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Miocene paleogeography and biostratigraphy of the Slovenj Gradec Basin: a marine corridor between the Mediterranean and Central Paratethys

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Abstract: The Miocene evolution of the area transitional from the Eastern Alps to the Pannonian Basin System was studied through the paleogeographic evolution of the Slovenj Gradec Basin in northern Slovenia. It is based on mapping, section logging, nannoplankton biostratigraphy, and petrography. The results are correlated with the lithological column of the borehole MD-1/05. The evolution of the basin is connected with the development of the Pannonian Basin System, and the global 3rd order cycles, which influenced the connection with the Mediterranean Sea. Sedimentation started in the Karpatian in a fluvial to lacustrine environment and terminated at the end of the Early Badenian. During this period, three transgression–regression cycles were recorded. The first transgression occurred in the Karpatian and corresponds to the TB 2.2. cycle. The sediments reflect proximity of the hinterland. After a short break in sedimentation, the Early Badenian deposition followed. It marks the second transgression into the SGB, the first Badenian, correlated with the TB 2.3 cycle. There are signs of a transitional environment, which evolved to marine in advanced stages. At the high-stand system tract, the sea flooded the entire Slovenj Gradec Basin. Subsequent reduced quantity and diversity of the microfossils marks the onset of the second regression stage. It is followed by the third transgression, the second in the Badenian, correlated with the TB 2.4 cycle. The late Early Badenian deposition continued in the lower-energy, though occasionally still turbulent environment. Silty sediments with upward increasing content of organic matter indicate shallowing of the basin, until its final diminishing. Layers of fresh-water coal already bear witness to the existence of restricted swamps. After the Early Badenian, the area of the Slovenj Gradec Basin became dry land, exposed to erosion.

Keywords: Slovenj Gradec Basin, Central Paratethys, Pannonian Basin System, Miocene, biostratigraphy, paleogeography, sequence stratigraphy.

Introduction

The Central Paratethys represents a large Oligocene to Miocene paleogeographic unit. It formed due to the Tethys closure, and continental collision of the European plate and Adriatic micro plate, and the consequent rise of the Alpine, Dinaric, Karpatian and Pontian mountain chains (Royden 1988; Báldi 1989; Rögl 1998; Rasser et al. 2008; Kováč et al. 2017b). The subsequent (Ottnangian and later) compressional regime and movements of the crustal plates, resulted in reduction of the Central Paratethys to a smaller area, known as the Pannonian Basin System (PBS) (Horváth & Royden 1981; Royden 1988; Horváth 1993, 1995; Rögl 1998; Kováč et al. 1998). The basement of the PBS structurally consists of two major crustal blocks: ALCAPA (northern part), and Tisza–Dacia (southern part) separated by the WSW–ENE trending Mid-Hungarian fault zone (Csontos et al. 1992; Tari et al. 1993; Csontos & Nagymarosy 1998; Lorinczi & Houseman 2010) (Fig. 1). In the course of the PBS's evolution, these two blocks underwent a complex process of rotation and extension (e.g., Lorinczi & Houseman 2010), which left a significant imprint on the internal structure and morphology of the PBS. The basement of the south-western margin of the PBS is, however, formed by the Southern Alps and Dinaric units (Schmid et al. 2008).

Marginal parts of the western Central Paratethys with Southalpine/Dinaric basement are cropping out in the sedimentary successions of eastern Slovenia, including the area east of Celje, and the wider Laško and Krško area, whereas the basins of north-western Slovenia, including the herein investigated Slovenj Gradec Basin (SGB), have ALCAPA basement (Mioč & Žnidarčič 2001; Hasenhüttl et al. 2001; Rižnar et al. 2002; Otoničar & Cimerman 2006; Schmid et al. 2008; Vrabec et al. 2009; Poljak et al. 2016; Ivančič et al. 2018). The sediments were formed in two main basins: the Mura–Zala, and the Styrian Basins (Mioč & Žnidarčič 1989; Stingl 1994; Ebner & Sachsenhofer 1995; Piller et al. 2004, 2007; Hohenegger et al. 2009; Vrabec et al. 2009; Fodor et al. 2011). In this context, the SGB represents one of the marginal Central Paratethyan subbasins (Ivančič et al. 2018). It is related mostly to the Mura–Zala Basin, but similarly to the Lavanttal subbasin, it also shares characteristics with the Styrian Basin.

The aim of the present paper is to elucidate the Miocene sedimentary evolution of the SGB and its connection with the surrounding basins (Lavanttal, Mura–Zala, Styrian, and North Croatian Basins). An effort was made to identify the role of the global sea-level changes in the SGB sedimentary formations, and to put the paleogeographic evolution of the SGB into the wider context of the western part of the Central Paratethys and PBS. The proposed model of the SGB evolution is based on previously published data (Ivančič et al. 2018), a model of the Pohorje tectonic block (Trajanova 2013), and the results of new investigations. The latter comprises a record of an additional section, petrography, revaluation of the results from the borehole MD-1/05 (Ćorić et al. 2011), and nannoplankton based biostratigraphy and paleoecology.

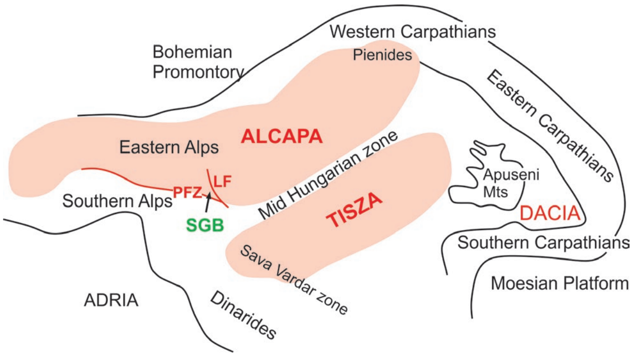

Fig. 1. Major tectonic units of the Carpathian–Pannonian Basin, slightly modified after Lorinczi & Houseman (2010); LF — Labot fault, SGB — Slovenj Gradec Basin, PFZ — Periadriatic fault zone.

Geological setting

The SGB is situated in northern Slovenia (Fig. 2A). It is surrounded by tectonic units of the Eastern and Southern Alps, toward which the contacts are normal or reversely reactivated faults, and it belongs to the PBS by origin (Trajanova 2011, 2013). The basin is underlain by Old-Paleozoic formations, Mesozoic carbonate rock (Mioč & Žnidarčič 1976; Mioč 1978), and Oligocene tonalite (Ivančič et al. 2018), and filled with the Middle Miocene typical molasse sedimentary succession named Ivnik beds. They consist of alternating beds of conglomerates, sandstones, siltstones, marlstones, and claystones, and are overlain by Pliocene–Quaternary clastic sediments (Mioč 1978; Mioč & Žnidarčič 1983; Ivančič et al. 2018). Broadly south–north compression and tectonic activity along two major tectonic structures, the Periadriatic and Labot faults, are responsible for later deformation of the SGB. The studied area is characterized by two synclines, and one

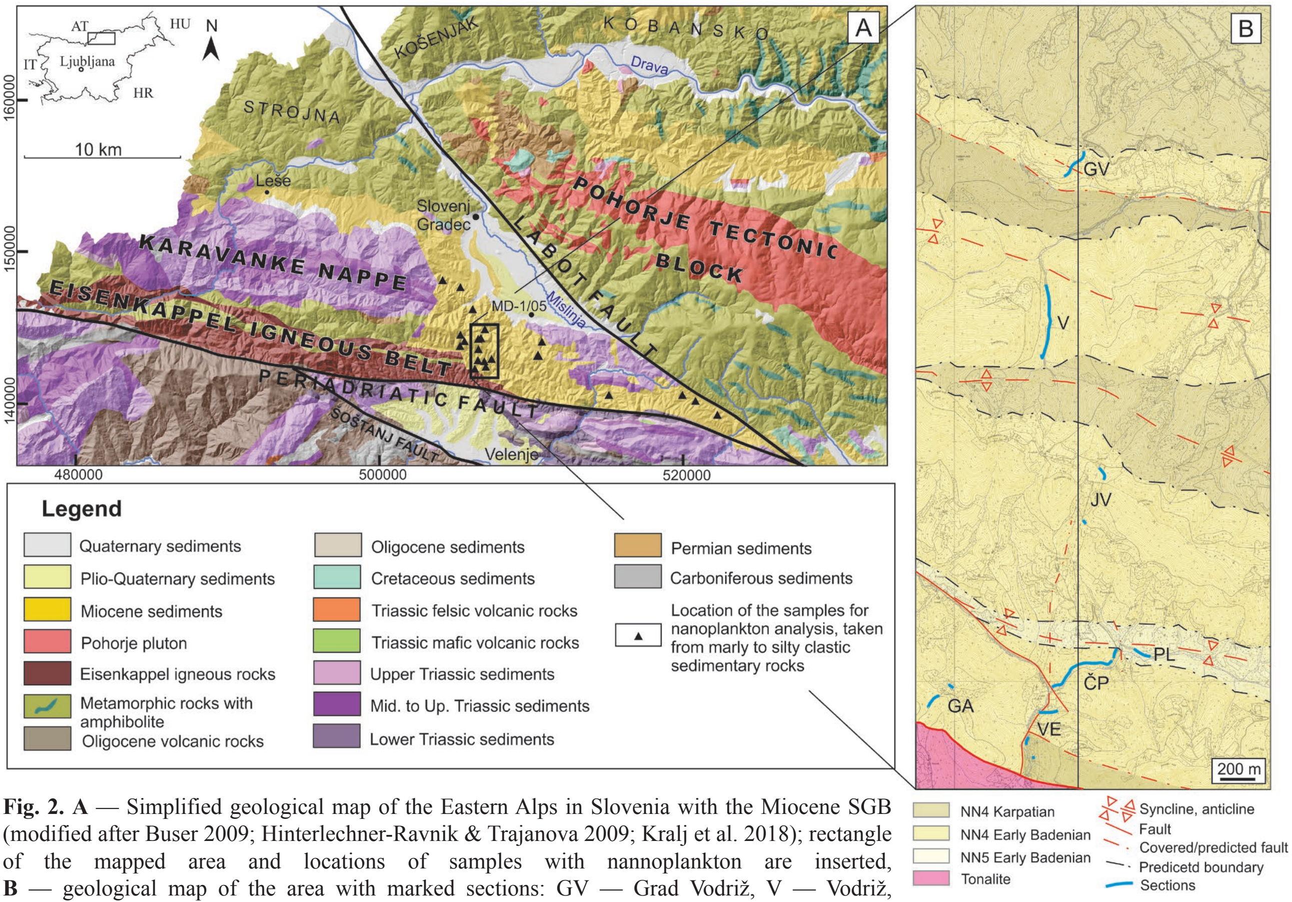

Fig. 2. A — Simplified geological map of the Eastern Alps in Slovenia with the Miocene SGB (modified after Buser 2009; Hinterlechner-Ravnik & Trajanova 2009; Kralj et al. 2018); rectangle of the mapped area and locations of samples with nannoplankton are inserted, **B** — geological map of the area with marked sections: GV — Grad Vodriž, V — Vodriž, JV — Juvanov vrh, PL — Plešivec, ČP — Črni potok, VE — Velunja, and GA — Gaberke.

anticline (Fig. 2B), crosscut by several local faults trending prevailingly NW–SE and SW–NE.

Sampling and methods

The investigated area was mapped in the 1:5000 scale. Based on the map, six individual sections were located and recorded in the 1:100 scale (Ivančič et al. 2018), and one additional section (Gaberke, GA) in the south-west (Figs. 2B, 3). From the successions, 25 additional standard thin sections were made for sedimentological and petrographic analysis and 70 previously made samples were re-evaluated. The lithological column of the borehole MD-1/05 was interpreted on the basis of the drilling cuttings and petrography, and biostratigraphy determined on the basis of nannoplankton assemblages (Ćorić et al. 2011). From the borehole, 93 samples were investigated when the borehole was drilled in 2005. Samples from 36 m to 852 m contain rich calcareous nannofossil assemblages and were quantitatively analysed (at least 300 specimens were counted). Because of low nannofossil content in sediments from 600 m to 852 m only presence/absence investigations were performed. Changes in abundances are expressed in percentages and plotted in Figure 4. Apart from the borehole, twenty-one samples were semi-quantitatively examined for nannoplankton (Fig. 2A) from the SGB, of which only four were acquired from the marly to silty layers in the sections. All smear slides were prepared following the standard procedure described by Perch-Nielsen (1985). The slides were investigated under microscope Leica DMLP with 1000× magnification (crossed and parallel polarizers). For the biostratigraphic definition, the standard zonation of Martini (1971) was applied. The Mediterranean Neogene Nannoplankton (MNN) zonation (Fornaciari et al. 1996) was used for correlation with the Mediterranean region.

Results

Lithological column of the borehole MD-1/05

The 1260 m deep borehole MD-1/05 was drilled on the southern margin of the Pliocene-Quaternary fill of the SGB in the central part of the Miocene basin, north-east of the investigated sections (Fig. 2A). It represents the thickest continuous cross-section through the Miocene sediments in the SGB.

The sedimentary succession starts with mainly carbonate conglomerate, and conglomeratic breccia, containing big dolomitic blocks. Upward, thin layers of sandstone, siltstone, and marlstone are interlayered in conglomerates (Fig. 5). Frequently, coal fragments can be found, and some fragments of hardened bituminous material. Carbonate rocks prevail over quartz, phyllite, chert, slates, and quartzite pebbles in the conglomerate. Limestone cutting with nummulitidae was found in the conglomerate. In the lower part of the borehole, coarse- to very coarse-grained sediments predominate, containing big limestone blocks in the lower 340 metres. Drilling rock chippings testify of rock blocks up to 1 m in size.

The borehole section between 450 and 920 m consists of alternating fine- to coarse-grained sediments. Most frequent are conglomerates with variable content of sandy matrix and again interlayered with sandstone, siltstone, and marlstone (Fig. 5). In the conglomerate, carbonate (dolomite and limestone) and quartz pebbles prevail, though some intervals are rich in siliciclastic, mostly metamorphic rocks. An interruption in sediment continuity at the depths between 586 and 576 m is indicative. Practically no rock chippings were recovered by drilling up to 576 m. This about 10 m thick interval is characterized by alternating lighter and dark silty/clayey layers, which are enriched with organic matter. Above this layer, conglomerate was deposited, and further upwards corallinacean (lithothamnium) limestone (from 525 m to 550 m) with thin interlayers of mudstone.

From 525 m to 550 m marly limestone is found. Frequent fossil fragments in the chippings point to minor occurrences of corallinacean (lithothamnium) limestone.

In the upper 450 m of the borehole, fine-grained sediments prevail. They are represented mostly by siltstone, which is exceptionally interrupted by thin layers of conglomerate (Fig. 5) and by dark marly intervals, rich in organic, often bituminous matter. The conglomerate consists of pebbles of quartz, gneiss, and mica schist. Dark marly intervals occur between 270 and 160 m depth. The column ends with about 40 m of dark, clayey to silty interval with upwardly increasing content of organic matter until a coal layer about 3 m thick was reached at the depth of 23–25 m. Biostratigraphic ages are reliably documented only from 38 m to 658 m, and with some doubt from 658 m to 830 m. They range from Ottnangian(?), reliably documented from Karpatian to Badenian (Langhian–lowermost Serravallian).

The uppermost 38 m of the column belongs to Pliocene–Quaternary sediments, which overlay unconformably the Miocene succession.

General characteristics of the sections

The position of the sections is shown in the geological map of the area in Figure 2B.

The total length of the investigated SGB sections is 656 m. A common characteristic of all the sections is frequent alternation of conglomerate and sandstone, interlayered with beds of siltstone, marly siltstone (section VE, GA, PL and GV), and marlstone (GA, ČP and V sections) of varying thicknesses. Conglomerate is coarse- to fine-grained, with the thickness of beds reaching up to 7 m. Clasts mainly belong to quartzite, carbonate and metamorphic rocks, while igneous rocks are rare, except in the immediate proximity of the Eisenkappel/Železna Kapla igneous belt. Sandstone is fine- to coarse-grained with beds up to 10 m thick. The beds are graded, locally laminated, cross-bedded, and contain relatively frequent plant remains. In the composition of sandstone, lithic

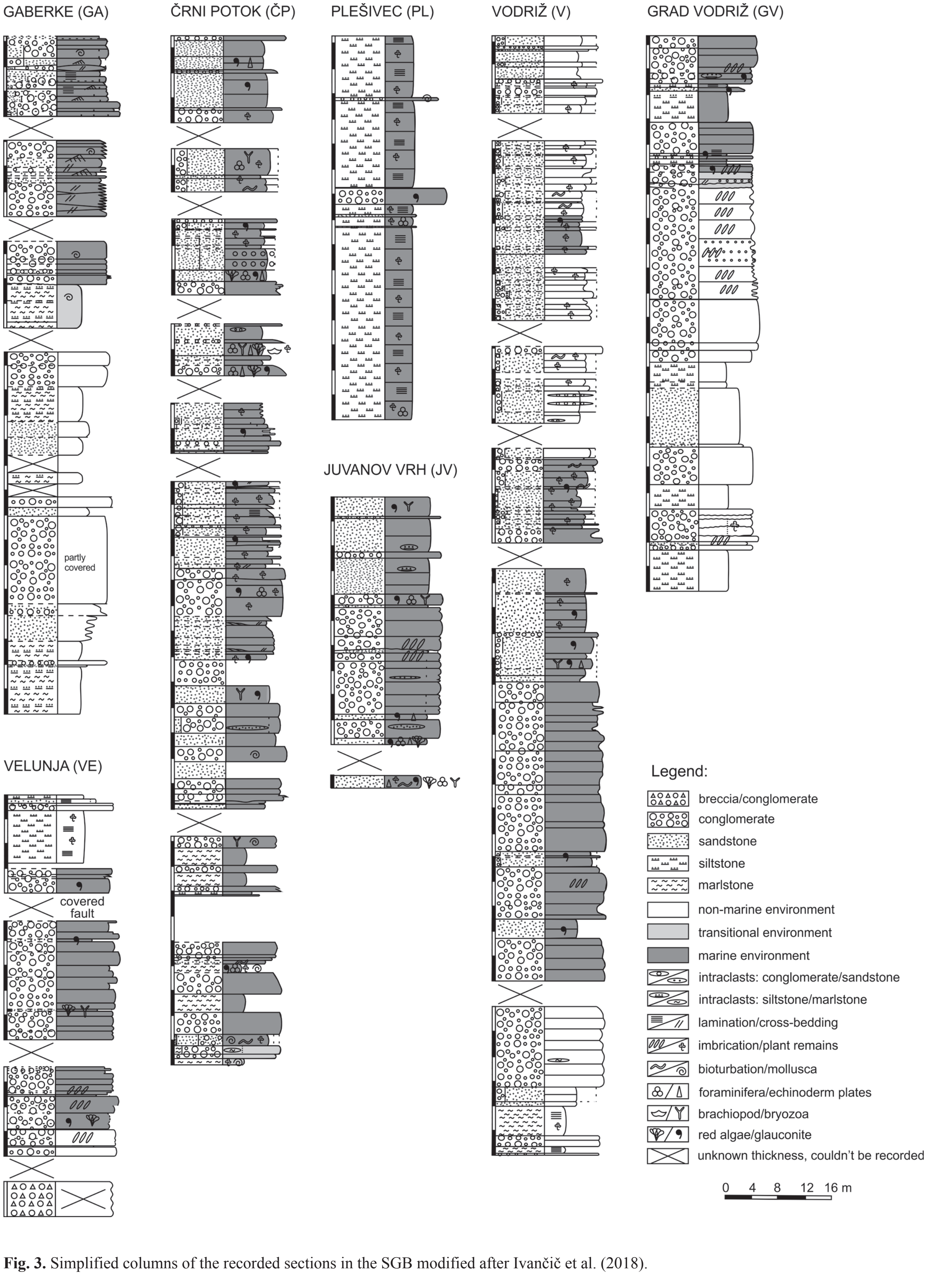

Fig. 3. Simplified columns of the recorded sections in the SGB modified after Ivančič et al. (2018).

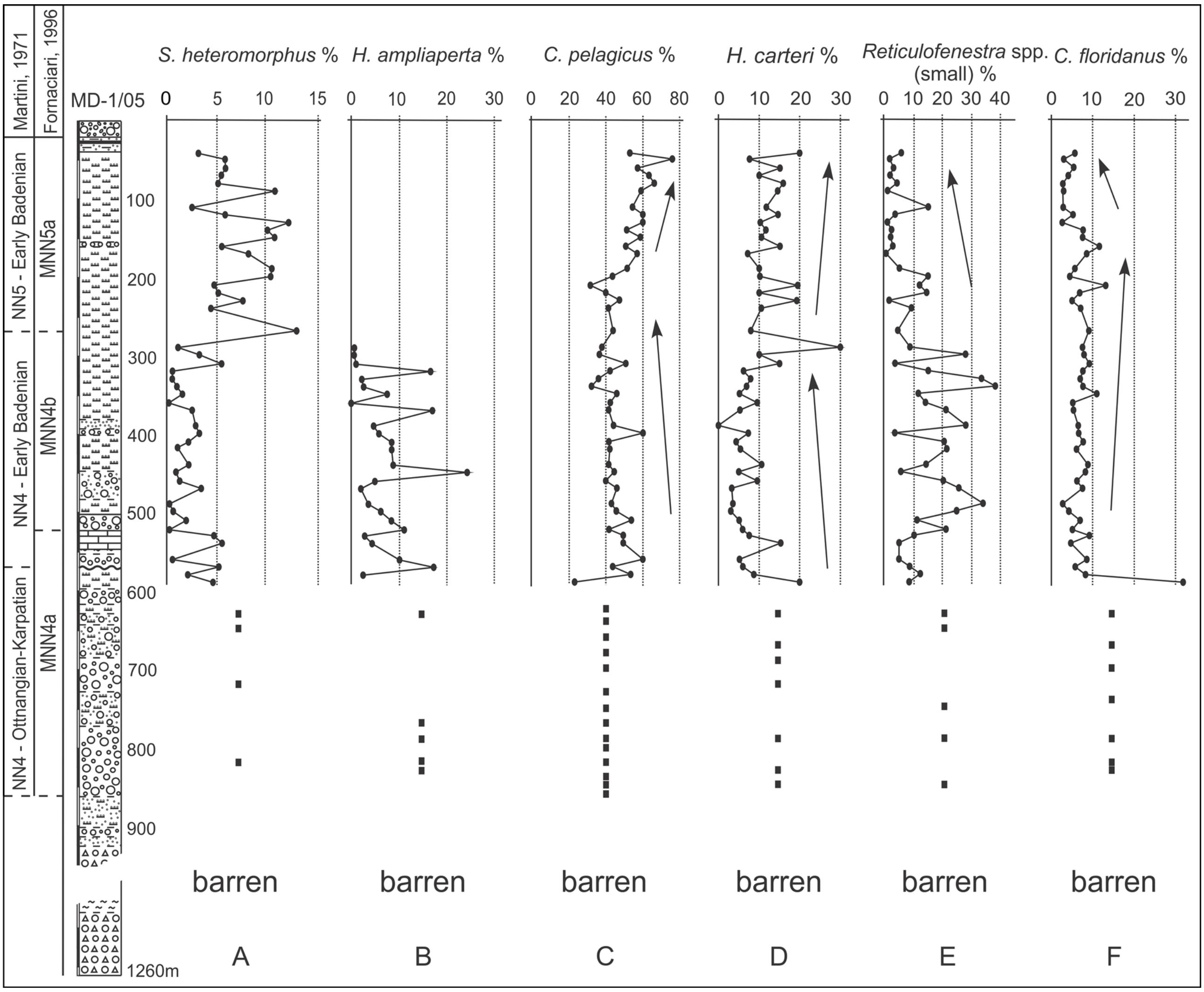

Fig. 4. Changes in abundances of calcareous nannofossils, recorded in the borehole MD-1/05: **A** — *Sphenolithus heteromorphus*, **B** — *Helicosphaera ampliaperta,* **C** — *Coccolithus pelagicus*, **D** — *Helicosphaera carteri*, **E** — *Reticulofenestra* spp., **F** — *Cyclicargolithus floridanus.*

grains prevail, belonging mostly to metamorphic and carbonate rocks, while fragments of igneous rocks are rare. Common constituents are mono and polycrystalline quartz, and fragments of monocrystalline phyllosilicates, while feldspars, accessory minerals, and allochemical components are rare. The latter belong to glauconite, red algae (Fig. 6A), bryozoan, benthic and planktic foraminifera (Fig. 6B), brachiopods, and echinoderm plates. Thicknesses of the siltstone and marly siltstone beds range up to 30.8 m, and of marlstone up to 4.8 m (Ivančič et al. 2018).

North-west of the Velunja section, an additional section has been recorded in the vicinity of Gaberke (GA). It comprises a 101 m thick succession of alternating fine- to coarse-grained bedded polymict conglomerate, medium- to coarse-grained sandstone, silty marlstone and silty claystone. The most frequent clasts are carbonates, quartz of metamorphic origin, and tonalite. In the upper part of the section, a layer with predominating tonalite pebbles (Fig. 6C) occurs. The conglomerate is grain supported, and in places normally graded. Conglomerate and sandstone are cross bedded (Fig. 6D), and form dunes (Fig. 6E), and ripples (Fig. 6F). Sandstones are laminated in places. The gastropod *Terebralia lignitarium lignitarium* (Eichwald, 1830) (Fig. 6G), oyster shells, and plant remains were found in the upper part of the section. Allochemical components of glauconite and red algae were found in the coarse-grained sandstone and fine-grained conglomerate, in the uppermost part of the section.

Calcareous nannofossils

Biostratigraphy

Nannoplankton associations are the base for the chronostratigraphic definition of the SGB sedimentary fill. They were determined in the sections PL and ČP, borehole MD-1/05 (Fig. 7), and in the central and south-eastern parts of the SGB (Fig. 2A).

Based on qualitative and quantitative analyses of calcareous nannofossils, the sedimentary succession in the borehole MD-1/05 can be subdivided into the following units:

- 0–38 m Quaternary
- 38 m–270 m Early to Middle Badenian, NN5 (*Sphenolithus heteromorphus* Zone, Martini, 1971); Species rich nannoflora is dominated by: *Coccolithus pelagicus* (Wallich 1877) Schiller, 1930, *Cyclicargolithus floridanus* (Roth & Hay,

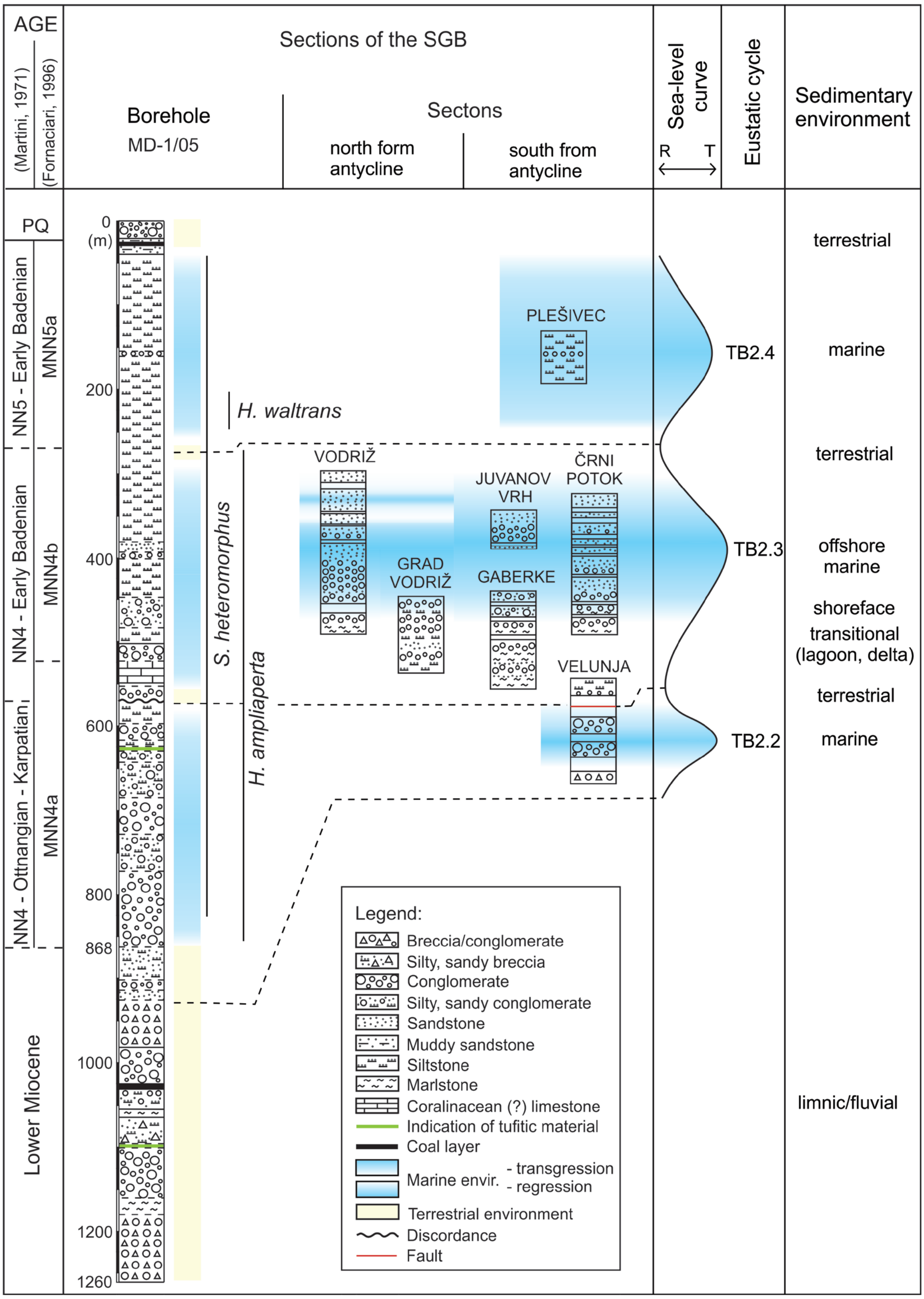

Fig. 5. Simplified sedimentological column of the borehole MD-1/05 (with the range of biostratigraphic markers) correlated with the sections recorded in the SGB, and their common correlation with the regression-transgression stages in the Karpatian and Early Badenian, correlated to the Haq et al. (1988). There are differences in type of sedimentary environment, due to location of the borehole (distal part) and separate sections (marginal part).

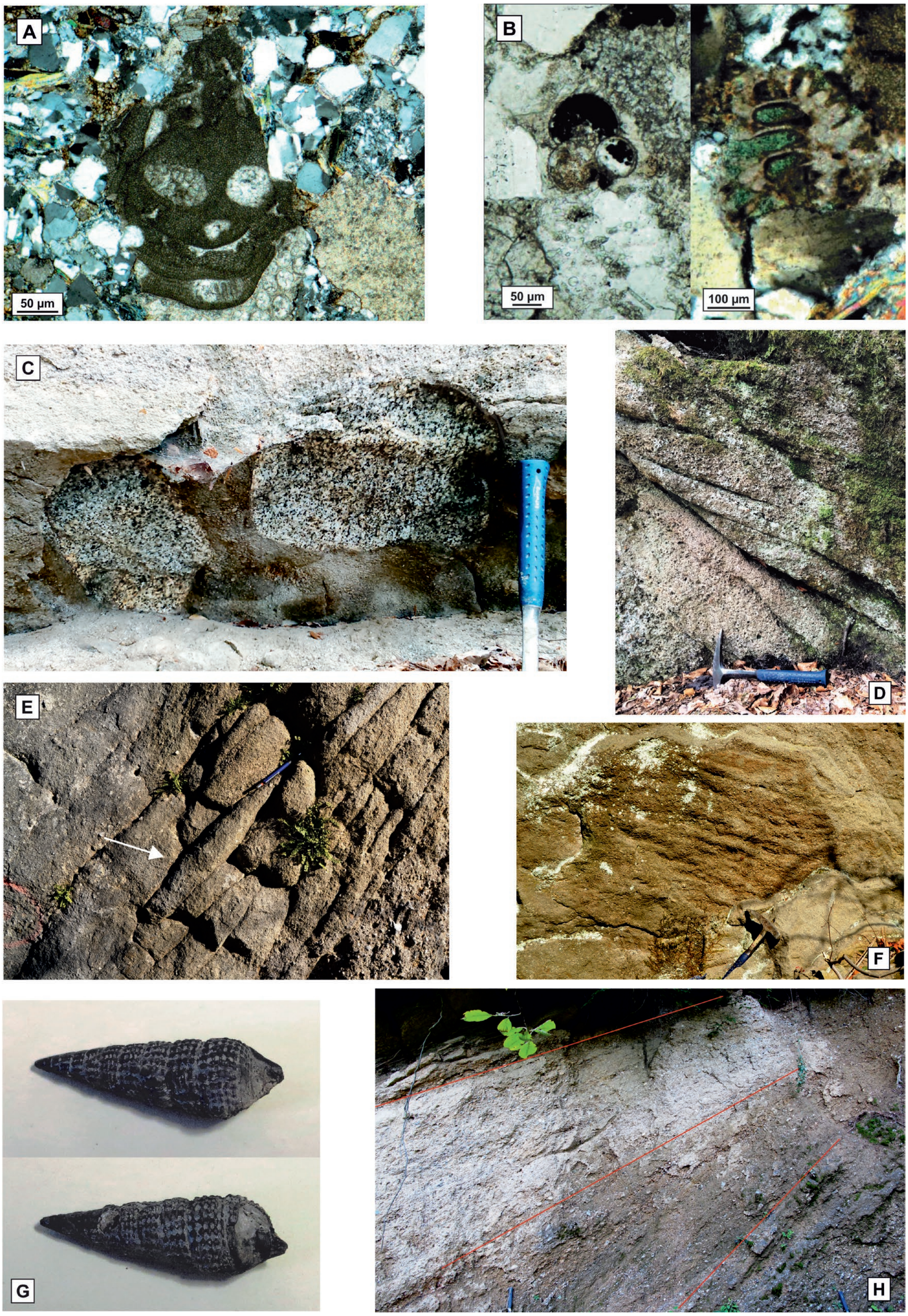

Fig. 6. A — grain of red algae, indicating marine environment, from VE section; **B** — left: planktic foraminifera, right: benthic foraminifera with glauconite, from ČP section; **C** — big tonalite pebbles in the Lower Badenian sediments, from GA section; **D** — cross-stratification in the fine-grained conglomerate, from the GA section; **E** — dune, marked with an arrow, in the coarse- grained sandstones, from the GA section; **F** — ripples in the fine-grained conglomerate; **G** — gastropod *Terebralia lignitarium lignitarium*; **H** — delta sediments, with horizontal bedding above the upper line, and three foresets, each below the separate line, from the GV section.

in Hay *et al.* 1967) Bukry, 1971, *Helicosphaera carteri* (Wallich 1877) Kamptner, 1954, *Helicosphaera walbersdorfensis* Muller, 1974, *Pontosphaera multipora* (Kamptner 1948 ex Deflandre in Deflandre & Fert 1954) Roth, 1970, reticulofenestrids (*Reticulofenestra gelida* (Geitzenauer 1872) Backman, 1978, *Reticulofenestra haqii* Backman, 1978, *Reticulofenestra minuta* Roth, 1970, *Reticulofenestra pseudoumbilicus* (Gartner 1967) Gartner, 1969), *Sphenolithus heteromorphus* Deflandre, 1953, *Sphenolithus moriformis* (Bronnimann & Stradner 1960) Bramlette & Wilcoxon, 1967 etc. Rare discoasters are represented by *Discoaster adamanteus* Bramlette & Wilcoxon (1967), *Discoaster deflandrei* Bramlette & Riedel, 1954, *Discoaster musicus* Stradner, 1959 and *Discoaster variabilis* Martini & Bramlette, 1963.

The stratigraphic attribution of this part of the borehole into NN5 is based on the absence of *Helicosphaera ampliaperta* Bramlette & Wilcoxon, 1967 and the presence of *Sphenolithus heteromorphus* Deflandre 1953 (Fig. 4A,B). The last occurrence of *Helicosphaera waltrans* Theodoridis, 1984 was observed in a sample from 228 m (Fig. 8). This event is dated to 14.357 Ma (Anthonissen & Ogg 2012). The boundary NN4/NN5 is defined by the last occurrence of *H. ampliaperta* and dated by 14.91 Ma (Anthonissen & Ogg 2012). An increase in percentages of *S. heteromorphus* (Fig. 4A) allows the correlation of this unit with Mediterranean Zone MNN5a (*Sphenolithus heteromorphus–Helicosphaera walbersdorfensis* Interval Subzone; Fornaciari et al. 1996).

Rare reworking (max. 3.68 % in sample 218 m) from the Paleogene (*Reticulofenestra bisecta* (Hay 1966) Roth, 1970, *Toweius* sp., *Zygrhablithus bijugatus* (Deflandre 1954) Deflandre, 1959 etc.), and Cretaceous (*Prediscosphaera cretacea* (Arkhangelsky 1912) Gartner, 1968, *Retecapsa crenulata* (Bramlette & Martini 1964) Grün, 1975, *Watznaueria britannica* (Stradner 1963) Reinhardt, 1964, *Watznaueria fossacincta* (Black 1971) Bown, 1989 etc.) could be identified in the lower part of this interval, but they do not exceed 5 % of the total fossil assemblage.

- 270 m–570 m Early Badenian, NN4 (*Helicosphaera ampliaperta* Zone, Martini, 1971); species rich nannoplankton assemblages contain *Helicosphaera ampliaperta,* and *Sphenolithus heteromorphus* accompanied by high percentages of *C. pelagicus*, *Cy. floridanus*, *P. multipora*, reticulofenestrids (*R. pseudoumbilicus, R. gelida*, *R. minuta* etc.), helicoliths (*H. carteri, Helicosphaera scissura* Miller, 1981, *H. walbersdorfensis*), and discoasters (*D. deflandrei*, *D. musicus*, *D. variabilis*). The uppermost part 288 m–520 m of this unit is characterized by the decrease in the content of *S. heteromorphus,* and therefore can be correlated with the MNN4b Zone (*Sphenolithus heteromorphus* Absence Interval (Paracme)) defined for the Mediterranean region (Fornaciari et al. 1996).
- 570 m–868 m Ottnangian–Karpatian, NN4 (*Helicosphaera ampliaperta* Zone, Martini 1971); rare lower Miocene nannofossils dominated by *H. ampliaperta,* and *S. heteromorphus*. The following species also occur: *C. pelagicus*, *C. floridanus*, *H. carteri*, *P. multipora*, *R. gelida*, *R. haqii*, *R. minuta,* and *R. pseudoumbilicus*. Based on higher amounts of *S. heteromorphus* (Fig. 4A), this unit can be correlated with Zone MNN4a (*Helicosphaera ampliaperta–Sphenolithus heteromorphus* Interval Zone; Fornaciari et al. 1996).
- 860 m–1260 m Lower Miocene(?); 18 samples from this part were barren for calcareous nannofossils, and no biostratigraphic attribution was possible.

Samples from the locality Plešivec contain assemblage with common *Coccolithus pelagicus accompanied by Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947, *Coccolithus miopelagicus* Bukry, 1971, *Cyclicargolithus floridanus, Discoaster musicus*, *Helicosphaera carteri*, *Reticulofenestra pseudoumbilicus,* and *Sphenolithus heteromorphus*. This association allows attribution to NN5 and can be correlated with the uppermost part of the borehole MD-1/05 (Fig. 5).

Sedimentary successions in the SGB and their significance

Sedimentary successions, and particularly the mapped area, are chronostratigraphically divided into four units: Lower Miocene (Ottnangian–Karpatian), Karpatian, Early Badenian, and late Early Badenian.

Lower Miocene (Ottnangian–Karpatian)

The occurrence of Lower Miocene sediments in the SGB is uncertain. In the interval between 860 m and 1260 m of the borehole MD-1/05, samples contained no calcareous nannofossils, so biostratigraphic attribution is not possible. As reconstructed from the rock chippings, unsorted rock material similar to breccia or conglomerate with angular pebbles represents a proximal, high energy terrestrial environment. The succession is more or less continuous up to the 868 m depth, with an interruption at around 1026 m, where a distinct layer of coal occurs. Reduced water energy is marked by deposition of silty sands in the upper part of the Ottnangian–Karpatian succession.

Karpatian

The oldest sediments in the SGB, unambiguously confirmed by nannoplankton, belong to the Karpatian. Sediments are found in the lower part of the VE section, below the fault (Figs. 3, 5), and in the borehole MD-1/05 (Figs. 4, 5). The initial succession is characterized by a pile of about 40 m thick basal conglomerate and conglomeratic breccia, with a thin interlayer of sandstone that overlies the tonalite basement in the VE section. Presence of minor fine-grained lithologies and absence of marine biota indicate that the sediments were deposited in a high-energy terrestrial environment, most probably as rockfall breccia, and alluvial fan deposits. These sediments are conformably overlain by at least 30 metres of conglomerate containing abundant glauconite grains, fragments of red algae,

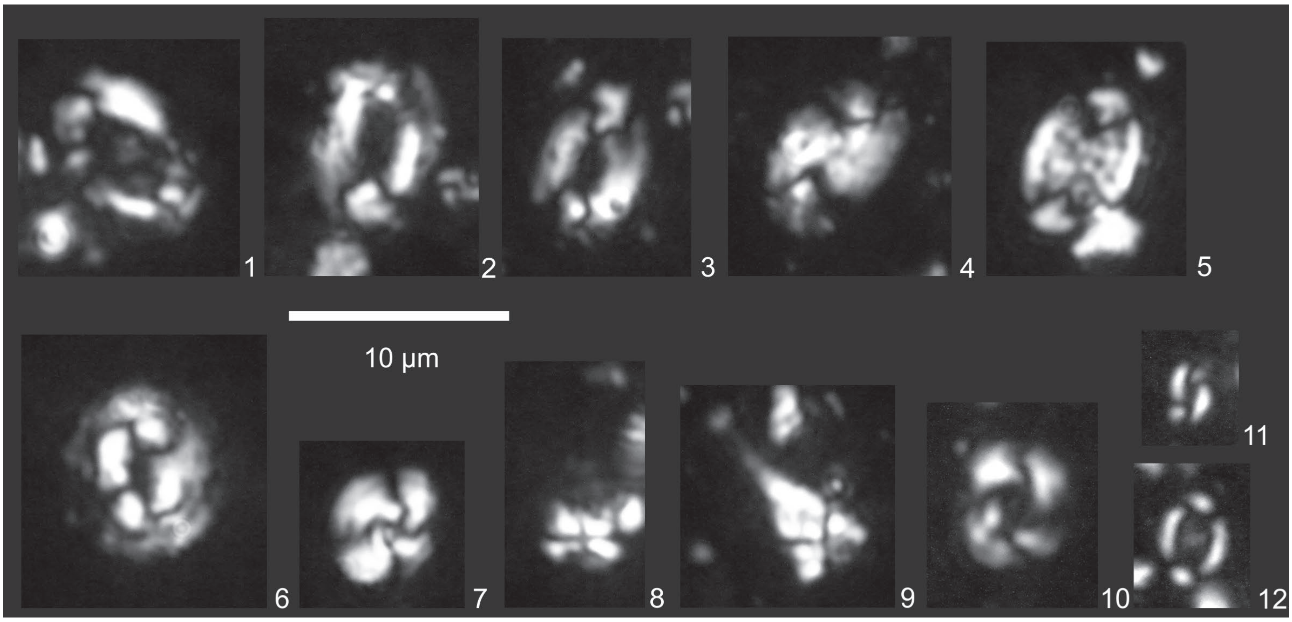

Fig. 7. Calcareous nannofossils found in the borehole MD-1/05 with depth indicated: **1–3** — *Helicosphaera ampliaperta* Bramlette and Wilcoxon, 1967; 510 m; **4** — *Helicosphaera carteri* (Wallich 1877) Kamptner, 1954; 510 m; **5** — *Pontosphaera multipora* (Kamptner 1948 ex Deflandre in Deflandre & Fert 1954) Roth, 1970; 510 m; **6** — *Coccolithus pelagicus* (Wallich 1877) Schiller, 1930; 510 m; **7** — *Cyclicargolithus floridanus* (Roth & Hay, *in* Hay *et al.* 1967) Bukry, 1971; 510m; **8, 9** — *Sphenolithus heteromorphus* Deflandre 1953; 230 m; **10** — *Reticulofenestra pseudoumbilicus* (Gartner 1967) Gartner, 1969; 230m; **11** — *Reticulofenestra minuta* Roth, 1970; 510 m; **12** — *Coronosphaera mediterranea* (Lohmann 1902) Gaarder, in Gaarder & Heimdal, 1977; 230 m.

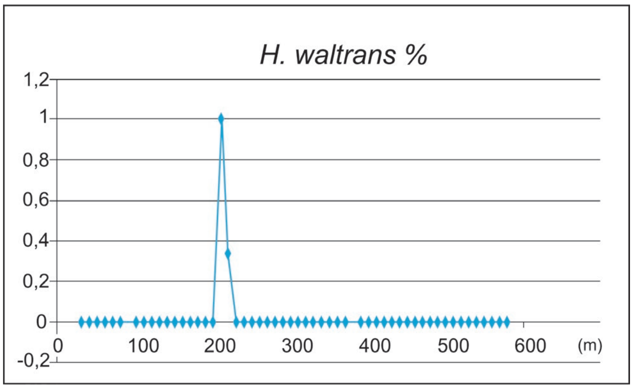

Fig. 8. Samples containing stratigraphically significant form of *Helicosphaera Waltrans*.

and bryozoans, which indicate sedimentation in a shallow-marine environment (Fig. 3). The transition from terrestrial to marine environment is gradual, marked by the absence of coarse-grained conglomeratic breccia.

Early Badenian

Due to vegetation cover, no direct exposure of the Karpatian/Badenian transition was found in the investigated area, but it is clearly marked in the borehole MD-1/5 at the depth of around 576 m by a change of lithology.

The succession continues with the Early Badenian sediments, recorded in the upper part of the VE section (above the fault), ČP, GA, JV, GV, and V sections and in the borehole MD-1/05 (Figs. 5, 9B,C). Initial Early Badenian sedimentation is characterized by alternation of fine- to coarse-grained layers of common thickness up to 60 m, deposited in the terrestrial environment documented in the GA, VE and GV sections (Fig. 3). Terrestrial deposits are overlain by up to 16 m of prevailingly fine-grained sediments, including silty marlstone and marlstone (VE, and GA), or by up to 20 m of conglomerate (GV), deposited in the transitional environment. The sediments reflect the onset of the first Badenian transgression in the SGB (Fig. 9B). A lagoonal environment was formed, determined by the occurrence of the gastropod *Terebralia lignitarium lignitarium* (Eichwald 1830) (Fig. 6G), found in the GA and ČP sections. The environment with deposition of marlstone appears to be similar in the V section, though no gastropods were found there. In the GV section, an accretionary Gilbert-type delta environment developed (Fig. 6H). Sedimentation continued in the marine environment, determined in the GA, ČP, JV, V, and GV sections, and in the borehole MD-1/05 (Fig. 9C). In the GA section, cross lamination (Fig. 6D), dunes (Fig. 6E), and ripples (Fig. 6F) represent shoreface deposits. A shallow marine environment is indicated by allochemical grains, mostly glauconite, and bryozoa. In the upper part of the GA section, a layer with predominating tonalite pebbles occurs. It is correlated with a similar layer in the ČP section (marked by the same level in Fig. 5), and documents the same sediment provenance and contemporaneous sedimentation. In the ČP, and JV sections, the maximum transgression is marked by the highest variety and

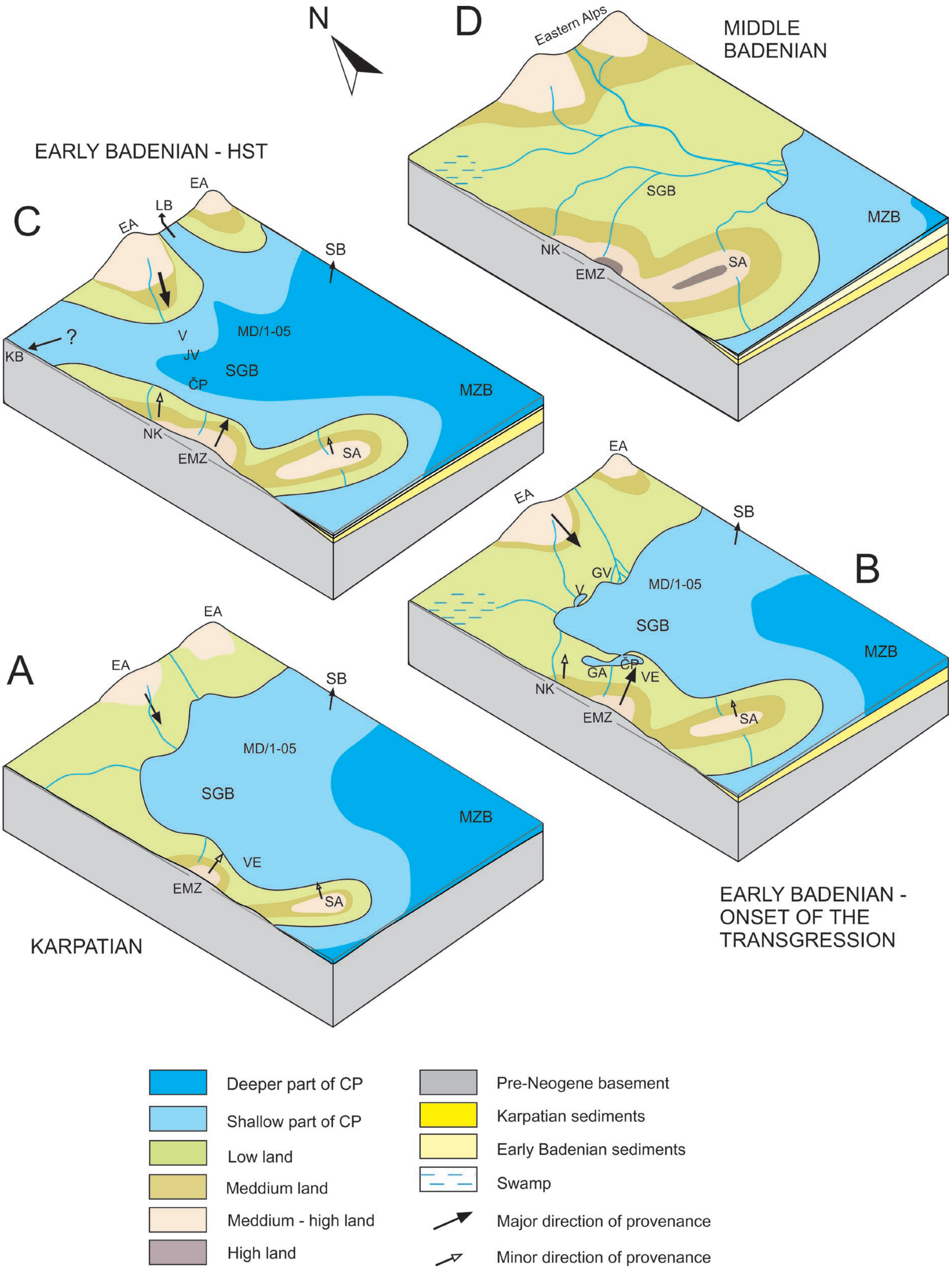

Fig. 9. Paleogeographic reconstruction of the SGB, and its nearer surroundings. The models are not to scale. **A** — The first transgression in the Karpatian with deposition of mostly coarse-grained sediments; **B** — initial transgression in the Early Badenian; lagoons and delta were formed, and fresh water coal originated in the swamp; **C** — the Early Badenian high stand system tract; proposed northward transgression toward the Lavanttal Basin and westward, towards the Klagenfurt Basin; **D** — post Early Badenian uplift in the area — dry land and erosion in the SGB; SGB — Slovenj Gradec Basin, SB — Styrian Basin, MZB — Mura–Zala Basin, EA — Eastern Alps, NK — Northern Karavanke, SA — Southern Alps, EIZ — Eisenkappel igneous zone, LB — Lavanttal Basin, KB — Klagenfurt Basin.

quantity of allochemical components, which is reflected in the V section as well (Figs. 3, 5). Presence of planktic foraminifera found in the ČP, and JV sections points to an offshore transition environment. A lot of plant remains, similar to sea grass define proximity of the coast in the V, and part of the ČP sections. In the V section, marine and terrestrial environment are alternating (Fig. 3) (Ivančič et al. 2018). Generally, in the lower part of the ČP, JV, and V sections, conglomeratic deposits of the first Badenian transgression prevail, while in the upper part of these sections, sandstone layers of the following regression stage prevail (Fig. 3).

Late Early Badenian

The youngest sediments in the SGB belong to the uppermost part of the Early Badenian, assigned here as late Early Badenian. They were found in the PL section and in the upper part of the borehole MD-1/05. Deposition of finer-grained sediments (siltstones) prevailed, containing glauconite, benthic, planktic foraminifera, calcareous nannofossils, and a lot of plant remains similar to sea grass, found in the PL section. Siltstones are practically without thick layers of conglomerate. Only one characteristic conglomeratic layer occurs (Fig. 5) in the section and the borehole. It has been used as a marker of simultaneity. Sedimentation took place in a shallow marine environment with low water energy. Dark, silty to marly intervals in the borehole MD-1/05 between 270 and 160 m depth are rich in organic and bituminous matter. Above, the succession continues with lighter intervals. The uppermost part ends with a coal layer, and dark clays, which mark the end of sedimentation in the SGB (Fig. 5).

Discussion

The sedimentary succession of the SGB presented here enables more detailed correlation of the SGB with the surrounding basins (Fig. 10). The correlation is based on the 3rd order sequences after Haq et al. (1988), and Hardenbol et al. (1998). However, the standard geological time scale does not take into account the regional and local geodynamics of processes and the changing of marine gateways (Kováč et al. 2018). Consequently, our sequences could not necessary coincide precisely to the global sequences but may slightly deviate from them. Therefore the 3rd order sequence boundaries of the SGB are also correlated with the sequences of the Central Paratethys after Hohenegger et al. (2014) (Fig. 10).

Paleoecology based on changes in calcareous nannofossils assemblages

Nannofossils are a good tool for the reconstruction of paleoenvironments in the water column, and for the correlations between individual basins. Changes in calcareous nannoplankton assemblages usually reflect oscillations in depth, temperature and salinity of marine water, and nutrient supply.

The investigated sediments from the lowermost part of the borehole MD-1/05 lack calcareous nannofossils (860 m to 1260 m). The rest, which contain nannofossils, are dominated by *C. pelagicus*, helicoliths, and small reticulofenestrids. For the reconstruction of paleoconditions in the SGB, we used oscillations in percentages of these species.

Coccolithus pelagicus is well known as an r-strategist, which is abundant in cold and nutrient rich waters (Okada & McIntyre 1979; Winter et al. 1994). The average content of *C. pelagicus* (Fig. 4C) in the lower part of the borehole (from 200 m–590 m) is about 45 %, and increasing in the upper part (40 m–220 m), reaching maximum (78 %) in the sample from the depth of 50 m. High percentages of *C. pelagicus* (50–76 %) indicate high nutrient input (usually caused by upwelling conditions) and eutrophic conditions in the water column during NN4 and lower NN5. Increasing content of *C. pelagicus* in the upper part of NN5 (max. 76 % in sample form 50 m) accompanied by high percentages of helicoliths characterize shallowing of the sea.

Helicoliths are common in shallow, near continental environments and indicate an upwelling regime (Perch-Nielsen 1985). *Helicosphaera carteri* (stratigraphic range from NN1 until extant) is the most common species among helicoliths in the borehole. The distribution pattern of this cosmopolitan species (Fig. 4D) is very similar to *C. pelagicus,* signifying shallowing of the sea, as recorded in the upper part of the borehole (NN5).

Small reticulofenestrids (*Reticulofenestra haqii* and *R. minuta*) generally dominate assemblages along continental margins (Haq 1980). They were used for the paleoecological interpretation of Lower/Middle Miocene sediments in the Austrian Alpine–Carpathian Foredeep (Molasse Basin; Ćorić & Rögl 2004) and Middle Miocene sediments from the Vienna Basin (Ćorić & Hohenegger 2008). Higher percentages of small reticulofenestrids indicate warmer, significantly stratified water columns (reduced eutrophic conditions) in contrast to assemblages with the dominance of *C. pelagicus*. The distribution pattern of small reticulofenestrids in the borehole (Fig. 4E) has the opposite trend of *C. pelagicus*. This confirms more stable conditions during the NN4/lower NN5 and the shallowing trend in the upper NN5.

Cyclicargolithus floridanus (Fig. 4F) occurs in all investigated samples from the borehole. Shcherbinina (2010) considered that *Cyclicargolithus* genera point to eurytopic conditions and usually adapts to a large spectrum of paleoenvironmental conditions. Auer et al. (2014) interpreted the increased amount of *C. floridanus* as a result of reduced upwelling conditions. Melinte-Dobrinescu & Brustur (2008) investigated Oligocene/Miocene calcareous nannofossils from the Eastern Carpathians (Romania) and concluded that higher percentages of *C. floridanus* indicate warmer and stable climate conditions.

This cosmopolitan species participates in the whole nannoplankton assemblages from 3.01 % to 32.00 % (mean value 8.21 %) in the lower part of the borehole (140 m–590 m). In the upper part (38 m – 130 m) the mean value decreased to 3.89 % (min. 2.67 %; max. 5.67 %). A slight increase in

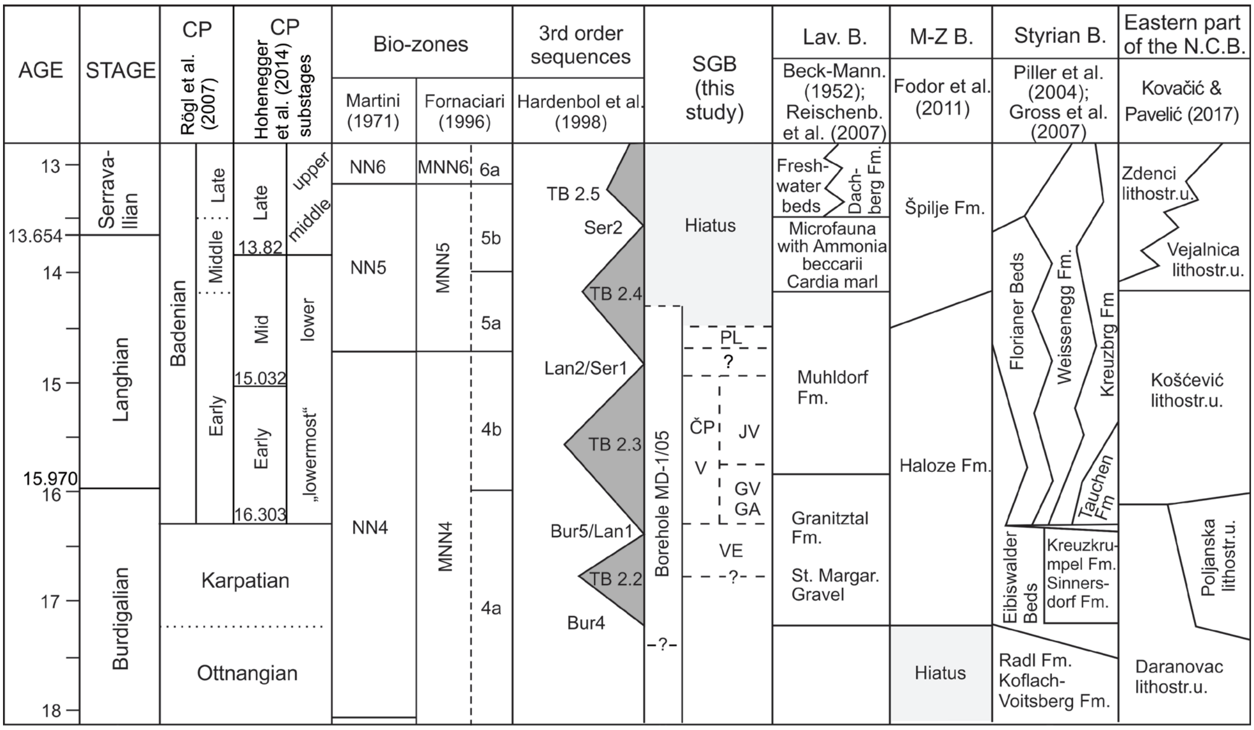

Fig. 10. Stratigraphic time scale and correlation of investigated sections in the SGB with the global 3rd order sequences, and with formations of the surrounding basins (Lav. — Lavanttal; M–Z — Mura–Zala; N.C. — North Croatian) for Ottnangian, Karpatian and Badenian in the Central Paratethys; lithostr.u. — lithostratigraphic unit.

the lower part of the borehole (NN4, lower NN5) points to relatively stable paleoconditions, whereas the decrease in the upper part (upper NN5) indicates a shift to a more unstable, more turbulent environment in the upper part.

Discoasters belong to the K-strategists group, and are generally common in oligotrophic, warm, and deep oceanic water, and point to stable paleoenvironments (Aubry 1992; Lohmann & Carlson 1981; Young 1998). Low percentages of these forms, which do not exceed 1 %, point to a eutrophic sedimentation milieu close to the coast.

Helicosphaera waltrans, present in the upper part of the borehole, is usually correlated with a warm surface water layer and a change from estuarine to anti-estuarine circulation (Holcová et al. 2018), which could point to the beginning of the isolation of the SGB.

Depositional sequences and correlation

Sedimentation in the SGB is the temporal and partly facial equivalent of the surrounding basins. Its initial Early Miocene evolution reflects the syn-rift phase of the PBS evolution (Royden 1988; Tari et al. 1992).

Lower Miocene (Ottnangian–Karpatian?)

Initial sedimentation in the SGB is represented by breccia and conglomerates with big limestone blocks. These terrestrial deposits, considered to accumulate along steep slopes as talus deposits, most probably represent rock-fall breccia, partly redeposited, and mixed with alluvial fan sediments. They represent nonmarine (limnic/fluvial) environment. Their age is uncertain due to the lack of faunal evidence; therefore, the Ottnangian to Karpatian age is presumed. An important phenomenon for correlation is the occurrence of the coal layer at the depth of around 1026 m in the MD-1/05 borehole. In similar limno-fluvial coarse-grained sediments lignite remains and seams are found also in the Ottnangian of the Styrian Basin (Hohenegger et al. 2009). The coal bearing layers were found in other parts of the Central Paratethys as well (Vass et al. 1979, 1999; Sachsenhofer 1996; Kováč et al. 2017b). Muddy breccia and conglomerates were also found in the Mura–Zala Basin (Fodor et al. 2011), but in the shallow marine environment. In North Croatia, rock-fall breccia and conglomerate are equally interpreted as Lower Miocene talus and alluvial fan deposits, deposited in a continental sedimentary environment (Pavelić & Kovačić 1999, 2018).

Karpatian

The deposition of coarse-grained sediment continued in the marginal parts of the SGB in the Karpatian. The high-energy terrestrial deposits are similar to those from the Lower Miocene. Comparable limnic-fluvial Karpatian sediments are known from the Lavanttal Basin as Margarethen Gravel (Beck-Mannagetta 1952; Reischenbacher et al. 2007).

The Karpatian events were marked by the establishment of the east–west trending sea-way from the Central Paratethys to the Mediterranean via Slovenia, following the contours of the Mid-Hungarian Line (Sant et al. 2017). According to Jelen et al. (2008), the Karpatian sediments in Slovenia represent the infill of the accommodation space, established due to E–W to NE–SW directed back-arc extension and rifting. Some authors attribute the initial rift phase of the PBS to the Karpatian (17.5–16.5 Ma) opening of pull-apart basins at the margins of the Pannonian basin, and pure extension to the Badenian (16.5–14 Ma) (Royden et al. 1983; Horváth 1993; Csontos 1995; Huismans et al. 2001). In the model of Trajanova (2013), the origin of the SGB is presumably of pre Karpatian age, developed initially along local faults related to the E–W opening of the Labot fault; its initiation is not considered to be a pull-apart basin, but as an Early Miocene rifting related extensional basin developed on the passive margin, like the Pohorje intrusion. Despite differences in the interpretations, it is clear that transgression reached several newly established basins, including the SGB, already in the Karpatian. This stage is correlated to the sea-level cycle TB 2.2 of Haq et al. (1988).

The Karpatian transgression to the SGB followed, which affected the Mura–Zala (Fodor et al. 2011) and the Styrian Basins, where marine fine-grained sediments predominate (Hohenegger et al. 2009), pointing broadly to the eastward deepening of the sea. According to Rögl et al. (2007), this transgression influenced mostly the western part of the PBS.

According to the provenance analyses of the Karpatian sediments, significant amounts of the rock material was derived from the lithic recycled orogen, corresponding to the Austroalpine units (Ivančič et al. 2018). The latter formed a hilly area in the Egerian (Frisch et al. 1998), and mostly remained dry land throughout the SGB filling up. At that time, the Pohorje tectonic block is considered to occur north of its present position and granodiorite intrusion was still not exposed to erosion (Trajanova 2013). Strong inflow is documented from the uplifting Northern Karavanks. Based on the Eisenkappel tonalite pebbles, individual sediment influx pulses are recorded from the Periadriatic fault zone. Abundant clasts of carbonate rocks indicate that the Southern Alps were partly unroofed, which enabled sediment delivery also from the south (Fig. 9A). The Karpatian transgression established a new connection with the Mediterranean basin via the Trans-Tethyan-Trench-Corridor (Bistricic & Jenko 1985; Rögl 1998). According to the paleogeographic reconstruction of the Central Paratethys (Kováč et al. 2017a), the corridor ran south of the SGB (Fig. 9).

Karpatian/Early Badenian boundary

Contact of the Karpatian and Early Badenian sediments cannot be traced on the surface in the SGB; however, it has characteristics of a short break in sedimentation in the borehole MD-1/05 (Fig. 5). The regression stage is characterized by deposition of conglomerate, marlstone, and sandstone. Localized equivalents of this succession occur in the westernmost part of the basin at localities Leše and Holmec, where the abandoned coal mines are located (Mioč & Žnidarčič 1983). Coal layers originated in a fresh water environment (Gostiša et al. 1984), which marks the most notable turnover in the sedimentation environment.

Continuous sedimentation from Karpatian to Lower Badenian has equally not been found in the Central Paratethys yet (Harzhauser & Piller 2007). Hence, we consider the Karpatian–Early Badenian contact in the SGB as discontinuity (Fig. 5). A very prominent and well known erosional discontinuity is exposed south of Leibnitz, in the old brickyard of Wagna (Spezzaferri et al. 2002, 2004; Gross et al. 2007; Rögl et al. 2007). Sea-level drop at the Karpatian/Badenian boundary is recorded in the entire Central Paratethys (Rögl et al. 2002), and is considered a consequence of global events and regional tectonics, which caused the uplift of separate crustal blocks in the PBS (Horváth 1993; Pavelić 2005). The regression stage in the SGB (Fig. 10) could be related to the Bur5/Lan1 of Hardenbol et al. (1998). On the other hand, in semi-enclosed basin it is important to take into consideration the local tectonic processes, therefore the boundary cannot coincide with the global sequence boundary (Kováč et al. 2018) and is most probably closely related to the boundary after Hohenegger et al. (2014), which is positioned at 16.303 Ma (Fig. 10).

Early Badenian

The base of the Badenian flooding is characterized by deposition of sand and gravel in most of the Central European basins; the sediments frequently contain admixtures of reworked fossils (Sant et al. 2017). The first Badenian transgression stage was relatively short and indicates interplay of the tectonic uplift and eustatic sea-level rise (Pavelić 2005). In the SGB, this stage corresponds to the NN4 Zone, and correlates well with the first Badenian transgression of the Central Paratethys. There is evidence of rapid deepening from the shallow water to offshore environment. In the northwestern part of the SGB, coal layers were covered with brackish and marine sediments (Gostiša et al. 1984). Corallinacean (lithothamnium) limestone and calcareous nannofossils show evidence of stable paleoconditions in the central part of the SGB. On the margin, increasing quantity and variety of allochemical components evidence transgression until the highstand system tract (HST) (Figs. 5, 9C), correlated with the global 3rd order cycle TB 2.3 (Fig. 10). It is suggested that advanced rifting and extension widened lowland area along the Labot fault (Trajanova 2013) therefore enabling ingression of the sea into the Lavanttal Basin from the south (Fig. 9C), and formation of a marine embayment. Local more frequent alternation of marine and non-marine environment (V section) is presumably a reflection of inflows into the shallow sea and of near-shore paleomorphology.

The Early Badenian transgression in the SGB is temporal and partly facies equivalent to the transgression recorded in the surrounding basins of the PBS: Mura–Zala, Styrian, Lavanttal, North Croatian (e.g., Reischenbacher et al. 2007; Ćorić et al. 2009; Hohenegger et al. 2009; Fodor et al. 2011; Pavelić & Kovačić 2018). Similar evolution is found in the Lower Badenian Mühldorf formation of the Lavanttal Basin, expressed by deltaic-estuarine offshore transition, shoreface, and lagoon (Reischenbacher et al. 2007). Gilbert-type fan deltas, determined in the GV section of the SGB, also formed in the North Croatian Basin, and offer a proof for the existence of coastal area during the earliest Badenian (Pavelić 2005). A lagoonal environment existed at the same time in the SGB. The *Terebralia lignitarium lignitarium*, and oyster shells were found, but they are not indicative for biostratigraphic subdivision. Similar fauna was determined on the northern margin of the Oberpullendorf Basin (north-west of the Styrian Basin) within the Middle Badenian (Harzhauser et al. 2013).

Regression after the HST is correlated to the expansion of the East Antarctic ice sheet (Flower & Kennett 1993; Shevenell et al. 2004), and corresponds to the Lan2/Ser1 sequence boundary (Piller et al. 2007) (Fig. 10). This event is recorded as deposition of sandstone above conglomerates in the SGB sedimentary succession and as reduced diversity and quantity of allochemical components.

The main delivery of the sediment to the SGB was from the north-west, and west (Ivančič et al. 2018). Tonalite pebbles, up to 50 cm in size, testify that the Periadriatic fault zone was its proximal hinterland, which delivered much more sediment to the SGB in the Early Badenian than in the Karpatian. This reflects relatively rapid uplift and exhumation of the Eisenkappel igneous belt. It was not possible to identify sediment delivery from the Southern Alps. The sediment provenance and environmental characteristics in the Early Badenian are a sign of a direct connection of the SGB with the Lavanttal basin (Reischenbacher et al. 2007). The first Badenian transgression probably formed an embayment in the direction of the Klagenfurt Basin as well (Fig. 9C).

Late Early Badenian

This period is characterized by the third transgression in the SGB, the second in the Badenian, correlated with the cycle TB 2.4. It is defined by the occurrence of *H. waltrans*, which is significant for the base of this transgression (Holcová et al. 2018). At that time, the main extensional phase in the PBS was still in progress (Royden et al. 1982). Sea ingression into the SGB and sea level oscillations are marked by the occurrence of dark sediments indicating changed conditions with abundant flora, which caused frequent changes in the near-bottom oxygenation. Sedimentation took place in more quiet conditions, as reflected in deposition of fine-grained sediments. The calcareous nannoplankton assemblages argue for an unstable environment, more turbulent paleoconditions, and shallowing of the sea water. Their age is correlated with the NN5 Zone. Co-occurrence of the NN5 Zone in the Lavanttal Basin and SGB points to the existence of the sea connection between the two basins, suggesting a northward trending embayment.

Contemporary sedimentation is recorded in the Styrian (Hohenegger et al. 2009), Northern Croatian (Ćorić et al. 2009; Brlek et al. 2016; Pavelić & Kovačić 2018), Mura–Zala (Fodor et al. 2011) and Lavanttal basins (Reischenbacher et al. 2007). Marine sedimentation continued into the Middle Badenian in all the stated basins, but ceased in their shallower peripheral parts, in the SGB, and in the Lavanttal Basin, after the late Early Badenian. Deposition of clayey material with coal layer continued without break on the top of the NN5 zone in the MD-1/05 borehole, which marks the end of the Miocene sedimentation in the SGB. After the break, sedimentation in the SGB continued in a fluvial regime in the Plio-Quaternary.

This late Early Badenian regression could be correlated to a sea-level drop in the upper part of the Upper Langhian (sequence boundary 2 (SB2), Fig. 10) (Strauss et al. 2006). SB2 is correlated with the first Antarctic cooling step at 14.2 My (Shevenell et al. 2004). This event is not expressed globally and could be confined to the Central Paratethys only (Rögl et al. 2007).

Post Early Badenian

Absence of the Middle Badenian and younger sediments in the SGB was the result of several contemporaneous events. Apart from the sea-level drop, additional reasons for the cessation of sedimentation could be interrupted connection of the SGB with the surrounding basins around the end of the Lower Badenian. It was presumably caused by the uplift and exhumation of the Pohorje tectonic block, and its oblique shift and rotation along the Labot fault (Trajanova 2011, 2013). Uplift of the Pohorje tectonic block, and its synchronous counter-clockwise rotation (Márton et al. 2006) gradually cut the connection of the SGB with the Lavanttal basin to the north, and with Mura-Zala and Styrian Basins to the north-east and south-east (Trajanova 2011, 2013) (Fig. 9D). Erosion of the Miocene sediments started and led to thickness reduction and the absence of Karpatian and Lower Badenian sediments on the fold hinges. A synchronous erosional event can also be traced in the shallower parts of the North Croatian Basin (Avanić 1997; Pavelić 2005).

Conclusions

The evolution of the SGB is correlated to the evolution of the PBS. The sedimentary successions record three transgression-regression cycles, which generally correspond to the global 3rd order sequences.

- The evolution of the SGB started in the Lower Miocene, in the terrestrial environment of the Ottnangian/Karpatian with deposition of talus and alluvial fan sediments.
- The first transgression of the cycle TB 2.2 followed, correlated to the NN4 Zone.
- Regression stage at the Karpatian/Badenian boundary is correlated to the Bur5/Lan1. Sedimentation took place in a terrestrial environment.
- The second transgression in the SGB occurred in the Early Badenian initiated in a transitional environment with simultaneous deposition of lagoonal and deltaic sediments.

Transgressions reflected in gradual increase in variety and quantity of marine microfossils until the HST, when the entire area of the SGB was flooded. This transgression is correlated to the TB 2.3 cycle. The calcareous nannoplankton assemblages indicate stable paleoconditions of the water column.

- The following regression is correlated to the Lan2/Ser1 sequence boundary.
- The second Badenian transgression is correlated to the global sea-level rise and corresponds to the TB 2.4 transgression cycle. The calcareous nannoplankton assemblages demonstrate unstable paleoconditions with shallowing trend of the sea water, and turbulent environment. Assemblages with domination of *C. pelagicus* are a sign of shallow, nutrient rich paleoenvironment.
- The diminishing of the basin is marked by deposition of clayey, coal bearing sediments, and is correlated to the SB2.
- Based on investigations of calcareous nannofossils, the Mediterranean zones MNN4a, MNN4b and MNN5a were identified. The connection with the Mediterranean region was established during NN4 (MNN4a), and probably interrupted in regression stages between the Karpatian/Early Badenian and NN4 Early Badenian/NN5 Early Badenian, and finally interrupted in the upper NN5 (MNN5a).
- No younger sediments were recorded in the basin, which indicates cessation of sedimentation in the late Early Badenian and subsequent erosion prior to the onset of the Pliocene–Quaternary fluvial sedimentation.

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