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Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys)

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ABSTRACT

The Pannonian Basin System (PBS) originated during the Early Miocene as a result of extensional processes between the Alpine-Carpathian and the Dinaride Orogenic Belts. The Paratethys Sea flooded the new basins successively during the Karpatian (late Burdigalian, Early Miocene) and the Early Badenian (middle Langhian, Middle Miocene). The North Croatian Basins (NCB) occupied the south-western margin of the PBS and the Central Paratethys Sea. Their initial marine flooding has until now been dated as Karpatian in age. The transgression into the NCB invaded a lacustrine environment, representing the northern prolongation of the vast Dinaride Lake System extending southwards as far as the Adriatic Plate. We reinvestigate two sections from opposite margins of the NBS – from Mt. Medvednica in the west and from Mt. Požeška in the east, including the corresponding lowermost marine Miocene deposits, in order to critically examine the Karpatian datum. Our new biostratigraphic data, integrating calcareous nannoplankton, planktic and benthic foraminifera, diatom and mollusc records, have substantially revised the previous interpretation. The presence of a calcareous nannoplankton assemblage of the NN5 Zone and the planktic and benthic foraminifera of the regional Lower Lagenidae Zone now place the transgression into the main Early Badenian transgressive pulse of Central Paratethys. Consequently, the initial marine transgression correlates accurately with the middle part of the Early Badenian, which is more than 2 m.y. younger than the previously inferred datum, and at least 1 m.y. younger than the lower boundary of the Badenian and the Middle Miocene, respectively. Finally, the basal lacustrine infill of the NCB, previously dated as Ottnangian (middle Burdigalian, Early Miocene) and continuously grading into marine deposits, has also to be reconsidered as Early Badenian.

Keywords: Pannonian Basin System, North Croatian Basins, Central Paratethys, Dinaride Lake System, Middle Miocene, biostratigraphy

1. INTRODUCTION

North Croatian Basins (NCB) occupies the south-western margin of the Pannonian Basin System (Fig. 1). Their basal infill comprises freshwater sediments with fluvial deposition, grading upwards into open lake deposits. The marine transgression intruded into the basins during the open lake phase, as suggested by an unchanged lithology across the transition. The boundary can be traced exclusively by the first occurrence of marine fauna such as planktic and benthic foraminifera, indicating a salinity increase and an established connection to the open sea. The age inference of the bound-

Figure 1: Position of the North Croatian Basins in the Pannonian Basin System and the Central Paratethys Sea (after PAVELIĆ et al., 2003).

ary was determined solely on the interpretation of an impoverished, species-poor foraminiferal assemblage that has been originally regarded to correlate with Karpatian assemblages from the northern and western Central Paratethys (ŠIKIĆ, 1968) (Fig. 2).

The lake deposits of the basal infill bear freshwater molluscs and ostracods absent from Central Paratethys and endemic to the Dinaride Neogene basins adjoining the NCB to the south (KOCHANSKY-DEVIDÉ & SLIŠKOVIĆ, 1978; KOCHANSKY-DEVIDÉ, 1979; KRSTIĆ et al., 2003). Such a faunal composition of the basal parts of the NCB classifies it with the palaeobiogeographic entity termed the Dinaride Lake System (DLS) (KRSTIĆ et al., 2003; HARZHAUSER & MANDIC, 2008a, b). Consequently DLS includes the basal NCB together with the Dinaride Neogene basin fresh water deposits. The dating of the DLS deposits is still subject to debate, especially due to a lack of the possibility for marine biostratigraphy (HARZHAUSER & MANDIC, 2008a, b). The original correlation of the basal DLS deposits with the Ottnangian, is rooted in the interpretation of a small characean flora combined with their stratigraphic position directly below the formerly Karpatian-dated deposits (ŠIKIĆ, 1968; KOCHANSKY-DEVIDÉ & SLIŠKOVIĆ, 1978). As will be shown by new data, the latter age inference turned out, however, to be incorrect.

This paper critically examines the datum for the initial marine flooding of the NCB by means of integrative biostratigraphy, combining data on calcareous nannoplankton, foraminifera, molluscs and diatoms. This yields a more precise dating of the geodynamic history and rifting of the Pannonian Basin System (PBS). It also provides more insight into the palaeoenvironmental turnover in the south-western margin of the PBS resulting from the back-stepping of the DLS and the landward progradation of the Central Paratethys Sea.

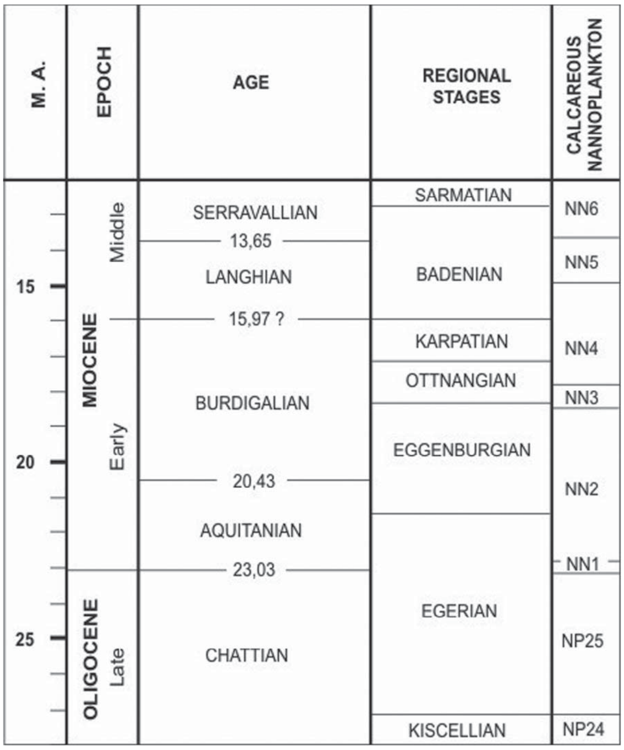

Figure 2: Oligocene–Middle Miocene chronostratigraphy of the Central Paratethys correlated to the standard geochronologic scale and the calcareous nonnoplankton zone of MARTINI (1971) (simplified, after PILLER et al., 2007). Note the correlation of the Middle Miocene boundary after GRADSTEIN et al. (2004), defining it with the base of the palaeomagnetic chron C5Br. In contrast, biostratigraphically, the Middle Miocene boundary is defined by the First Appearance Datum for the planktonic foraminiferal genus *Praeorbulina* at 16.3 Ma, as indicated by RÖGL et al. (2007).

2. HISTORY OF INVESTIGATION

PAUL (1872, 1874) was the first author to consider the basal freshwater deposits exposed at Mt. Medvednica N of Zagreb, as temporal equivalents of the Socka beds in NE Slovenia. Accordingly, he dated them as Late Oligocene. GORJANOVIĆ-KRAMBERGER (1908), setting the initial milestone in the development of stratigraphic nomenclature for the North Croatian Basin deposits, followed Pauls opinion. Furthermore, he referred the superposed sediments, representing the initial marine transgression into the basins, to "Early Mediterranean" based on correlation with the Eggenburgian strata of Lower Austria. Finally, the younger marine strata on top of the latter deposits were dated as "Younger Mediterranean" (Fig. 3).

POLIĆ (1935) advocated the earlier correlation of freshwater deposits. Based on the terrestrial macroflora he also suggested an Oligocene age. KOCHANSKY-DEVIDÉ (1944) provided the first extensive biostratigraphic investigation on the macro- and micro-fauna from marine deposits of the Mt. Medvednica environs. Following the advance in regional stratigraphic nomenclature, she referred the "Early Mediterranean beds" to the Burdigalian and the "Younger Mediterranean beds" to the Helvetian and Tortonian (note, however, the historical misuse of Helvetian and Tortonian in Central Paratethys as discussed by HARZHAUSER et al., 2003).

The intensive application of micropalaeontology for solving the stratigraphy of the NCB goes back to the 1960s. MULDINI-MAMUŽIĆ (1965) interpreted the ostracod record as support for the Late Oligocene age of the basal freshwater deposits. Furthermore, the foraminifera seemed to indicate Oligocene and Burdigalian age for the initial marine beds. This was discussed in detail and substantially revised by ŠIKIĆ (1966, 1968), ultimately establishing the currently applied stratigraphic concept for the marine part of the NCB infill (PAVELIĆ et al., 2003). Based on foraminiferal distributions, the lowermost marine beds were correlated with the Karpatian (therein also termed the Late Helvetian) beds from the Alpine Carpathian Foredeep and the western and north-western Pannonian Basin System. Furthermore, the underlying freshwater deposits bearing Charophyta related to the Upper Freshwater Molasse in Bavaria are referred to as being Helvetian s.str. and Ottnangian in age (Fig. 3).

Subsequently, the Ottnangian correlation was adopted by KOCHANSKY-DEVIDÉ & SLIŠKOVIĆ (1978). They regarded the freshwater deposits of the NCB as the initial deposits of the "Early lacustrine beds with congerians", currently termed the Dinaride Lake System (KRSTIĆ et al., 2003; HARZHAUSER & MANDIC, 2008a, b). Additionally, at

Deposition	GORJANOVIĆ-KRAMBERGER (1908)	KOCHANSKY (1944)	ŠIKIĆ (1968)	KOCHANSKY-DEVIDÉ & SLIŠKOVIĆ (1978)	KOCHANSKY-DEVIDÉ (1979)	This paper
Marine	II. Mediterranean	Tortonian	Late Tortonian			
		Helvetian, "Schlier"	Early Tortonian (previous Helvetian "Schlier" and Čučerje beds)			
	Older Mediterranean	Burdigalian	Karpatian (Late Helvetian)		Karpatian	Early Badenian
Fresh-water	Late Oligocene		Helvetian s. str. (Early Helvetian)	Ottnangian	Ottnangian	

Figure 3: Milestones in the history of stratigraphic correlation of the North Croatian Basins.

Mt. Požeška, besides an Ottnangian age a Karpatian age has also been presumed for the upper part of the basal, lacustrine NCB deposits. This was based on the more advanced evolutionary stage of the recorded dreissenid bivalves (KOCHANSKY-DEVIDÉ, 1979).

Given the above considerations, further palaeontological studies (as a part of a geological mapping effort), assigned the freshwater deposits to the Lower Helvetian, i.e. Ottnangian, and the first marine Miocene sediments to the Upper Helvetian, i.e. Karpatian (BASCH, 1983; JAMIČIĆ et al., 1987, 1989; ŠPARICA & BUZALJKO, 1984; ŠPARICA et al., 1980). Analyses of freshwater ostracods suggested a “Middle Miocene”, “Helvetian” and Karpatian age (SOKAČ, 1987; SOKAČ & KRSTIĆ, 1987). More modern studies of terrestrial flora from the freshwater deposits indicated an Ottnangian age (JUNGWIRTH & ĐEREK, 2000), as did the mollusc associations (Unionidae) from some localities in North Croatia (ŽAGAR-SAKAČ, 2003, 2004).

Complex sedimentological studies, micropalaeontological and palynological analyses dated these freshwater deposits as Ottnangian, and the overlying marine sediments as Karpatian on Mounts Požeška, Mt. Medvednica and Mt. Kalnik (AVANIĆ et al., 1995a, 1995b, 1995c; AVANIĆ, 1997; PAVELIĆ et al., 1998, 2001, 2003) (Fig. 1). The same concept was applied in some regional works (LUČIĆ et al., 2001; PAVELIĆ, 2001, 2002, 2005; SAFTIĆ et al., 2003). A list of important foraminifera and mollusc species of these Croatian initial marine deposits, attributed to the Karpatian, has been compiled by BAJRAKTAREVIĆ & PAVELIĆ (2003). More recent research on ostracods at several localities in North Croatia indicates an Ottnangian age for the freshwater deposits, a latest Ottnangian to earliest Karpatian age for the brackish-water sediments, and a Karpatian age for the marine deposits (HAJEK-TADESSE, 2006).

Based on these former results, all currently available reconstructions of the general evolution of Central Paratethys presumed erroneously a vast marine cover over the NCB during the Karpatian (RÖGL & STEININGER, 1983; PAVELIĆ, 2001, 2005; BAJRAKTAREVIĆ & PAVELIĆ, 2003; RÖGL, 1996; KOVÁČ et al., 2003). Only very few studies suggested a younger age for those freshwater and early marine deposits. One such example is the palynological-based study by KRIZMANIĆ (1995). It related the bentonite clays containing remains of *Prodeinotherium bavaricum* KAUP on Mt. Moslavačka to the Miocene climatic optimum, specifically correlating them with the time-span between the Late Karpatian and the Early Badenian. The overlying marine beds bearing foraminiferal associations of the Upper Lagenidae Zone and the calcareous nannoplankton association of NN5 were previously dated as Early Badenian (BAJRAKTAREVIĆ, 1981; KRIZMANIĆ, 1995).

3. GEOLOGICAL SETTING

The Paratethys Sea evolved in the Early Oligocene at the northern margin of the pre-Mediterranean Tethys Ocean after Alpine and Dinaride orogenesis triggered the first disturbance of water mass circulation patterns. This was followed by faunal extinction and endemic events (RÖGL, 1996). The distribution of the Paratethys Sea was mainly controlled by regional geodynamic evolution, resulting in a separate chronostratigraphic scale (Fig. 2). The Western Paratethys of the Alpine Foredeep had already dried out in the Early Miocene. The Central Paratethys of the Alpine-Carpathian Foredeep and the Pannonian Basin System disintegrated at the end of the Middle Miocene, giving rise to the Late Miocene Lake Pannon. The disintegration of Eastern Paratethys, today divided into the Black Sea, Caspian Sea and Aral Lakes, is still ongoing.

The Dinaride Lake System (DLS) developed during the Early Miocene on the land block located between Central Paratethys and the Mediterranean Tethys (MANDIC et al., 2008). It was inhabited by highly diversified but almost completely endemic aquatic organisms such as molluscs or freshwater ostracods (KRSTIĆ et al., 2003; HARZHAUSER & MANDIC, 2008a, b). It represented, as shown by HARZHAUSER & MANDIC (2008b), a separate palaeobiogeographic entity, different from any marginal environment of Paratethys or of the Mediterranean Tethys. Extending originally into the Pannonian Basin System, the DLS retreated mainly due to Paratethys Sea transgression, becoming mainly restricted to the Dinaride Block.

North Croatia occupies the south-western margin of the Pannonian Basin System (PBS). The PBS, induced by extensional processes and rifting between the Carpathian, Alpine and Dinaride Chains, did not appear to exist prior to the late Early Miocene (Fig. 1). Consequently, after the origin of Paratethys and prior to the origin of the PBS, most of North Croatia was represented by dry land, only occasionally developing freshwater wetland environments. The only exception was a small north-westernmost area of Hrvatsko Zagorje, Mura and a marginal part of the Drava Basin (ŠIMUNIĆ et al., 1990; JELEN et al., 1998; PAVELIĆ et al., 2001). The E–W striking basin system became a Central Paratethys marine setting during the Late Oligocene or the earliest Early Miocene (PAVELIĆ et al., 2003). It then represented a side gulf of the Transtethyan or North Slovenian Corridor connecting the Paratethys Sea with the Mediterranean Tethys Ocean (RÖGL & STEININGER, 1983; RÖGL, 1996).

The extensive North Croatian Basins are located southeast of the Hrvatsko Zagorje Basin (Fig. 1). The main constituents of the NCB are the Sava, Drava, Bjelovar, Požega and Slavonia – Srijem Basins. Following the former stratigraphic concept presented above, their evolution started in the Early Ottnangian. It was characterized by the predominance of coarse-grained siliciclastics from braided alluvial fans alternating with salina-type lakes under semi-arid climate conditions. After the end of this alluvial deposition, a freshwater lake formed in the Late Ottnangian, covering the whole area. It was characterized by fine-grained deposits such as limy silt, with high organic matter content and occurrences of pyroclastics (Fig. 4). The shift from a semi-arid to humid climate contributed significantly to the environmental turnover, substantially increasing the lake's water volume (PAVELIĆ, 2001). The highly variable thickness of freshwater infill resulted from the palaeotopography and synsedimentary tectonic movements following the PBS rifting. Its maximal thickness in marginal settings is about 450 m, but in basin depocentres it can be 2 to 3 times thicker (PAVELIĆ, 2001) (Fig. 4). Palaeomagnetic measurements of open lake deposits suggested a palaeogeographic position of the basin much further to the south than today, at an estimated palaeolatitude of about 30^0 (MÁRTON et al., 2005). The aquatic fossil assemblage accurately correlates these lake deposits with the oldest DLS deposits (KOCHANSKY-DEVIDÉ & SLIŠKOVIĆ, 1978; KOCHANSKY-DEVIDÉ, 1979).

The gradual shift from a freshwater lacustrine to a marine environment without any lithological change can be traced throughout the North Croatian Basin (ŠIKIĆ, 1968; PAVELIĆ et al., 1998; PAVELIĆ, 2001; HAJEK-TADESSE, 2006). Since the depositional style remains unaltered, the recognition of a transitional boundary is based solely on the first occurrences of the marine fossil assemblage. The succession from Mt. Medvednica represents the only known exception to that rule. A relative tectonic standstill reduced the subsidence rate so the transition from the lacustrine to marine environment is marked by a prograding clastic system and occurrence of coarse-grained deposits at the end of lacustrine deposition (PAVELIĆ et al., 2003).

The environmental shift represents the initial marine ingression of Central Paratethys into the NCB, possibly reflecting the reestablished Paratethyan seaway to the Mediterranean Tethys along the Slovenian corridor (RÖGL & STEININGER, 1983; RÖGL, 1996). The environment was characterized by inner shelf deposition of mostly lime silt with some coarse-grained intercalations. That marine phase ended with a sea-level fall, causing regression and deposition of sandstone. The maximal thickness of the NCB initial marine deposits is about 100 m in marginal settings, becoming thicker in basin depocentres (Fig. 4).

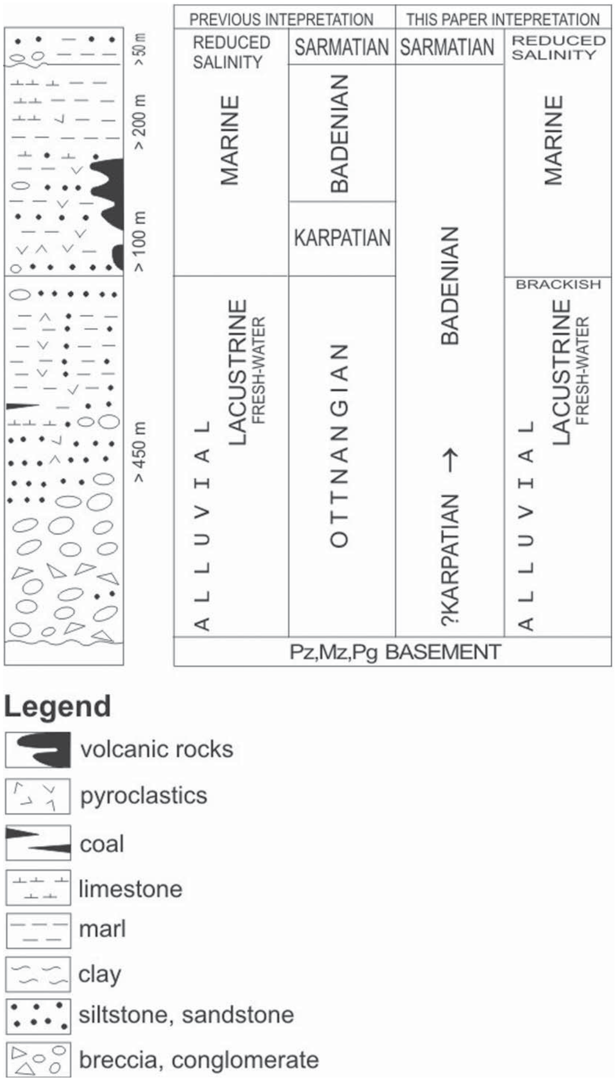

Figure 4: Geological column of the lowermost North Croatian Basins infill (after PAVELIĆ, 2005), presenting the new stratigraphic interpretation.

The overlying deposits are correlated with the Lower and Upper Badenian based on foraminifera biostratigraphy. The architecture of these deposits reflects the global sea-level fluctuations during the Middle Miocene (HAQ, 1991; PAVELIĆ et al., 1998; PAVELIĆ, 2001, 2005; KOVÁČ et al., 2007). The characteristic sedimentological feature is enhanced carbonate production controlled by strong volcanism. This induced deposition of marls and limestones, intercalated with tephra beds. The end of the Badenian is marked by a sea-level fall. The superposed Sarmatian deposits already reflect water chemistry events induced by progressive Paratethyan isolation toward the end of the Middle Miocene (HARZHAUSER & PILLER, 2007) (Figs. 2 and 4).

4. RESULTS

Two sections representing the initial marine NCB deposits have been studied in detail. The Čučerje Section is located on the south-eastern slope of Mt. Medvednica, about 10 km NE of the city of Zagreb. The Sokolovac Section is located on the southern slope of Mt. Papuk, about 1 km SSW of the village Gornji Vrhovci and 15 km NNW of the city of Požega (Fig. 1). The micropalaeontological samples comprised nannoplankton, diatoms, as well as planktonic and benthic foraminifera. Additionally, for Čučerje (Fig. 1), the mollusc macrofauna from the Coll. Kochansky collection (Croatian Natural History Museum) has been taxonomically revised and biostratigraphically reevaluated.

4.1. Čučerje Section (Mt. Medvednica)

The Čučerje Section (Fig. 5) shows a 42 m thick succession composed of 3 parasequences. The base of the section is at GPS N 45° 53' 45.5" E 16° 03' 17.3". For sample positions see Fig. 5. The section was initially described by GORJANOVIĆ-KRAMBERGER (1923) as the "Plaz" locality. KOCHANSKY-DEVIDÉ (1944) described it as a large outcrop above the brook SW of Podplaz and NW of the church of Čučerje. She attributed its deposits, based on micro-and macrofaunal content, to the Burdigalian, correlating them with the lower Ottnangian beds from Lower Austria. Although she originally noticed the conspicuous difference in faunal composition to the latter beds, in a subsequent publication she erroneously identified one Eggenburgian–Ottnangian index fossil from the same locality (KOCHANSKY-DEVIDÉ, 1956). ŠIKIĆ (1968) investigated foraminifers' samples from that locality, attributing them to the Karpatian. Finally, AVANIĆ et al. (1995b) (see also AVANIĆ, 1997) provided a detailed description and interpretation of the depositional history for the section. Although already correlating its middle and upper parts with the Lower Badenian, the authors still referred its lower parasequence to the Karpatian.

4.1.1. Sedimentology

The lower parasequence is 15 m thick and represents a coarsening upward succession with marls at the base followed by predominantly silt deposition on top, intercalated with thin sandy layers. The coarsening has been interpreted as an environmental shift and shallowing, grading from shelf conditions up to the transitional zone close to the palaeoshore. The middle parasequence comprises partly bedded sands and sandstones representing a high-energy, shallow-water shoreface to nearshore depositional environment. The upper parasequence superposes a tephra layer at 36 m up of the section. It reflects renewed deepening of the environment, comprising predominantly silt deposition.

4.1.2. Calcareous nannoplankton biostratigraphy

Ten samples (Fig. 5) have been investigated for the biostratigraphic evaluation of calcareous nannoplankton.

The assemblages from this section are dominated by high percentages of helicoliths and small reticulofenestrids (Table 1). Helicoliths are represented by: *Helicosphaera carteri* (WALLICH, 1877) KAMPTNER (1954), *H. walbersdorfensis* MÜLLER (1974), *H. wallichii* (LOHMANN, 1902) BOUDREAUX & HAY (1969), and *H.* cf. *waltrans* THEODORIDIS (1984), whereas the small reticulofenestrids are represented by *Reticulofenestra minuta* ROTH (1970) and *R. haqii* BACKMAN (1978). The accompanying forms are: *Braarudosphaera bigelowii* (GRAN & BRAARUD, 1935) DEFLANDRE (1947), *Coccolithus pelagicus* (WALLICH, 1877) SCHILLER (1930), *Coronosphaera mediterranea* (LOHMANN, 1902) GAARDER (1977), *Cyclicargolithus floridanus* (ROTH & HAY, 1967) BUKRY (1971), *Perforocalcinela fusiformis* BÓNA (1964), *Pontosphaera multipora* (KAMPTNER, 1948) ROTH (1970), *Reticulofenestra pseudoumbilica* (GARTNER, 1967) GARTNER (1969), *Rhabdophaera sicca* STRADNER (1963), *Sphenolithus heteromorphus* DEFLANDRE (1953), *S. moriformis* (BRÖNNIMANN & STRADNER, 1960) BRAMLETTE & WILCOXON (1967), *Triquetrorhabdulus milowii* BUKRY (1971), and *Umbilicosphaera jafari* MÜLLER (1974).

The regular occurrence of the zonal marker *Sphenolithus heteromorphus* DEFLANDRE (1953) and the absence of *Helicosphaera ampliaperta* BRAMLETTE & WILCOXON (1967) in all investigated samples allow an identification of nannoplankton Zone NN5 (MARTINI, 1971).

4.1.3. Foraminifera biostratigraphy

The foraminiferal associations were analyzed in samples HR 9, no. 1, no. 2, no. 3, no. 4, and HR 10 covering the lower parasequence and the lowermost 10 m of the section, respectively (Fig. 5). See Table 2 for the complete list of identified species.

The lowermost sample in section (HR 9) originated from grey silty micaceous shale. The rich assemblage is characterized by coarse-grained agglutinated foraminifera, typically Badenian calcareous benthic species, and stratigraphically indifferent planktonic forms. The occurrences of the following microfossils are interesting, *incertae sedis*: *Bachmayerella laqueata* RÖGL & FRANZ, and *Bolboforma moravica* REDINGER. Benthic foraminifera species such as *Uvigerina grilli* SCHMID, *U. macrocarinata* PAPP & TURNOVSKY, *U. uniseriata* JEDLITSCHKA and *Pappina parkeri* (KARRER) are of stratigraphic importance. The planktonic assemblage consists mainly of five-chambered globigerinids (e.g. *Globigerina ottnangiensis* RÖGL) together with several *Globigerinoides* species (e.g. *G. bisphericus* TODD). The uppermost studied sample HR 10, comprises gray-brown sediment residue, with cemented fine-grained quartz and silt and contains a mixed assemblage of shallow and deep-water species. Stratigraphically important taxa occur together in the sample HR9 (Table 2). The poor planktonic fauna is again dominated by small species such as *Globigerina praebulloides* BLOW or *Tenuitellinata selleyi* LI, RADFORD & BANNER. Microfossils incertae sedis *Bachmayerella tenuis* RÖGL & FRANZ and *Bolboforma* sp. are also present.

The lower part of the section represents a rather deep, probably outer shelf environment as indicated by the presence of agglutinated foraminiferal taxa (*Bathysiphon, Hy-*

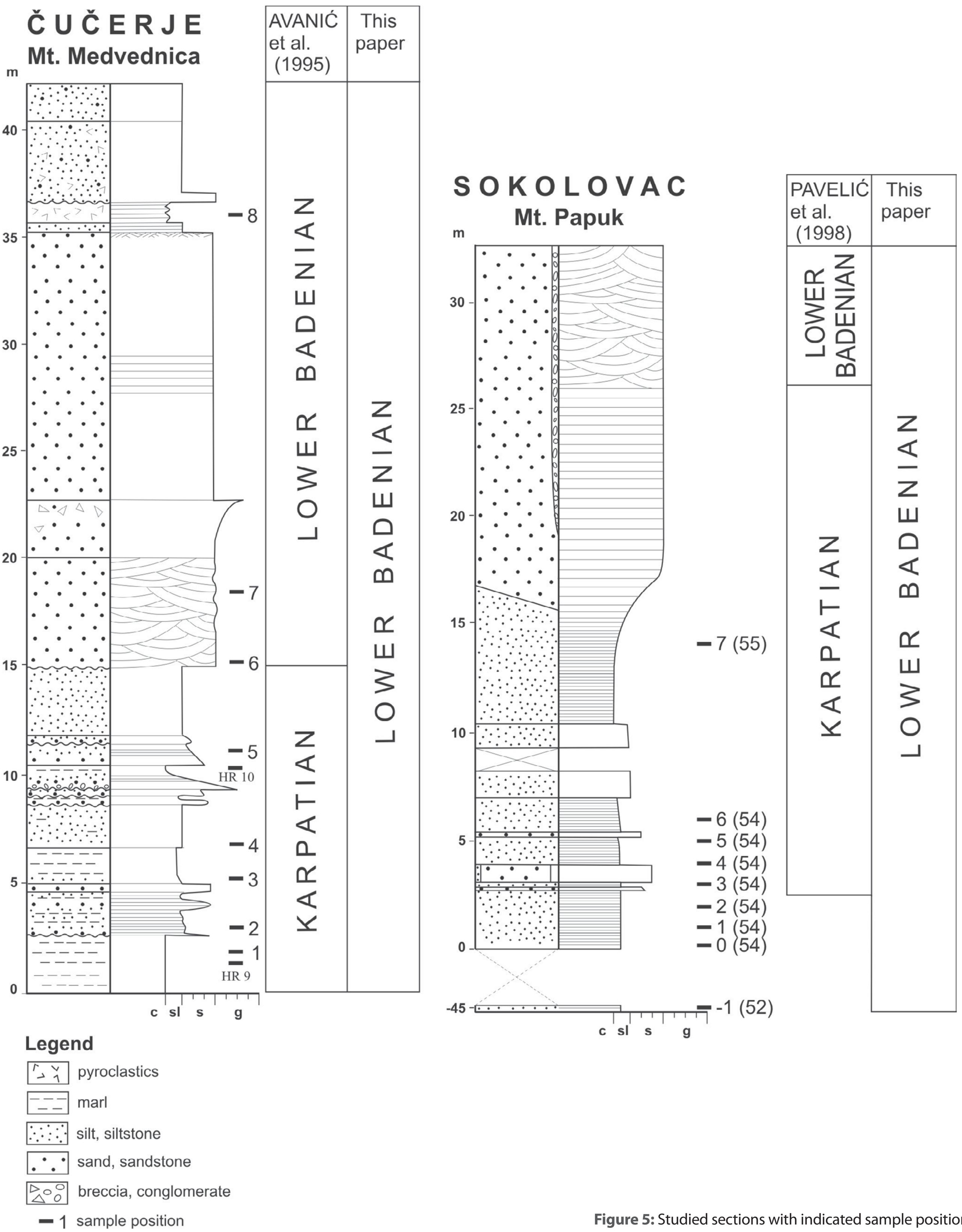

Figure 5: Studied sections with indicated sample positions.

perammina, Reophax, Reticulophragmium, Cyclammina). A larger sediment input from shallow water is documented by the occurrence of miliolids, elphidiids, *Ammonia, Pararotalia*, and *Amphistegina*. *Asterigerinata planorbis* (D'ORBIGNY), *Ammonia viennensis* (D'ORBIGNY), *Cibicidoides ungerianus ungerianus* (D'ORBIGNY), and *Amphistegina mammilla* (FICHTEL & MOLL) and characterized by a large number of individuals.

Biostratigraphically, this part of the section belongs to the Early Badenian, corresponding with the Lower Lageni-

Table 1: Nannofossil distribution (following ODP terminology) in samples from the Čučerje Section.

Samples	preservation	abundance	*Braarudosphaera bigelowii* (GRAN & BRAARUD, 1935) DEFLANDRE (1947)	*Coccolithus miopelagicus* BUKRY (1971)	*Coccolithus pelagicus* (WALLICH, 1877) SCHILLER (1930)	*Coronocyclus nitescens* (KAMPTNER, 1963) BRAMLETTE & WILCOXON (1967)	*Coronosphaera mediterranea* (LOHMANN, 1902) GAARDER (1977)	*Cyclicargolithus floridanus* (ROTH & HAY, 1967) Bukry (1971)	*Helicosphaera carteri* (WALLICH, 1877) KAMPTNER (1954)	*Helicosphaera walbersdorfensis* MÜLLER (1974)	*Helicosphaera* cf. *waltrans* THEODORIDIS (1984)	*Helicosphaera walichii* (LOHMANN, 1902) BOUDREAUX & HAY (1969)	*Perforocalcinela fusiformis* BÓNA (1964)	*Pontosphaera multipora* (KAMPTNER, 1948) ROTH (1970)	*Pontosphaera* sp.	*Reticulofenestra haqii* BACKMAN (1978)	*Reticulofenestra minuta* ROTH (1970)	*Reticulofenestra pseudoumbilica* (GARTNER, 1967) GARTNER (1969)	*Rhabdosphaera sicca* STRADNER (1963)	*Sphenolithus heteromorphus* DEFLANDRE (1953)	*Sphenolithus moriformis* (BRÖNNIMANN & STRADNER, 1960) BRAMLETTE & WILCOXON (1967)	*Triquetrorhabdulus milowii* BUKRY (1971)	*Umbilicosphaera jafari* MÜLLER (1974)	reworked	*Micula decussata* VEKSHINA (1959)	*Watznaueria barnesae* (BLACK, 1959) PERCH-NIELSEN (1968)
Čučerje 8	G/M	C	r	r	f	r		r	f	r	r	r	r	r		f	c		r							
Čučerje 7	G	A			r		r	r	f/c	r	r	r	r	r		f	c		r	r						
Čučerje 6	G	C	r		r			r	f	r	r	r		r		f	c	r	r	f						
Čučerje 5	G	C			f			r	f	r	r	r			r	f	c	r		r	r		r			
HR 10	G	C	r		r			r	f/c	r	r	r	r			f	c			f	r		r			
Čučerje 4	G	C			f			r	f	r	r	r	r			f	c	r		r	r					r
Čučerje 3	G	C			f			r	f	r	r	r	r			f	c		r	r		r	r			
Čučerje 2	G	C			f			r	f	r	r	r	r			f	c		r	r		r	r			
Čučerje 1	G	A	r		r			r	f/c	r	r	r				f	c		r	r	r	r				
HR 9	G	C	r		r			r	f/c	r	r					r	c			r						

dae Zone of the Vienna Basin. In sample no. 3 the Early Badenian is explicitly documented by the planktonic species *Orbulina suturalis* BRÖNNIMANN. For regional stratigraphic correlation with the Lower Lagenidae Zone (comp. RÖGL et al., 2002; SPEZZAFERRI et al., 2004), the key-species discovered in the Čučerje samples are: *Uvigerina macrocarinata* PAPP & TURNOVSKY, *Pseudogaudryina lapugyensis* (CUSHMAN), *P. sturi* (KARRER), and *Amphistegina mammilla* (FICHTEL & MOLL). The microfossil *Bolboforma moravica* REDINGER is also a typical species of the Early Badenian (SPIEGLER & RÖGL, 1992).

4.1.4. Mollusc biostratigraphy

This review is based on field observations combined with re-examination of the collection of KOCHANSKY-DEVIDÉ housed at the Department of Geology and Palaeontology of the Croatian Natural History Museum in Zagreb. The collection includes specimens originally studied and published by KOCHANSKY-DEVIDÉ (1944, 1956).

The lowermost marine parasequence bears the nautilid *Aturia aturi*, indicating an open marine connection of the depositional environment. The shells of the neritic, offshore-living *Nautilus* can float for thousands of kilometres after the animal dies, drifting on surface currents, before settling to the bottom or becoming washed ashore. *Aturia aturi* (BASTEROT) was present in Paratethys throughout the Lower and Middle Miocene (LUKENEDER & HARZHAUSER, 2002).

The second sandy parasequence comprises a leached macrofauna with aragonite representatives traced exclusively by moulds and steinkerns (endocasts). The calcite shells, in contrast, are fairly well preserved, and with the single exception of calcified *Nototeredo norvegica* (SPLENGLER) siphonal tubes, belong to pteriomorphian bivalves. The following taxa occur: *Crassadoma multistriata* (POLI), *Aequipecten macrotis* (SOWERBY), *A. scabrellus* (LAMARCK), *Oppenheimopecten revolutus* (MICHELOTTI), *Flabellipecten solarium* (LAMARCK), and *Anomia ephippium* BROCCHI in BRONN. All except *Anomia ephippium* BROCCHI are scallops. The absence of ostreid shells is conspicuous. Note the erroneous identification of *Flabellipecten solarium* (LAMARCK) as *Pecten pseudobeudanti* DEPERET & ROMAN by KOCHANSKY-DEVIDÉ (1956). The specimen reinvestigated at the Croatian Natural History Museum is a single right valve with a length of 10 cm, labeled with the numbers 667

Table 2: Distribution of benthic and planktic foraminifera from the Čučerje Section.

Samples	*Textularia* sp.	*Pseudogaudryina lapugyensis* (CUSHMAN)	*Pseudogaudryina sturi* (KARRER)	*Triloculina* sp.	*Quinqueloculina* cf. *akneriana* D'ORBIGNY	*Spiroloculina canaliculata* D'ORBIGNY	*Lenticulina inornata* (D'ORBIGNY)	*Globulina gibba* D'ORBIGNY	*Guttulina communis* (D'ORBIGNY)	*Glandulina ovula* D'ORBIGNY	*Bolivina antiqua* D'ORBIGNY	*Bolivina* sp.	*Fursenkoina acuta* (D'ORBIGNY)	*Bulimina subulata* CUSHMAN & PARKER	*Bulimina* cf. *subulata* CUSHMAN & PARKER	*Uvigerina acuminata* HOSIUS	*Uvigerina* cf. *macrocarinata* PAPP & TURNOVSKY	*Uvigerina* cf. *pygmoides* PAPP & TURNOVSKY	*Uvigerina grilli* SCHMID,	*Uvigerina macrocarinata* PAPP & TURNOVSKY	*Uvigerina* sp.	*Uvigerina uniseriata* JEDLITSCHKA	*Pappina parkeri* (KARRER)	*Cibicidoides ungerianus ungerianus* (D'ORBIGNY)	*Asterigerinata planorbis* (D'ORBIGNY)	*Amphistegina mammilla* (FICHTEL & MOLL)	*Melonis pompilioides* (FICHTEL & MOLL)	*Chilostomella ovoidea* REUSS	*Alabamina armellae* POPESCU	*Svratkina cichai* POPESCU	*Ammonia viennensis* (D'ORBIGNY)	*Elphidium* cf. *rugosum* (D'ORBIGNY)	*Elphidium fichtellianum* (D'ORBIGNY)	*Elphidium flexuosum* (D'ORBIGNY)	*Globigerinita uvula* (EHRENBERG)	*Tenuitellinata selleyi* LI, RADFORD & BANNER	*Globigerina ottnangiensis* RÖGL	*Globigerina praebulloides* BLOW	*Globigerina subcretacea* LOMNICKI	*Globigerina tarchanensis* SUBBOTINA & CHUTZIEVA	*Globigerina* cf. *tarchanensis* SUBBOTINA & CHUTZIEVA	*Globigerina* sp.	*Globigerinoides bisphericus* TODD	*Globigerinoides quadrilobatus* (D'ORBIGNY)	*Globigerinoides trilobus* (REUSS)	*Orbulina suturalis* BRÖNNIMANN
HR 10		x																		x			x			x									x	x		x	x							
no. 4					x							x	x		x			x						x	x	x						x	x													
no. 3						x			x		x			x		x					x		x	x	x	x					x											x				x
no. 2	x																						x		x	x	x				x										x					
no.1				x		x	x	x	x	x	x		x				x					x		x	x			x						x				x							x	
HR 9			x																x	x		x	x			x			x	x							x		x	x			x	x	x	

and 692. Its large size, high initial shell convexity, 19 massive, and subquadrangular ribs refers it accurately to *Flabellipecten solarium* (LAMARCK). The latter beds were originally correlated with the Ottnangian Zogelsdorf Formation environs in Lower Austria. *Flabellipecten solarium* (LAMARCK) however is restricted in the Central Paratethys to Badenian deposits.

The topmost parasequence, starting with a tephra bed and continuing with fine clastic deposition, contains a single, previously absent pectinid species, the cementing *Hinnites brussoni* (DE SERRES) a long-lived taxon that occurs in Central Paratethys throughout the Lower and Middle Miocene.

4.2. Sokolovac Section (Mt. Papuk)

The section follows a N–S striking brook and is today largely covered by vegetation. The GPS position of the lowermost partial outcrop (–45m of the section) is N 45°27'27.8" E 17°33'51.4". The second outcrop, located about 144 m north of the first one, represents the partial section between 0 and 6 m. Its GPS position is N 45°27'32.7" E17°33'51.6". The bedding orientation measured was 056/25. The third partial outcrop is located about 26 m north of the second one, representing a partial section around 15 m. Its GPS position is N 45°27'33.4" E17°33'51.9". For sample positions see Fig. 5. The section was originally studied by PAVELIĆ et al. (1998) referring it largely to the Karpatian based on foraminifera biostratigraphy.

4.2.1. Sedimentology

The succession is one single coarsening upward sequence. The lowermost part is dominated by silt and siltones intercalated with sandstone layers bearing a well-preserved fossil leaf assemblage, representing freshwater, open lake deposition. Following a covered interval of about 45 m very similar silts with some sandy interlayers outcrop. They represent a transition from lacustrine to marine conditions. At 4 m along this part of the section (Fig. 5) a prominent sand bed occurs, representing a subaqueous debris flow event. Sand deposition starts at about 15 m along the section, marking the onset of shallow-water environmental conditions. The top of the section is marked finally by trough cross-bedded sands, indicating a shoreface depositional regime.

4.2.2. Calcareous nannoplankton and diatom biostratigraphy

Nine samples were investigated for calcareous nannoplankton and diatoms from the Sokolovac Section (Poljanska) (Table 3).

Only sample Sokolovac 7 contains a rich and well-preserved nannoflora with *Coccolithus pelagicus* (WALLICH, 1877) SCHILLER (1930), *Helicosphaera carteri* (WALLICH, 1877) KAMPTNER (1954), *H. walbersdorfensis* MÜLLER (1974), *Perforocalcinela fusiformis, Reticulofenestra gelida* (GEITZENAUER, 1972) BACKMAN (1978), *R. haqii* BACKMAN (1978), *R. minuta* ROTH (1970) and *R. pseudoumbilica* (GARTNER, 1967) GARTNER (1969).

Samples from the lower part of the section mostly lack calcareous nannoplankton. Only samples Sokolovac 0 and Sokolovac 1 contain rare *Coccolithus pelagicus* (WALLICH, 1877) SCHILLER (1930), *H. carteri* (WALLICH, 1877) KAMPTNER (1954), *R. haqii* BACKMAN (1978), *R. minuta* ROTH (1970) and *Umbilicosphaera jafari* MÜLLER (1974). Smear slides from samples Sokolovac 0, 1, 2 and 7 contain

Table 3: Nannofossil distribution (following ODP terminology) in samples from the Sokolovac Section.

Samples	preservation	abundance	*Coccolithus pelagicus* (WALLICH, 1877) SCHILLER (1930)	*Helicosphaera carteri* (WALLICH, 1877) KAMPTNER (1954)	*Helicosphaera walbersdorfensis* MÜLLER (1974)	*Perforocalcinela fusiformis* BÓNA (1964)	*Reticulofenestra gelida* (GEITZENAUER, 1972) BACKMAN (1978)	*Reticulofenestra haqii* BACKMAN (1978)	*Reticulofenestra minuta* ROTH (1970)	*Reticulofenestra pseudoumbilica* (GARTNER, 1967) GARTNER (1969)	*Umbilicosphaera jafari* MÜLLER (1974)	reworked	*Watznaueria barnesae* (BLACK, 1959) PERCH-NIELSEN (1968)
Sokolovac 7	G	C	f	r	r	r	r	r	c	r			
Sokolovac 6	barren												
Sokolovac 5	barren												
Sokolovac 4	barren												
Sokolovac 3	barren												
Sokolovac 2	barren												
Sokolovac 1	G	F	f	f				r	c		r		
Sokolovac 0	P	R	x	x					x				x
Sokolovac -1	barren												

fossil resting spore determined as *Truncatulus tortonicus* (HAJOS) SUTO. Although the zonal marker *Sphenolithus heteromorphus* DEFLANDRE (1953) was not identified in the samples containing nannofossils (Sokolovac 0, 1 and 7) the composition of the nannoplankton assemblage dominated by *Reticulofenestra minuta* indicates nannoplankton Zone NN5. This biostratigraphic contribution can be confirmed by the presence of *Reticulofenestra pseudoumbilica* with diameters from 5 to 7µm.

Truncatulus tortonicus (HAJOS) SUTO is related to the marine planktonic diatoms *Chaetoceros* EHRENBERG, described by HAJÓS (1986) from the Hungarian Middle Miocene diatomite (locality Szurdokpüspöki). It occurs from the early Middle Miocene diatom Zone NPD 4B to the upper late Pliocene Zone NPD 9. The genus *Chatetoceros* is an important marine producer in nearshore upwelling regions (SUTO, 2006).

4.2.3. Foraminifera biostratigraphy

Three samples from the lower part of the section have been studied. The samples no. 0 (54) and no. 1 (54) lacked microfossils. Sample no. 7 (55) contained a poorly preserved, but diverse assemblage of 45 species. With the exception of one specimen of *Cassigerinella globulosa* (EGGER), only benthic species are present, dominated by small agglutinated forms. Calcified casts of pteropods (*Spirialis*) are frequent.

The faunal assemblage is characteristic for the Karpatian/Badenian transition. *Uvigerina macrocarinata* PAPP & TURNOVSKY is a marker species for the Early Badenian (Lower Lagenidae Zone).

5. DISCUSSION AND CONCLUSION

This study revises the age for the lowermost marine beds of the North Croatian Basins. These originally Karpatian-dated sediments are now provided with a new age framework. Accordingly, our results based on integrative biostratigraphic studies prove a Middle Miocene, Early Badenian age.

All investigated samples from Čučerje and the uppermost sample from Sokolovac indicate nannoplankton Zone NN5, with the zonal marker species *Sphenolithus heteromorphus* DEFLANDRE (1953). Nannoplankton assemblages with blooms of helicoliths and small reticulofenestrids indicate a nearshore, nutrient-rich environment. This coincides with the results from the benthic and planktic foraminiferal assemblages. *Uvigerina macrocarinata* PAPP & TURNOVSKY, *Pseudogaudryina lapugyensis* (CUSHMAN), *P. sturi* (KARRER), *Amphistegina mammilla* (FICHTEL & MOLL), and *Orbulina suturalis* BRÖNNIMANN characterize the Lower Lagenidae Zone of the Badenian in the Vienna and Styrian Basins (RÖGL et al., 2007). Additionally, the presence of the microfossil *Bolboforma moravica* REDINGER, together with the mass occurrence of the planktonic gastropod "*Spirialis*", confirm the Early Badenian age. The diatom flora with *Truncatulus tortonicus* (HAJOS) SUTO determined from the transitional part of the Sokolovac Section suggests a Badenian age. The pectinid bivalve *Flabellipecten solarium* (LAMARCK) from the Čučerje Section also indicates a Badenian age.

The assemblages point to a Badenian age correlated with the upper part of the Lower Lagenidae Zone (Fig. 6). The first occurrence of *Orbulina suturalis* BRÖNNIMANN, dated at 14.74 Ma and found at about 5 m up the Čučerje

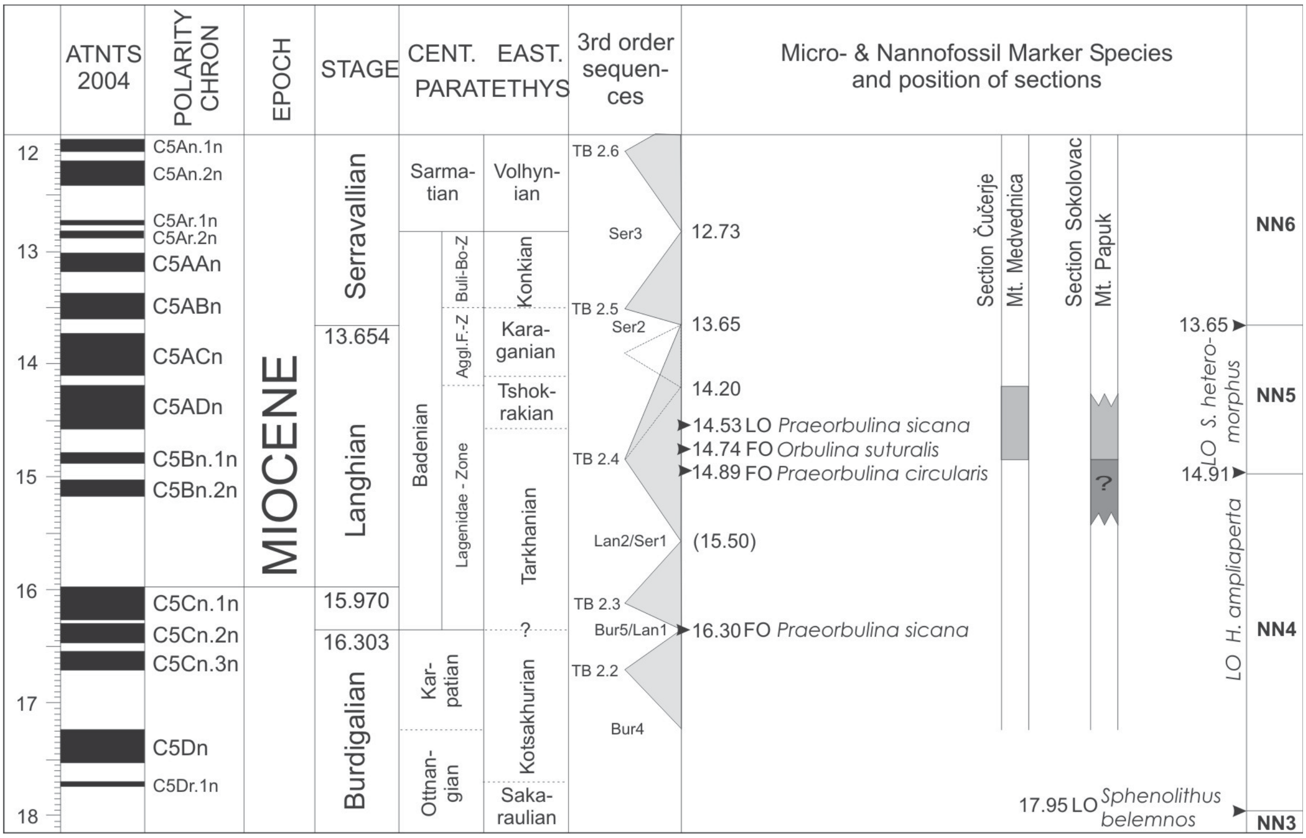

Figure 6: Stratigraphic time scale and correlation of investigated sections (modified after Rögl et al., 2007).

Section, demonstrates a much higher stratigraphic level for the succession than previously considered. The depositional evolution in both sections suggests a position above the maximal flooding surface and within the High Stand System Tract, which can be biostratigraphically correlated with the 3rd order sequence TB 2.4 (Fig. 6). The age of the marine transgression lies within the lower part of nannoplankton Zone NN5, having its base at 14.91 Ma. This places the initial marine sedimentation in the NCB at least 1 m.y. above the Middle Miocene lower boundary. The position of the Early-Middle Miocene boundary is currently under discussion. Hence, GRADSTEIN et al. (2004) placed it on top of the palaeomagnetic Chron C5Cn, whereas its biostratigraphic definition relates to the First Appearance Datum of the planktic foraminferal genus *Praeorbulina* (see LOURENS et al., 2004).

The transition from the lake deposits to the marine environment was observed in the Sokolovac Section. There is no sedimentological break between the lacustrine and marine deposits, suggesting continuous sedimentation throughout the Lower Badenian. Based on a time interval of 1 m.y., the resulting mean sedimentation rate for freshwater sedimentation would be 0.45 mm/y.

Surprisingly the present study suggests a distinctly younger age for the Neogene sedimentation in the North Croatian Basins than formerly considered. Probably the complete depositional cycle of its lower basinal infill, comprising the lacustrine and the early marine sediments, belongs to the Middle Miocene, Badenian stage. This completely changes the palaeogeographic picture for the south-western part of the Pannonian Basin System. Instead of Ottnangian freshwater beds and a Karpatian marine transgression, aquatic environments existed solely during the Badenian.

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