Member (up to 10 m thick) dominated by mudstone with abundant pumice fragments. The Vinice Formation is discordantly overlain by the Opava and Lysec andezite formations.

MATERIAL AND METHODS

For this study, seven sections from the South Slovakian basin and one from the Danube Basin were chosen to cover the facial diversity of the Burdigalian/Langhian interval. Additional study was performed in the same area, between Hámor, Ľuboriečka and Malý Krtíš vicinity by LKŠ-1, N-80, N-65, N-91 hydrological wells (Figures 1, 2). Foraminifera and calcareous nannoplankton study of the well cores were published and stratigraphically ranked according to Zlinská and Šutovská (1991) and Holcová (1996).

Field sedimentological analysis followed standard procedures. The outcrops were leveled by shovels and palette knives. Partial layers were measured, labeled, and photo documentation of key sections was then made by an SLR camera. The uncovered sedimentary structures and textures were documented according to Owen et al. (2011), Rossi et al. (2017) and Patruno et al. (2018) (Appendix 1).

For the purpose of calcareous nannoplankton study standard slides were prepared for a light microscope (normal and crossed nicols, 1000x magnification). About 200–500 specimens of calcareous nannoplankton were determined from each sample and abundances of taxa were enumerated. If the number of individuals was not sufficient the abundances of taxa were expressed semiquantitatively. Determination of calcareous nannoplankton was based on Nannotax database (Young et al., 2020). Dinoflagellate genus *Thoracosphaera* was included into the calcareous nannoplankton category. Presence of diatoms in nannoplankton slides was also recorded - rare, common and abundant occurrences were distinguished and analyzed (Appendix 2). In total, 79 samples were analyzed, 33 were analyzed quantitatively, 35 did not contain calcareous nannoplankton and 11 could not be analyzed quantitatively due to their scarcity. Abundance of nanoplankton in rock was expressed following the method of Holcová and Zágoršek (2008).

Foraminifers were gained from 200 g of dried material treated with H_2O_2 (10%) and subsequently washed using sieves with a mesh size of 1.25 and 0.071 mm. Finally, 250 specimens (benthos and plankton separately) were separated from the samples. If fewer specimens had been present, all foraminifer's tests have been picked from two standardized residuum loads (Appendix 3). A com-

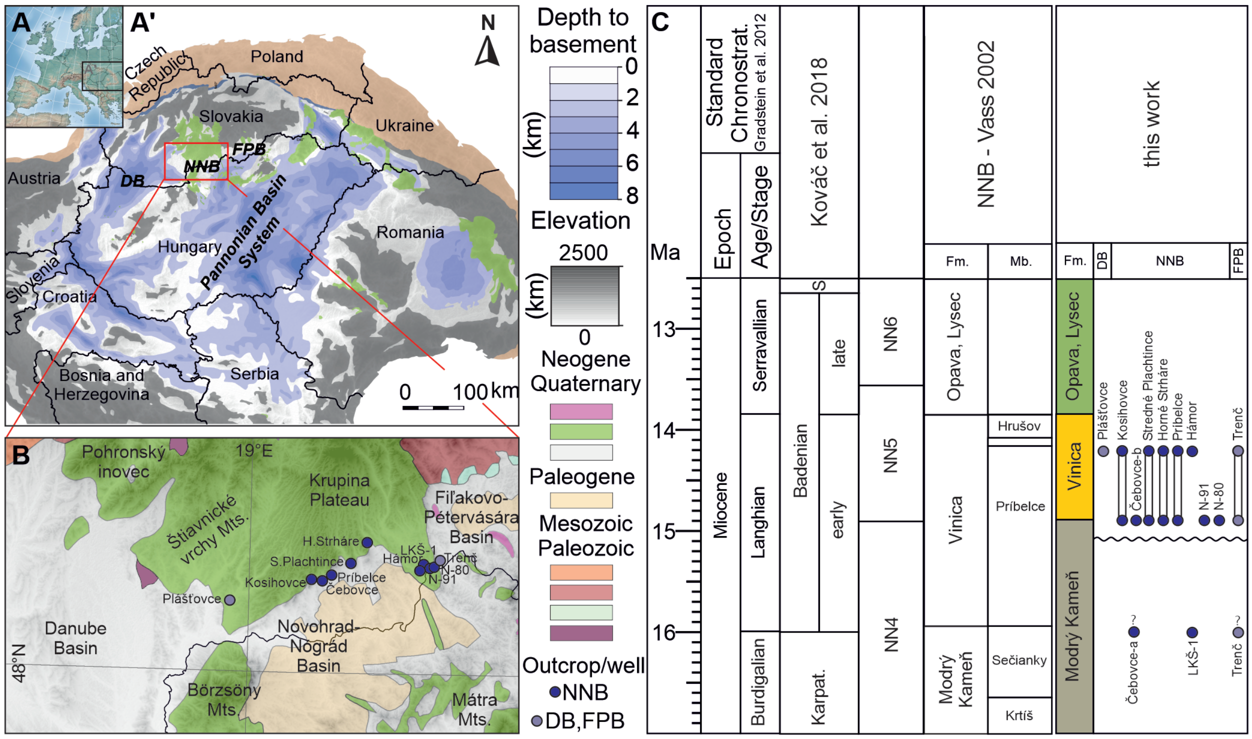


FIGURE 1. Location map. A, A) Position of Novohrad-Nógrád Basin within the Pannonian Basin System. Modified from Rybár et al., 2016. B) Location map of studied sections. C) Lithostratigraphic scheme. Explanatory notes: FPB-Fiľakovo-Pétervására Basin; DB- Danube Basin; NNB-Novohrad-Nógrád Basin. Modified from Gradstein et al., 2012.

bination of the binocular stereoscopic microscope (Olympus SZ75), the biological polarizing microscope and the scanning electron microscope QUANTA FEG 250 were used during determination and imaging. The taxonomical approach followed Loeblich and Tappan (1992), Cicha et al. (1998) and Holbourn et al. (2013). Due to the poor preservation, some specimens remained in open nomenclature. Paleoenvironmental interpretation of the benthic foraminiferal assemblages is based at diversity and abundance study (Murray, 1973, 2006), and paleoecological parameters were evaluated based on the presence and dominance of taxa (Boltovskoy and Wright, 1976; Murray, 2006). The two-step method developed by Hohenegger (2005) was used for estimation of the paleo water depth of the sedimentary basin. Depth ranges of the foraminifers (Appendix 3C) were adapted mostly from Sgarrella and Montcharmont-Zei (1993), Murray (2006), Spezzaferri and Tamburini (2007) and Sen Gupta et al. (2009).

The stratigraphical correlation was based on stratigraphic ranges of index species from world oceans (Gradstein at al., 2012) and from the Mediterranean (Di Stefano et al., 2008; Abdul Aziz et al., 2008; Hüsing et al., 2010; Iaccarino et al., 2011). The local Paratethys biostratigraphy was based on the Cicha et al. (1975), Cicha et al. (1998) and Brzobohatý et al. (2003).

Foraminifera and calcareous nannoplankton assemblages were classified quantitatively and analyzed statistically using the Principal Component Analysis (PCA) of PAST software (Hammer et al., 2001) and nMDS analysis using R package (Venables and Ripley, 2002; R Core Team, 2014; Oksanen et al., 2017).

With regards to the pollen analysis, the samples of dry sediment (20g per sample) were treated using cold concentrate hydrofluoric and hydrochloric acids to remove mineral matter – carbonates and silicates. The application of heavy liquid ($ZnCl_2$) with a density of 2g/cm^3 was used to concentrate fraction with pollen (in organic rich ring), spores and other organic particles. The microscope slides were prepared using glycerin as a mounting medium, and one to three slides per sample were examined by Axioscope Zeiss with magnification 40x and 63x. Photos were taken using AxioCamERc5s under the 63x magnification. Pollen spectra were statistically visualized and treated using Polpal software (Nalepka and Walanus, 2003).

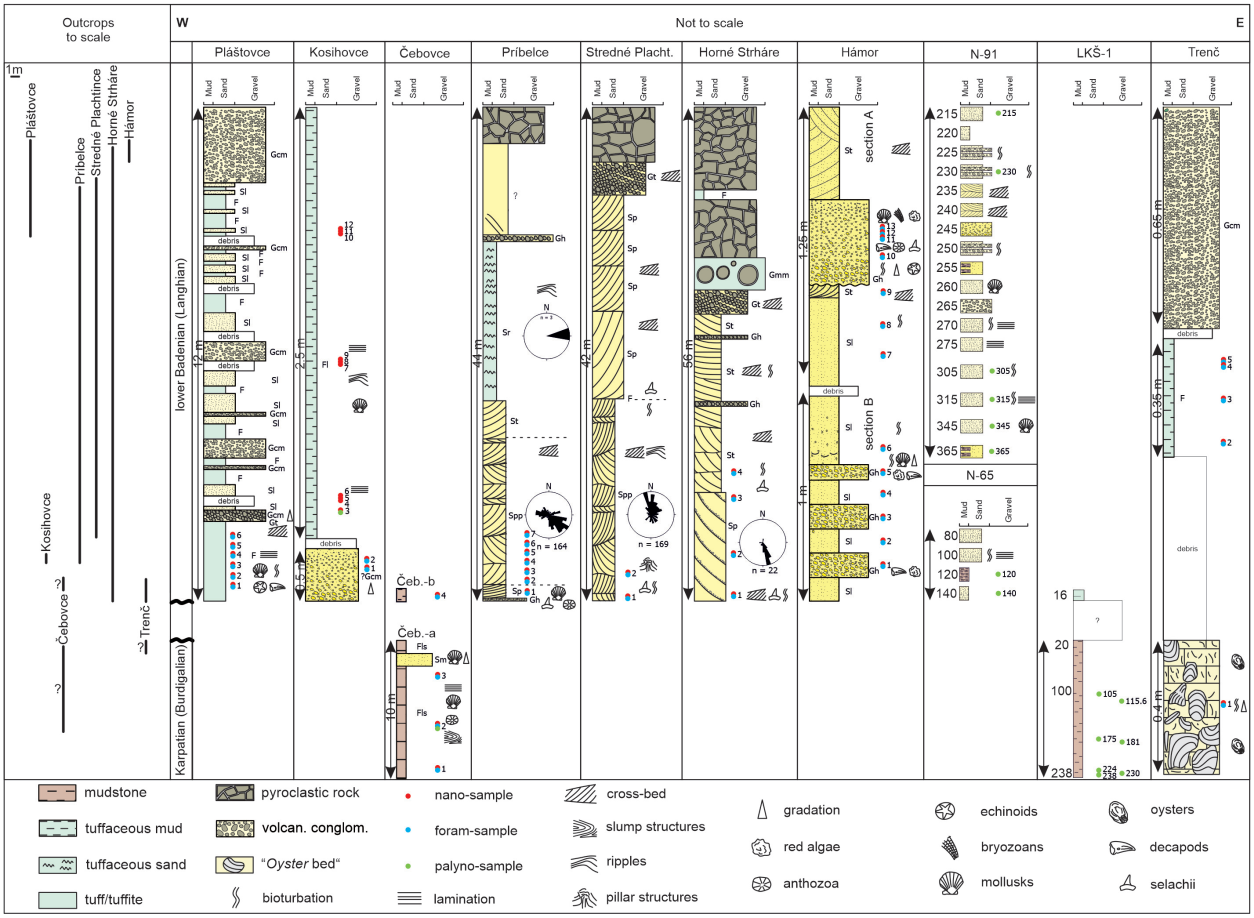


FIGURE 2. Lithology of the studied sections with sedimentological logs and paleoflow orientation. For codes of lithofacies see Appendix 1.

Conventional C and O isotope analysis was performed by using GasBench II (ThermoFisher Scientific) equipped with a CTC Combi-Pal (PAL-SYSTEM) autosampler and linked to a MAT253 isotope ratio mass spectrometer (ThermoFisher Scientific) in a Continuous Flow IV (ThermoFisher Scientific) system at the Charles University in Prague. The internal precision (SD) measured over these six peaks is typically 0.02 and 0.09 ‰ for raw $\delta^{13}C$ and $\delta^{18}O$ values, respectively, given a sample size above 50 µg. Calibration of the raw results versus the V-PDB scale is achieved using in-house calcite standards (subsequent to linearity correction) that have been calibrated against NBS-18, L-SVEC and IAEA-603 international reference materials (IAEA, Vienna, Austria). Stable carbon and oxygen isotopes were studied on the tests of *Globigerina* sp. div. (surface water marker), *Cibicidoides* sp. div. (bottom water marker) and *Melonis pompilioides* (sediment pore water marker). The *Melonis* data can be served only for the Burdigalian because the taxon does not occur in sufficient quantity in the Langhian sections.

LITHOLOGY AND FOSSIL CONTENT OF THE STUDIED SECTIONS

The Čebovce outcrop (Figures 2, 3) is 10 meters high, facially monotonous and consists of mudstones ranked to the Sečianky Member (Vass, 2002). The section starts by layered, faintly laminated mudstone with soft sediment deformations and common marine fossils (Fls - lithofacies; Appendix 1). Next thick fine to coarse, occasionally pebbly sandstone layer follows and yields abundant casts of mollusks. In the northernmost part of the section mudstones facies continue. Calcareous nannoplankton is common to very abundant and dominated by *Coccolithus pelagicus, Reticulofenestra haqi* and *Sphenolithus moriformis* (Appendix 2). The palynological study has found only gymnosperms: bisaccate *Pinus* and *Abies*. The nonpollen palynomorphs are represented only by

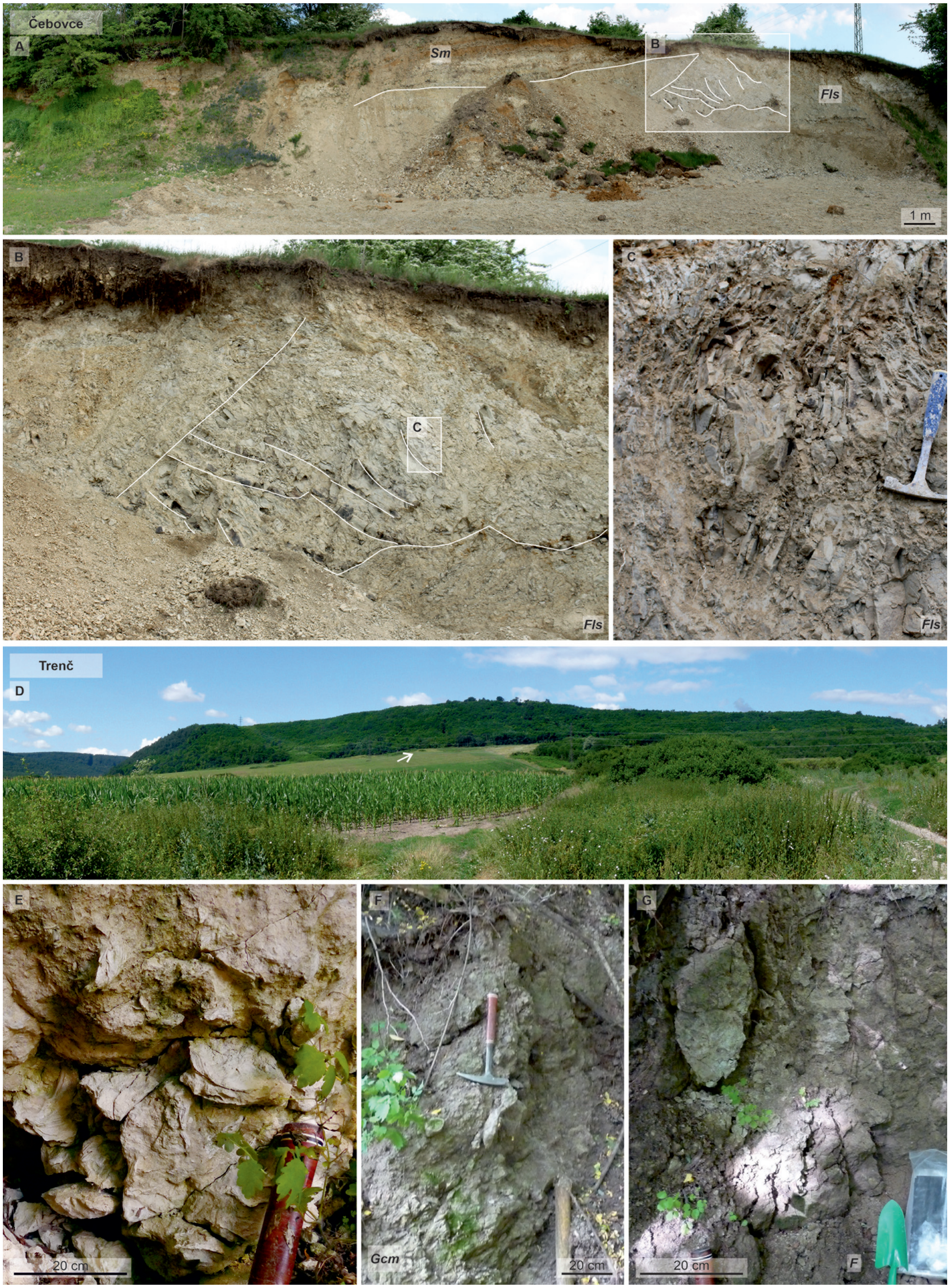


FIGURE 3. Photoplate of the Čebovce and Trenč sections: A-C. Čebovce section, lat. 48°11'17.88"N, lon. 19°13'38.94"E, mud with faint lamination with slump bodies overlain by fine to coarse grained sand with pebbles. D-G. Trenč section, lat. 48°13'20.47"N, lon. 19°14'44.42"E. D) Southern foot of the Strážna hora hill with oyster reefs outcropping at the forest boundary. E) *Ostrea* bed. F) Clast supported massive gravels. G) Fine-grained tuffite. For codes of lithofacies marked in italic see Appendix 1.

the *Botryococcus braunii* algae (Appendix 4). Washed residua rich in microfossils are markedly dominated by globigerinid foraminifers *Ciperoella concinna, C. ciperoensis, Turborotalita quinqueloba* and *Globigerina regularis*. In the benthic fauna, *Hoeglundina elegans*, *Bulimina* div. sp. and *Bolivina* div sp. are frequent. $\delta^{18}O$ values range from -0.5 to -1.3‰ for *Cibicidoides* and from -0.5 to -1.8‰ for *Globigerina* in the section Čebovce (a). In this section $\delta^{13}C$ range from -0.4 to -0.8‰ for *Cibicidoides* and from 0 to -0.8‰ for *Globigerina* thus, they partially overlap. $\delta^{18}O$ in the *Melonis pompiloides* tests vary from -0.2 to -0.5‰ for Čebovce (a) section, $\delta^{13}C$ values range from -0.3 to 0.2‰. Rich diatom assemblages are dominated by *Actinoptychus splendes* (Shadbolt) Ralfs, *Triceratium* aff. *favus* Ehrenberg, and *T. favus* Ehrenberg.

Čebovce (b) section is an additional sample taken from the uppermost part of the section, which contain common to very abundant calcareous nannoplankton dominated by *Coccolithus pelagicus*, *Reticulofenestra haqii*, *Helicosphaera carteri* and *Pontosphaera multipora*. Discoasters were also observed within this section. The foraminiferal assemblage contains a diversified fauna with *Globorotalia archeomenardii*, *Uvigerina graciliformis* and *Lenticulina* cf. *echinata.*

The Trenč (Figures 2, 3) site was first mentioned by Čechovič and Seneš (1950). Today the outcrops are scattered in up to 2 m wide forest gutters. At the base, limestones dominate and yield articulated *Ostrea* shells which become fragmented higher up. The *Ostrea* beds pass into tuffaceous mudstones with faint layering (F). Above, clast supported massive gravels with indistinct normal gradation (Gcm) follow. The pebbles are mostly composed of volcanic rocks (up to ~10 cm in diameter). These sediments are almost entirely barren of calcareous nannoplankton and diatoms. Preservation of nannofossils is poor, only dissolution resistant species occur (*Coccolithus pelagicus*, *Watznaueria* sp.). In the oyster bed planktic foraminifera are rare, *Ammonia parkinsoniana* and *Pararotalia calcariformata* strongly dominate together with other epiphytic taxa like *Cibicidoides lobatulus* and *Biasterigerina* cf. *planorbis*. Residuum from the mudstones yield badly preserved foraminiferal rests often present as calcite casts, mostly without original calcite wall, planktic *Globigerinoides (Trilobatus)* group prevails. *Praeorbulina* is present as molds and test fragments, Globorotaliids (*G. bykovae* and *G. transsylvanica*) are common. Benthic foraminifera are represented by casts of lagenids and miliolids. Uvigerinids are rare (*Uvigerina* cf. *macrocarinata, Nodosaria* sp). Higher up (sample 6; Figure 2) symbiont bearing miliolids (*Borelis melo, Peneroplis pertusus*) and quinqueloculinids prevail.

The facies, fauna and flora of the Kosihovce (Figures 2, 4) section were previously studied by Hano (1950), Vass et al., (1979) Vass (1989) and Holcová (2001). Today the section is located in an abandoned quarry. It is discontinuous and approximately 2.5 m high and 4 m wide. Fine-grained tuffaceous sands with faint lamination and ripples commonly yield marine fossils (Fl). These sediments are underlain by clast supported massive gravels with indistinct normal gradation (?Gcm). Calcareous nannoplankton is abundant, *Coccolithus pelagicus* slightly dominates (30–60%), *Helicosphaera carteri* and *Reticulofenestra haqi* are common. Reworked Oligocene species are rare, Cretaceous ones occur in only a few samples. Poriferan spicules are very abundant. Foraminiferal tests are poorly preserved and bear signs of dissolving and abrasion. Planktic assemblage dominates by *Trilobatus trilobus* and *Ciperoella ciperoensis*. Benthic assemblage is significantly more diversified and is composed from *Nonion communis, Cassidulina laevigata, Hansenisca soldanii, Bolivina* sp. div., *Porosonion granosum, Ammonia parkinsoniana* and cibicidids. The mudstones contain diversified pollen spectra, dominated by various bisaccate pollen grains *(Pinus, Cathaya, Picea,* and *Abies)* accompanied by *Botryococcus braunii* algae and prasinophyts. Rarely, *Corrugatisporites* bot. aff. Lygodiaceae, *Lygodium*, Fagaceae – Quercoideae, *Platycarya, Engelhardia, Momipites, Castanea/Castanopsis, Carya a*nd Sapotaceae are present.

The Príbelce (Figures 2, 4) section is the type locality for the Príbelce sand member and was previously studied by Vass (1977), Vass et al. (1979) and Vass (2002). The outcrop is situated in an occasionally mined sand pit positioned west from the Horné Príbelce village. The exposed wall is about 50 m high and ~200 m wide. The Príbelce section starts with a 5–20 cm thick horizontally bedded clast supported gravel with sandy matrix and marine fauna (Gh). It continues with a ~1 m thick, north east dipping, grouped, planar, unidirectional, cross-beded sand, which contain bioturbations, mud drapes and marine fauna and flora (Sp). Above, a ~12 m thick packet of grouped, planar, bidirectional, sandy cross-beds is present. Each individual bed is about 15 cm thick. Bioturbations, mud drapes and marine fauna and flora is com-

FIGURE 4. Photoplate of the Kosihovce and Príbelce sections: A-C. Kosihovce section, lat. 48°11'15.16"N, lon. 19°31'35.74"E. A) Fine-grained tuffites with faint lamination and symmetrical ripples. B) Detail of the sampling points. C) Fine-grained tuffite with faint lamination. For codes of lithofacies marked in italic see Appendix 1. D-J. Príbelce section, lat. 48°11'49.89"N, lon. 19°14'44.42"E. D) Type locality of the Príbelce Member, E) Fine to very coarse sand with grouped unidirectional cross-beds. F) Fine to very coarse sand with grouped bidirectional cross-beds, G) Detail of the symmetrical ripple composed of sand and tuffite. H) Grouped unidirectional trough cross-bedded sand. I) Pyroclastic breccia. J) Fossiliferous horizontally bedded clast supported gravels with sandy matrix. For codes of lithofacies marked in italic see Appendix 1.

mon. Main dip of the beds is towards the SE, and the less pronounced dip is towards the NW (Spp). Higher up another packed (3.5 m thick) of east dipping unidirectional sandy trough cross-beds follows. Individual beds are about 0.6 m thick (St). These beds are followed by a 12 m thick layer of laminated tuffaceous sands which yields symmetrical ripples (Sr). The top of these beds is erosive and overlain by a horizontally bedded clast supported gravel with sandy matrix. The layer occasionally yields cobble and boulder size clasts of volcanic rocks (Gh). The following beds are ~8 m thick, and part of the main section remains enigmatic due to its unreachable position within the section. The topmost part of the section is exposed in the forest located above the main section and yields a 2 m thick patch of pyroclastic brecciass.

The washed residuum from the studied samples is composed mainly of poriferan spicules, pteropods, ostracod valves and echinoid spines. Planktic foraminifera like *Ciperoella ciperoensis* and *Globigerina praebulloides* (=*Globigerinella obesa*) are rare and fragmented. The foraminiferal assemblage is dominated by benthic forms; tests are abundant, but not well preserved. Cibicids (*Hanzawaia boeueana*, *C. refulgens* and *C. pachyderma*) are the most dominant and well preserved. *Bulimina schischkinskayae*, *Bolivina* cf. *plicatella* and *Nonion commune* are common. In the lower part of the section, nannoplankton assemblage includes *Coccolithus pelagicus* and *Reticulofenestra haqii.* Diatoms are rare, Cretaceous and Paleogene redeposit also occur. Sediments in the middle part of the section are barren for calcareous nannoplankton. In the upper part *Reticulofenestra haqi* dominates over *Coccolithus pelagicus*. Oligocene redeposits are abundant.

The Stredné Plachtince (Figures 2, 5) section is correlated with the Príbelce sand member (Vass, 1977; Vass et al., 1979). It is located in an actively mined sandpit situated on the eastern margin of the Stredné Plachtince village. The section begins with a 16 m thick packet of fossiliferous, bioturbated, bidirectional, planar sandy cross-beds with abundant mud drapes. Individual beds are about 15 cm thick and yield pillar structure and symmetrical ripples. The major dip is towards the north, and the secondary dip is towards the south (Spp). Above an 8 m thick unidirectional sandy cross-bed follows and dips towards the south (Sp). In the overburden multiple large-scale cross-beds (~10 m thick) are present and dip towards the south-east (Sp). They are overlain by multiple beds (together about 3 m thick) of unidirectional, clast supported, trough cross-bedded gravels with erosional bases (Gt). The section ends with packet pyroclastic breccias (5 m thick). Microfauna and nannoflora are absent, only sporadic finds of mollusks and shark teeth (*Carcharias* sp.) were recorded.

The Horné Strháre (Figures 2, 5) section was described as a part of the Príbelce sand member (Vass, 1977; Vass et al., 1979). Locality is situated in an occasionally mined sand pit positioned west from the Horné Strháre village. The outcrops are spread throughout six quarry levels, and the section is about 54 m high and ~250 m wide. The section begins with a 12 m thick coarse-grained, fossiliferous, large scale, unidirectional, south dipping, planar, sandy cross-bed, with bioturbations and mud drapes (Sp). It is followed by a 21 m thick packet of medium to fine-grained, grouped, unidirectional, trough cross-bedded sands with mud drapes. The dip of the cross-beds is scattered between the south and west (St). The packet also includes rare 1–5 cm thick horizontally bedded, clast supported gravels with sandy matrix (Gh). A 3 m thick layer of clast supported through cross-bedded gravel follows. It is covered by a matrix supported paraconglomerate (clasts reach up to 1.5 m in diameter) with tuffaceous ground mass (Gmm). The section ends with a 14 m thick interval of pyroclastic breccias intercalated by tuff and tuffites. Microfauna and nannoflora were not recorded. However, abundant vertebrate fossils occure: *Odontaspis cuspidata*, *O. acutissima*, *Hexanchus* sp., *Carcharias priscus*, *Galeocerdo aduncus*, *Isurus* sp., ?*Carcharodon* sp., Myliobatidae indet., Actinopterygii indet., Testudines indet., Cervidae indet.

The facies and the fossil content of the Plášťovce (Figures 2, 6) section were originally described by Molčíková (1964), Melioris and Vass (1982), Vass (2002), Sukatcheva et al., (2006) and Hyžný et al. (2015). Today the site is composed of numerous outcrops that are scattered accros the Plášťovce village and vicinity. The studied composite section begins with fine-grained tuffite with faint layering (F). Bioturbation is common, and the layers are rich in marine fauna (echinoids, bivalves, gastropods, decapods). These layers are commonly incised by clast supported through cross-bedded gravels and/or by massive gravels (Gt, Gcm). These are overlain by fine- to coarse-grained sands with faint low angle lamination (Sl). This lithofacies association repeats rhythmically through the whole section. In the tuffites abundant *Ophiomorpha* trace fossils, composed of vertical shafts with a circular cross section and horizontal

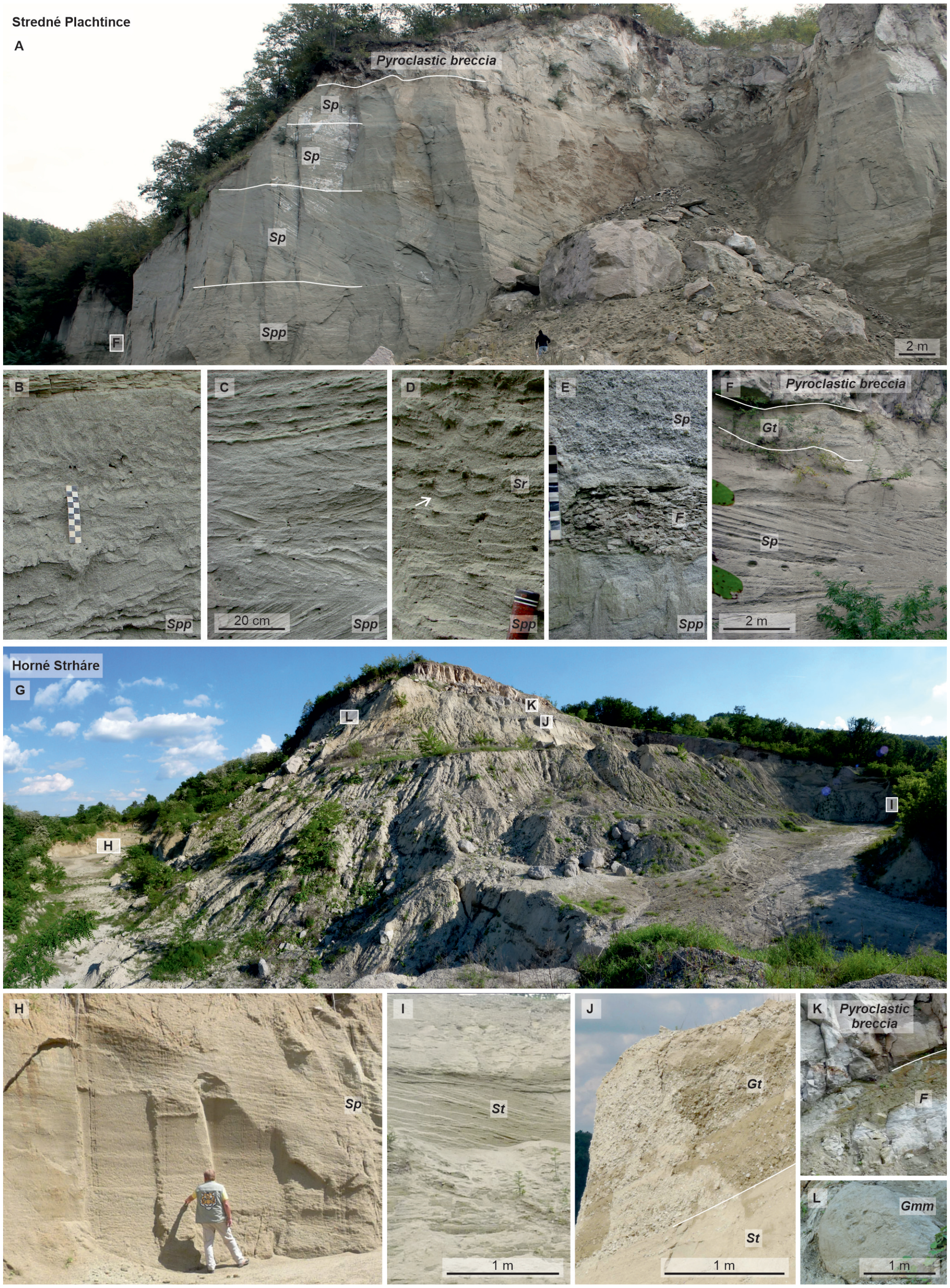


FIGURE 5. Photoplate of the Stredné Plachtince and Horné Strháre sections: A-F. Stredné Plachtince section, lat. 48°13'20.69"N, lon. 19°18'18.54"E. A) Main quarry wall exposing Príbelce sand topped by pyroclastic breccias. B-C) Bioturbated grouped bidirectional planar cross-bedded sand. D) Sand with symmetrical ripples marked by arrow. E) Contact between bidirectional and unidirectional cross-beds marked by tuffite layer. F) Contact between unidirectional cross-beds and through cross-bedded gravels topped by pyroclastic breccias. G-K. Horné Strháre section, lat. 48°15'57.91"N, lon. 19°21'9.08"E. G) Overall view of the quarry. H) unidirectional planar sandy cross-beds. I) Trough cross-bedded sand with mud drapes. J) Contact between trough cross-bedded sand with mud drapes and clast supported through cross-bedded gravels. K) Contact between tuffites and pyroclastic breccias. L) Boulder-sized clast of the paraconglomerate facies. For codes of lithofacies marked in italic see Appendix 1.

FIGURE 6. Photoplate of the Plášťovce and Hámor sections: A-C. Plášťovce section. A) lat. 48°9'23.53"N, lon. 18°57'26.67"E, fine grained tuffites. B) Lat. 48° 9'14.61", lon. 18°56'47.80", clast supported through-cross bedded gravels overlying fine grained tuffites. C) Lat. 48°9'28.24"N, lon. 18°57'28.60"E, main quarry wall exposing fine to coarse grained sand, clast supported massive gravels. D-G. Hámor section, lat. 48°12'51.66"N, lon. 19°31'35.74"E, D) Overall view of the outcropping sand. E-G) Alteration of through cross-bedded low-angle laminated sands and clast supported gravels with sandy matrix.

tunnels occurred, complete crab exoskeletons are also preserved. Foraminiferal tests are rare, some samples yield molds of *Globigerina* sp., *Nodosaria* sp. and *Bulimina elongata*.

The Hámor (Figures 2, 6) site was first mentioned by Čechovič and Seneš (1950) and later by Vass et al. (1979). It is located NE from the Hámor village. The section consists of two parts, section A and section B, and both are about 1 m high and ~20 m wide. Section B consists of two facies types which repeat rhythmically. The first type consists of fine to coarse occasionally pebbly sandstones (Sl); the second type is represented by horizontally bedded clast supported gravels with sandy matrix which yield abundant marine fauna and flora (Gh). Section A includes the mentioned facies (Sl) and (Gh), but also includes bioturbated, unidirectional trough cross-bedded sands (St). Calcareous nannoplankton (Figure 7, Appendix 2) is very rare except for two samples where *Reticulofenestra minuta* dominates. Dinoflagellate *Thoracosphaera* sp. was also documented and is very abundant in section A. The washed residua contain poriferan spicules and rhaxi, bivalve shells, echinoid spines and plates, ostracod shells, bryozoans, serpulids, fish teeth and fish bones as well. Foraminifera (Figure 8, Appendix 3) show strong secondary calcification which covers the original ornamentation of the test and hides the chamber organization. Assemblages are diversified and benthic taxa strongly prevail (Figure 9). The epiphytic group (e.g., *Asterigerina* sp., *Hanzawaia boueana*, *Cibicidoides lobatulus*, high spiral *Ammonia parkinsoniana*, *Textularia* sp.) dominates throughout the whole section with the most prevalence in samples Hámor-10 and 13 (Appendix 3). Within the planktic forms, *Globigerinoides/Trilobatus* group is dominant.

Lithology and Fossil Content of the Studied Wells

Studied sections were complemented by several wells (LKŠ-1, N-65, N-80, N-91), which penetrated sediments synchronous to those studied in the sections. Sediments of the Príbelce member were found only in the N-80 well. They consist of massive tuffitic sandstone to siltstone bodies in a thickness of about 100 m. Fragments of pumice stone with a bubble-like structure dominate the washed residue. They do not contain any organic content. This is probably the delta sediment described by Vass (1977). The most common lithotype of the well cores is fine-grained sandstone to siltstone with layers of coarser sand, shell fragments and mica scales. Bioglyphs with domichnia are characteristic of being filled with coarser material (N-91, N-65). Cross-bedding occasionally occur with thin clay lenses (dimensions 0.5 to 1 cm x 3 to 10 cm), and very rarely gradation layering occurs (gradation layers have a thickness of up to 3 cm and grain size range from coarse to fine sandstone). The breccias with sharp-edged fragments of pumice material alternate with breccia with oysters at the bottom of the formation (N-80). Stable carbon and oxygen isotopes were studied in the upper Burdigalian foraminiferal tests obtained from the the LKŠ-1 core (145-165 m); Čebovce section and N83 well (details see Holcová et al., 1996). $\delta^{18}O$ values range from 0.7 to -1.4‰ for *Cibicidoides* and from 0.8 to -1.6‰ for *Globigerina* in the LKŠ-1 core. $\delta^{13}C$ values are slightly higher for *Cibicidoides* in this core and range from 0.1 to 1.1‰ in comparison with -0.4 to 0.4 for *Globigerina*. $\delta^{18}O$ in the *Melonis pompiloides* tests vary from -0.6 to 0.6‰.

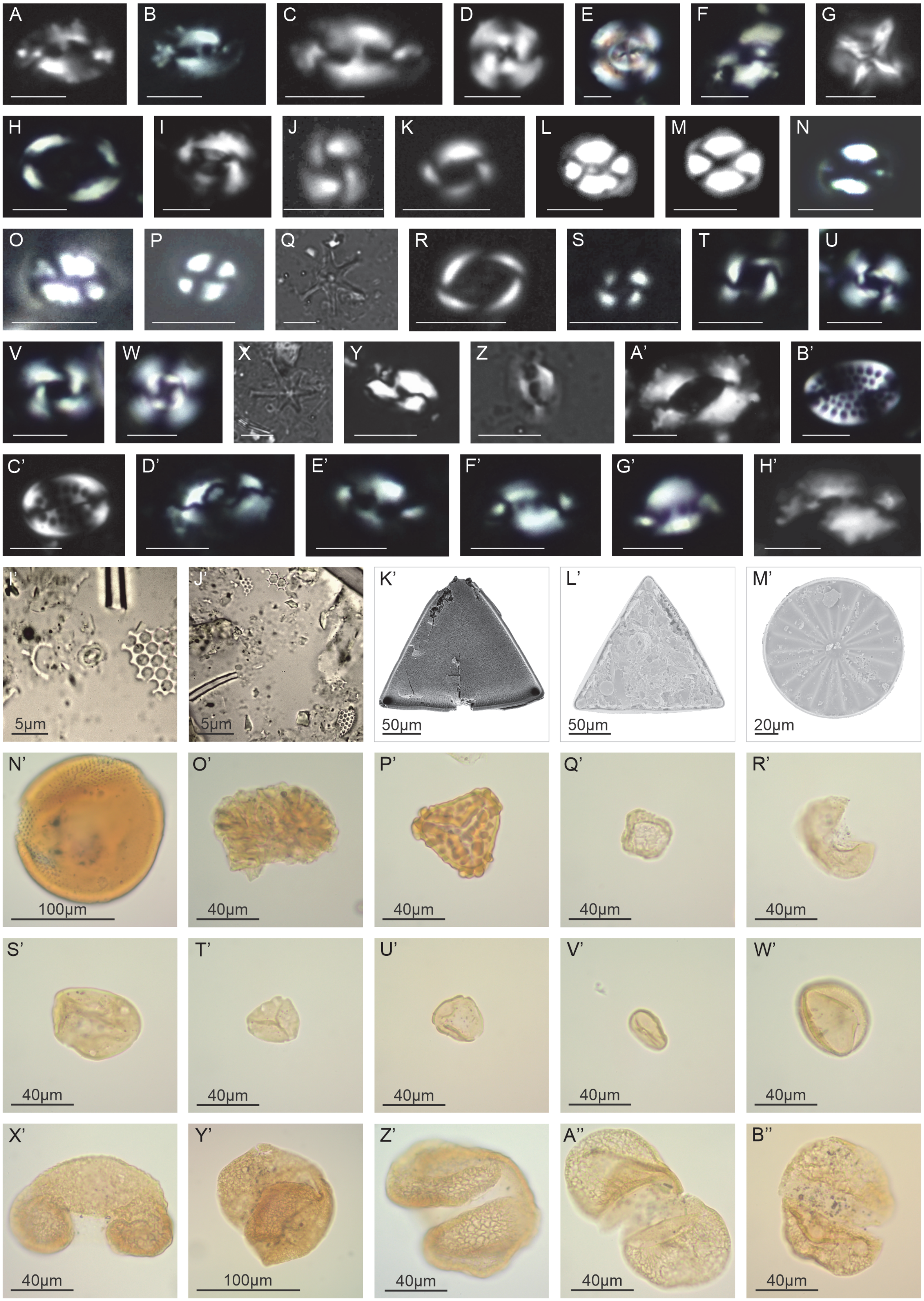
The lower Badenian (Langhian) plankton and benthos isotopic values are: $\delta^{18}O$ range from 0.5 to 0 ‰ for *Cibicidoides* and from -1.7 to -2.3‰ for *Globigerina*; $\delta^{13}C$ ranging from 0 to -0.5‰ for *Cibicidoides* and from -1.1 to -2.5‰ for *Globigerina* (Figure 9Fa-c).

INTERPRETATION AND DISCUSSION OF BIOSTRATIGRAPHY

The stratigraphic correlation relies on 79 studied microsamples (Figure 2). Planktic foraminifera and calcareous nannoplankton enabled to distinguish four stratigraphic levels (Figures 1, 2).

(1) Burdigalian: NN4 Zone with *Helicosphaera ampliaperta*, *Sphenolithus heteromorphus* and *Trilobatus bisphericus* together with absence of *Praeorbulina* were determined in the Čebovce (a) locality. The presence of local stratigraphical markers *T. bisphericus* and *Uvigerina graciliformis* (Cicha et al., 1998; Cicha et al., 2003) allow us to rank the site into the upper Burdigalian (Karpatian) stage.

(2) Langhian: uppermost part of the NN4 Zone with *Helicosphaera ampliaperta*, *H. waltrans* (as mentioned in Švábenická, 2002; Holcová et al., 2018), accompanied with *H. walbersdorfensis*, *Sphenolithus heteromorphus*, *Discoaster exilis*, *D. variabilis*, *D. petaliformis* and together with *Globorotalia archeomenardii*, *Uvigerina graciliformis* and *Lenticulina* cf. *echinata* is observed within Kosihovce lowermost part and Čebovce (b) sections.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(3) Langhian: NN5 Zone with planktic foraminiferal species *Praeorbulina circularis* and *T. bisphericus* together with the absence of *Orbulina* sp. in the Kosihovce, Príbelce and Trenč sections indicate the lowermost Badenian (lower Langhian) age. These sediments were ranked into the regional lower Badenian substage (*sensu* Hohenegger et al., 2014). Co-occurrence of *P. circularis* (14.9 Ma) in the Mediterranean (Di Stefano et al., 2008) together with *H. waltrans* (LCO 14.357 Ma in the Mediterranean; Abdul Aziz et al., 2008) determines the absolute age of these sections to ~14.7–14.4 Ma. It agrees with the estimated age of *H. waltrans* event in the Central Paratethys (Holcová et al., 2018; Sant et al., 2020. Presence of *H. ampliaperta* in the Kosihovce section is probably due to reworking, otherwise (based on foraminifera) the coarse sandstones to fine conglomerates of the Kosihovce section would be deposited during the short interval of the uppermost NN4 Zone (~14.9 Ma). Despite the Sr isotope age of 15.94 Ma (Fordinál et al., 2014; processed on the *Oyster* valves) the base of the Trenč outcrop was assigned the lower Badenian (Langhian) based on the presence of *Pararotalia* sp.. However, no other index foraminifers or calcareous nannoplankton was recorded. Regarding Sr data, there is a discrepancy, whenever we compare the age of 87/86 Sr obtained from oyster shells with the age of 87/86 Sr obtained from foraminiferal shells, molluscs or bulk sediment, oyster shells usually give older age (Fordinál et al., 2014; Less et al., 2015; Kováč et al., 2017). Therefore, the Oyster bed age remains questionable. Nonetheless the ~15.9 Ma age cannot be excluded and if considered correct, correlation with Kleinebersdorf localities from lower Austria would be possible (Zuschin et al., 2004).

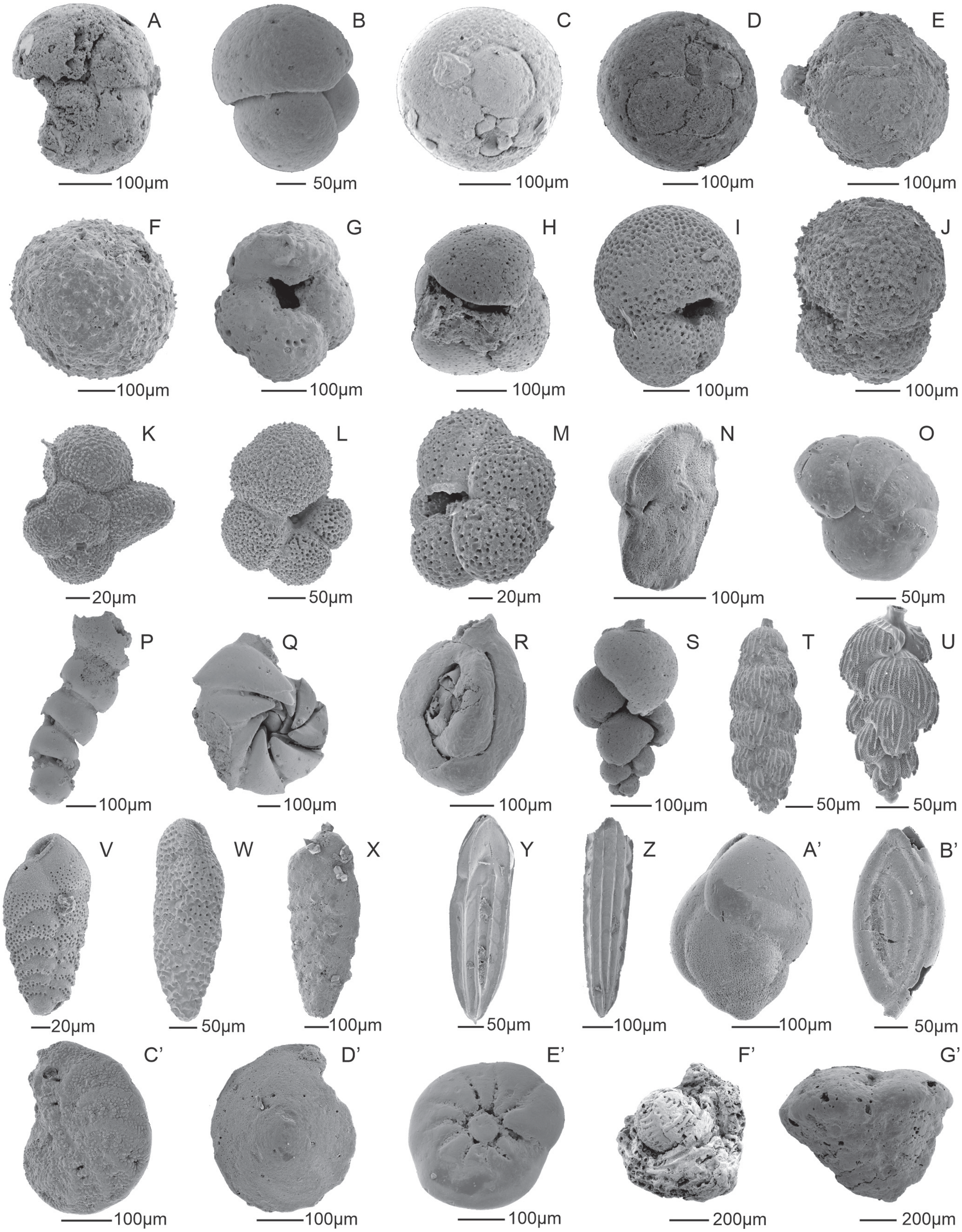
(4) Late Langhian sediments occur in the Hámor section, which yields an assemblage where the presence of *O. suturalis* and *T. bisphericus* is combined with the absence of both *H. waltrans* and *H. ampliaperta.* This allows correlation of this section into the NN5b-5c Zone (younger than 14.4 Ma).

Biostratigraphic markers have not been found in the Plášťovce, Stredné Plachtince and Horné Strháre sections, however, they were stratigraphically correlated based on the similar lihofacies and close proximity to the other sites (Figure 2).

Statistical Analyses

Only a minority of the calcareous nannoplankton assemblages was suitable for statistical treatment (Figure 9, Appendix 2). Nannoplankton was not recorded in approximately half of analyzed samples (in 35 from 79 samples). Very abundant assemblages were obtained from the Čebovce section. In sections Hámor, Kosihovce, Príbelce and Plášťovce the horizons with common to abundant nannoplankton assemblages alternate with layers nearly barren of calcareous nannoplankton.

FIGURE 7 (on previous page). Photoplate of the nannofossils, diatoms and pollen. A-K. Kosihovce site (NN5a Zone); scale bar equals 5 µm. A-C) *Helicosphaera waltrans* Theodoridis, 1984. D) *Cyclicargolithus floridanus* (Roth and Hay, in Hay et al., 1967) Bukry, 1971. E) *Cyclicargolithus abisectus* (Muller, 1970) Wise, 1973, reworked Oligocene. F) *Helicosphaera recta* (Haq, 1966) Jafar and Martini, 1975, reworked Oligocene. G) *Micula staurophora* (Gardet, 1955) Stradner, 1963, reworked Upper Cretaceous. H) *Pontosphaera latoculata* (Bukry and Percival, 1971) Perch-Nielsen 1984, reworked Oligocene. I) *Reticulofenestra daviesii* (Haq, 1968) Haq, 1971, reworked Oligocene. J-K) *Reticulofenestra haqii* Backman, 1978; L-J'. Čebovce site (NN4 Zone); scale bar equals 5 µm. L-P) Morphological variability of *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930. Q) *Discoaster exilis* Martini and Bramlette, 1963. R) *Coronosphaera mediterranea* (Lohmann, 1902) Gaarder in Gaarder and Heimdal, 1977. S) *Reticulofenestra minuta* Roth, 1970. T) *Reticulofenestra haqii* Backman, 1978. U-W) Morphological variability of *Cyclicargolithus floridanus* (Roth and Hay, in Hay et al., 1967) Bukry, 1971. X) *Discoaster pentaradiatus* Tan, 1927. Y-Z) *Helicosphaera waltrans* Theodoridis, 1984. A') *Helicosphaera ampliaperta* Bramlette and Wilcoxon, 1967. B') *Pontosphaera multipora* (Kamptner, 1948 ex Deflandre in Deflandre and Fert, 1954) Roth, 1970. C') *Pontosphaera enormis* (Locker, 1967) Perch-Nielsen, 1984; reworked Oligocene. D') *Helicosphaera euphratis* Haq, 1966. E') *Helicosphaera vedderi* Bukry, 1981. F'-G') *Helicosphaera* cf. *vedderi* Bukry, 1981. H') *Helicosphaera carteri* (Wallich 1877) Kamptner, 1954. I'-J') Assemblages with coccoliths, centric diatoms and sponge spicules. K') *Triceratium* aff. *favus* Ehrenberg, Čebovce site. L') *T. favus* Ehrenberg, Čebovce site. M') *Actinoptychus splendes* (Shadbolt) Ralfs, Čebovce site. N') *Tasmanites* sp., Kosihovce site. O') *Botryococcus braunii* Kützing, Čebovce site. P') Polypodiaceae indet., Kosihovce site. Q') Ulmaceae indet., Kosihovce site. R') Cupressaceae inet., Kosihovce site. S') *Carya* sp., Kosihovce site. T') Juglandaceae indet., Kosihovce site U') Juglandaceae indet., Kosihovce site. V') *Castanea* sp., Kosihovce site. W') Fagaceae indet., Kosihovce site. X') *Abies* sp., Čebovce site. Y') *Abies* sp., Kosihovce site. Z') *Pinus* sp., Čebovce site. A'') *Cathaya* sp., Kosihovce site. B'') *Cathaya* sp., Kosihovce site.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In the Trenč section calcareous nannoplankton was extremely rare and badly preserved. No calcareous nannoplankton was recorded in the Horné Strháre section.

The multivariate statistics was used to identify possible groups of calcareous nannoplankton assemblages. Comparison of results of the following multidimensional methods (PCA, DCA, nMMDS and cluster analysis) gave comparable results and here we presented the most readily outputs (PCA; Figure 9). Two groups of calcareous nannoplankton asssemblages were obtained: (1) homogenous group characterized by abundant *Coccolithus pelagicus* was recorded in the lower part of the Kosihovce section (Gmg facies), lower part of Príbelce section and mainly Čebovce a section; (2) dispersed group of assemblages dominated by small-sized reticulofenestras which could be further subdivided into three subgroups according to prevalence of (2.1) *Reticulofenestra minuta* (section Hámor and one sample from section Plášťovce); (2.2) *Reticulofenestra haqii* (upper part of Príbelce section and Plášťovce section); and (2.3) by *Thoracosphaera* spp. (limestone intercalations from Hámor and Plášťovce section). Specimens of *Thoracosphaera* spp. were also recorded in the limestones of the Trenč section and in the upper part of the Kosihovce section, but very low nannoplankton abundances in its assemblages do not allow statistical treatment.

Foraminifera were collected from the all studied localities (8 sites). Five of the samples were barren of the foraminifera tests (Trenč 10, 11, 13, Stredné Plachtince, Príbelce). Abundance and species diversity varied between the localities and samples. Preservation of the foraminiferal tests was excellent (Čebovce) to very poor (Hámor). Samples Trenč 1, 4, 5, Hámor 12, Kubáňovo, Kosihovce 2, Plášťovce 1-6 possessed bad preserved foraminifera, therefore were treated semiquantitatively or qualitatively (Figures 8, 9).

The following multivariate statistics methods (Cluster analysis, NMDS and DCA) gave us the most readable results and were used for group identification in the benthic foraminiferal assemblage. Cluster analysis using Wards method of clustering shows two distinct groups (Figure 9C). First group (A) consists of Hámor outcrop samples (H6, H11p, H13p, H1p, H 10p), which are dominated by epiphytic foraminifera (*Asterigerina* cf. *planorbis, A. mammilla, Amphistegina* sp.) and Shannon_H diversity of benthic assemblages reach from 2.01 to 2.38. The second group (B) comprises all other analyzed samples and can be divided into two sub-groups at distance level 150. In the B1 subgroup assemblages from the Hámor and Kosihovce outcrops dominates (samples H9v, H5, H12, H2, Ko1, H1); benthic foraminiferal assemblages with average Shannon_H diversity 1.5–2.39 are dominated by *Asterigerinata* cf. *planorbis* and *Ammonia parkinsoniana*; while in the B2 subgroup consists of the samples from Trenč, and Kosihovce Čebovce localities (samples Tr 1, Tr 6p, C1, H7, C2, Ku1, Tr2, Tr 10, Ko2, C-3, Tr4, Tr5), where low Shannon_H diversity (0.6 to 2.2) in foraminiferal assemblages and common infaunal species are observed. Non-metric Multidimensional Scaling (NMDS) confirms dividing into the two main groups (Figure 9) divided by decreasing content of shallow water – epiphytic foraminifers *(Borelis, Asterigerinata, Amphistegina*) versus increasing content of shallow – to deep infaunal dwellers (*Uvigerina, Bolivina*). Paleoenvironmental analysis was processed by the Shannon_H and Fisher α ratio (Murray, 2006). Two groups of samples were gained - marsh and brackish marginal

FIGURE 8 (on previous page). Photoplate of the foraminifers. A) *Trilobatus bisphericus* (Todd, 1954), Trenč 5. B) *Trilobatus bisphericus* (Todd, 1954), Trenč 6. C) *Praeorbulina curva* (Blow, 1956), Trenč 5. D) *Praeorbulina circularis* (Blow, 1956), Trenč 6. E) *Praeorbulina circularis* (Blow, 1956), Hámor 8. F) *Orbulina suturalis* Brönnimann, 1951, Hámor 1. G) *Dentoglobigerina altispira* (Cushman and Jarvis, 1936), Trenč 5. H) *Dentoglobigerina altispira* (Cushman and Jarvis, 1936), cast, Trenč 5. I) *Trilobatus trilobus* (Reuss, 1850), Kosihovce 2. J) *Trilobatus trilobus* (Reuss, 1850), Hámor 8. K) *Beella* sp. *B.* cf. *praedigitata* (Parker, 1967), Čebovce 1. L) *Globigerinella obesa* (Bolli, 1957), Čebovce 3. M) *Turborotalita quinqueloba* (Natland, 1938), Čebovce 5. N) *Globorotalia archeomenardii* Bolli, 1957, Čebovce-b. O) *Cibicides crassiseptatus (*Łuczkowska, 1960), P) *Nodosaria* sp., cast, Trenč 1. Q) *Lenticulina* sp. cast, Trenč 01. R) *Cycloforina badenensis* (d'Orbigny, 1846), Trenč 1. S) *Uvigerina macrocarinata* Papp and Turnovsky, 1953, cast, Trenč 1. T) *Uvigerina graciliformis* Papp and Turnovsky, 1953, Čebovce 5. U) *Uvigerina acuminata* Hosius, 1895, Čebovce 10. V) *Bolivina pokornyi* Cicha and Zapletalová 1961, Čebovce 5. W) *Bolivina hebes* Macfadyen, 1930, Čebovce 10. X) *Bolivina dilatata* Reuss, 1850, Hámor 13. Y) *Plectofrondicularia digitalis* (Neugeboren, 1850), Čebovce 10. Z) *Plectofrondicularia digitalis* (Neugeboren, 1850), Čebovce 10. A') *Protoglobobulimina pupoides* (d'Orbigny, 1846), Čebovce 5. B') *Spirosigmoilina tenuis* (Cžjžek, 1848), Čebovce 1. C') *Elphidium margaritaceum* Cushman, 1930, Hámor 8. D') *Heterolepa dutemplei* (d'Orbigny, 1846), Hámor 13. E') *Ammonia parkinsoniana* (d'Orbigny, 1839). F') *Borelis melo* (Fichtel and Moll, 1798), Hámor 6. G') *Sahulia conica* (d'Orbigny, 1839), Hámor 11.

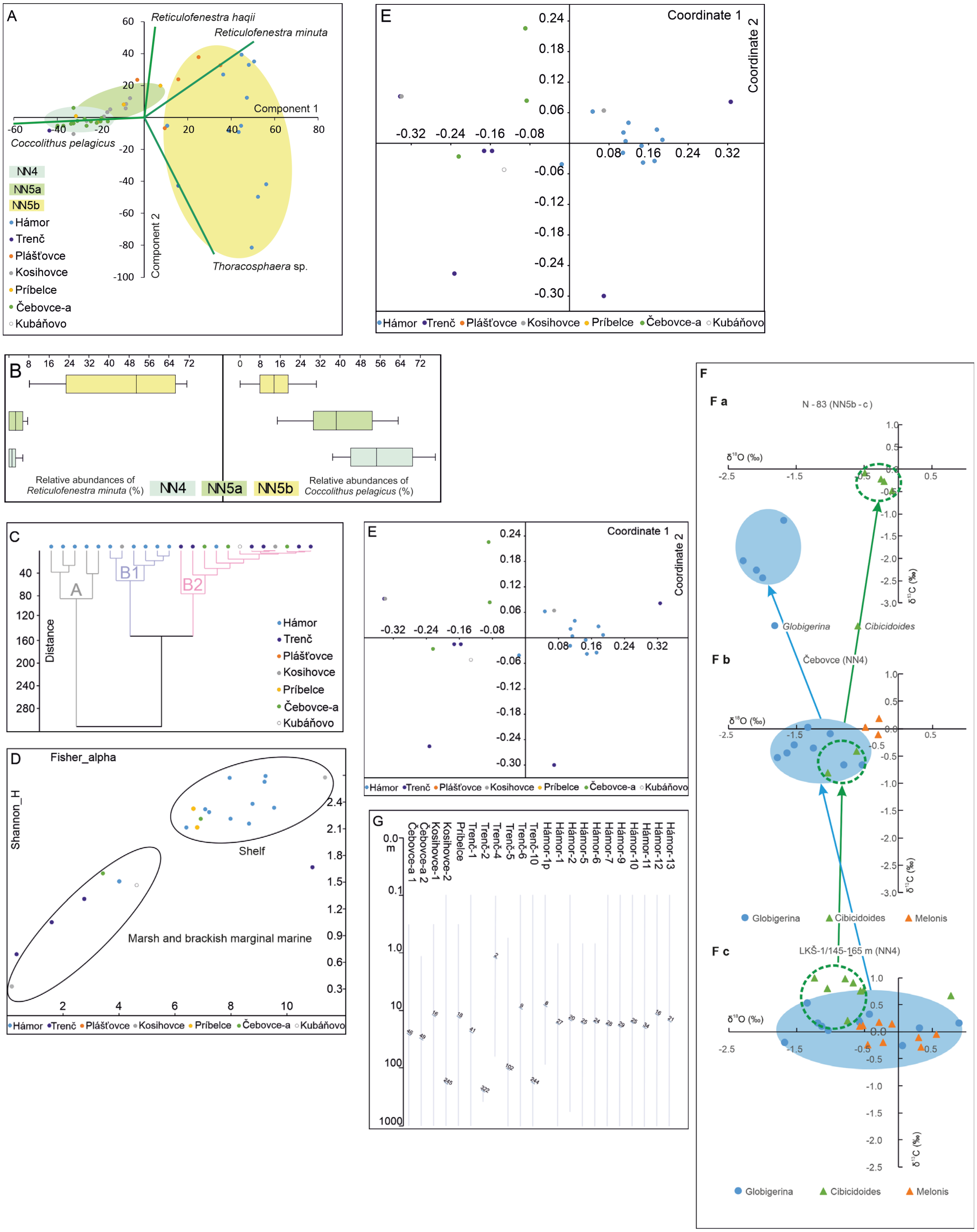

FIGURE 9. Foraminifera and nannofossils – statistical results. A. Principal Component Analysis (PCA) of the nannofossil assemblages. B. Relative abundances of *Reticulofenestra minuta* and *Coccolithus pelagicus* in the main stratigraphic levels. C. Cluster diagram (Ward algorithm analysis) of the benthic foraminifera assemblages, D. Species diversity of benthic foraminifera showing relation to typical environment adopted from Murray (2006), E. Non-metric multidimensional scaling (nMDS) diagram of benthic foraminifera, F. Isotope analysis ($\delta^{18}O$, $\delta^{13}C$), G. Estimated paleodepths based on benthic foraminifera.

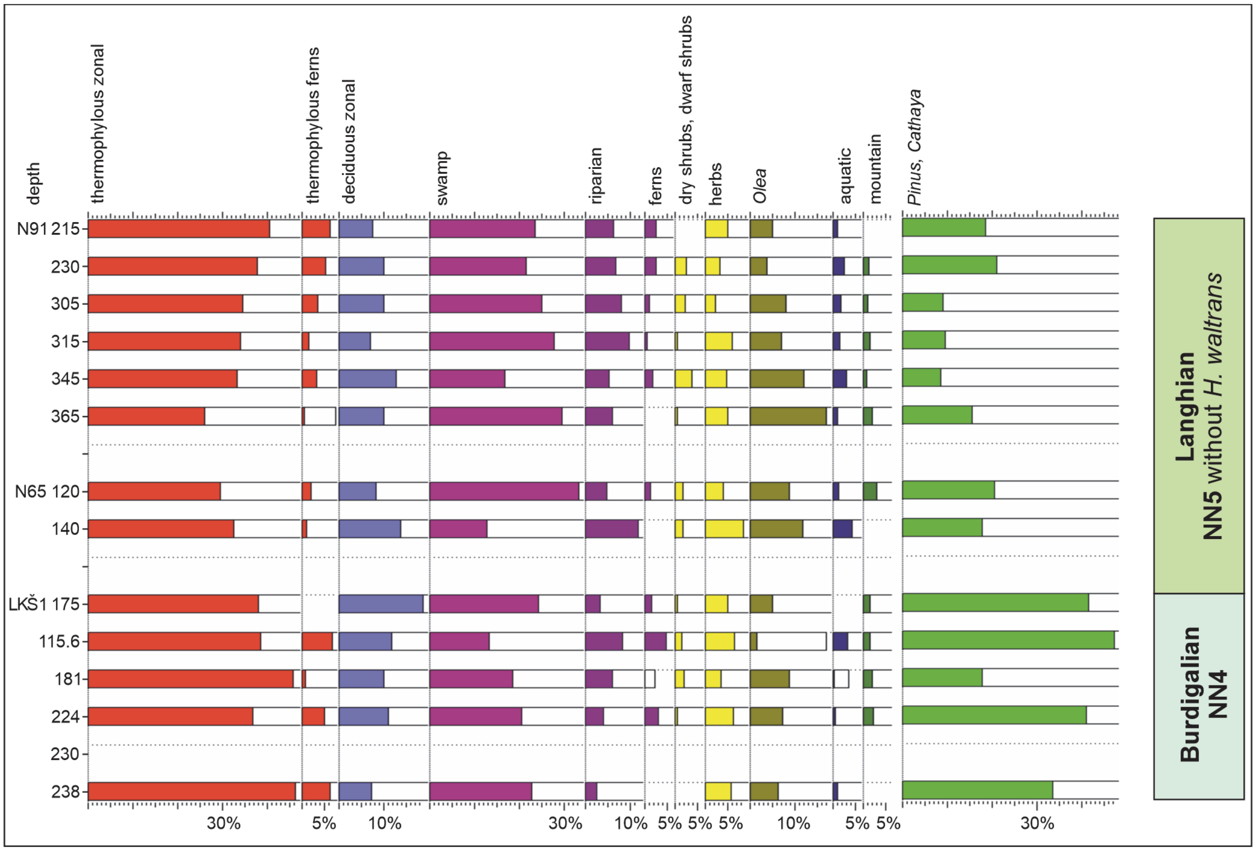

FIGURE 10. Polpal outcome chart – climate and ecology.

marine (Hámor, Kosihovce), and shelfal (Čebovce, Príbelce, Kosihovce, Trenč). Water depth analysis show the deepest marine environment of the studied associations in the Kosihovce 2 (ca 245m) and Trenč 5b (ca 102m) localities, while the shallowest are from the Trenč 4 (2 m), Trenč 6 (9 m) and Hámor 1 (8 m) sites. Generally, the estimated water depths reach an average from 2 to 38 m (Hámor), 8–34 m (Trenč), 38–49 m (Čebovce), 18 m (Príbelce) and 21 m (Kosihovce; Figure 9G).

Samples from the Čebovce and Kosihovce localities were only positive for rare palynomorphs due to a very unfavorable sediment for pollen preservation. Pollen analysis of samples from the nearby borehole LKŠ-1 shows the dominance of well diversified bisaccate pollen grains (*Pinus, Cathaya, Picea*) accompanied by algae *Botryococcus braunii* and *Tasmanites* (Figure 10, Appendix 4). In the samples from the borehole LKŠ-1 the paleotropical elements dominate (Sapotaceae, Palmae, Castaneoideae, Cyrillaceae, Araliaceae, Myricaceae, some of Polypodiaceae, less common Rutaceae, Proteaceae). Minor portion of the obtained spectra contain arctotertiary group of flora (*Carya*, Ulmaceae, *Alnus*, *Juglans*, *Sciadopitys*, together with rare *Betula*, *Celtis*, *Fagus*, *Plantago*). In the samples from N-65 and N-91 boreholes the swamp flora increase, the lower samples contain the pollens of the wet land vegetation (Polypodiaceae, *Selaginella*) and aquatic plants *Sparganium*, ?*Potamogeton* and *Nymphaea* as well.

PALEOENVIRONMENT AND PALEOECOLOGY

The Karpatian (upper Burdigalian) sediments outcropped in the Čebovce locality are composed of faintly laminated mudstones with soft sediment deformations (Fls). This indicates deposition from suspension and subsequent deformation by mass gravity movements. The intercalating massive pebbly sandstones (Sm) were highly likely a product of local debris flows. Both lithofacies are therefore interpreted as the shelf break slope environment (Patruno et al., 2018). Shallow water depth indicated by benthic foraminifera can be explained by redeposition caused due to slumping from the shelf towards the shelf break slope. This claim can be supported by high abundance of planktic foraminifers. An eutrophic environment, typical for upwelling conditions is documented by domination of high-nutrient markers like *Coccolithus pelagicus*

(Okada and McIntyre, 1979; Winter et al., 1994; Cachão and Moita, 2000) accompanied by abundant radiolarians, diatoms and acme of *Turborotalita quinqueloba* (Reynolds and Thunell. 1989; Grunert et al., 2010; Meilijson et al., 2016). Planktic foraminifers in the samples (lack of warm water indicators as *Globigerinoides* gr.) indicate cool or temperate-cool surface water similar to those in Vienna Basin (Spezzaferri and Ćorič, 2001), Styrian basin (Spezzaferri et al., 2009) or Salgótarján Basin (Soron, 2011). Neither nannoplankton nor planktic foraminifera yield warm water associations such as the late Oligocene in this area (Ozdínová and Soták, 2014) and expected in the MMCO. High presence of diatoms in the environment is obviously linked to high nutrient input during cool episodes or upwelling. Besides the high nutrient content, blooms of diatoms can indicate disoluted SiO_2 in the basin, most likely of volcanic origin (Baron and Baldauf, 1995; Cermeño et al., 2015). Water rich in nutrients led to microplankton blooming and subsequent decomposition documented in dominance of infaunal foraminifers of *Bolivina*, *Bulimina*, *Loxostomina* and *Cassidulina,* genera able to withstand dysoxic conditions (Kaiho, 1994; Murray 2006; Meilijson et al., 2016) while the occurrence of oxiphylic *Hoeglundina elegans* and cibicidoids indicate oxygen decrease within the sediment, hence a oxic/hypoxic boundary in sediment is expected. Similar foraminiferal assemblage is present in the Garáb Fm. in the Salgótarján Basin (Soron, 2011). In the Karpatian (upper Burdigalian), no difference in oxygen isotopic composition of epifaunal and planktic foraminifera (*Globigerina* vs. *Cibicidoides*) were observed (Figure 9Fb,c); $\delta^{13}C$ in the *Melonis pompiloides*, tests from the LKŠ-1 core and the Čebovce section are comparable. The lower Badenian (Langhian) plankton and benthos isotopic values are different (Figure 9Fa). Generally, *Globigerina* $\delta^{18}O$ values slightly decreased in time, while $\delta^{13}C$ values stay comparable in the Burdigalian and decrease in the lower Badenian (Figure 9F). *Cibicidoides* $\delta^{18}O$ slightly increased from the Burdigalian towards the Langhian, $\delta^{13}C$ values decrease during Burdigalian and then remain similar. Analogous oxygen isotope values between benthic and planktic foraminifera suggest a mixed water column. However, positive carbon isotope values measured in *Cibicidoides* tests doubts massive accumulation and decomposition of organic matter at the sea floor. On the other hand, different epifaunal and infaunal isotope values (*Cibicidoides* div. sp. and *Melonis pompiloides*) indicate differences between seafloor and sediment water chemistry that is in agreement with interpretation based on composition of foraminiferal assemblages. Thus lower carbon isotope values are expected for infauna in comparison with epifauna (as we recorded in the LKŠ-1 core). The opposite situation recorded in the Čebovce sections have been documented also from the Middle Miocene of the Carpathian Foredeep. Here, an increase of pH in sediment is suggested as a reason of this “inverse” carbon isotope values (Scheiner et al. 2018, 2020). The identified pollen spectra represented by paleotropical flora (Palmae, Castaneoideae, Cyrillaceae, Araliaceae, Myricaceae) indicate subtropical climate (Figure 10, Appendix 4). Similar, or even warmer (tropical to subtropical), climate conditions were previously reported from other Karpatian (upper Burdigalian) sediments of south Slovakia (Planderová, 1990; Holcová et al., 1996).

The Kosihovce, Príbelce, Stredné Plachtince, Horné Strháre and Trenč sections are the best examples of sediments correlated with the beginning of the lower Langhian (lower Badenian) stage. In the Príbelce, Stredné Plachtince and Horné Strháre sections, the strata are dominated by unidirectional and bidirectional cross-bedded sands with mud drapes, which intercalate with tuffaceous muds and sand that points to a tide and wave dominated inner shelf (Patruno et al., 2018). Tidal environment can be further supported by the common occurrence of pillar structures (soft sediment deformations) in the Stredné Plachtince (Rossi et al., 2017). These deposits usually pass into clast supported, trough cross-bedded gravels (Gt), which indicate deposition by channelized traction current in downstream migrating channel bars located in the deeper part of a river channel (Miall, 2006). These lithofacies point to a transition from the inner shelf to a delta top or alluvial environment. Outer shelf conditions are expected in the Kosihovce section where the tuffaceous sands and muds yield symmetrical ripples that document tide activity (Rossi et al., 2017) and gravity transport cannot be excluded (Talling et al., 2012). The nannofossil associations from the Kosihovce and Príbelce sections point to transition from high-nutrient *C. pelagicus* (outcrop base) to low nutrient *Reticulofenestra haqii* assemblages (outcrop top). Abundant diatoms (e.g., Kosihovce 5, Príbelce 1, Appendix 2) together with the planktic foraminifers *(G. bulloides,T. quinqueloba)* confirm temperate to cold water and high nutrient water. The oyster beds in the Trenč are interpreted as patch reef. The overlying tuffaceous muds (F; deposition from suspen-

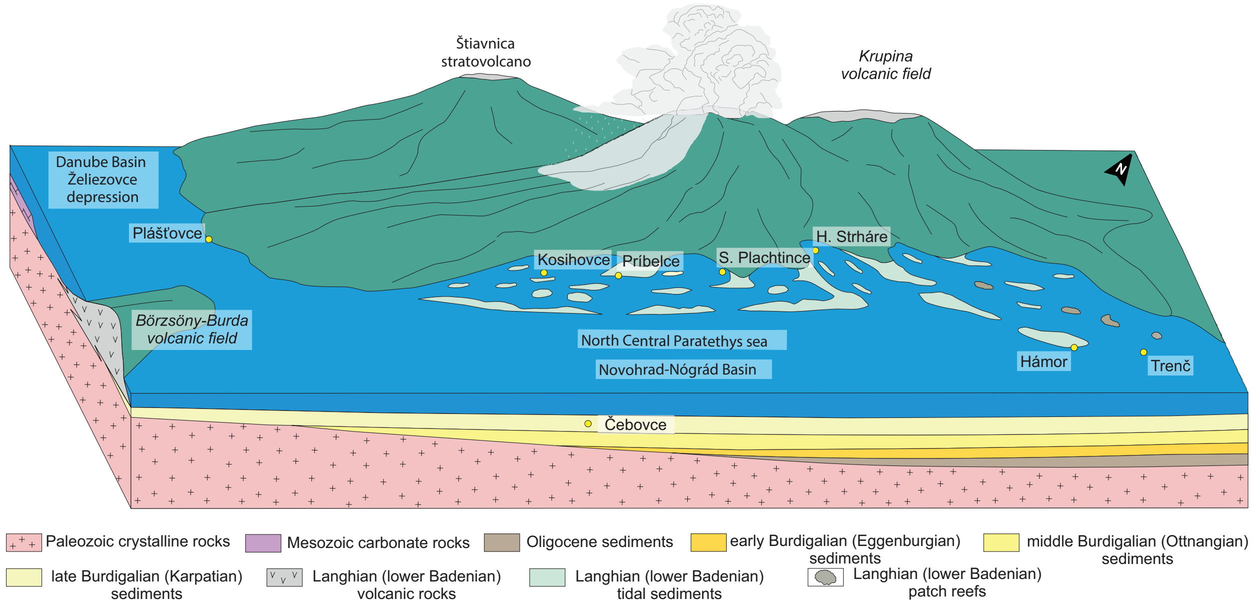

FIGURE 11. Blockdiagram showing paleogeography of the northern Paratethys Sea affected by activity of the Krupina volcanic field during early Badenian.

sion) are connected to the inner shelf environment. Clast supported massive gravels (Gcm) in the overburden point to possible termination of marine conditions. The Trenč section also yields a high portion of *Trilobatus* sp., which documents warm, low nutrient surficial water (Pearson and Shackleton, 1995; Spezzaferri et al., 2004) that can agree with MMCO culmination. Higher abundance of deep dwelling planktic foraminifera from globorotaliids (*G. bykovae* and *G. transsylvanica*) point to a slightly deeper water environment in the area (Be and Hutson, 1977; Rupp and Hohenegger, 2008). Benthic foraminiferal association is dominated by cibicids that documents well aerated, shelf conditions (*Hansenisca soldanyi*, *Lenticulina* sp., nodosariids). Large, symbiont bearing miliolids (*Borelis melo*, *Peneroplis pertusus*) and quinqueloculinids that prevail in the tuffaceous muds (F) of the Trenč section may have been transported from proximal small patch reefs (Figure 11). Decreased rainfalls (aridification) are indicated by increased content of dry shrubs, herbs and *Olea* pollen within studied associations from the N-65 well. This event may coincide with the Mediterranean aridification dated to 15.01 Ma by Hüsing et al. (2010). Generally, terrestrial environment shows slight climate cooling within the subtropical conditions. Swamps developed along the coast (Cupressaceae, *Sciadopytis*), and evergreen broadleaved forests are expected in lowlands. Higher altitudes were most likely dominated by pine tree forests (Figure 10, Appendix 4).

During the upper Langhian, deposition continues in the vicinity of the Plášťovce and Hámor sections. The fossil assemblage is similar, however, and the depositional environment differs. The Plášťovce section yields fine-grained tuffites (F) deposited from suspension and the intercalating through cross-bedded sands and massive gravels (Gt, Gcm, Sl) point to deposition by a channelized and unchannalized traction. Therefore, an alluvial or fan-delta environment is expected (Mial, 2006). Such alteration of marine and terrestrial facies may be explained by close proximity of the Central Slovak Volcanic field (Pécskay et al., 2006), where the expansions and contraction of magma may cause autocyclic bulging before eruptions and rapid subsidence after eruptions (Figure 11). In the Hámor section the pebbly sandstones (Sl) were possibly deposited by shallow unchanalized traction that indicates deposition in scours, dunes or antidunes (Miall, 2006). Horizontally bedded clast supported gravels (Gh) indicate wave reworking. The trough cross-bedded sands (St) in section A point to tidal activity within basin-ward migrating tidal channels. These lithofacies point to the inner shelf environment (Patruno et al., 2018) that can be supported by the 20 m paleodepth estimation derived from the benthic foraminiferal assemblages with dominated epiphytic group (*Asterigerina* cf. *planorbis*, *Hanzawaia boueana*, *Cibicidoides lobatulus*, high spiral *Ammonia parkinsoniana*, *Textularia* sp.) (Figures 8, 9). Similar associations of the same age are recorded from the Carpathian Foredeep (Studencka, 1994; Studencka and Jasionowski, 2011; Holcová et al., 2015a) and Vienna Basin (Wiedl et al., 2013; Pivko et al., 2017). The sporadic occurrence of planktic foraminifera, which cannot survive in the shallow coastal environment of the Hámor section, could be transported from the central to marginal part of the basin by surface currents that agrees with the anti-estuarine circulation model suggested for Central Paratethys during NN5 Zone (Báldi, 2006; Kováč et al., 2017). The change from estuarine to antiestuarine circulation is supported by a trend of carbon and oxygen isotope values (Figure 9Fa-c). Decreased oxygen isotope values of *Globigerina* between Burdigalian and Langhian might be related to an increase of surface water temperature after the end of the cold bottom-water uprise. Decreased primary productivity during the Langhian can be supported by the lower carbon isotope values in the tests of *Globigerina bulloides* (Peeters et al., 2002). Accumulation of the organic matter at the sea floor is questionable due to high carbon isotope values of *Cibicidoides* tests.

The sediments from the Plášťovce and Hámor sections contain small *Reticulofenestra minuta*, which tolerate salinity and/or nutrients oscillations (Wells and Okada, 1997; Flores et al., 1997; Kameo, 2002; Wade and Brown, 2006) indicating increased stress in surface waters. Similar calcareous nannoplankton assemblages are typical for the Central Paratethys Langhian sediments (Spezzaferri et al., 2009; Holcová, 2013) and might reflect changes from estuarine to antiestuarine circulation (Kováč et al., 2017; Holcová et al., 2018). Higher abundances of *Dentoglobigerina* sp. can also document unstable environmental conditions (Keller, 1985; Pearson and Shackleton, 1995). Co-occurrences of large *Globigerina bulloides* and *Globigerinoides* (*Trilobatus*) spp. indicates seasonal changes in water temperature – warmer summer surface water with *Globigerinoides* and cooler spring water with a bloom of *G. bulloides* (Kretschmer et al., 2018). Isotope analysis confirms stratification of water column from oxygen and carbon isotopes. Benthic foraminiferal assemblages (e.g., base of the Plášťovce section) contain shallow-water oligotrophic *Amphistegina* sp., epiphytic assemblage *Asterigerinata* sp., *Cibicidoides lobatulus*, corroded *Cibicidoides* sp. indet., and *Ammonia* sp., tolerating salinity oscillations. Eutrophic conditions with possible hypoxia on the sea floor (or in sediment only) are documented by an increase of *Bolivina dilatata* and *Bulimina elongata.* It can reflect both, (1) variegated paleoenvironment (intra-/interannually); or (2) oligotrophic oxic environment at the sea floor locally covered by sea-grass meadows with hypoxic sediment in higher nutrient content. The co-occurrence of common epiphytic and rare hypoxic and high-nutrient foraminifera is rather common e.g., in substrate accompanying recent Mediterranean sea-grass meadows where low-oxic environment with high organic matter develops in sediment between *Posidonia* root system (Borum et al., 2006).

CONCLUSIONS

In studied sections, four stratigraphic levels were distinguished:

The upper Burdigalian (Karpatian) NN4 Zone with *Helicosphaera ampliaperta* and *Sphenolithus heteromorphus* and with *Trilobatus bisphericus*, *Uvigerina graciliformis* was identified in high-nutrient facies deposits of shelf break slope in Čebovce section (a).

The upper Burdigalian – lower Langhian (Karpatian? /earliest Badenian 14.9 Ma and older) top NN4/base NN5 Zone with *Helicosphaera waltrans*, *H*. *walbersdorfensis*, *H*. *ampliaperta*, *Sphenolithus heteromorphus*, *Discoaster exilis*, *D. variabilis* and *D*. *petaliformis* were identified in deposits of shelf break slope in Čebovce (b) section and Kosihovce lowermost part.

Langhian (lower Badenian) sediments were divided into two distinct intervals where the presence of the genus *Orbulina* and absence of both *H. waltrans* and *H. ampliaperta* served as the discriminant factors.

The lower Langhian (lower Badenian) deposits of NN5 Zone outcropped in the Kosihovce, Príbelce, Stredné Plachtince, Horné Strháre and Trenč sections are estimated to be ~14.9–14.4 Ma old.

The upper Langhian (lower Badenian) sediments from the Hámor section yield assemblages where *O. suturalis* and *T. bisphericus* are present and *H. waltrans* and *H. ampliaperta* are absent and points to an age of 14.4 Ma or younger (NN5b-5c Zone).

The described lithofacies reveal several distinct depositional environments. The older Burdigalian shelf break slope sediments, controlled by gravity deposition are toward overlying strata bounded by an unconformity. The lower Langhian shelf deposition was dominated by tide and wave processes and later passed into alluvial sediments on the margin of the Central Slovak Volcanic field. This might have been triggered due to pronounced volcanic activity, which shed larger volumes of material into the marine environment that partly overshadowed the climatic changes.

Change from warmer to cooler condition in the marine water mass has not been fully documented. The assemblages from the Karpatian sediments do not provide warm water conditions, however, warmer water was documented in the lower Langhian sediments. More visible changes are in the nutrient content, which changes from high nutrient during upper Burdigallian to low nutrient in the youngest studied sediments. Changes are probably a result of regional volcanic activity.

Landmass altitudinal zonation is shown in strikingly diversified pollen spectra composed of swamps, riparian forests, lowland aquatic and meadows growths, up to the mountain vegetation. Post-Burdigalian (Karpatian) cooling and aridification, followed by retreat of warmer and more humid conditions at the end of the Langhian (Badenian) is observed. Regional fluctuations in temperature and/or humidity can be considered partly as an impact of inicial MMCT in the epicontinental Central Paratethyan Sea domain.

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APPENDICES

All appendices are included in a zipped file for download at https://palaeo-electronica.org/content/2020/3198-south-slovakia-neogene-basins.

APPENDIX 1.

Description and interpretation of lithofacies in the studied sections.

APPENDIX 2.

List of nannoplankton from non-barren samples.

APPENDIX 3.

List of foraminifera. A. Planktic foraminifera from non-barren samples. B. Benthic foraminifera from non-barren samples. C. Depth ranges of foraminifera.

APPENDIX 4.

Polpal outcome chart – list of palynomorphs.