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Correlation of bio- and magnetostratigraphy of Badenian sequences from western and northern Hungary

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Abstract: Lithological, magnetostratigraphic and paleontological (nannoplankton, foraminifers, molluscs) studies were carried out on the Badenian successions of boreholes Sopron-89, Nagylózs-1 and Sáta-75 in Hungary. The correlations with the ATNTS2004 scale show that the Badenian sedimentation began during Chron C5Br thus the earliest Badenian deposits are missing in the sections. The first occurrence of *Orbulina suturalis* Brönnimann has been observed in Subchron C5Bn.1r, at 14.9 Ma. Although it is older than the interpolated age of 14.74 Ma in Chron C5ADr in the ATNTS2004, it is consistent with the age of 15.1 Ma obtained from recent calibration of planktonic foraminiferal bioevents. The base of the Bulimina-Bolivina Zone has been determined at 13.7 Ma in Chron C5ABr, and the Badenian/Sarmatian boundary is recorded within Chron C5AAn, at 13.15 Ma.

Key words: Middle Miocene, Badenian, Paratethys, Pannonian Basin, Eisenstadt-Sopron (Sub-)Basin, biostratigraphy, magnetostratigraphy.

Introduction

The threefold Badenian stage, based on planktonic foraminifers, was introduced by Papp & Cicha (1968). Although the Badenian sediments are widespread in the Central Paratethys, the exact age of its boundaries and biozones has been under debate. Concerning the biostratigraphy, a basic trouble is that the benthic foraminiferal zones of Grill (1941, 1943) have also been used, though the relationship between the benthic and the planktonic zonations has not been established. Dozens of studies on Badenian sediments and stratigraphy have been published during the past decade, and the results are summarized in Kováč et al. (2007), and relevant references herein.

Kováč et al. (2007) subdivided the Badenian into two parts: Early and Late Badenian, and it is also proposed by Hohenegger & Wagreich (2011). In this study we follow this twofold subdivision because many biostratigraphic (nannoplankton and planktonic gastropod) data from the Hungarian deposits support it.

Magnetostratigraphic studies are scarce on Badenian sequences. Paleomagnetic directions in the Grund Formation were measured from seven surface outcrops in the Vienna Basin System and the Molasse Zone, and all display a single polarity interval for the Badenian sediments (Scholger & Stingl 2004). The sections of the Wagna and Retznei quarries (Styrian Basin) contain several polarity zones which were assigned to the distinct chrons of the time scale between 16.6 and 14.3 Ma by means of biostratigraphic markers (Hohenegger et al. 2009). Due to several sedimentary gaps and the fact that large parts of the reversed polarity zones are not represented in the sections, the correlations, however, are questionable. A magnetostratigraphic study has been published from Badenian sediments of the P-3 borehole near Zbudza, East Slovak Basin (Túnyi et al. 2005). The polarity zones of the section were correlated with the polarity time scale in two variants, but none of them fits with the biostratigraphy as described in Kováč et al. (2007).

Several attempts have been made to date different horizons by sequence stratigraphy or cyclostratigraphy lacking any true age control. The ages obtained in this way can be useful but should be considered only approximate. Sequence stratigraphy is effective for correlations providing stratigraphic time lines but it cannot give ages itself, and identification of a sequence boundary with a dated but widely separated horizon may be uncertain. Cyclostratigraphy can give ages in ideal cases, but the accumulation in reality is not strictly uniform, therefore independent time control is necessary for a correct age.

The Geological Institute of Hungary drilled a series of continuously cored stratigraphic test holes to investigate the correlation and dating of the Middle and Late Miocene strata in the Pannonian Basin. Detailed lithological, paleontological and paleomagnetic studies were carried out on the cores. Four holes penetrated Badenian deposits: Berhida-3, Sopron-89, Nagylózs-1 and Sáta-75. The Berhida-3 borehole, located southeast of the Bakony Mts, is the only published section, its polarity zones were correlated with the geomagnetic time scale from 17 to 7 Ma (Kókay et al. 1991). The correlation, however, is debatable (Vass 1999) due to several gaps in the sequence. This section is being studied at present (Kókay pers. comm. 2010), and has been excluded from the recent study.

During the evaluation of the samples from the boreholes the Geological Institute of Hungary was cut back and due to its complete reorganization all stratigraphic researches were broken off. The new publications on Badenian deposits in the past decade inspired us to continue the investigations and complete the description of the Hungarian Badenian sections and their correlations. Preliminary results were reported by Nagymarosy et al. (2005). We present here the results of magnetostratigraphic and paleontological studies on the Badenian sediments in Sopron-89, Nagylózs-1 and Sáta-75 boreholes and propose their joint correlation with the time scale.

Geological setting and stratigraphy

The three boreholes were drilled in the northern part of the Pannonian Basin (Fig. 1). Lithological descriptions have been abstracted primarily from geological records kept by the National Archive of the Hungarian Office for Mining and Geology.

North-west Hungary

Borehole Sopron-89 and Nagylózs-1 are located in the vicinity of the Sopron Mts. After a continental fluvial and brackish-water sedimentation in the Early Miocene, a rapid subsidence and transgression occurred in the area during the Early Badenian. Due to tectonic movements in this period fault structures of approximately N-S direction came into being in the eastern forelands of the Sopron Mts and the western part of the Kisalföld (Danube Basin). East of the Csapod Trough an elevated high, i.e. the Mihályi Ridge separated the study area from the Kisalföld (Danube Basin) depocenter.

Pelitic sediments of Badenian age are known in the area of Sopron (under the town) as well as N, S and E of it (in the surroundings of Balf). The thickness of these sediments may reach 400 m in the vicinity of Sopron. Towards the Fertőrákos-Rust Ridge (Fertőrákos-Ruster Hügelland) the thickness decreases and the fine-grained siliciclastic sediments are replaced by coralline limestone-calcareous sand and sandstone.

The Sopron borehole is located in the Eisenstadt-Sopron (Sub-)Basin; Miocene formations are of the same facies here as those of the Vienna Basin, since this area was a satellite sedimentary basin of the Vienna Basin (Rasser & Harzhauser 2008).

According to seismic profiles and gravity measurements (Magyar, pers. comm.; Šefara & Szabó 1997) the Nagylózs-1 borehole penetrated the succession of a small Miocene trough between two smaller tectonic highs which are located in the area between the Fertőrákos-Rust Ridge and the Mihályi Ridge, and runs parallel to them. The Nagylózs area may have been a deeper, rapidly subsiding zone with considerable siliciclastic sedimentation during the Badenian, whereas in the surroundings of the Leitha Mountains gravels, sands and coralline algae limestones ("Leithakalk") are more frequent.

At the Badenian/Sarmatian boundary a significant sea-level fall occurred. This has been correlated to the Ser 3 sequence boundary in Strauss et al. (2006). A considerable erosion took place along the basin margins, however, a hiatus can also be traced throughout the basinal areas.

Borehole Sopron-89

It was drilled at the eastern foot of the Sopron Mts, West Hungary, between Sopron and Kópháza (Koljnof) in 1989. The Miocene core samples were studied by T. Hámor (unpublished well report). The drilling penetrated the sediments of a

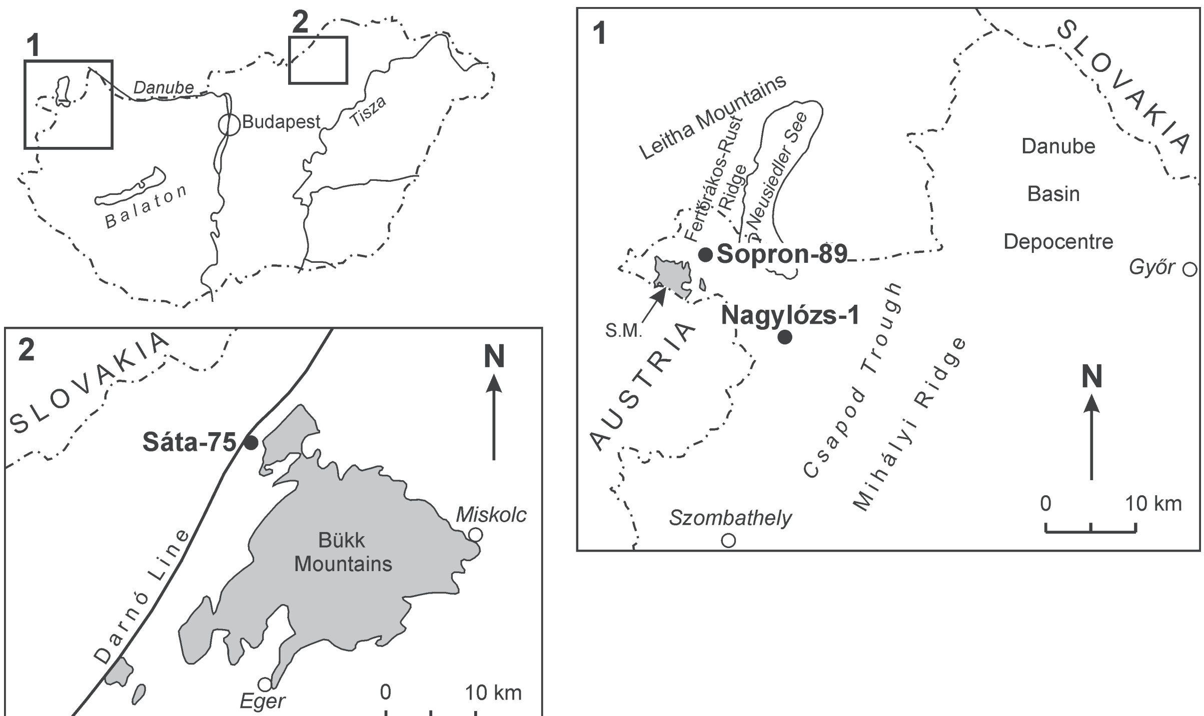

Fig. 1. Location map. **S.M.** — Sopron Mts.

sub-basin WNW of the Csapod Trough. The Paleozoic basement is overlain by the almost 200-meter-thick Badenian succession with a sharp unconformity. Its top is cut by erosion, and unconformably overlain by Quaternary sediments.

The Badenian succession (11.2–209.9 m) starts with gravel/conglomerate and pebbly sandstone beds ('Ruszt Gravel', 193.7–209.9 m), which overlie the basement with a considerable hiatus and angular unconformity (Fig. 2). The pebbles are derived from metamorphic rocks of the basement. The fine-grained, sandy-silty sediments of the Baden Clay Formation develop from these basal beds with a gradual transition. The Baden Clay Formation in the vicinity of Sopron is slightly different from the characteristic greyish-blue basinal marl and clay ("Baden Tegel") which was exposed in the stratotype locality Baden-Soos (Rögl et al. 2008), and is known as "Baden clay of schlier facies" (Vendel in Deák 1981, p. 45). Nevertheless, it was classified into this lithostratigraphic unit. Above the basal pebbly beds the lower part of the succession comprises some pebbly sandstone interbeddings with a thickness of some tens of centimeters, and small fining-upward cycles can be observed. The pebbly-sandy-clayey silt transected between 157.1 and 158.1 m is chaotically contorted due to synsedimentary tectonic movements.

Deposition took place during the Early Badenian. Data available (Kováč et al. 1997, 1999) indicate that the transected succession represents the upper part of the Lower Badenian.

Borehole Nagylózs-1

It was drilled on the western rim of the present Kisalföld (Danube Basin) west of the deepest zone of the Csapod Trough, in 1989–90. The description has been provided by Don and Zsámbok (unpublished well report).

The Badenian succession represents a complete sedimentary cycle. The lowermost — approximately 30-meter-thick part of the Badenian sequence (1304.2–1335.2 m) is made

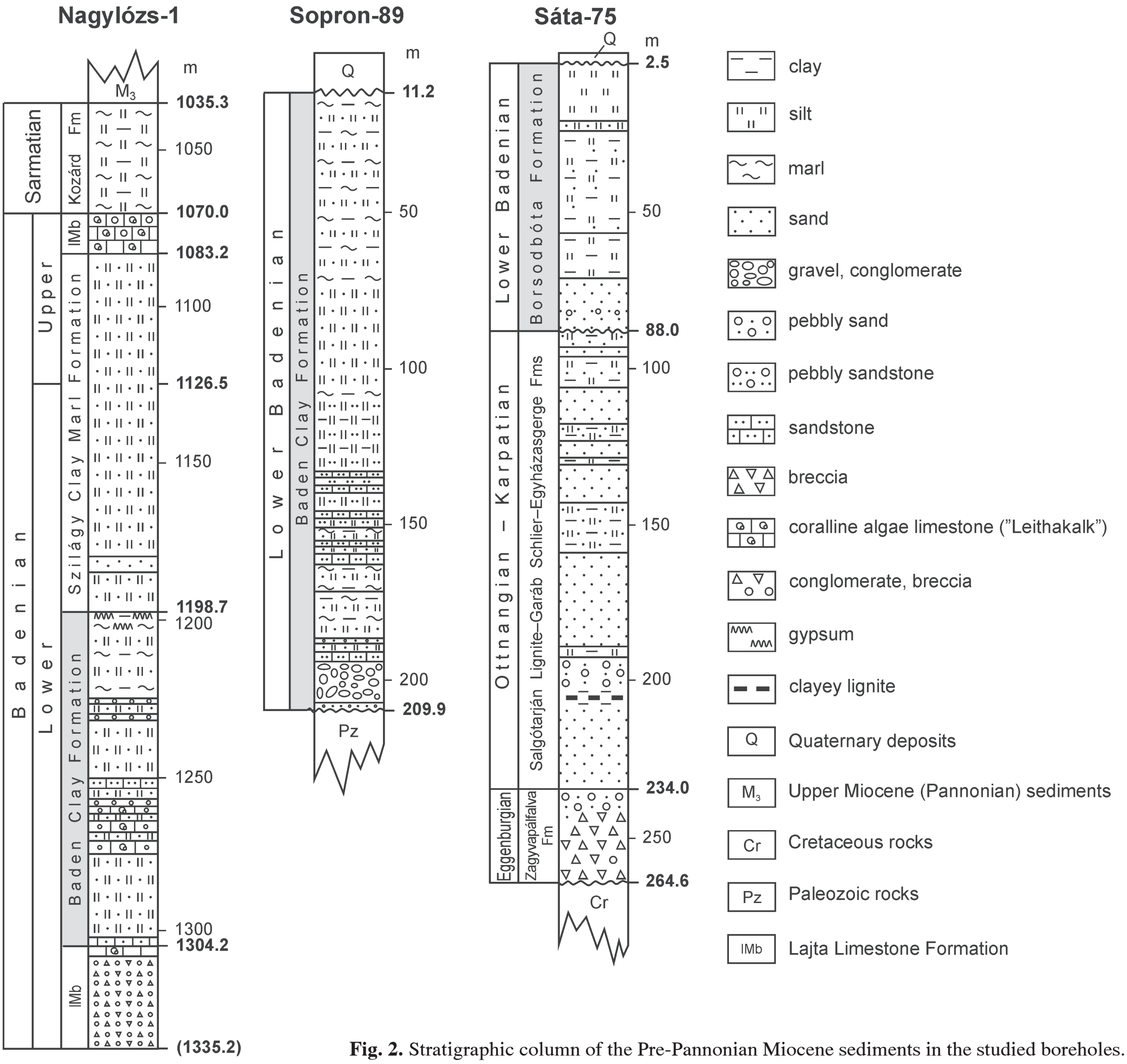

Fig. 2. Stratigraphic column of the Pre-Pannonian Miocene sediments in the studied boreholes.

up of conglomerate and breccia beds the material of which is derived from the crystalline basement and from the formerly deposited fluvial sequence. In the upper part of the pebbly basal beds coralline algae limestone (Lajta Limestone Formation) intercalations can be observed; according to their stratigraphic position they were formed in the Early Badenian. Pebbles and clasts from the crystalline basement are also frequent in these coralline algae limestones.

The calcareous-coarse-grained deposits are overlain predominantly by siliciclastic sediments of a thickness of more than 200 m (Fig. 2). From 1198.7 to 1304.2 m "schlier-like" sediments (sandy silt, silty sand) were transected, which are equivalent to the Baden Clay Formation. The presence of the 0.3–3.5-meter-thick coralline algae limestones and calcareous conglomerate interbeddings can be explained by gravitational re-deposition on the submarine slopes, triggered by the tectonic movements in the area during the Early Badenian. Gravitational re-deposition in this section (1256.1–1276 m) is confirmed by the scatter and shallowing in inclination.

The upper boundary of the Baden Clay Formation was drawn approximately at the top of the layer the upper part of which is characterized by thin gypsum and gypsum-bearing dolomite interbeddings and strips (at a depth of 1198.7 m (10-cm-thick) and 1201.4 m (25-cm-thick)). The sandy silt and micaceous fine-grained sand (Szilágy Clay Marl Formation, 1083.2–1198.7 m) were deposited during the late Early and the Late Badenian.

Coralline algae limestones occurring again in the upper part of the Badenian sedimentary cycle (1070.0–1083.2 m) indicate the prograding carbonate ramp towards the basin. This refers to the relative decrease of water level. The Badenian sequence ends with pebbly limestone, coralline algae-bearing calcareous sandstone and conglomerate with fine siliciclastic interbeddings.

The Sarmatian succession starts with a 1.5-centimeter-thick gravel bed. Upwards pelitic sediments can be observed (Kozárd Formation), with a 1 mm-thick dacite tuff interbedding at a depth of 1044.8 m.

North-east Hungary — W Borsod Basin, borehole Sáta-75

The basement of the area is made up of the north-western extensions of the Paleozoic and Mesozoic rocks of the Bükk Mountains, the eroded surface of which is overlain by Miocene formations. These formations can be followed along the Darnó Line, with a NE-SW strike (Fig. 1). The Lower Miocene is represented by fluvial and marsh sediments, and is overlain by Karpatian marine deposits: near-shore–coastal plain pebbly sand and schlier. In the southern part of the area Lower Badenian pelitic sediments overlie the Karpatian schlier conformably, whereas in the North a considerable hiatus can be detected between them. Miocene successions comprise volcanic rocks. The close vicinity of borehole Sáta-75 may have been an uplifted area during the Miocene.

Borehole Sáta-75 was drilled in NE Hungary, in the western part of the Borsod Basin in 1989, and a description has been given by Radócz (unpublished well report; 2004).

The basal beds (234.0–264.6 m) of the Miocene succession are built up of terrigenous grey sand and pebbly sand and basal breccia with clasts derived from the Mesozoic basement, presumably of Eggenburgian age (Zagyvapálfalva Formation).

The Ottnangian and Karpatian beds were penetrated from 88.0 to 234.0 m (Fig. 2). An exact boundary between the two stages cannot be precisely drawn. The Ottnangian succession is made up of sand, pebbly sand and clayey silt intersected by clayey brown coal, coaly clay and huminitic silty sand layers. The succession represents a paralic environment and belongs to the Salgótarján Lignite Formation.

The Karpatian part of the succession is made up predominantly of clayey silt with sand interbeddings. The fine-grained sediments (Garáb Schlier Formation) contain molluscs and foraminifers. From 159.8 to 189.7 m grey, calcareous sand with scattered, small pebbles can be found (Egyházasgerge Formation). However, Karpatian age has not been definitively confirmed, the beds have been classified into this age mainly on the basis of lithostratigraphic considerations.

The Lower Badenian is bounded by unconformities: the uppermost part of the Lower Badenian has been cut by erosion, and at its base (88.0 m) a tectonic contact is presumed between the Karpatian and Lower Badenian successions: several structural features were observed during the evaluation of the sequence, which may have significantly reduced the real thickness of the Badenian. Some Lower Badenian successions drilled in the close vicinity of borehole Sáta-75 are more complete; their thicknesses are often twice as large as in the Lower Badenian succession of Sáta-75.

The Lower Badenian section (Borsodbóta Formation) is dominated by clayey silt and (tuffaceous) sandy silt comprising *Bathysiphon* and holoplanktonic gastropod (pteropods) remains (2.5–76.7 m). The lower part (76.7–88 m) is characterized by sand and tuffaceous, pebbly sand.

Pyroclastics within the Badenian marine succession can be related to the Early Badenian rhyolite tuff explosion, the K/Ar age of which is 14.8 ± 0.3 Ma (Bohn-Havas et al. 1998; Radócz 2004). The "Middle Rhyolite Tuff" is present only in the form of thin tuff strips within the following sections: 22.1–22.6 m tuff intercalation; 50.0–58.0 m and 71.0–88.0 m — dust tuff and tuffaceous silt/sand interbeddings. K/Ar datings have been carried out on pyroclastic samples derived from boreholes in the vicinity of Sáta-75, and the K/Ar age mentioned is considered to be an average value for the time of the tuff explosion.

Biostratigraphy

The following description contains only the most important or stratigraphically significant foraminiferal and mollusc taxa, the complete faunal list can be found in Bohn-Havas et al. (2007) in 12 pages.

Sopron-89 borehole

Calcareous nannoplankton

Samples between 112.0 and 208.0 m contained no nannofossils, although the lithofacies and the marine character of the sequence would mean no controversy to find nannoplankton in this interval.

Nannoplankton assemblages with medium diversity and abundance occurred between 20.0 and 112.0 m. The interval belongs to the NN5 nannoplankton Zone based on the almost continuous presence of *Sphenolithus heteromorphus* Deflandre and the lack of *Helicosphaera ampliaperta* Bramlette & Wilcoxon. This biostratigraphical position is also confirmed by the presence of *Discoaster exilis* Martini & Bramlette and *Discoaster musicus* Stradner.

Foraminifera

Foraminifers were studied from 21.0 to 190.1 m in the borehole, and 37 samples were collected at 4–5 m intervals. Between 105.3 and 190.1 m agglutinated taxa of low diversity and abundance are predominant, such as *Bathysiphon filiformis* M. Sars, *Haplophragmium pseudospirale* Williamson, *Martinottiella communis* d'Orbigny, accompanied by sporadic *Globigerina* sp. (Fig. 3). Besides the agglutinated taxa *Paragloborotalia mayeri* (Cushman-Ellisor) appears at 105.3 m, and the *Globigerina* species become more frequent.

In the interval from 21.0 to 59.0 m the diversity and abundance of *Globigerina* and *Globigerinoides* increase, in addition two biostratigrafically significant species appear, the *Uvigerina macrocarinata* Papp & Turnovsky at 55.0 m, and the *Orbulina suturalis* Brönnimann at 50.0 m.

The *Paragloborotalia mayeri*, *U. macrocarinata* and *O. suturalis* occur together in the interval from 21.0 to 50.0 m, therefore the sediments between 21.0 and 59.0 m may have been deposited during the late Early Badenian (Cicha et al. 1998; Rögl & Spezzaferri 2003; Ćorić et al. 2004, 2009).

Molluscs

Macrofaunal studies have been carried out from the section between 21.0 and 171.0 m. Molluscs have been found only in the clayey, silty, sandy deposits from 21.0 to 109.0 m, and besides molluscs echinoids were frequent accompanied by trace fossils, coral and worm remains. The alternating sandy silt, sandstone and conglomerate layers between 109.0 and 171.0 m comprise only trace fossils.

In the silty sand and sandstone layers between 67.1 and 109.0 m (8 samples) *Vaginella austriaca* (Kittl) has been detected above 86.0 m and very scarce, small, indet. molluscan fragments and, more frequently, trace fossils of a great variety were found.

The clayey-sandy silt succession between 21.0 and 67.1 m (72 samples) comprises a poorly preserved benthic mollusc fauna of small species and specimen number and a relatively rich planktonic mollusc fauna (Fig. 3). The predominance of pteropods such as *Limacina valvatina* (Reuss), (2.5–76.7 m) *Limacina* sp. 1, *Clio fallauxi* (Kittl), *Vaginella austriaca* (Kittl) and *Diacrolinia aurita* (Bellardi) as well as carnivorous gastropods (*Nassarius*, *Euspira*, *Trigonostoma*, *Fusus* and *Mitraefusus*) is characteristic. Bivalves occurred rarely and only fragments of them have been found.

Benthic mollusc species are of long range and occur during the Miocene, but the holoplanktonic gastropods (pteropods) in the section from 21.0 to 86.0 m are considered to be stratigraphically significant. *Clio fallauxi* and *Diacrolinia aurita* are present only in layers deposited during the Early Badenian all over the Central Paratethys realm (Janssen & Zorn 1993; Bohn-Havas & Zorn 1993, 2002).

Nagylózs-1 borehole

Calcareous nannoplankton

The basal coarse-grained sediments contained no nannofossils. Between 1297.0 and 1301.0 m nannofloras with medium diversity occurred containing a few specimens of the diagnostic taxon *Sphenolithus heteromorphus* Deflandre. This taxon defines the nannoplankton Zone NN5, because *Helicosphaera ampliaperta* Bramlette & Wilcoxon was missing. *S. heteromorphus* becomes quite rare above 1297 m, and its highest stratigraphic position is at 1126.5 m, defining the boundary of the NN5/NN6 Zones. Samples of the Baden Clay Formation yielded euhaline nannoplankton assemblages of medium diversity and abundance. This interval is one of the richest in nannofossils.

The nannoplankton assemblages above 1226 m are somewhat poorer. Abundance of *Helicosphaera kamptneri* (W.H. Hay & H. Mohler) and *Sphenolithus moriformis* (Brönnimann & Stradner) drop dramatically. The first occurrence of *Umbellosphaera irreguralis* Paasche in Markali & Paasche and *Pontosphaera discopora* Schiller at 1219 m refers to the higher part of Zone NN5. Above 1154 m both diversity and abundance of the nannofloras increase. New floral elements are *Rhabdosphaera pannonica* Báldi-Béke and *Pontosphaera multipora* (Kamptner) Roth with much higher abundances.

The Lajta Limestone Formation is the last Badenian one here. Since no specimens of the index fossil of nannoplankton Zone NN7, *Discoaster kugleri* Martini & Bramlette have been found, these beds belong to the Zone NN6 too.

Although basal Sarmatian beds still contain a few marine species such as *P. multipora*, *Cyclococcolithus macintyrei* Bukry & Bramlette, *Reticulofenestra pseudoumbilica* (Gartner), *Reticulofenestra haqii* Backman, the predominance of *Braarudosphaera bigelowii* (Gran & Braarud) indicates fluctuating salinity if not brackish conditions.

Foraminifera

The foraminiferal fauna was investigated in 67 samples from the Middle Miocene deposits from 1022.9 to 1303.2 m. The alternating silty and coralline algae limestone layers between 1231.6 and 1303.2 m contain rich planktonic and benthic fauna. In the silty sediments the globigerine taxa are predominant among the planktons, *Globigerina bulloides* d'Orbigny and *Globigerinoides trilobus* (Reuss) are abundant, as well as some other *Globigerina* species, which cannot be determined exactly because of the strong encrustation and fragmentary preservation of the specimens. The first occurrence of *Orbulina suturalis* Brönnimann has been detected at 1295.0 m, and was represented by a few single specimens upward.

The *Uvigerina semiornata semiornata* d'Orbigny and *U. semiornata urnula* d'Orbigny are the predominant benthic

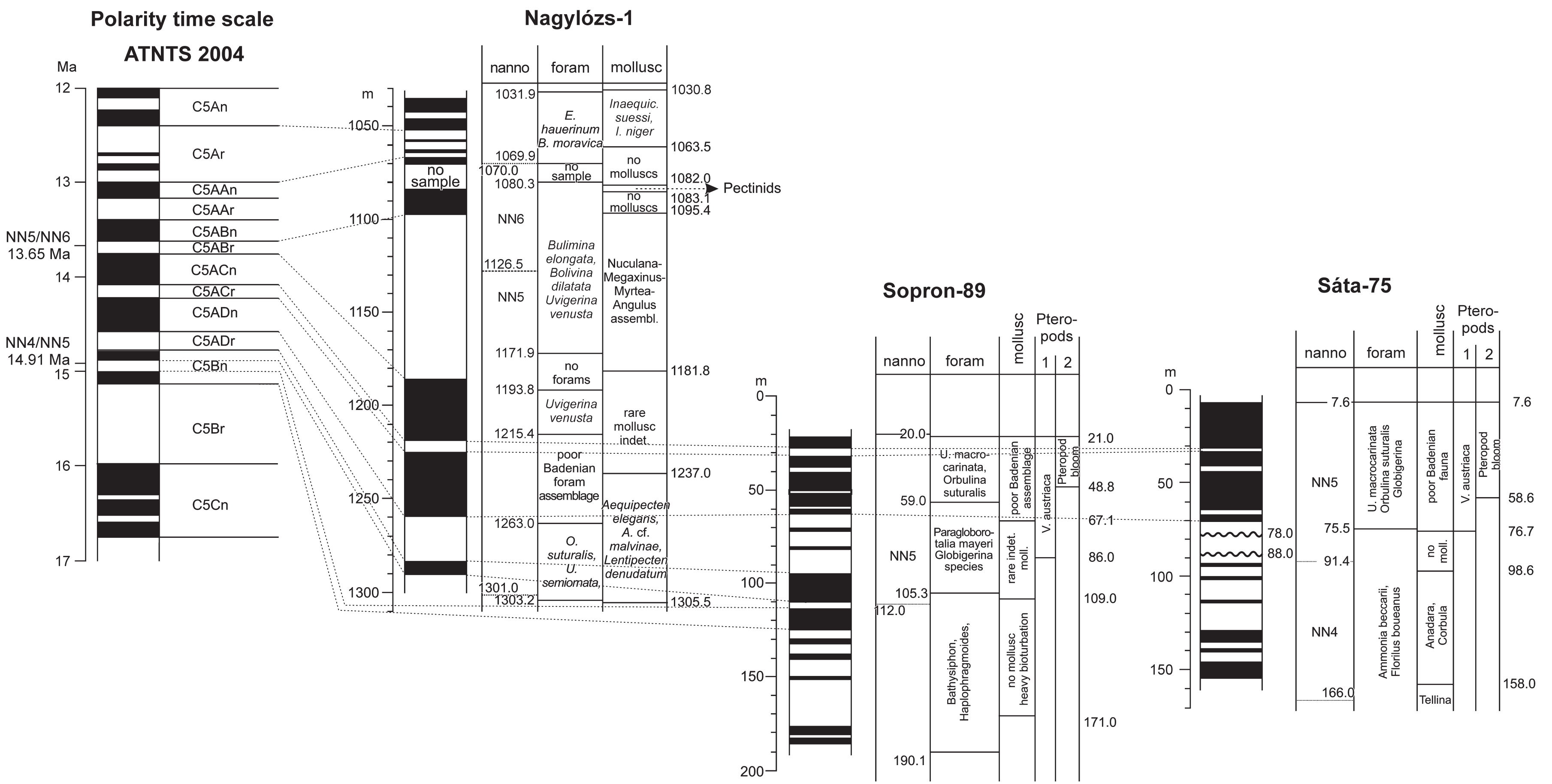

Fig. 3. Magneto- and biostratigraphic correlation of Badenian sediments in Nagylózs-1, Sopron-89 and Sáta-75 boreholes. ATNTS2004: Astronomically Tuned Neogene Time Scale (Lourens et al. 2004a,b). **Black** — normal polarity, **white** — reversed polarity.

species here, accompanied by species that are insignificant from a stratigraphic point of view due to their long range. In the coralline algae-bearing interbeddings *Amphistegina mammilla* (Fichtel & Moll) is frequent. An intense decreasing trend in abundance and diversity have been recognized between 1248.9 and 1215.4 m, and the planktonic species disappear. Most foraminifers have been recrystallized and encrusted.

The occurrence of *O. suturalis* and the planktonic association suggests an Early Badenian age for the deposits between 1215.4 and 1303.2 m, and the younger part of Early Badenian is likely (Fig. 3).

The section above 1215.4m up to 1193.8 m is characterized by the significant occurrence of *Uvigerina venusta* Franzenau, together with a few specimens of *Asterigerinata planorbis* (d'Orbigny) and *Pseudotriloculina consobrina* (d'Orbigny). No foraminifers have been found in the section from 1171.9 to 1193.8 m.

The sediments between 1082.3 and 1171.9 m contain a *Bulimina elongata* assemblage of low abundance and varying diversity. The determination of the species is difficult because of the hard encrustation in the silty beds. Besides the *B. elongata* d'Orbigny association *Bolivina* cf. *dilatata* (Reuss), *Eponides haidingerii* (d'Orbigny), *Quinqueloculina* sp., *Fursenkoina schreibersiana* (Czjžek) taxa of low abundance have been detected. This fauna is much poorer than the fauna of the Bulimina-Bolivina assemblages reported from the Vienna Basin, and from boreholes in the Mecsek Mts and other parts of Transdanubia (Papp et al. 1978; Korecz-Laky 1987).

In the sand and silt interbeddings of the coralline algae limestone ranging from 1080.3 to 1082.3 m a great abundance of *Elphidium fichtelianum* (d'Orbigny), *E. crispum* (Linnaeus), *B. elongata* is typical, accompanied by *U. venusta*.

The joint occurrence of *B. elongata* and *Bolivina dilatata* suggests a Late Badenian age of the sediments between 1069.9 and 1171.9 m. However, the precise identification of the Early/Late Badenian boundary on the basis of foraminifers is difficult.

Foraminifers indicative of Sarmatian age appear at 1069.9 m. The *Elphidium hauerinum* d'Orbigny, *Bolivina moravica* Cicha & Zapletalová, association in the grey, silty, clayey marl from 1031.9 to 1069.9 m has been assigned to the *Elphidium hauerinum* Zone (Görög 1992). On the basis of the foregoing observations, the age of the sediments between 1031.9 and 1069.9 m are considered to be Early Sarmatian s.s., but we have to emphasize the lack of the characteristic association of the *E. reginum* Zone indicative of the basal beds of the Early Sarmatian s.s. (Görög 1992; Tóth 2009).

Molluscs

Molluscs were studied between 1030.8 and 1305.5 m. Pelitic sediments transected from 1030.8 to 1063.5 m comprise a typical Sarmatian fauna. From this section 47 samples were examined. The mollusc fauna in the coralline algae-bearing, sandy and silty beds from 1082.0 to 1305.5 m is indicative of the Badenian, and 62 samples were collected here. The Badenian molluscs (bivalves) are predominant; in certain sections coralline algae can be found in rock-forming quantities.

In the alternating, pebbly, coralline algae limestone, conglomerate, sandstone and sandy silt strata from 1237.0 to 1305.5 m, especially within 1253.8–1302.4 m, pectinids are predominant. They are characteristic of the Early Badenian according to the Hungarian zonation (Bohn-Havas et al. 1987). In the coralline algae-bearing sediments *Flabellipecten solarium* (Lamarck), *Crassadoma multistriata* (Poli), *Manupecten fasciculatus* (Millet), *Aequipecten elegans* (Andrzejowski), *Ae. macrotis* (Sowerby), *Ae.* cf. *malvinae* (Dubois) occur almost exclusively. In the sandy, silty clay beds the abundant *Lentipecten denudatum* (Reuss) is typical. No molluscs have been identified over a long section above 1237.0 m.

A significant change in the fauna has been observed at 1181.8 m: the *Nuculana*, *Megaxinus*, *Angulus* association appears. This association is frequent in the Badenian, and contains long-range species.

The interval from 1083.1 to 1095.4 m is free of molluscs, and the coralline algae limestone between 1082.0 and 1083.1 m comprises recrystallized, undetermined pectinid remnants. The silt, coralline algae limestone and sandstone strata above 1082.0 m are also free of molluscs.

The typical Sarmatian mollusc fauna appears at 1063.5 m, the striking predominance of *Inaequicostata niger* (Zhizhchenko) (=*Cardium gleichenbergense* Papp) have been noted in the clay marls, this taxon is frequent and characteristic of the Early Sarmatian s.s. It is noteworthy that the *Abra reflexa* (Eichwald) and *Inaequicostata inopinata* (Grischkevitsch) assemblage, indicating the lowermost part of the Early Sarmatian in Hungary (Bohn-Havas 1983), is missing here. Additionally, this fauna has been observed only in similar facies of the earliest Sarmatian s.l. (earliest Volhynian) in both the Carpathian Foredeep Basin and Euxine-Caspian System Basin (Grischkevitsch 1961; Kojumdgieva 1969; Studencka 1999).

A new fauna characteristic of the Late Sarmatian s.s. appears at 1049.4 m; the sediments contain small lymnocardiids such as *Inaequicostata suessi* (Barbot de Marny), *I. pia pia* (Zhizhchenko), *I. pia pestis* (Zhizhchenko) and *Obsoletiforma sarmatica* (Kolesnikov) accompanied by representatives of the genera *Musculus*, *Modiolus*, *Gastrana* and *Irus* which are common in the Sarmatian.

Summarizing the evaluation of the mollusc fauna, the age of the deposits between 1082.0 and 1305.5 m is Badenian, and between 1237.0 and 1305.5 m it is Early Badenian. The mollusc assemblages of the section from 1082.0 to 1237.0 m, however, do not allow the exact determination of the upper boundary of the Lower Badenian. Pelitic sediments between 1030.8 and 1063.5 m comprise a fauna indicating an Early and probable early Late Sarmatian s.s. age.

Sáta-75 borehole

Calcareous nannoplankton

Most samples between 178.0 and 239.6 m were free of nannofossils. Sporadic nannoplankton assemblages occurred in the samples from 235.0, 224.5 and 216.0 m, the predominant nannoplankton species of which were *Coccolithus pelagicus* (Wallich), *Reticulofenestra minuta* Roth, *Reticulofenestra* *pseudoumbilica* (Gartner) and *Reticulofenestra haqii* Backman. A few specimens of *Discoaster druggii* Bramlette & Wilcoxon also occurred at 235.0 m.

Nannoplankton assemblages between 91.4 and 166.0 m indicate Zone NN4. *Helicosphaera ampliaperta* Bramlette & Wilcoxon occurs quite permanently, while *Sphenolithus heteromorphus* Deflandre only sporadically. Although the assemblages are rather poor, *Discoaster adamanteus* Bramlette & Wilcoxon, *Discoaster variabilis* Martini & Bramlette and *Coronosphaera mediterranea* (Lohmann) Gaarder also show up.

Between 7.5 and 91.4 m the nannoplankton assemblages refer to the Zone NN5. *H. ampliaperta* is missing here, but *S. heteromorphus* has been found in almost all samples. *Coccolithus miopelagicus* Bukry, *Umbilicosphaera jafari* Müller, *Micrantholithus vesper* Deflandre, *Discoaster musicus* Stradner, *Discoaster exilis* Martini & Bramlette and *Rhabdosphaera pannonica* Báldi-Béke are typical and quite frequent elements of these nannofloras. Although their time range is longer than Badenian, they occur in pre-Badenian samples only very rarely and sporadically in Hungary.

Foraminifera

Along the section 80 samples were collected from 7.6 to 229.0 m. Two significantly distinct associations have been observed in the borehole. The foraminiferal fauna between 75.5 and 229.0 m is almost exclusively represented by a few, poorly preserved *Ammonia beccarii* (Linnaeus) and *Florilus boueanus* (d'Orbigny) taxa (Fig. 3).

In the interval from 7.6 to 75.5 m *Uvigerina macrocarinata*, *Globigerinoides trilobus*, *Globorotalia scitula*, *Orbulina suturalis* association has been identified. In the lower part of this interval up to 49.8 m, planktonic species are characterized by high diversity and abundance in the clayey silt, while upwards the diversity and abundance show a decreasing trend (without any changes in the composition of the association). The predominating planktonic forms are as follows: *Globorotalia scitula* (Brady), *Globoquadrina dehiscens* Chapman-Parr-Collins, *Globigerinoides trilobus* (Reuss) and *Globigerina bulloides* d'Orbigny. *Orbulina suturalis* Brönnimann appears in this association at 72.4 m, and it is present up to 18.2 m although in small numbers. Benthic assemblages are characterized by high diversity, but low abundance. Their significant representatives are the *U. macrocarinata* as well as *Lenticulina*, *Bolivina*, *Nodosaria*, *Hoeglundina* and *Bathysiphon* taxa. The rich planktonic fauna and the presence of *O. suturalis* and *U. macrocarinata* Papp & Turnovsky clearly indicate that the sediments between 7.6 and 75.5 m accumulated during the late Early Badenian. The lower part of the succession cannot be dated.

Molluscs

The mollusc fauna of the Miocene deposits was studied between 7.6 and 240.2 m, with special regard to the abundant Badenian holoplanktonic gastropods (pteropods).

From the interval between 98.6 and 240.2 m 22 samples were collected. The *Anadara-Corbula* and *Tellina* assemblages are predominant in the alternating beds of silt, sand and sandstone (Bohn-Havas et al. 2007). Similar assemblages have been reported from Karpatian sediments from the adjacent boreholes in the Borsod Basin and some other holes in N Hungary (Bohn-Havas & Nagymarosy 1985).

Along the Badenian section (7.6–76.7 m) 40 samples were investigated. The alternating silt, sand and pebbly sand layers are characterized by the predominance of gastropods, mainly due to the abundance of the biostratigrafically significant pteropods (Fig. 3). *Vaginella austriaca* (Kittl) is the first pteropod that appears at 76.7 m, followed by *Clio fallauxi* (Kittl), *C. pedemontana* (Mayer) and *Diacrolinia aurita* (Bellardi) at 58.6 m. The presence of *V. austriaca* and the rapid increase in diversity is typical of the younger part of the Early Badenian (Janssen & Zorn 1993; Bohn-Havas & Zorn 1993, 2002).

Diversity and abundance of benthic molluscs are low. The occurrence of *Parvamussium duodecimlamellatum* (Bronn) also indicates an Early Badenian age (Bohn-Havas et al. 1987; Studencka et al. 1998).

Magnetostratigraphy

Sampling and laboratory procedures

Paleomagnetic samples were collected at 0.5 m intervals from undisturbed and unaltered strata, except the limestones in the Nagylózs-1 borehole, because dispersed metamorphic particles were common in these rocks. The samples were cut from the central parts of the cores and trimmed into cubical shapes with a brass knife or diamond saw, then immediately placed in plastic boxes and sealed. Altogether, 1270 oriented samples were collected from the three holes.

The samples were processed at the joint laboratory of the Geological Institute of Hungary and the Eötvös Loránd Geophysical Institute. Laboratory measurements employed a two-axis CCL (Cryogenic Consultants Limited) cryogenic magnetometer. Following measurements of the natural remanent magnetization (NRM), a series of pilot samples representing different lithologies, depths and inclinations were selected for progressive alternating field (AF) demagnetization. The samples were demagnetized in a one-component Schoenstedt demagnetizer up to 90 mT or until the intensity decreased below the noise level of the magnetometer.

The demagnetization behaviour of the pilot samples is depicted in orthogonal demagnetization diagrams (Fig. 4A–D). Most samples exhibited two components of magnetization (Fig. 4A–B), and the relatively soft secondary magnetizations disappeared at 15–20 mT. Most pilot samples displayed no changes in polarity with demagnetization, only about 10 percent of the inclinations changed polarity (Fig. 4D). The majority of inclinations thus exhibited no hint of different polarities near the threshold level of stability. The remaining samples from Nagylózs-1 and Sáta-75 boreholes were demagnetized in 15–25 mT and samples from the Sopron-89 borehole in 10–15 mT because the magnetic intensity decreased near the noise level of the magnetometer at higher demagnetization field (Fig. 4C). Samples that did not contain stable directions were discarded. All samples below

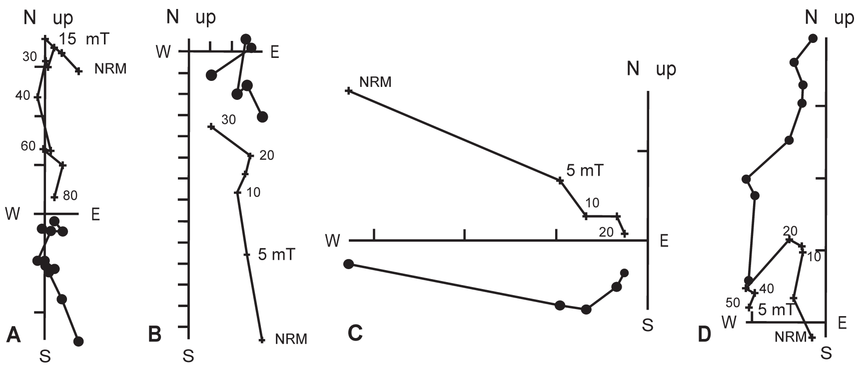

Fig. 4. Diagrams of demagnetization for samples: **A** — borehole Nagylózs-1 1122.9 m, **B** — borehole Nagylózs-1, 1259.1 m; **C** — borehole Sopron-89, 187.6 m; **D** — borehole Sáta-75, 156.1 m; + — vertical plane; • — horizontal plane.

160 m in the Sáta-75 borehole were discarded because of a lack of stable magnetic directions.

Micromineralogical studies indicate that detrital magnetite is the principal carrier of the stable magnetization and the sources of the sediments included metamorphic rocks mainly in the Eastern Alps and Western Carpathians (Thamó-Bozsó 2002). Geological studies indicate a rapid burial, and the sediments have remained undisturbed and unexposed since burial and the strata exhibited a grey colour. Additionally, the abundant amphibole and biotite indicate minor weathering therefore the stable directions are considered to reflect original magnetization acquired during deposition.

The inclination plots and polarity zones of the three sections are shown in Fig. 5. Reversals controlled by a single sample were not used for development of polarity zonation. The inclination records in the Sáta-75 and Sopron-89 boreholes are rather "noisy". In Sáta-75 hole, the noise is a result of dispersed tuff above 88 m and of strong secondary magnetizations in the sandy deposits in the lower part. In the Sopron-89 borehole, the noise may be related to either bioturbation or post-depositional magnetizations that have not been removed completely in several samples because of the low demagnetization field. Therefore the narrow, spurious polarity reversals were excluded from the magnetostratigraphic correlations.

Correlation with the Astronomically Tuned Neogene Time Scale (ATNTS2004)

The NN5/NN6 nannoplankton Zone boundary was detected at 1126.5 m in a reversed polarity zone in the Nagylózs-1 borehole (Fig. 3), and it has been dated to 13.65 Ma within Chron C5ABr in the ATNTS2004 for the Mediterranean (Lourens et al. 2004a,b). The base of the polarity record in the Nagylózs-1 section is still in the NN5 Zone, and the NN4/NN5 boundary is in C5Bn.1r at 14.91 Ma in the ATNTS2004. Thus, the polarity zones of the borehole have been correlated straightforwardly with Subchrons C5Bn.1r, C5Bn.1n and Chrons C5ADr, C5ADn, C5ACr, C5ACn and C5ABr. The normal polarity zones above 1126.5 m have been assigned to Chrons C5ABn, C5AAn and C5An taking into account the slower accumulation of the limestone and additional constraint from the correlation of the overlying Pannonian (Late Miocene) part of the section (Magyar et al. 2007).

The Sopron-89 sequence from 20 to 112 m belongs to the NN5 nannoplankton Zone (Fig. 3), providing a temporal window that allows the correlation of the polarity record with Chrons C5Br, C5Bn, C5ADr, C5ADn and C5ACr in the polarity time scale. The short normal polarity intervals around 180 m may be related to bioturbation or post-depositional magnetizations.

A fracture zone was observed around 78 m in the Sáta-75 borehole within the nannoplankton Zone NN5 during sampling, therefore the polarity zones above 78 m have been correlated with Chrons C5ADr, C5ADn, C5ACr and C5ACn (Fig. 3). This assignment is in accord with the average radiometric age of 14.8 ± 0.3 Ma obtained from several adjacent boreholes for the rhyolite tuff observed only as thin tuff strips between 50 and 88 m in the Sáta-75 section (Bohn-Havas et al. 1998; Radócz 2004). The correlation of the polarity record below 78 m is

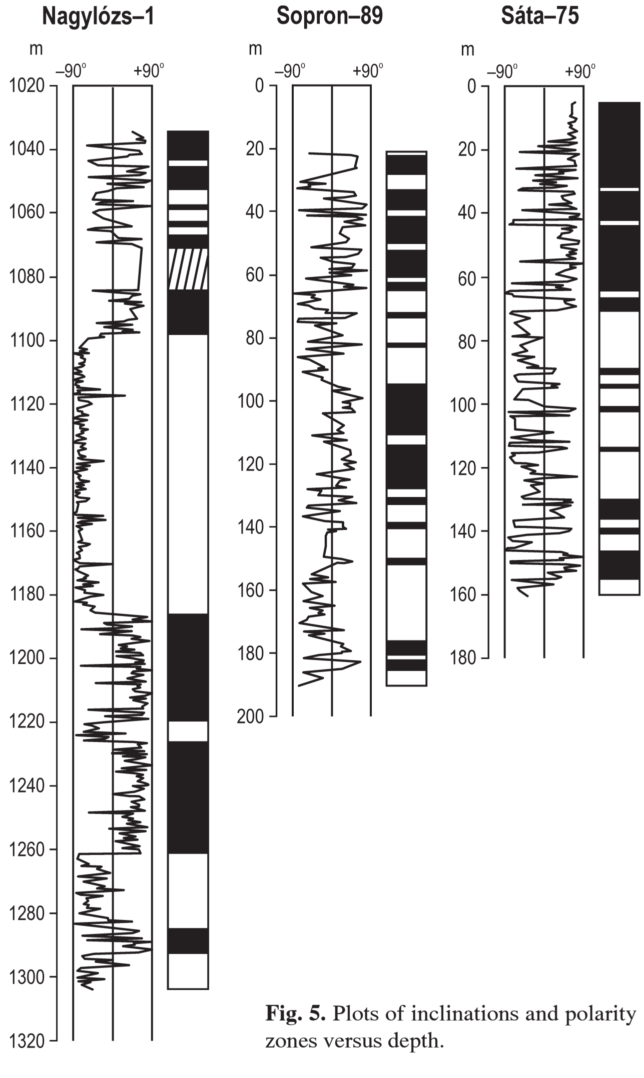

Fig. 5. Plots of inclinations and polarity zones versus depth.

ambiguous due to the unconformities but the paleontological data suggest that the age of the sediments below 98.6 m is Karpatian.

Discussion

The base of the Badenian

The base of the Badenian, defined by the FAD of the genus *Praeorbulina* (Papp & Cicha 1978), is isochronous with the base of the Langhian because of the same definition. The astronomically calibrated age for the *Praeorbulina* FAD in the ATNTS2004 is 16.27 Ma, at the base of Subchron C5Cn.1n (Lourens et al. 2004b). Although the base of the Langhian is defined by the FAD of *Praeorbulina* in their text, this horizon is marked at the top of Subchron C5Cn.1n, at 15.974 Ma in their fig. 21.1, without any comments (Lourens et al. 2004a). We accept the original biostratigraphic definition for the base of the Badenian and consequently, also of the Langhian, which was later re-calibrated to 16.303 Ma, at the base of Subchron C5Cn.1r (EEDEN time scale; Kováč et al. 2007). Recent revision and calibration of planktonic foraminiferal bioevents resulted in an age of 16.40 Ma in Subchron C5Cn.2n for the FAD of *Praeorbulina* (Wade et al. 2011). Further problems of the Karpatian/Badenian boundary are discussed in Kováč et al. (2007).

No Karpatian diagnostic fossils have been identified in the three Hungarian sections, thus the Karpatian/Badenian boundary cannot be determined. Additionally, *Praeorbulina* has not been found in the sequences, suggesting the lack of the basal beds of the Badenian. The base of the Baden Clay Formation in the Nagylózs-1 borehole has been recorded at about 15 Ma, and somewhat earlier in the Sopron-89 borehole, in Chron C5Br (Fig. 3). The sedimentation of the underlying basal gravel and conglomerate was a short event, thus the lower Lower Badenian deposits are missing here.

The gap in the sedimentation around the Karpatian/Badenian boundary in the studied sections is not unique. The genus *Praeorbulina* appeared together with the genus *Orbulina* in the lowermost Badenian strata of the Central Pannonian Basin (e.g. Kováč et al. 2007) and "continuous sedimentation from Karpatian to Badenian has never been observed" (Piller et al. 2007). The duration of the sedimentation gap at the Karpatian/Badenian boundary in the Styrian Basin has recently been estimated by Hohenegger et al. (2009), and a gap of 400 kyr was obtained.

The Badenian/Sarmatian boundary

The Badenian/Sarmatian boundary was recorded at 1070 m in the Nagylózs-1 borehole (Figs. 2, 3), within a normal polarity interval correlated with Chron C5AAn, and an age of 13.15 Ma has been interpolated for the boundary.

Although the presence of *Bolivina moravica* indicates Early Sarmatian s.s. age (Görög 1992), the lack of *Elphidium reginum* suggests that the oldest Lower Sarmatian deposits corresponding to the lower part of *E. reginum* Zone are missing. The *Abra reflexa* and *Inaequicostata inopinata* mollusc assemblage, indicating the lowermost part of the Lower Sarmatian s.s., is also missing here. The duration of the gap in sedimentation can be estimated as 50–100 kyr. This hiatus is in accord with the observation that a widespread unconformity has been found around the Badenian/Sarmatian boundary in the Central Paratethys (Piller et al. 2007; Lirer et al. 2009).

The previously estimated age of 13.0 Ma for the Badenian/Sarmatian boundary (e.g. Rögl 1998; Harzhauser et al. 2003; Ćorić et al. 2004) is close to the age of 13.15 Ma, proposed in this work. Recently an age of 13.32 Ma has been obtained for the boundary from power spectral studies (Lirer et al. 2009). The small difference may be due to a mismatch in the comparison between the eccentricity curve and the lithological record, because the 65 m wavelength for the 100 kyr periodicity in the 1118-m-thick Sarmatian sediments (Lirer et al. 2009; Fig. 4) should give an age of 13.14 Ma for the boundary.

Harzhauser & Piller (2004) suggested an age of 12.7 Ma for the Badenia+Sarmatian boundary, which contrasts with all foregoing ages. The authors correlated the boundary with an unconformity, and its age was estimated as 12.7 Ma by an analogue, lacking any direct chronostratigraphic data. Unfortunately, this tentative age has become general in the past few years.

The Early/Late Badenian boundary

Recently Kováč et al. (2007) proposed the twofold subdivision of Badenian, and the boundary between the Early and Late Badenian is marked by the first appearance of the warm-water planktonic foraminifer *Velapertina indigena* Łuczkowska in the Central Paratethys. The boundary was close to the Langhian/Serravallian boundary at 13.65 Ma, but the GSSP of the Serravallian has been dated at 13.82 Ma (Hilgen et al. 2009). The Early/Late Badenian boundary corresponds to a 3rd order sequence stratigraphic boundary (Strauss et al. 2006; Kováč et al. 2007). Vakarcs et al. (1994) also described and traced a sequence boundary at 13.8 Ma in Hungary, although this horizon cannot be seen in the seismic profile through the Nagylózs-1 borehole (Magyar pers. comm.).

V. indigena occurs only in limited areas of the Central Paratethys (no specimens have been found in Hungary yet), therefore it cannot be used as a marker for practical purposes. Its first appearance is somewhat younger than the NN5/NN6 boundary at 13.65 Ma, thus the Early/Late Badenian boundary roughly correlates with the NN5/NN6 boundary. However, the diagnostic taxon *S. heteromorphus* is sparse before its last occurrence in many places. We suggest using the base of the Bulimina-Bolivina Zone as an approximate marker for the base of Upper Badenian. This biohorizon is also in Chron C5ABr in the Nagylózs-1 borehole, having an age of 13.7 Ma (Fig. 3). The base of the Bulimina-Bolivina Zone coincides with the NN5/NN6 boundary in Harzhauser et al. (2003) and Strauss et al. (2006), and is somewhat younger (13.5 Ma) in Kováč et al. (2007), Rögl et al. (2008) and Ćorić et al. (2009).

The first appearance of the Orbulina suturalis

The first occurrence of *Orbulina suturalis* ranges from 14.9 to 14.4 Ma in the studied sections reflecting the different developments and depositional environments of the sediments. The first occurrence of *O. suturalis* has been observed at a depth of 1295.0 m in the Nagylózs-1 borehole, in Subchron C5Bn.1r, at 14.9 Ma (Fig. 3). This position and age is not in agreement with the Chron C5ADr and age of 14.74 Ma for the FAD of *Orbulina* in the ATNTS2004.

Although the age for the polarity zones in the ATNTS2004 were generally astronomically tuned, the reversal boundaries between 23 and 13 Ma were interpolated (Lourens et al. 2004a,b). Astronomical ages were determined for the calcareous nannofossil and planktonic foraminiferal events in the equatorial Atlantic (ODP Leg 154). As a reliable magnetostratigraphic record is lacking for the ODP Leg 154 sites, the marine magnetic anomaly profiles between Australia and Antarctic were chosen for establishing a high-precision polarity time scale (Lourens et al. 2004a). This construction results in the lack of direct astronomical ages for polarity reversals as well as direct correlation between magnetostratigraphy and biostratigraphic events in the interval 23–13 Ma. We note that an orbitally tuned time scale has been developed for Leg 154 sediments in the Ocean Drilling Program, and 15.1 Ma was determined for the base of *O. universa* (= *suturalis)* (Pearson & Chaisson 1997; Table 1). The *O. suturalis* was not distinguished from *O. universa* in the ODP Leg 154 sites because of poor preservation and dissolution (Pearson & Chaisson 1997), and only *O. universa* is shown in Table A2.3 of ATNTS2004 (Lourens et al. 2004b). The *O. suturalis*, however, has been distinguished from *O. universa* in the Mediterranean area, and the FAD of *O. suturalis* is the older.

An even younger age was obtained for the FAD of *O. suturalis* from the only complete polarity record between 15.8 and 13.2 Ma in the Mediterranean area, in Site 372 (DSDP Leg 42A) drilled in the Balearic Basin, Western Mediterranean Sea (Abdul Aziz et al. 2008). The FAD of *O. suturalis* was observed in the lowermost part of Chron C5ADn, at 14.56 Ma. Compared to the age of 14.9 Ma in the Nagylózs-1 borehole, this datum seems to be too young, moreover, the age of 14.6 Ma in Chron C5ADr in the Sáta-75 section is still older than this.

The FAD of *O. suturalis* is significantly older in the time scale of Berggren et al. (1995), marked in Subchron C5Bn.2n, at 15.1 Ma. Recent revision and calibration of planktonic foraminiferal bioevents retained the age of 15.1 Ma in Subchron C5Bn.2n for the base of *O. suturalis* (Wade et al. 2011). The polarity and biostratigraphic records of DSDP Leg 73, Site 521 in the South Atlantic support this age. Here the FAD of *Orbulina* spp. was also determined in Subchron C5Bn.2n (Poore et al. 1984; Fig. 4), and according to ATNTS2004 its age is now 15.1 Ma. (Here *O. universa*, *O. suturalis* and *Biorbulina* were recorded as *Orbulina* spp. (Poore 1984).) Therefore, the first appearance of *O. suturalis* in the Nagylózs-1 borehole in Subchron C5Bn.1r, at 14.9 Ma is considered valid.

O. suturalis was an important zonal index taxon in the area of the Central Paratethys: its first appearance datum marked the boundary between the Lower and Upper Lagenidae Zones (e.g. Cicha et al. 1998). Later it turned out that it already appeared in the Lower Lagenidae Zone (Ćorić et al. 2004, 2009; Kováč et al. 2007; Hohenegger et al. 2009). Due to the different correlations concerning the first appearance datum of *O. suturalis* compared to the boundaries and the unambiguous facies dependency of the zones, authors do not use the Lower and Upper Lagenidae Zones for the division of the Lower Badenian.

Pteropod events

The main advantage of the holoplanktonic gastropods (pteropods) is their wide geographic distribution pattern. A subgroup of the IGCP project 124 tested the planktonic molluscs as useful tools for long distance correlation of marine deposits, and biozonations have been developed for the North Sea Basin (Janssen & King 1988) and for the Mediterranean Sea Basin (Robba in Seneš 1985).

In the Karpatian, 3 species from 2 genera are known from the area of the Central Paratethys, whereas 15 species from 8 genera appeared in the Early Badenian (Bohn-Havas & Zorn 2003). The Badenian pteropod fauna is rich in the Sopron-89 and Sáta-75 sections but totally missing from the Nagylózs-1 borehole. The first pteropod, which appears in Chron C5ADr at 14.7 Ma in the Sopron-89 and Sáta-75 boreholes, is the monospecific *Vaginella austriaca*. An abrupt increase in diversity happened after 14.4 Ma (Chron C5ADn), and the increasing diversity coincides with an increase in numbers of specimens. Here *Vaginella austriaca* is accompanied by *Clio*, *Limacina* and *Diacrolinia* species, and this assemblage is present only in the Early Badenian all over the Central Paratethys (Janssen & Zorn 1993; Bohn-Havas & Zorn 1993, 2002).

Conclusions

The magnetobiostratigraphic correlations indicate a hiatus in the early period of the Early Badenian in the studied sections, and provide ages for several biostratigraphic events and the Badenian/Sarmatian boundary, as well. Although paleogeography is outside the scope of this study, several results of the correlations are worthy of remark.

First, the time intervals of sedimentation in the Sopron-89 and Nagylózs-1 sequences are different, even though they are only 20 km apart. Accumulation of Badenian sediments (excluding the basal coarse-grained sediments) lasted from about 15.0 Ma until the Sarmatian in the Nagylózs-1 borehole, whereas in the Sopron-89 borehole the sedimentation began earlier and terminated at 14 Ma (Fig. 3). A NW-SE structure transect, based on seismic profiles, indicates two troughs between the Eisenstadt-Sopron (Sub-)Basin and the Mihályi Ridge (Tari 1996). The original W-E seismic profile through the Nagylózs-1 borehole shows a structurally elevated block west of the borehole, and another east of it, both covered by thin, probably Middle Miocene deposits under the relatively uniform Pannonian sediments (Magyar pers. comm.). The multinational residual gravity map reveals the same morphology (Šefara & Szabó 1997; Fig. 3). These data suggest that the sub-basin around Nagylózs belonged neither to the Eisenstadt-Sopron (Sub-)Basin nor to the Kisalföld (Danube Basin) permanently during the Badenian.

Secondly, the first appearance of *O. suturalis* has been recorded at 14.9 Ma in the Nagylózs-1 sequence. The FAD of *O. suturalis* was observed at 14.56 Ma in the Western Mediterranean Sea, at Site 372 (Abdul Aziz et al. 2008). If the 14.56 Ma is valid for the entire Western Mediterranean, the fauna must have immigrated from another direction to Nagylózs. By the time of the Badenian no connection existed with the North Sea (e.g. Studencka et al. 1998; Harzhauser & Piller 2007). Several possibilities for a marine seaway to the Indo-Pacific are discussed by Rögl (1998), and he also proposed a highly speculative seaway between the southern border of the Black Sea plate and the Pontides in Anatolia. Such a connection would explain why *O. suturalis* appeared earlier in the Nagylózs-1 section than in Site 372.

Lourens et al. (2004a) noted that the astronomical tuning in the 23–13 Ma interval had not been independently verified. The FAD of *O. suturalis* was determined at 15.1 Ma, in Subchron C5Bn.2n in the recent calibration of Wade et al. (2011). In the ATNTS2004, however, the FAD of *Orbulina* is at 14.74 Ma, in Chron C5ADr (Lourens et al. 2004a,b). Moreover, 14.91 Ma is the age of the NN4/NN5 boundary in the ATNTS2004. Since *O. suturalis* appears in the nannofossil Zone NN5, the NN4/NN5 boundary should be older than 15.1 Ma, as marked at 15.5 Ma for the Mediterranean area by Di Stefano et al. (2008). In addition, an age of 15.8 Ma was obtained for the NN4/NN5 boundary from an earlier astronomical tuning for the ODP Leg 154 in the equatorial Atlantic (Shipboard Scientific Party 1995). These data suggest that this part of the time scale needs reconsideration.

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