Geological Quarterly, 2018, **62** (1): 3–17
DOI: http://dx.doi.org/10.7306/gq.1399

Timing of Langhian bioevents in the Carpathian Foredeep and northern Pannonian Basin in relation to oceanographic, tectonic and climatic processes

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Holcová, K., Doláková, N., Nehyba, S., Vacek, F., 2018. Timing of Langhian bioevents in the Carpathian Foredeep and northern Pannonian Basin in relation to oceanographic, tectonic and climatic processes. Geological Quarterly, **62** (1): 3–17, doi: 10.7306/gq.1399

The succession of bioevents in planktonic foraminifer and calcareous nannoplankton communities is reviewed and summarized for the Carpathian Foredeep and northern Pannonian Basin in the time interval between ~16 and 13.5 Ma. This succession can be subdivided into three principal intervals: (1) an interval with rare *Praeorbulina sicana* and *P. glomerosa*. It was characterized by a limited immigration of index taxa linked to the lack of a warm surface water layer in the Central Paratethys. This interval can be correlated with the first Badenian transgression near the Burdigalian/Langhian boundary. The rare occurrence of biostratigraphical markers does not allow its precise dating and interregional correlation; (2) a brief interval of the first occurrences of *Praeorbulina circularis, Orbulina suturalis* and *Helicosphaera waltrans*. This can be related to the formation of a warm surface water layer suitable for the survival of orbulinas and praeorbulinas and a change from estuarine to anti-estuarine circulation. This interval can be correlated with the second Badenian transgression, which, however, was not isochronous over the area as inferred from different successions of these first occurrences; (3) a limited appearance of new index taxa in the Central Paratethys prior to the Wielician Salinity Crisis. This time interval was characterized by increased seasonality and salinity oscillations followed by climate cooling. A "reverse" migration of the stress-tolerant species *Helicosphaera walbersdorfensis* from the Central Paratethys to the Mediterranean is suggested. Several local bioevents with limited stratigraphic correlation potential have been recognized in this interval.

Key words: Miocene, Central Paratethys, biostratigraphy, calcareous nannoplankton, foraminifera, palynology.

INTRODUCTION

The correlation of the Langhian Stage with the local Central Paratethys stratigraphy has been recently widely discussed. Piller et al. (2007) correlated its base with the Karpatian/Badenian boundary. This boundary, defined by the first occurrence of *Praeorbulina* (Papp et al., 1978), was subsequently redefined by Hohenegger et al. (2014) to a level corresponding to the uppermost Burdigalian. This correlation was based on dating of the first occurrence of *Praeorbulina* in the world oceans. The top of the Langhian is correlated with the Moravian/Wielician local substage boundary (i.e., Early/Middle Badenian *sensu* Papp et al., 1978). Hohenegger et al. (2014) proposed correlation of the Moravian substage with the Early and Middle Badenian. However, this new subdivision is not generally accepted and causes confusion in terminology and stratigraphic correlations.

The Badenian marine biostratigraphy based on local (eco)zones of Grill (1943) and Cicha et al. (1975) has been generally accepted since the 1970s (Papp et al., 1978). However, complementary stratigraphic data such as magnetostratigraphy (Hohenegger et al., 2009a; Selmeczi et al., 2012; de Leeuw et al., 2013) and new radiometric and Sr-ages (Radócz, 2004; Handler et al., 2006; de Leeuw et al., 2010; Fordinál et al., 2014) showed that the concept of such a seemingly distinct system no longer applies even for the local stratigraphy (Hohenegger et al., 2014).

Despite emerging new stratigraphical methods and data, biostratigraphy remains the most widely used correlation method. The occurrence of common index taxa that migrated in the system of interconnected basins enable interregional correlations of the Lower Badenian deposits in the Central Paratethys (Rögl, 1998; Popov et al., 2004). However, the timing of such bioevents was not entirely synchronous in the individual basins with many factors, such as local tectonics and climate, water chemistry and circulation regime, playing a role in their distribution.

In this paper we discuss the timing of the Langhian Central Paratethys bioevents based on a case study of the northern Pannonian Basin and the Moravian part of the Carpathian Foredeep. Our results are compared to the world oceans

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Received: September 12, 2017; accepted: November 29, 2017; first published online: January 26, 2018

and/or the Mediterranean region and the recorded differences are related to climatic, oceanographic and tectonic factors that may have affected the spatial and temporal distribution of index microorganisms.

GEOLOGICAL SETTING

Our study area includes the Pannonian Basin System (South Slovak Basin) and the Carpathian Foredeep (Seneš, 1961; Fig. 1).

The South Slovak Basin (SSB) belongs to the northeastern part of the Pannonian Basin System. The area was inundated from the Oligocene to the Ottnangian (Middle Burdigalian) and then again during the Karpatian (Late Burdigalian). After the late Early Miocene upheaval event, the subsidence was rejuvenated around the Karpatian/Badenian (Burdigalian/Langhian) boundary but only for a short time. Sedimentation was controlled by NNW–SSE faults and was accompanied by the Badenian marine transgression. Depocentres were situated in the west where the SSB continued to the Danube Basin. Subsidence was followed by a volcanic paroxysm and extensive volcanism in adjacent terrestrial and marine areas. Volcanic bulging caused rapid uplift and marine regression in the area (Vass, 1995; Vass et al., 2007).

Sedimentation in South Slovakia started with the tide-influenced Príbelce Member overlain by the Vinica Formation deposited in littoral to neritic environments. Tuffaceous sandstones and siltstones with common bioturbation dominated by domichnia overlie the basal coarse volcaniclastic deposits. Algal bioherms locally occur within the sandstones and siltstones (Vass et al., 2007).

The formation and basin evolution of the Carpathian Foredeep (CF) – as a peripheral foreland basin – was related to the subsurface loading of the Alpine-Carpathian orogenic belt on the Bohemian Massif margin during the Early to Middle Miocene (Nehyba and Šikula, 2007; Nehyba et al., 2008). The basin continues south into the Alpine Molasse Zone and north into the Polish segment of the CF Basin (Oszczypko et al., 2006). The infill and basin architecture varies throughout the CF Basin, local and regional unconformities are developed due to the varying intensity and orientation of flexural loading and different geological and tectonic histories of the basement, along with a polyphase nature of the active basin margin and gradual change of its position (Brzobohatý and Cicha, 1993; Nehyba, 2000; Kováč et al., 2004; Oszczypko et al., 2006).

The stratigraphic range of the sedimentary infill of the studied CF Basin segment is Eggerian to Lower Badenian (Brzobohatý and Cicha, 1993). The Lower Badenian deposits reveal a distinctive basin infill geometry because they are almost symmetrically located in the central parts of the basin. The Lower Badenian sedimentary sequence is dominated by a lithologically uniform package of pelitic sedimentary strata (known as “Tegel”) with a thickness reaching several hundreds of metres. These pelites are interpreted as deposits of the middle to outer shelf or even hemipelagites (Papp et al., 1978; Cicha, 2001; Nehyba et al., 2008). Coarse-grained sandstones and conglomerates represent the second dominant lithofacies being generally described as “basal or marginal coarse clastics” (Krystek, 1974; Nehyba et al., 2008). Bioherms of red-algal limestones (Doláková et al., 2008) form laterally and volumetrically restricted bodies within the mudstones. Thin volcanoclastic beds (acidic tuffs and tuffites) interpreted as distal tephra fallout are rare (Nehyba et al., 1999).

MATERIALS AND METHODS

We synthesize multiproxy data from boreholes from the CF: LOM-1 (Holcová et al., 2015a), ZIDL-1 and ZIDL-2 (Doláková et al., 2014), RY-1 (Kopecká, 2012), OV-1 and OV-2 (Nehyba et al., 2016); from the SSB (boreholes N-45, N-48, N-68, N-80, N-83, N-95, N-91; Holcová et al., 1996; for location of all boreholes see Fig. 1). In addition, palynological data from the following boreholes from the CF were used: IK-1 (Basistová and Doláková, 2011; Doláková et al., 2011), HJ-1, HJ-2, HJ-103 (Hladilová et al., 1999, 2001).

Foraminifera were analysed in the fraction between 0.063 and 2 mm, calcareous nannoplankton was studied from smear slides. Assemblage quantitative evaluation was based on 200–300 specimens for foraminifera and 300–500 specimens for calcareous nannoplankton. The method of Zágoršek et al. (2007) was used for our purposes.

Standard maceration in HCl (20%), HF, KOH and HCl (10%) and $ZnCl_2$ (density = 2 g/cm^3) was used for palynological samples. Pollen diagrams were processed using *POLPAL* software (Walanus and Nalepka, 1999) with a minimum of 150 determined pollen grains and spores, excluding *Pinus* and undetermined conifers. The terminology of Stuchlik et al. (1994), Kvaček et al. (2006) and Kovar-Eder et al. (2008) was employed for the classification of vegetation units.

We have used published ^{18}O data from foraminiferal tests for further palaeoenvironmental interpretations (Holcová and Demeny, 2012; Doláková et al., 2014; Scheiner, 2015). Four different datasets have been distinguished , each characterizing specific levels in the water column: (1) data from *Globigerinoides bulloides* characterize surface waters during periods of enhanced productivity (probably spring bloom; Schiebel et al., 1997); (2) data from *Globigerinoides* characterize surface summer stratified waters (Reynolds and Thunell, 1985; Hemleben et al., 1989), (3) data from epifaunal *Cibicidoides* spp. reflect the quality of the bottom water (Kaiho, 1994; Murray, 2006); (4) pore water chemistry in the sediment was documented by isotopic values from shallow infaunal *Melonis* spp. and *Gyroidina* spp. and deep infaunal *Uvigerina* spp. (Caralp, 1989; Hermelin, 1992; Sjoerdsma and Van der Zwaan, 1992; Sen Gupta and Machain-Castillo, 1993; Miao and Thunell, 1993; Rathburn and Corliss, 1994).

PALYNOLOGICAL ANALYSIS

Two principal zonal forest assemblages have been recognized from the study of palynoflora: (1) subtropical broad-leaved forests characterized by a high abundance of evergreen elements (relative abundance up to 38%), such as Sapotaceae, palms, *Engelhardia*, *Platycarya*, evergreen Fagaceae, *Reevesia*, *Cornus-Mastixia*, and Rutaceae; (2) a warm to temperate mixed mesophytic and broad-leaved deciduous forest type with broad-leaved elements (relative abundance 12–21%), i.e., *Quercus*, *Celtis*, *Juglans, Tilia*, *Betula,* and *Acer*. Increased diversity and quantity of “deciduous oak type” pollen grains have been recorded here by contrast with the Lower Miocene. Occurrences of mountain forest components (*Cedrus*, *Tsuga* and *Picea*; Doláková et al., 1999, 2011, 2014; Kováčová et al., 2011), coastal swamp (Taxodiaceae, Cyrillaceae, Myricaceae, *Decodon*) and riparian elements (*Alnus*, *Salix*, *Ulmus*, *Fraxinus, Liquidambar*, *Carya*) indicate the complex nature of zonal biotopes in the adjacent areas.

The highest proportion of thermophilous floral elements/lowest percentage of arctotertiary elements were de-

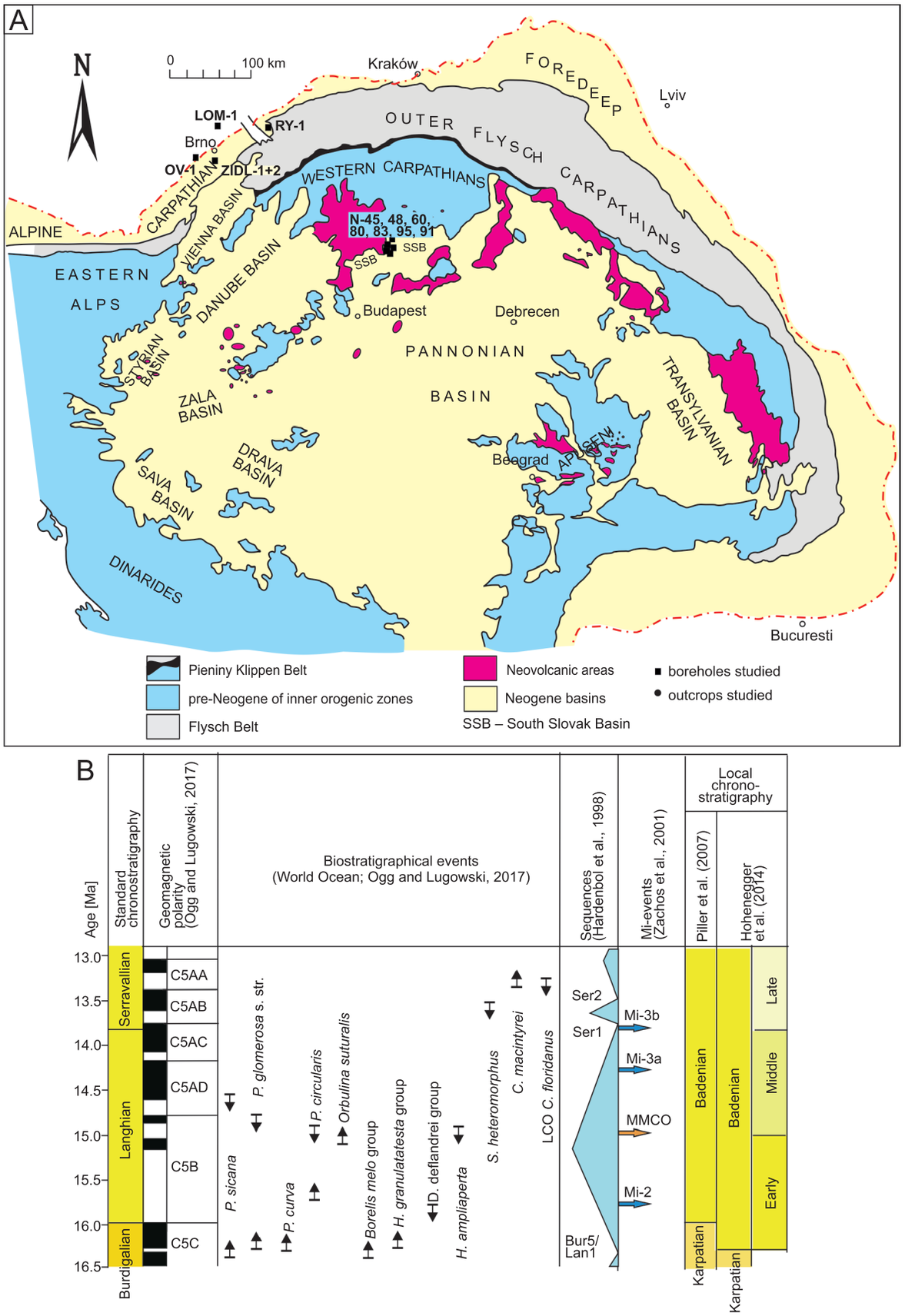

Fig. 1A – schematic map of the areas under study and their positions within the Carpatho-Pannonian region with location of the sections studied (map modified from Kováč et al., 2007);
B – chrono-, bio- and magnetostratigraphy of the interval studied

tected in palynospectra from the interval with *Praeorbulina sicana* and *P. glomerosa*. A relatively lower abundance of xerophilous elements such as *Engelhardia* and *Olea* has been observed here (Fig. 2A).

An increase in abundance of arctotertiary elements that coincides with increased abundances of xerophilous markers (such as dry herbs and heliophytes *Olea, Poaceae, Asteraceae, Caryophyllaceae, Chenopodiaceae, Ericaceae*) can be seen in the short interval between the FOs of *Praeorbulina circularis* and *Orbulina* (Fig. 2B, C). The disappearance of Sapotaceae and decrease in Cornoideae–Mastixioideae and evergreen Fagaceae and increase in arctotertiary elements were recorded around the LCO of *Helicosphaera waltrans*.

The interval with *Orbulina suturalis* and common *H. walbersdorfensis* is characterized by a dominance of conifers and marine dinoflagellates (sometimes referred to as the *Pinus* event; Fig. 2D). Pollen and spores completely disappear higher in the section in many of the boreholes studied.

BIOEVENTS SUCCESSION AND RELIABILITY OF THEIR USE IN STRATIGRAPHY

Several prominent bioevents have been recognized in the boreholes and sections studied. Their potential for local and interregional biostratigraphy is discussed below.

The first occurrences of *Praeorbulina sicana* and *P. glomerosa* and the last occurrence of *Helicosphaera ampliaperta*. The interval below the first occurrences (=FOs) of *Helicosphaera waltrans, Praeorbulina circularis* and *Orbulina suturalis* is characterized by scattered occurrences of *Praeorbulina sicana* and *P. glomerosa* (Appendix 1A*) that cannot be used for any reliable stratigraphic correlations. *Helicosphaera ampliaperta* rarely occurred in this interval; however, the position of its last occurrence (=LO) is inaccurate due to its scarcity along the sections (Appendix 1D). Its possible redeposition must also be taken into consideration.

The first occurrences of *Praeorbulina circularis* and *Orbulina suturalis*. The FOs of *Praeorbulina circularis* and *Orbulina suturalis* represent a very distinct bioevent. Besides the appearance of new index taxa, the abundance of plankton from the *Orbulina–Praeorbulina* group is considerably higher by contrast with the previous interval (Appendix 1A).

The FO of *Praeorbulina circularis* slightly preceded the FO of *Orbulina suturalis.* Before this event, the *Coccolithus pelagicus/Reticulofenestra minuta* ratio changed (Appendix 1B).

The last common occurrence of *Helicosphaera waltrans* and the last occurrence of *Sphenolithus heteromorphus*. Quantitative analyses of calcareous nannoplankton assemblages showed increased relative abundance of *H. walbersdorfensis* (Appendix 1C). The last common occurrence (=LCO) of *H. waltrans* coincides with increased abundances of *H. walbersdorfensis* and can be used as a reliable stratigraphical marker (Appendix 1C). This event occurred after the FO of *Orbulina*. Above the LCO, *H. waltrans* has been recorded only discontinuously in several samples.

The LO of *S. heteromorphus* is not a reliable marker in the sections studied because of its scarce occurrences (Appendix 1D). Marunteanu (1999) and Bartol (2009) recommended using the decreased abundance of *Cyclicargolithus floridanus* as an auxiliary indicator in the Central Paratethys. However, this has not been recognized in our study material (Appendix 1E) nor have other synchronous bioevents described (the LOs of discoasters, the FCO of *Reticulofenestra pseudoumbilica* >7 μm; Bartol, 2009).

Local bioevents: acme of *Reticulofenestra minuta, Spiroplectinella carinata* and *Globorotalia transylvanica*. The high abundance of *Reticulofenestra minuta* is characteristic of the studied sections above the FO of *Helicosphaera waltrans* (Appendix 1B). An increase in *R. minuta* abundance coincides with increasing numbers of *H. walbersdorfensis* (r = 0.74; p <0.001) and decrease in *C. pelagicus.* A negative correlation of relative abundances of *H. walbersdorfensis* and *C. pelagicus* species can also be detected (r = –0.56; p <0.001). The levels above the LCO of *H. waltrans* are characterized by higher variations in *R. minuta* frequency compared to the underlying interval (Appendix 1B).

An increase in abundance of biserial agglutinated foraminifera (primarily *Spiroplectinella carinata*) may be used for definition of a local (eco)zone Spiroplectinella carinata (Grill, 1943) that corresponds to the Middle Badenian *sensu* Papp et al. (1978). The stratigraphic distribution of this morphogroup, summarized in Appendix 1F, showed that the increase in abundance occurred above the LCO of *Helicosphaera waltrans.* However, this event has been recognized only locally (LOM-1, RY-1 and ZIDL-2 boreholes).

A *G. transylvanica* acme was recorded in the Polish and Romanian part of the CF prior to the Wieliczka salinity crisis. The generally positive trend in relative abundance of these endemic taxa with several cyclic oscillations detected in our samples (Appendix 1G) may indicate that a single *G. transylvanica* acme may be only a locally restricted event.

INTERREGIONAL CORRELATIONS AND BIOEVENTS TIMING

The first occurrences of *Praeorbulina sicana* and *P. glomerosa*. In accordance with our observations, *Praeorbulina sicana* and *P. glomerosa* have been recorded only discontinuously throughout the Central Paratethys in the time interval before the FO of *Orbulina*. Both species have been rarely found in the Styrian Basin (Spezzaferri et al., 2009; Hohenegger et al., 2009a), the Alpine Foredeep Basin (Austrian Mollase Basin; Ćorić et al., 2004), the Danube Basin (Rybár et al., 2015, 2016), the South Slovak Basin (Vass et al., 2007) and the Polish part of the CF (Oszczypko and Oszczypko-Clowes, 2012). This interval corresponds to local biozone of *Globigerinoides sicanus* (Cicha et al., 1975).

Bioevent numerical dating in this lineage for the Central Paratethys is not generally accepted due to the absence of reliable radiometric dating control. The timing of the praeorbulinas' first occurrences in the Mediterranean region markedly differs from those in the world oceans (Abdul Azis et al., 2008; Turco et al., 2011; Wade et al., 2011; Gradstein et al., 2012; Fig. 3). The use of bioevents for correlation between the global magnetostratigraphical chart and detected chrons in our study area may be misleading. A presumed pathway between the Atlantic/Indo-Pacific and the Central Paratethys in this period passed through the Mediterranean (Rögl, 1999; Popov et al., 2004; Kováč et al., 2007, 2017a, b) to present-day Slovenia and Croatia (this interval was reported from this region by Cicha et al., 1975; Bartol, 2009). A strongly hypothesized direct connection between the Paratethys and the Indo-Pacific realm may

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1399

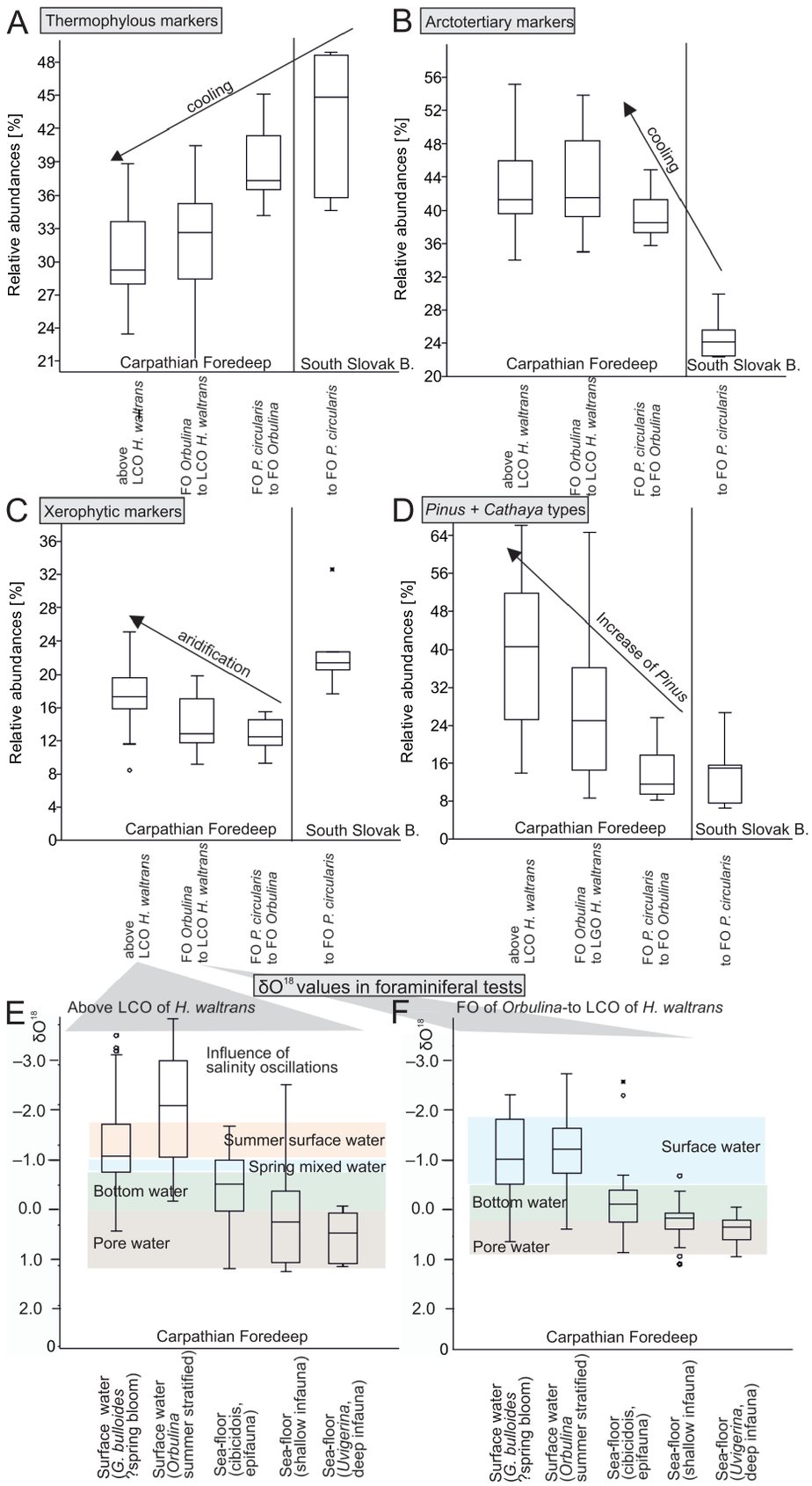

Fig. 2. Relative abundances of palaeoclimatological markers (A–D) terrestrial palynomorphs (E, F) ^{18}O values (data from Holcová and Demeny, 2012; Doláková et al., 2014; Holcová et al., 2015b; Scheiner, 2015)

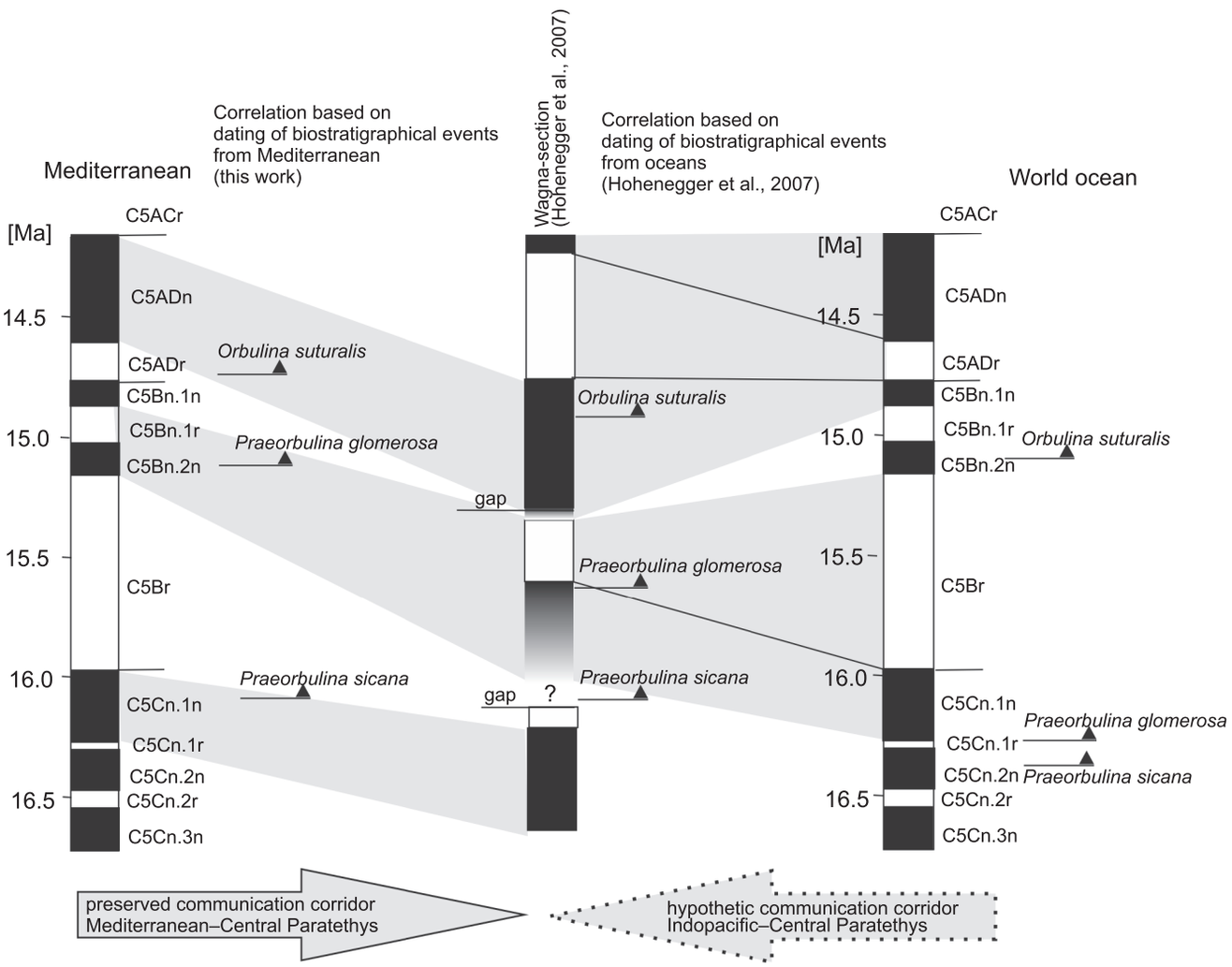

Fig. 3. Correlation of magnetostratigraphical chrons detected in the Central Paratethys (Hohenegger et al., 2009a) with a global magnetostratigraphical chart based on the FOs of index taxa in the world oceans and the Mediterranean

have led via the Central Paratethys and the Transylvanian and Pannonian basins further eastwards to the southern margin of the Black Sea plate and the Pontids (Rögl, 1998; Fig. 4). However, possible evidence for this marine pathway was destroyed during subduction of oceanic crust in the Alpine-Himalayan orogenic belt.

For the reasons described above, we prefer use of the Mediterranean bioevent dating for calibration of magnetostratigraphical chrons detected by Hohenegger et al. (2009a). The FO of *P. glomerosa* in the world ocean dated at 16.4–16.1 Ma (Wade et al., 2011) corresponds to C5Cn.1n chron (16.29–15.97 Ma; Gradstein et al., 2012). If the normal polarity chron with the FO of *P. glomerosa* in the Styrian Basin (Hohenegger et al., 2009a) is correlated with the Mediterranean datum of the FO of the same taxon (15.2–15.1 Ma; di Stefano et al., 2008, Iaccarino et al., 2011), chron C5Bn.2n (15.15–15.04 Ma; Gradstein et al., 2012) may be inferred (Figs. 3 and 4). Similarly, the reverse polarity chron with the FO of *P. sicana* can be interpreted ambiguously based on a heterochronous timing of the FO of *P. sicana* in the world oceans (16.97 Ma based on Gradstein et al., 2012 or 16.4 Ma from Wade et al., 2011) and in the Mediterranean (16.177 Ma; Iaccarino et al., 2011; Turco et al., 2011). If the Mediterranean age is accepted, the species would appear in the Central Paratethys in the earliest Langhian C5Br Chron (15.974–15.16 Ma) rather than in the latest Burdigalian Chron C5Cn.1r (16.3 Ma; Gradstein et al., 2012; Figs. 3 and 4). Moreover, praeorbulinas occurred only discontinuously in the sections studied, in which case, determination of their exact FOs may be misleading and their occurrence can be used only for approximate dating of strata with *P. sicana* at ~15.9–15.1 Ma and with *P. glomerosa* from 15.1 to 14.6 Ma.

Deposits with rare *Praerbulina sicana* and *P. glomerosa* appear to be restricted to the Central Paratethys. However, it is not exactly known to what extent they represent the original marine transgression. The occurrence of redeposited mudstone intraclasts with the Langhian microfossils in deposits of the second Badenian cycle indicates that it may have been reduced by subsequent erosion. On the other hand, they may have not been recognized in some areas due to a lack of rare praeorbulinas. Additional numerical dating would certainly help to resolve these questions.

The first occurrences of *Helicosphaera waltrans*, *Praeorbulina circularis* and *Orbulina suturalis*. The FOs of *Praeorbulina circularis, Orbulina suturalis* and *Helicosphaera waltrans* represent important bioevents recognized over the Central Paratethys. However, their succession may spatially and temporally vary or be absent in individual Central Paratethys basins (Fig. 5): *O. suturalis* with *H. waltrans* frequently appear simultaneously in the CF in Ukraine and in the

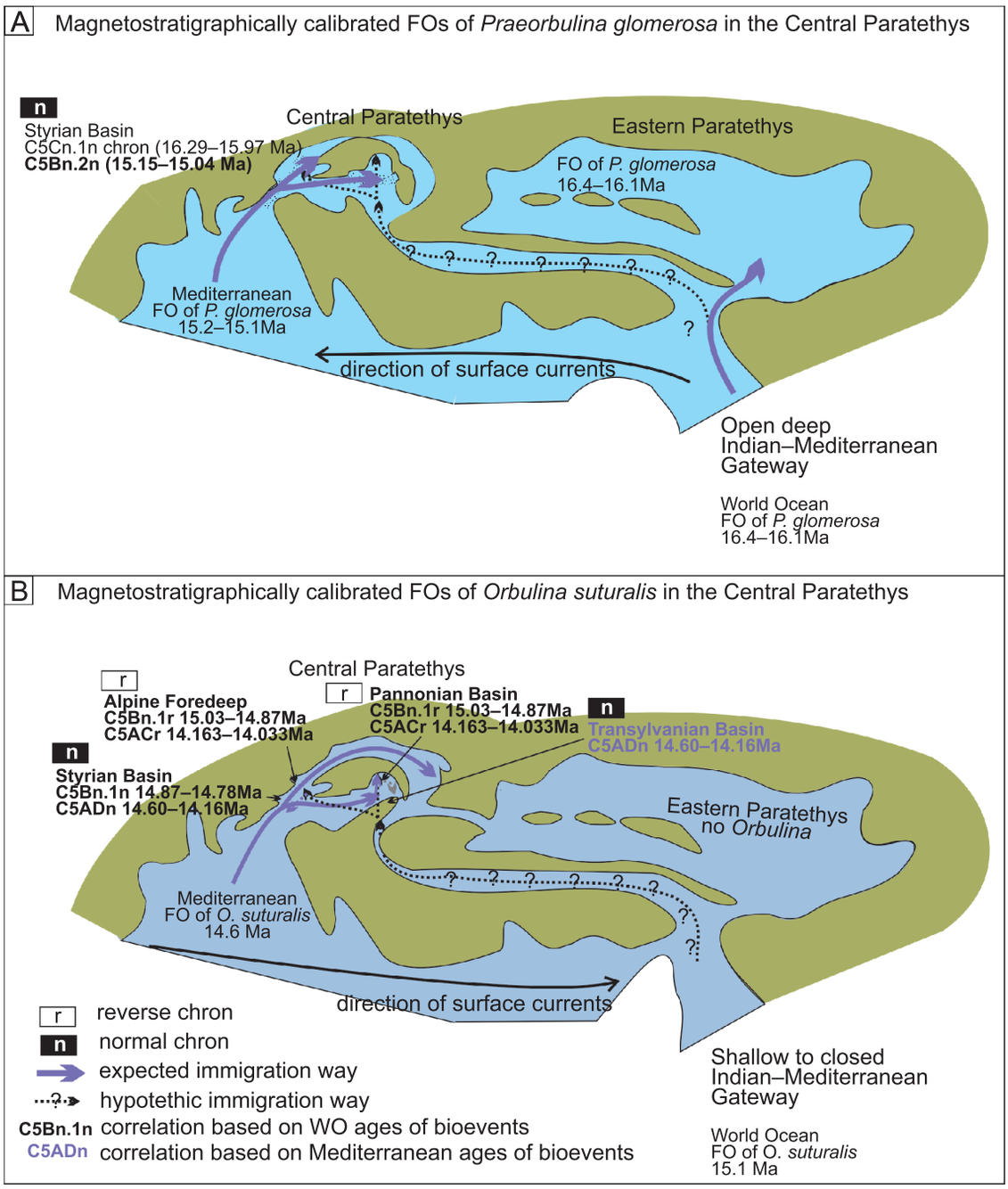

Fig. 4. Magnetostratigraphically calibrated FOs of *Orbulina* in the Central Paratethys (based on data of Ćorić et al., 2004; Hohenegger et al., 2009a; de Leeuw, 2011; Selmeczi et al., 2012) with possible immigration pathways (palaeogeographic reconstruction modified from Rögl, 1998 and Kováč et al., 2017a)

North Croatian Basin, while praeorbulinas do not occur here (Ćorić et al., 2009; Gozhyk et al., 2015). A *H. waltrans* occurrence without orbulinas has been reported from the Eastern Paratethys (Gozhyk et al., 2015). Orbulinas without *H. waltrans* were described from the northern part of the Danube Basin (Rybár et al., 2015).

The FO of *Orbulina suturalis* often coincides with the FOs of other praeorbulinas, primarily *P. circularis*. However, in the Styrian Basin, the Alpine Foredeep Basin and the CF, the FO of *P. circularis* slightly preceded the FO of *O. suturalis* (Cicha et al., 1975; Ćorić et al., 2004; Spezzaferri et al., 2009; Doláková et al., 2014; Fig. 5).

Orbulinas are the most widely distributed index microfossils in this time interval, which occur in all Central Paratethys basins (e.g., Ćorić et al., 2004, 2009; Tomanová-Petrová and Švábenická, 2007; Spezzaferri et al., 2009; Selmeczi et al., 2012; de Leeuw et al., 2013; Peryt, 2013; Doláková et al., 2014; Holcová et al., 2015a, b; Gozhyk et al., 2015; Rybár et al., 2015). The FO of *Orbulina* represents the base of the local biozone of *Praeorbulina-Orbulina suturalis* (Cicha et al., 1975).

The magnetostratigraphical timing of the *O. suturalis* FO differs in individual basins (Fig. 4). In the Transylvanian Basin it is calibrated at 14.6–14.17 Ma, which corresponds to the C5ADn Chron (de Leeuw, 2011). This is consistent with the Mediterranean dating (14.59 Ma; di Stefano et al., 2008; Figs. 3 and 4). In other basins, world-ocean bioevent ages for calibration of detected magnetostratigraphical chrons were used. In the Pannonian Basin, it appeared in the reverse chron correlated with C5Bn.1r Chron (15.03–14.87 Ma; Selmeczi et al., 2012). A similar age is suggested for the Alpine Foredeep Basin (Ćorić et al., 2004), while the species' first occurrence in the Styrian Basin is dated to the normal Zone C5Bn.1n (14.87–14.78 Ma). In the case of Mediterranean bioevents dating, detected magnetochrons can be re-calibrated to the C5ADn Chron as in the Transylvania Basin. This calibration can be also supported by radiometric dating of horizons close to the FO of *Orbulina* in Retznei Quarry: 14.21 and 14.39 Ma (Handler et al., 2006). Reverse chrons in the Alpine Foredeep and Pannonian basins can be correlated with C5ACr Chron (14.163–14.033 Ma) and may indicate a gradual appearance of *Orbulina* in the Central Paratethys from the south to the north.

The first occurrences of *Helicosphaera waltrans* and the last occurrences of *Helicosphaera ampliaperta*. Generally, last occurrences have limited correlation potential in epicontinental seas due to the effect of specific palaeoenvironments, which may locally accelerate or delay species extinction. Reworking of microfossils may commonly occur here. This may explain variable relative positions of the LO of *Helicosphaera ampliaperta* in comparison to other events (Fig. 5). In the world oceans and the Central Paratethys this event occurred after the FO of *P. glomerosa*. By contrast, a reverse bioevent succession can be traced in the Mediterranean.

The Mediterranean species *Helicosphaera waltrans* appeared in the Central Paratethys above the FO of *P. glomerosa,* simultaneously with the LO of *H. ampliaperta* (Ćorić et al., 2004; Bartol, 2009) or slightly later (Spezzaferri et al., 2009). The co-occurrence of both helicosphaeras (Švábenická, 2002) may reflect either specific conditions in the CF enabling co-occurrence of both species or redeposition of *H. ampliaperta* from older strata. The LOs of *H. ampliaperta* may be correlated with the LOs of other large helicosphaeras (*H. scissura, H. mediterranea*; Švábenická, 2002) which supports the first possibility.

However, both events have limited applicability in biostratigraphy: the FO of *H. waltrans* due to its scarcity and the LO of *H. ampliaperta* due to its possible reworking.

Last common occurrence of *Helicosphaera waltrans*. The timing of this easily recognizable event can be approximated from dating of the Sooss borehole (Vienna Basin) at 14.38–14.14 Ma (Hohenegger et al., 2009b). *H. waltrans* was not recorded in this borehole. In the Styrian Basin *H. waltrans* was recorded in a radiometrically dated horizon (14.39 Ma; Hohenegger et al., 2009a). This dating indicates that the event occurred at ~14.39–14.38 Ma, in accordance with the Mediterranean dating of this event (14.357 Ma, Abdul-Azis et al., 2008; 14.414 Ma, Hüsing et al., 2010).

The last occurrence of *Sphenolithus heteromorphus*. The LO of *S. heteromorphus* is a significant event in the Mediterranean (Hilgen et al., 2009) which is, however, poorly recognized in the Central Paratethys. Its stratigraphic range may be reduced in some basins (e.g., the northern part of the Danube Basin; Rybár et al., 2015).

Local bioevents. Local bioevents (acme of *Reticulofenestra minuta*, *Spiroplectinella carinata*, *Globorotalia transylvanica*and miliolids) can only be traced in the Central Paratethys. These events probably reflected specific local palaeoenvironments.

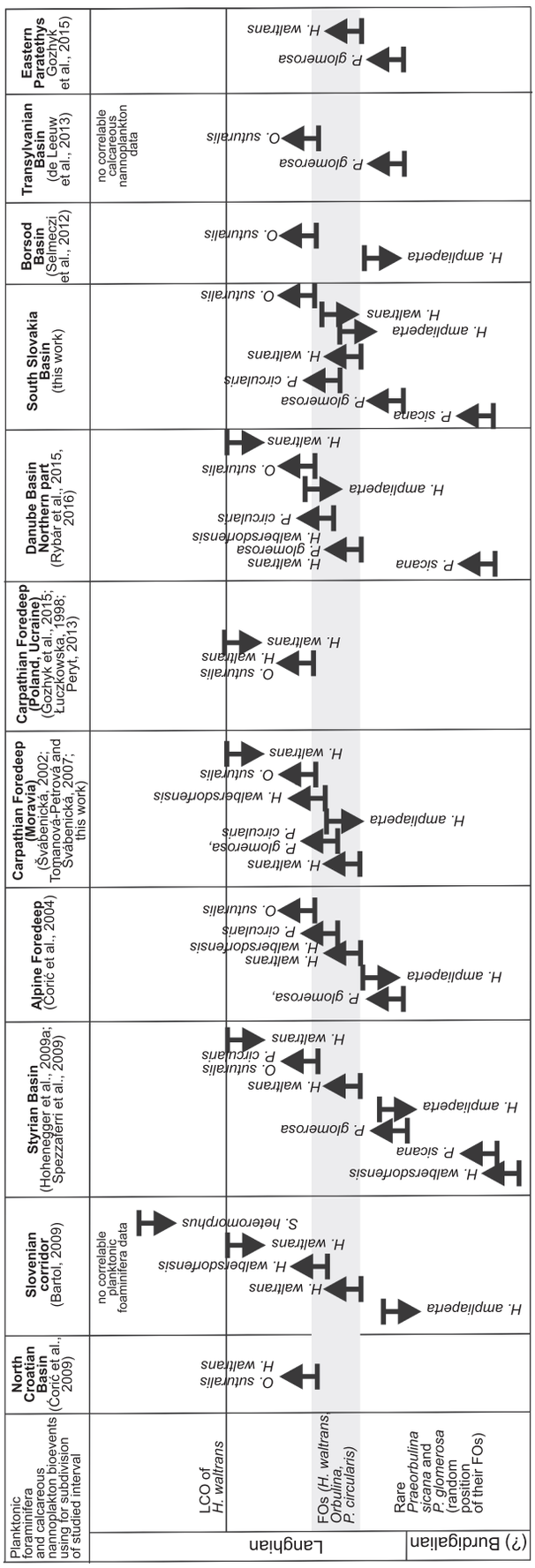

Fig. 5. Succession of planktonic foraminifera and calcareous nannoplankton bioevents in selected Central Paratethys basins during the Langhian

CLIMATOSTRATIGRAPHIC AND SEQUENCE STRATIGRAPHIC CORRELATION

Climatostratigraphy. The very low abundance of arctotertiary markers and high number of thermophylous elements in the interval with the first praeorbulinas can be correlated with the peak of the Middle Miocene Climatic Optimum (MMCO; 15 Ma; Gradstein et al., 2012). Increased abundances of xerophytic markers in the same interval correspond with the first Mediterranean aridification event dated at 15.074 Ma (Hüsing et al., 2010). These ages fit well to the calibration of magnetostratigraphical chrons using the Mediterranean bioevent dating.

Subsequent increase in abundance of arctotertiary markers indicates climate cooling around the FO of *Orbulina*; increased humidity can be inferred from a decrease in xerophytic markers. This change is followed by gradual cooling (increased abundance of arctotertiary markers) and aridification (increased xerophytic markers), which corresponds to the Mi-3a cooling event (14.3 Ma; Gradstein et al., 2012) and more distinctive Mi-3b event (13.8 Ma; Gradstein et al., 2012).

Sequence stratigraphy. Two depositional cycles have been identified within the Moravian sequence of the CF. The first cycle, correlated with TB2.3 of Haq et al. (1987), dates to the pre-Middle Badenian (Hohenegger et al., 2014). The second one, widely recognizable in the Paratethys Province (TB2.4; Haq et al., 1987), corresponds to the Middle Badenian (Hohenegger et al., 2014). Deposits of the first depositional cycle have been penetrated in boreholes in the Alpine-Carpathian Foredeep (Ćorić and Rögl, 2004). Although they have not been recognized in the outcrops and shallow boreholes we studied, their regional occurrence can be supported by the common presence of mudstone intraclasts (Eggenburgian to Early Badenian in age; Nehyba et al., 2006) redeposited in "the coarse-grained basal Badenian clastics" (Nehyba et al., 2008). They are interpreted as coarse-grained deltaic system deposits (Nehyba et al., 2008).

The second Badenian depositional cycle is mostly represented by outer shelf deposits or hemipelagites. These deposits volumetrically predominate in the part of the CF studied. They can also be found further westwards as scattered erosional relicts documenting the original extent of these deposits (Hladilová et al., 1999; Holcová et al., 2015a; Nehyba et al., 2016).

EARLY BADENIAN PALAEOENVIRONMENT AND ITS INFLUENCE ON BIOEVENT TIMING

Several key factors influenced the distribution of index taxa in the Central Paratethys: (1) the quality of the Central Paratethys water-masses (i.e., temperature, salinity, nutrient and oxygen content) played a role in the successful survival and reproduction of index taxa; (2) the circulation regime primarily in the Mediterranean–Paratethys system (estuarine vs anti-estuarine, see Fig. 6). The anti-estuarine regime may have triggered plankton immigration, while predominantly estuarine circulation may have had the opposite effect; (3) the existence, character (mainly depth) and water quality of communication corridors. Generally, the greater the depths of the communication pathway, the lesser the effect of climate, presence of other corridors or current regime on plankton exchange (this principally applies for depths >1,000 m). In shallower corridors (<200 m), exchange with the adjacent oceans may be highly sensitive to the above-mentioned factors (Vara, 2015). Since the latter arrangement is expected in our study area, the previously described factors must be taken into consideration.

For interpretation of circulation regime, sea-water stratification may be significant. The stratification was reconstructed from stable oxygen isotope data for the interval above the FO of *Orbulina*. The foraminifera tests from the interval below the FO of *Orbulina* were poorly preserved. The interval between the FO of *Orbulina* and the LCO of *Helicosphaera waltrans* is characterized by significant differences in surface and bottom water oxygen isotope values (Fig. 2E, F), which may indicate the presence of a well-stratified water column. Seasonal variations in isotope values between spring and summer can also be seen (Fig. 2E, F). This variation is less pronounced above the LCO of *Helicosphaera waltrans*, and can be interpreted as a result of mixing of surface and bottom waters during the spring plankton bloom and increased salinity/temperature variability in summer.

In the following chapter we discuss migration pathways and restrictions of new organisms in the three stratigraphic intervals distinguished.

Interval with *Praeorbulina sicana* and *P. glomerosa* dominated by estuarine circulation (15.9–14.3 Ma). The corridor between the Atlantic and the Mediterranean remained relatively deep during the Early Langhian, which enabled entry of cold Atlantic water as shown by the occurrence of psychrospheric ostracods (Benson, 1978). The palaeobiological evidence can be supported by carbon isotope data (Vergnaud-Grazzini, 1983, 1985), which demonstrates identical isotope composition in the Atlantic and western Mediterranean bottom waters. Central Mediterranean estuarine circulation is suggested for the Early Langhian up to the FO of *Orbulina* (upper part of the *P. sicana* Subzone, i.e. middle part of the MNN5a Subzone; Dall'Antonia et al., 2001). The Indo-Pacific connection remained open with the Circumequatorial Current in place (von der Heydt and Dijkstra, 2005) in the time interval prior to the FO of *Orbulina* (Gebhardt, 1999). The presence of diatoms, high-nutrient *Globigerina* and *Coccolithus pelagicus* and high-nutrient benthic foraminiferal taxa may also indicate an estuarine circulation in the Central Paratethys (Tomanová-Petrová and Švábenická, 2007).

The rare occurrence of *Praeorbulina sicana* and *P. glomerosa* in the Central Paratethys may be related to prevailing estuarine circulation and restricted plankton immigration (Fig. 6). Another factor that limited *Praeorbulina* occurrence in the Central Paratethys may be the lack of a suitable palaeoenvironment for this plankton group. Both *Orbulina,* and *Praeorbulina* thrived in stratified oceans with a summer warm water layer in place (Chapman and Davis, 2010). This can be evidenced by the identical isotopic composition of both groups in our study material (Scheiner, 2015). This warm surface water layer was probably absent in the Central Paratethys during the Early Badenian, which can also be documented by the rare occurrence of other warm-water elements as *Globigerinoides* or *Globigerinella*. *Helicosphaera ampliaperta* and *H. waltrans* co-occurrence in the Central Paratethys in contrast to the Mediterranean also indicates a different quality of surface waters in both regions. The earlier disappearance of *H. ampliaperta* in the Mediterranean at ~15.5 Ma (Iaccarino et al., 2011) may have accelerated the evolution of *Helicosphaera waltrans* in a Mediterranean vacant niche.

The MMCO at ~15 Ma can be correlated with this interval (Zachos et al., 2001; Gradstein et al., 2012). However, studies on microflora and macroflora from the Pannonian and Vienna basins showed some differences to the global trends over the Early and Middle Miocene. The Early Langhian temperature peak does not represent the Miocene temperature maximum in

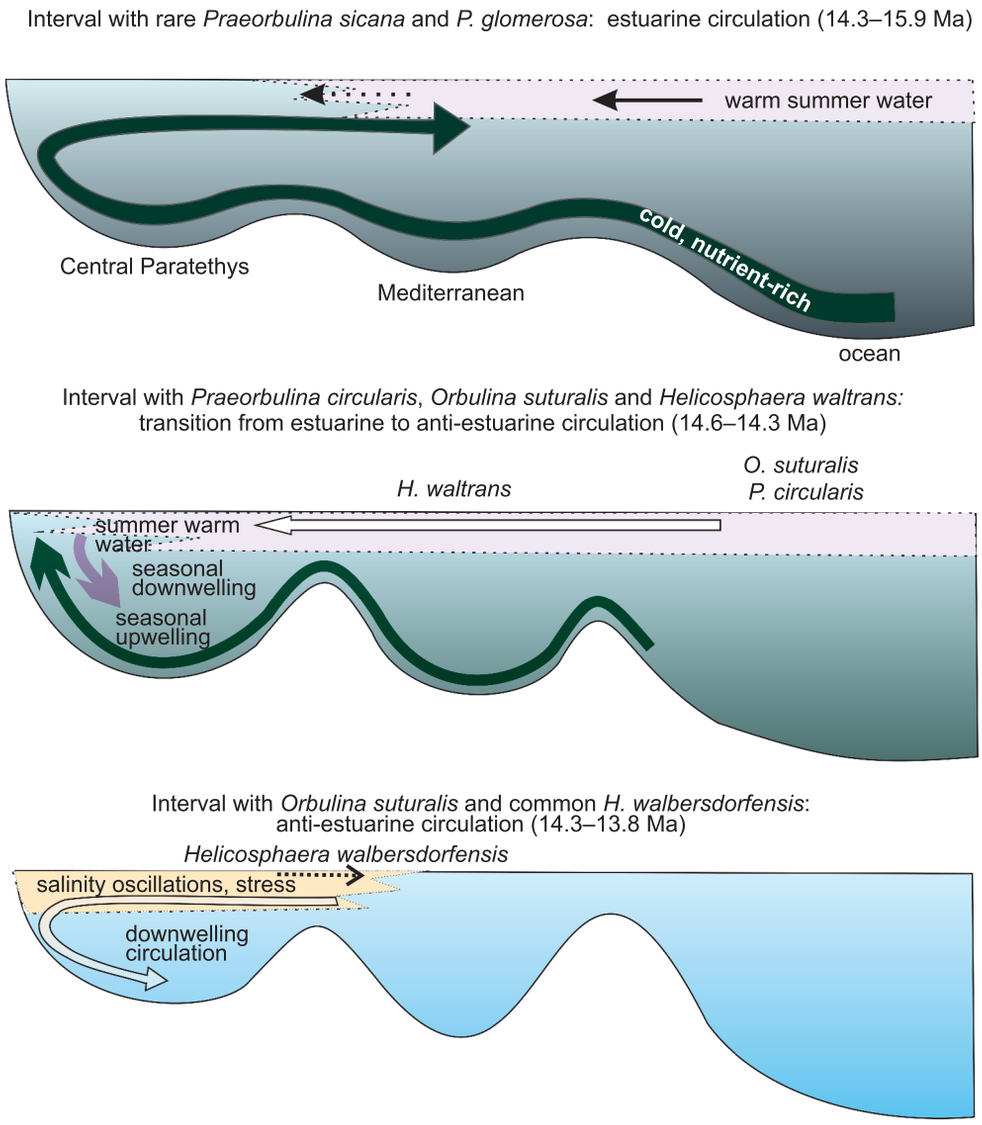

Fig. 6. Models of immigration of biostratigraphical index planktonic foraminifera and calcareous nannoplankton to the Central Paratethys during the Early Badenian (Langhian)

the study area. The warmest climate was recorded in the Eggenburgian–Ottnangian transition (~17–16 Ma; Knobloch et al., 1975; Planderová, 1990; Jiménez-Moreno et al., 2005, 2006; Kvaček et al., 2006; Doláková et al., 2011a, b; Kováčová et al., 2011; Doláková et al., 2014). This corresponds to the conclusions of Böhme et al. (2007), who described the succession from paratropical evergreen forest between 17.5–17.3 Ma, followed by subtropical semi-deciduous and oak-laurel subtropical forest (17–15.3 Ma) from the North Alpine Foredeep xyloflora. This probably reflects mesoclimatic changes caused by northerly plate tectonic shift and/or uplift of the Carpathian mountain chain.

Transition from estuarine to anti-estuarine circulation in the interval with *Praeorbulina circularis, Orbulina suturalis* and *Helicosphaera waltrans* (14.6–14.3 Ma). Closure of the Indian Gateway in the Middle Langhian caused a transition from estuarine to anti-estuarine circulation in the proto-Mediterranean (Kouwenhoven, 2000). This can be dated to the time interval between the FO of *O. suturalis* and the FO of *O. universa* (Russo et al., 2007) at 14.56–14.36 Ma (di Stefano et al., 2008). Change in the Mediterranean circulation regime also influenced circulation changes along the Mediterranean–Central Paratethys communication gateway and triggered several distinct bioevents (i.e., FOs of *Praeorbulina circularis, Orbulina suturalis* and *Helicosphaera waltrans* over a short period of time which coincides with the drop in the *Coccolithus pelagicus/Reticulofenestra minuta* ratio; Tomanová-Petrová and Švábenická, 2007; Spezzaferri at al., 2009). This is interpreted as a result of variations in surface water quality. *C. pelagicus* is an indicator of cold and nutrient-rich waters (Okada and McIntyre, 1979; Winter et al., 1994; Cachao and Moita, 2000), which is consistent with the estuarine circulations in the Early Langhian. On the other hand, the occurrence of *R. minuta* indicates environmental stress characterized by salinity and nutrient oscillations (Flores et al., 1997; Wells and Okada, 1997; Kameo, 2002; Wade and Brown, 2006). Deteriorating quality of surface waters may be linked to salinity oscillations in a downwelling circulation regime expanding from the

Mediterranean to the Paratethys. Our detailed analysis shows that the interval with *H. waltrans* represents a transition between both regimes with locally persisting coastal upwelling (Holcová et al., 2015a). Generally, this newly established anti-estuarine circulation triggered the formation of a warm summer surface water layer and the immigration of planktonic taxa such as orbulinas and praeorbulinas and also *Globigerinoides* spp. and *Globigerinella regularis* (Fig. 6; Holcová et al., 2015a).

The variegated succession of the FOs of *Praeorbulina circularis, Orbulina suturalis* and *Helicosphaera waltrans* and the position of the FO of *Orbulina* in normal and reverse magnetochrons suggests that the second Badenian transgression was not isochronous across different basins. This effect is generally recognized in peripheral foreland basins as the formation of accommodation space in distal and proximal parts (Heller et al., 1988; Catuneanu et al., 1997, 1998).

Interval with *Orbulina suturalis* and common *H. walbersdorfensis* dominated by anti-estuarine circulation and onset of the Wielician salinity crisis (14.3–13.8 Ma). No global bioevent has been recognized in the Central Paratethys during this interval. A local event characterized by a gradual substitution of large *H. waltrans* by small *H. walbersdorfensis* occurred at its base. The relative abundance of *H. walbersdorfensis* positively correlated with *Reticulofenestra minuta* (Holcová, 2017) suggests its stress-tolerance. The palaeoenvironmental changes during this event were summarized by Doláková et al. (2014), Holcová et al. (2015a, b), and Nehyba et al. (2016), being characterized by increasing aridity and decreasing riverine and terrestrial nutrient input with episodic heavy rainfalls. Increased seasonality caused perturbations in mixed and stratified water columns and seasonal variations in nutrient input. Increase in the surface water salinity during summers can be detected in the oxygen isotope record (Scheiner, 2015) and dinoflagellate assemblages (Nehyba et al., 2016). Aridification trends can also be traced in the increased percentage of xerophytic markers in the pollen spectra from our studied boreholes (Fig. 2C). A similar trend dated at 14.3 Ma was described by Böhme et al. (2010) from xyloflora of the Alpine Foredeep Basin.

The timing at ~14.3 Ma can also be approximated to the FCO of *H. walbersdorfensis*. The age of its FCO in the Mediterranean (14.05 Ma; Mourik et al., 2011) indicates the immigration direction from the Paratethys to the Mediterranean, which is expressed in the bioevents succession. The stress-tolerant *H. walbersdorfensis*, a typical Paratethyan species, reflected a varying quality of surface water in a small epicontinental basin which extended to the Mediterranean due to the Middle Miocene Climatic Transition, while closure of the Indian–Mediterranean Gateway and a change in the circulation pattern also occurred in the Atlantic–Mediterranean Gateway at the end of the Langhian (Gebhardt, 1999).

This interval is characterized by a dominance of conifers in the pollen spectra, which is sometimes referred to as the *Pinus* event. The accumulation of conifer pollen in offshore marine sediments may be explained by pollen mass production, long-distance aerial transport (from W or NW) and also by their high resistance to oxidation in water or sediment (Heusser, 1978; Hopkins and McCarthy, 2002). A cyclic arrangement of this mass accumulation is consistent with variations in abundance of biserial agglutinated foraminifera and *Globorotalia transylvanica/bykovae* and also with multiproxy cyclicity in the Sooss borehole (Vienna Basin), interpreted as Milankovitch climatic cycles (Hohenegger et al., 2008).

The interval was terminated by the Wielician salinity event that led to increased salinity of the surface water layer (Scheiner, 2015; Nehyba et al., 2016). This can be documented by an increase in miliolid abundance in the shallow-water deposits. This bioevent is dated at 13.73 Ma in the Danube Basin (Fordinál et al., 2014) which is consistent with dating of the salinity crisis (beginning at 13.81 Ma with a duration between 200 and 600 ky; de Leeuw et al., 2010).

Although the persistant anti-estuarine circulation should generally favour the immigration of biostratigraphic plankton markers to the Central Paratethys (the FO of *G. praemenardi* at 14.4 Ma in the world oceans or 13.9 Ma in the Mediterranean; Gradstein et al., 2012), the cooling (recorded in micro- and macroflora) and salinity oscillations in the surface waters probably restricted this process. The salinity crisis started prior to the LO of *S. heteromorphus* in the world oceans (13.5 Ma; Gradstein et al., 2012), which suggests that the bioevent occurred earlier in the Central Paratethys due to oscillating salinity.

Salinity oscillations accompanied by salt deposition can be detected all over the Mediterranean region (evaporite deposits in Egypt; Ied et al., 2011) and may be used as a correlation horizon in sequences with no index taxa.

The cooling event can be detected slightly later in the continental plant assemblages (at ~13.5 Ma; Planderová, 1990; Jiménez-Moreno et al., 2005; Jiménez-Moreno, 2006; Kvaček et al., 2006; Doláková et al., 2011, 2014; Kováčová et al., 2011). This disproportion has not yet been adequately explained.

CONCLUSIONS

1. The interval between the FO of *Praeorbulina* and the FO of *H. waltrans* and/or *Orbulina* correlates with the first Badenian transgression. Probably only the Mediterranean–Central Paratethys Gateway was in place at this time with no direct connection between the Central Paratethys and the world ocean. Therefore, the timing of biostratigraphical events recorded here must be coeval with or later than in the Mediterranean. In this case, correlation of the Karpatian/Badenian boundary with the Burdigalian/Langhian boundary (in the sense of Piller et al., 2007) is appropriate, and can be corroborated by climatostratigraphic data placing the top of the MMCO to this interval.

The first Badenian biostratigraphical markers (*Praeorbulina sicana* and *P. glomerosa*) were only rarely detected in the Central Paratethys. This is interpreted as a consequence of restricted immigration of the index taxa linked to the absence of a warm surface water layer in this region and predominantly estuarine circulation in the Mediterranean–Paratethys system. The scarcity or absence of standard biostratigraphical markers and/or presence of numerous gaps related to tectonic uplift complicate stratigraphic correlation in this interval, and more radiometric ages would certainly help understanding of this period.

2. The coeval FOs of *Praeorbulina circularis, Orbulina suturalis* and *Helicosphaera waltrans* at the base of the second Badenian transgressive cycle coincide with the change from estuarine to anti-estuarine circulation regime in the Mediterranean–Paratethys system. This was accompanied by establishment of a warm summer surface water layer in the Central Paratethys. Slightly different bioevent timings and their succession may indicate heterochrony of the transgression in individual basins and the formation of a summer surface water layer.

3. The Middle Miocene climatic transition significantly affected the Central Paratethys palaeoenvironment in the time in-

terval following the LCO of *Helicosphaera waltrans*. This resulted in climatic instability, and climate cooling followed by a regional salinity crisis. Its onset can be detected earlier in marine settings and later in continental environments. The absence of standard stratigraphical markers can be related to palaeoenvironmental fluctuations and salinity oscillations.

Acknowledgements. The study was supported by the projects PROGRES Q45, Ministry of Culture programme DKRVO 2016/04 (National Museum, 00023272). The authors greatly appreciate the constructive reviews of D. Peryt and M. Oszczypko-Clowes which improved the manuscript.

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