Received: 7 December 2016 | Revised: 14 April 2017 | Accepted: 15 May 2017
DOI: 10.1111/ter.12273

PAPER

WILEY Terra Nova

Changing seas in the Early–Middle Miocene of Central Europe: a Mediterranean approach to Paratethyan stratigraphy

Karin Sant[1] | Dan V. Palcu[1] | Oleg Mandic[2] | Wout Krijgsman[1]

[1]Paleomagnetic Laboratory Fort Hoofddijk, Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

[2]Geological-Paleontological Department, Natural History Museum Vienna, Vienna, Austria

Correspondence
Wout Krijgsman, Paleomagnetic Laboratory Fort Hoofddijk, Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands.
Email: w.krijgsman@uu.nl

Funding information
Netherlands Geosciences Foundation; Netherlands Organization for Scientific Research

Abstract

The Miocene palaeogeographic evolution of the Paratethys Sea is still poorly constrained. Here, we use modern Mediterranean biochronology to provide an up-to-date overview of changing seas in Central Europe. Instead of a Paratethys that waxed and waned with fluctuating global sea levels, we show that the development of different seas was mainly controlled by tectonic phases. The Early Miocene "Ottnangian Sea" (~18 Ma) was connected to the Mediterranean via the Rhône valley, while the "Karpatian Sea" (~16.5 Ma) was initiated by a tectonically induced marine transgression through the Trans-Tethyan gateway. In most Central European basins, the establishment of the "Badenian Sea" (<15.2 Ma), triggered by subduction-related processes in the Pannonian and Carpathian domain, is significantly younger (by ~1 Myr) than usually estimated. The updated palaeogeographic reconstructions provide a better understanding of the concepts of basin dynamics, land–sea distribution and palaeoenvironmental change in the Miocene of Central Europe.

1 | INTRODUCTION

During the Oligocene to Miocene, large parts of Europe and western Asia were covered by the epicontinental Paratethys Sea (Figure 1b). This sea progressively retreated through a complex combination of basin infill, glacio-eustatic sea-level lowering and tectonic uplift to its present-day remnants: the Black Sea and the Caspian Sea. Paratethys retreat also influenced European climate, ecosystems and depositional settings (e.g. Marzocchi, Flecker, van Baak, Lunt, & Krijgsman, 2016; Ramstein, Fluteau, Besse, & Joussaume, 1997) and generated large quantities of natural resources (oil, gas, salt) that are of economic importance for the region today (e.g. Dank, 1988; Hudson et al., 2008; Sachsenhofer, 1994).

The spatial and temporal evolution of the Paratethys Sea during the Early to Middle Miocene (~18–14 Ma) is still poorly constrained. Paratethys chronostratigraphy is generally considered to follow third-order global sea-level cycles, and the main palaeoenvironmental changes and regional stage boundaries have been correlated to seismic sequence boundaries, commonly interpreted as sea-level falls (Haq, Hardenbol, & Vail, 1988; Hardenbol et al., 1998) (Figure 1a). Recently, however, this paradigm was challenged by new age constraints and comparison with global palaeoclimatic proxy records and modelled sea-level curves (van de Wal, de Boer, Lourens, Köhler, & Bintanja, 2011; Zachos, Dickens, & Zeebe, 2008) showing that many Paratethyan events do not correspond to changes in global sea level but are more likely a reflection of geodynamically induced changes in basin connectivity (e.g. Grunert, Tzanova, Harzhauser, & Piller, 2014; Kováč, Baráth, Harzhauser, Hlavatý, & Hudáčková, 2004; Palcu, Tulbure, Bartol, Kouwenhoven, & Krijgsman, 2015; ter Borgh et al., 2013).

In many Paratethys basins, the chronologic framework to disentangle geodynamic and climatic processes affecting depositional environments is still poorly constrained. This is mainly due to the common presence of endemic fauna in the restricted Paratethys Sea (e.g. Popov et al., 2006), poor quality palaeomagnetic signals (e.g. de Leeuw et al., 2013) and lack of absolute age control (e.g. Piller, Harzhauser, & Mandic, 2007). In addition, the scarce marine micropalaeontological data from Paratethyan successions are commonly correlated to the Atlantic-based biozones of the Geological Time Scale (GTS). During the Early–Middle Miocene, however, Paratethys was connected to the Atlantic Ocean via the Mediterranean, which has its own specific biochronology. In this article, we

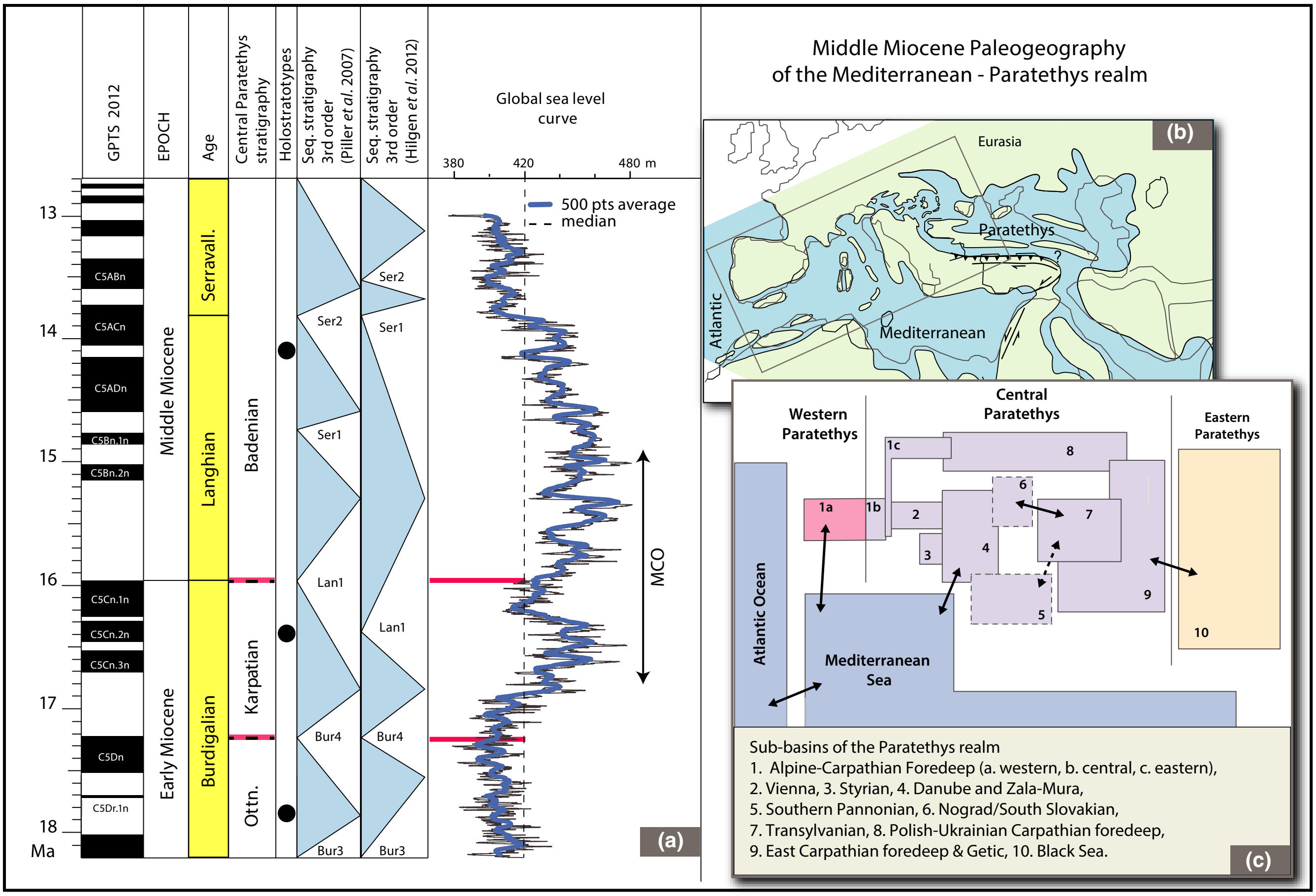

FIGURE 1 (a) Global Polarity Times Scale (GPTS; Hilgen et al., 2012) and international and regional time-scales plotted against two different 3rd-order sequence stratigraphic curves and a global sea-level curve based on benthic foraminifers $\delta^{18}O$ by Van de Wal et al. (2011). MCO, Miocene Climatic Optimum. (b) Impression of the configuration of the seas in Central Europe during the early Middle Miocene (~13 Ma), slightly modified after Rögl (1999). The study area is marked with a grey box. (c) Schematic block diagram of the studied Paratethys sub-basins and the most important connections. See Figure 3 and Data S1 for references [Colour figure can be viewed at wileyonlinelibrary.com]

incorporate the most recent Mediterranean biozones into our chronostratigraphic overview of the Paratethyan basins and present an up-to-date picture of the changing seas during the Early–Middle Miocene in Central Europe.

2 | REVISED BIOSTRATIGRAPHIC CONSTRAINTS

It has long been clear that the standard Atlantic M-biozonation (Berggren, Kent, Swisher, & Aubry, 1995) for planktonic foraminifers and the NN-biozonation (Martini, 1971) for calcareous nannofossils are of only limited applicability to marginal basins such as the Mediterranean and Paratethys Sea (Iaccarino, 1985; Iaccarino & Salvatorini, 1982). Mediterranean planktonic foraminifer assemblages are characterized by a marked provincialism and differ from the Atlantic low-latitude assemblages starting from the Middle Miocene (Iaccarino et al., 2011; Lirer & Iaccarino, 2005; Turco et al., 2002). This is partly related to global climate evolution and partly to the Mediterranean geodynamic evolution. Recently, detailed investigations of Early–Middle Miocene sedimentary successions have generated an improved regional calcareous plankton biochronologic framework for the Mediterranean region (Figure 2; Di Stefano et al., 2008, 2015; Foresi et al., 2011; Iaccarino et al., 2011; Turco et al., 2017). Remarkably, the revised Mediterranean biochronology has not yet been used to its full extent to re-date the Paratethyan successions.

Especially relevant in this context are the first occurrences (FO) of the planktonic foraminifers *Praeorbulina glomerosa glomerosa* (15.2 Ma in the Mediterranean [Iaccarino et al., 2011; Turco et al., 2017] vs. 16.4 Ma in the GTS [Wade, Pearson, Berggren, & Pälike, 2011]) and *Orbulina suturalis* (14.6 Ma in the Mediterranean [Abdul Aziz et al., 2008; Di Stefano et al., 2008] vs. 15.1 Ma in the GTS). The last occurrence (LO) of the calcareous nannofossil *Helicosphaera ampliaperta* (~14.9 Ma in the GTS), defining the top of the NN4 Zone, is another widely used event, which cannot be properly recognized in the Mediterranean (Di Stefano et al., 2008, 2015), indicating that applying the NN4/NN5 boundary in Paratethys chronostratigraphy is imprecise. In the Mediterranean, the last common occurrence (LCO) of *H. ampliaperta* is better defined and dated at 16.1 Ma, after which this species is still sporadically present (Iaccarino et al., 2011). The

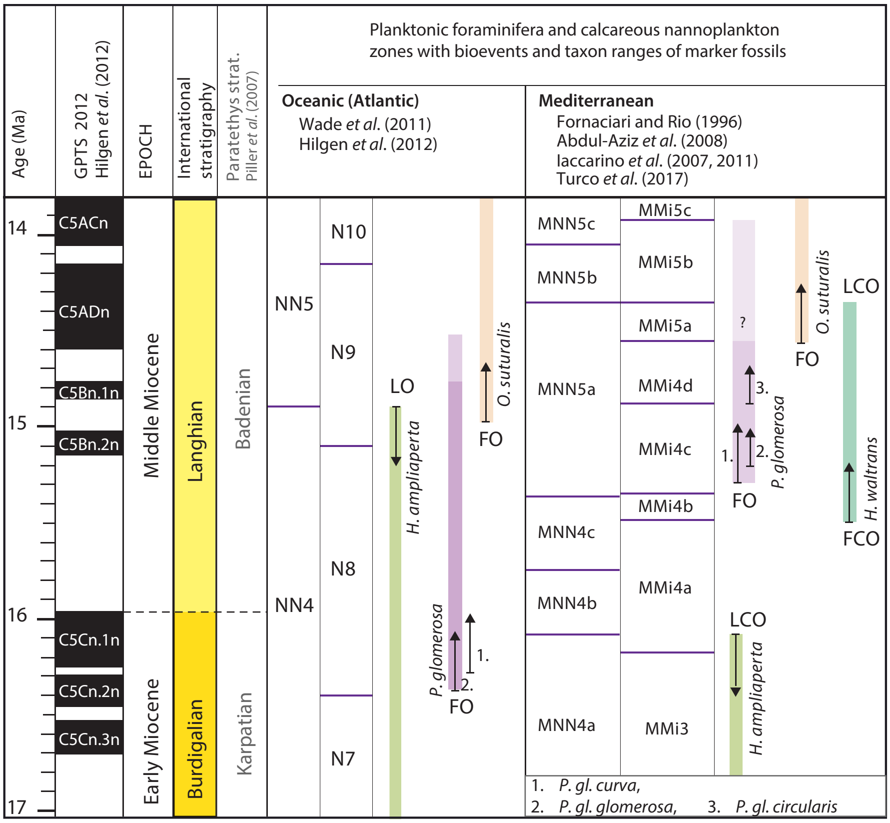

FIGURE 2 Biozones and dated bioevents used in the oceanic (Atlantic) and Mediterranean domains. The NN-zonation and LO of *H. ampliaperta* follow Hilgen et al. (2012). Note that in most recent publications, the LO and LCO of *H. ampliaperta* are considered unsuitable as marker levels due to the discontinuous and scattered distribution of *H. ampliaperta* in its upper range. For an overview of the definitions of the Mediterranean biozones, see Fornaciari and Rio (1996), Di Stefano et al. (2008) and Iaccarino et al. (2007, 2011) [Colour figure can be viewed at wileyonlinelibrary.com]

FCO of *Helicosphaera waltrans* (~15.5 Ma) and the FO of *P. glomerosa circularis* (~14.9 Ma) are additional events that can be used for biostratigraphic dating in the Paratethys (Abdul Aziz et al., 2008; Di Stefano et al., 2008; Iaccarino et al., 2011). In this article, we focus on the above-mentioned marker species that play a major role in the Paratethys correlation problems.

3 | CHANGING SEAS IN CENTRAL EUROPE

The Early–Middle Miocene transition is an enigmatic interval where both sea-level change and tectonic activity are suggested to have contributed to the palaeogeographic and palaeoenvironmental evolution of the Paratethys sea (Kováč et al., 2007; Piller et al., 2007). For this study, we have re-analysed the chronologic and biostratigraphic data (global calcareous plankton and regional benthic foraminifera and mollusc bioevents) from 10 individual Paratethyan sub-basins (Figure 1c) and revised the correlation of the corresponding sedimentary successions to the GTS (Figure 3). This provides an alternative view of the palaeogeographic evolution of the land–sea distribution in Central Europe.

3.1 | The Ottnangian Sea

Plotting all sites with marine Ottnangian records on a map reveals the palaeo configuration of the "Ottnangian Sea", stretching from the Carpathian basin in the east via the North Alpine Foreland Basin (NAFB) in southern Germany towards Switzerland and south-east France in the west (Figure 4a). The most recent GTS places the Ottnangian between 18.2 and 17.25 Ma (Piller et al., 2007; Hilgen, Lourens, & Van Dam, 2012; Figure 1a).

The Ottnangian Sea was probably not connected to the Black Sea region, which was an isolated lake at that time (Popov et al., 2004; Rögl, 1999). Stratigraphic studies in the Southern Pannonian Basin do not show evidence for a hypothetical connection to the Adriatic region (Mandic et al., 2012). The Ottnangian Sea was open to the west and connected to the Mediterranean via the NAFB and the Rhône Valley (Berger et al., 2005). In the NAFB, the Ottnangian Sea is marked by deposition of Upper Marine Molasse sediments. The retreat of the sea is dated between ~17.6 and 17.0 Ma in the south-west German Molasse basins (bio-magnetostratigraphy by Reichenbacher et al., 2013; Sant et al., 2017) (Figure 3). Termination of the marine gateway resulted in isolation of the Paratethys, turning it gradually into a system of brackish and freshwater lakes showing an explosive radiation of endemic *Rzehakia* fauna (Harzhauser & Mandic, 2008; Harzhauser & Piller, 2007). The termination of the brackish-water depositional setting is dated at ~17.2 Ma in the NE-Austrian Molasse basin ($^{40}Ar/^{39}Ar$ chronology and bio-magnetostratigraphy by Roetzel et al., 2014). In the central NAFB, in contrast, full freshwater environments installed progressively westward between ~16.7 Ma and ~16.0 Ma (Kälin & Kempf, 2009; Reichenbacher et al., 2013; Sant et al., 2017). Consequently, the disintegration of the Ottnangian Sea was strongly controlled by long-term tectonics in the Alpine domain, whereas short-term events could have been influenced by global sea-level fluctuations (e.g. Kempf, Matter, Burbank, & Mange, 1999). Continental and lacustrine sedimentation continued up to the Late Miocene in the central NAFB (Kirscher et al., 2016).

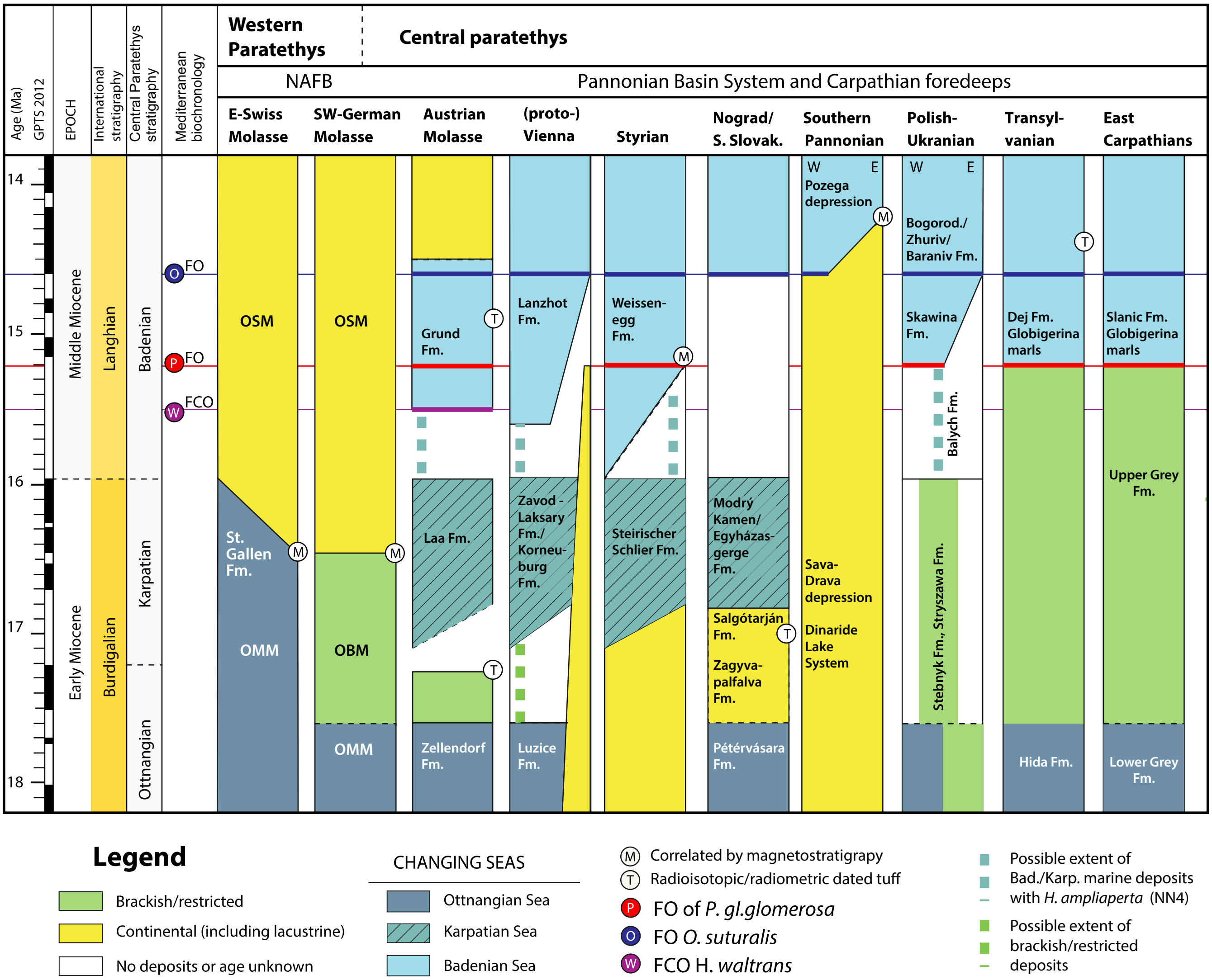

FIGURE 3 Compilation of environmental and age data (radioisotopic ages, magnetostratigraphy, biochronology) for 10 sub-basins in Central Europe. Biochronology follows the Mediterranean scheme shown in Figure 2. Time-scale (GPTS) after Hilgen et al., (2012). Note that the FO of *Praeorbulina* in the Central Paratethys refers to the FO of *P. gl. glomerosa*, occurring always together with *P. gl. curva* (Rögl, Spezzaferri, & Ćorić, 2002). When no boundary data were available, the top of the Karpatian Sea was provisionally set to the top of the Burdigalian; the base of the Karpatian Sea for the Vienna and Styrian basins was equalized to the base of the Austrian Molasse basin. OMM, Upper Marine Molasse; OBM, Upper Brackish Molasse; OSM, Upper Freshwater Molasse. Main literature used for the compilation of the basins: Swiss Molasse (Kälin & Kempf, 2009; Schlunegger et al., 1996); S-German Molasse (Abdul Aziz et al., 2010; Reichenbacher et al., 2013; Sant et al., 2017); Austrian Molasse (Ćorić & Rögl, 2004; Ćorić et al., 2004; Rögl et al., 2003); Vienna (Andreyeva-Grigorovič, Kováč, Halásová, & Hudáčková, 2001; Kováč et al., 2004; Rögl et al., 2002); Styrian (Auer, 1996; Hohenegger et al., 2009; Kollmann, 1965; Rögl et al., 2002; Spezzaferri, Ćorić, & Stingl, 2009); Nograd/South Slovakian (Mandic et al., 2012; Pálfy et al., 2007; Vass, 2002) [also Borsod basin: (Selmeczi, Lantos, Bohn-Havas, Nagymarosy, & Szegő, 2012) and Danube basin (Rybár et al., 2015; Rybár et al., 2016)]; Southern Pannonian (Ćorić, Pavelić, Rögl, Mandic, & Vrabac, 2009; de Leeuw, Mandic, Krijgsman, Kuiper, & Hrvatovic, 2011; de Leeuw, Mandic, Krijgsman, Kuiper, & Hrvatović, 2012; de Leeuw et al., 2010; Mandic et al., 2012; Pezelj, Mandic, & Coric, 2013); Polish–Ukrainian foredeep (Andreyeva-Grigorovich et al., 1997; Oszczypko & Oszczypko-Clowes, 2011); Transylvanian Basin (Beldean, Filipescu, & Bǎlc, 2010; de Leeuw et al., 2013; Székely, Beldean, Bindiu, Filipescu, & Săsăran, 2016); East Carpathian foredeep (Marunteanu, 1999; Popescu, 1975). Details of the main data sources can be found in Data S1 [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | The Karpatian Sea

The onset of marine Karpatian deposits indicates a completely different geodynamic setting in Central Europe (Figure 4b). The latest Karpatian successions generally contain the planktonic foraminifera species *Globigerinoides bisphericus* and the calcareous nannofossil species *Helicosphaera ampliaperta* (Brzobohatý, Cicha, Kováč, & Rögl, 2003). The most recent GTS places the Karpatian between

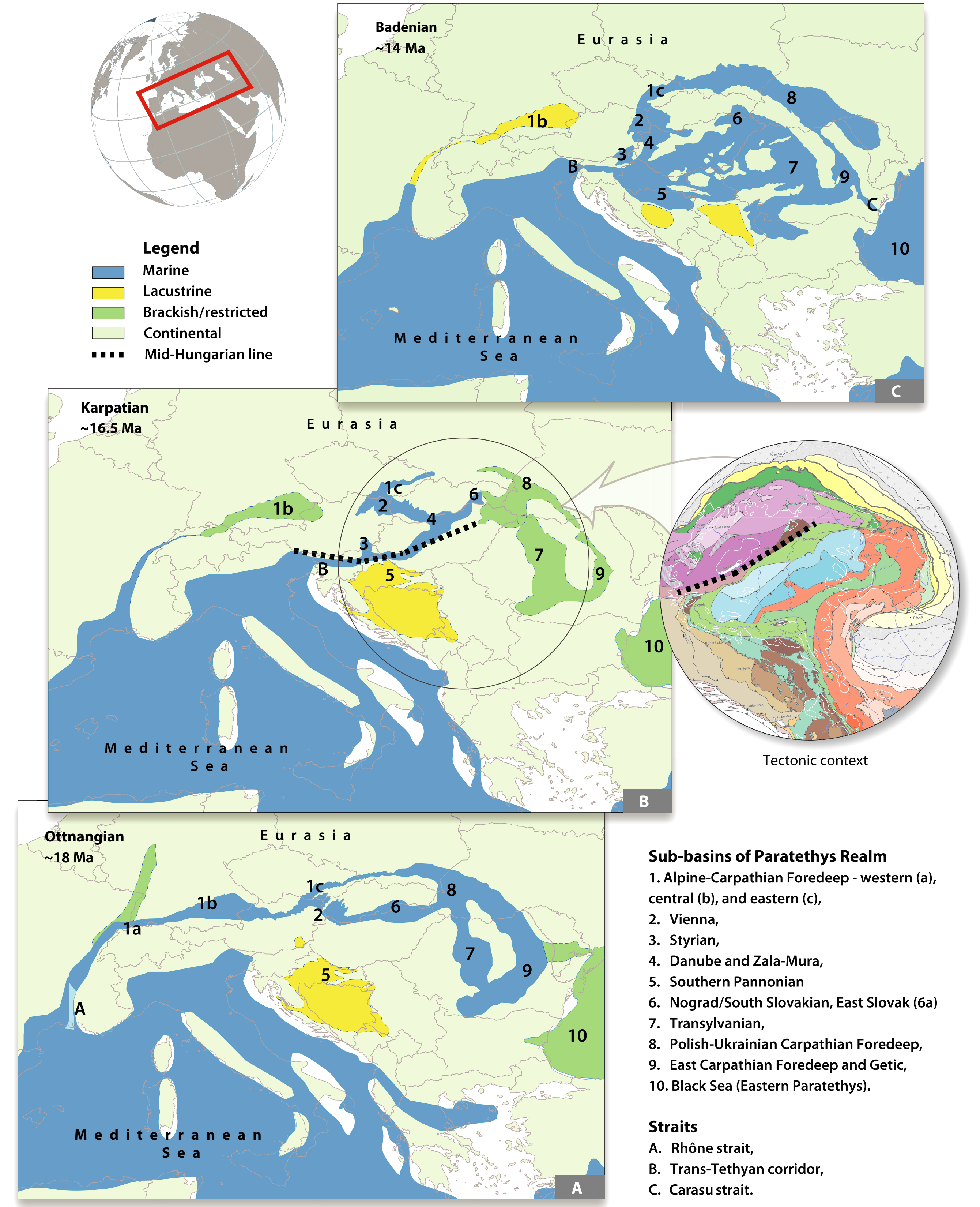

FIGURE 4 Present-day distribution of early–middle Miocene sediments (18, 16.5, 14.5 Ma old) highlighting the palaeogeographic changes in the European sub-basins of the Paratethys realm. Simplified palaeogeographic sketches based on previous reconstructions (Popov *et al.*, 2004; Rögl, 1999) and updated based on the literature review presented in Figure 3. Tectonic context after Ustaszewski et al., (2008). [Colour figure can be viewed at wileyonlinelibrary.com]

17.25 Ma and 15.96 Ma (Hilgen et al., 2012; Piller et al., 2007), although its upper boundary with the Badenian is still debated (e.g. Hohenegger, Ćorić, & Wagreich, 2014).

Marine Karpatian successions are known from the eastern Alpine–Carpathian Foredeep in the west to the Nograd/South Slovakian basin in the east (Figure 3). In all shallow-marine settings of the Central Paratethys, the marine Karpatian overlies the Ottnangian with an erosional unconformity (Brzobohatý et al., 2003 and references therein). Astronomical tuning of the gamma-ray record from the Korneuburg Basin (north-east Austria) dated the Karpatian marine transgression at 17.0 Ma (Zuschin, Harzhauser, Hengst, Mandic, & Roetzel, 2014).

The Black Sea basin does not provide any evidence for open marine conditions in Early Miocene times, excluding a marine gateway to the east (Popov et al., 2006). Consequently, the most logical connection to the Mediterranean is through the so-called Trans-Tethyan gateway (Kováč et al., 2007; Mandic et al., 2012) (Figure 4). The Trans-Tethyan gateway and the land–sea distribution of the Karpatian sea remarkably follow the contours of the Mid-Hungarian Line (MHL; Géczy, 1973), suggesting that tectonic shear, accompanied by differential block rotations between the ALCAPA and Tisza-Dacia mega-units (e.g. Márton, Tischler, Csontos, Fügenschuh, & Schmid, 2007), played a major role by re-connecting Central Paratethys basins with the open ocean, giving rise to the "Karpatian Sea" in the latest Early Miocene.

3.3 | The Badenian Sea

Originally, the base of the Badenian was tied to the base of the Langhian (Papp & Cicha, 1978; sensu Blow, 1969), because for both stages the so-called *Praeorbulina* datum—the FO of the planktonic foraminifera genus *Praeorbulina*—was the guiding criterion (Berggren et al., 1995; Lirer & Iaccarino, 2011). Hence, most authors consider the Karpatian–Badenian boundary equivalent to the Burdigalian–Langhian boundary (Piller et al., 2007), which has an age of 15.97 Ma according to the GTS (Hilgen et al., 2012). It must be noted here that the boundary criterion for the Langhian is not yet officially defined. It was provisionally set to the top of palaeomagnetic chron C5Cn.1n because of indications that the *Praeorbulina* datum might be discontinuous and/or slightly diachronous (Hilgen et al., 2012; Lourens, Hilgen, Laskar, Shackleton, & Wilson, 2004). Being aware of this discussion, we follow the Mediterranean biochronology and date the sediments with *P. glomerosa glomerosa*, the current FO *Praeorbulina* marker in the Paratethys, younger than 15.2 Ma (cf. Turco et al., 2017).

The "Badenian Sea" significantly expanded in Middle Miocene times by flooding the Transylvanian and Southern Pannonian basins and spreading all over the Carpathian foredeep (Figures 3 and 4c). In most Central European basins, the base of the Badenian flooding is characterized by a transitional zone with clastic material (sand and/or conglomerate) and reworked fossils. The surface outcrops in the north (Carpathian foredeep) and west (Vienna, NE-Austrian Molasse and Styrian basins) contain erosional features (e.g. Hohenegger et al., 2009), and a zone of reworking is observed in most drill cores (Ćorić & Rögl, 2004; Oszczypko and Oszczypko-Clowes, 2011; Selmeczi et al., 2012), complicating dating of the basal succession (Figure 3).

In the western (NE-Austrian Molasse, Vienna, Styrian) basins the initiation of the Badenian sea predates the FO of *H. waltrans* (Ćorić & Rögl, 2004; Hohenegger et al., 2009). Many other Badenian sedimentary successions contain the planktonic foraminifer *Praeorbulina glomerosa glomerosa* in their lower part (Kováč et al., 2007). Consequently, the Badenian transgression in these basins is dated at <15.2 Ma (Figure 3), significantly younger than commonly envisaged (~16 Ma), but in good agreement with their biostratigraphic records where the lowermost Badenian sediments generally do not extend far below the FO of the planktonic foraminifer *Orbulina suturalis* (de Leeuw et al., 2013; Kováč et al., 2007; Rögl et al., 2002).

The most logical connection of the Badenian Sea to the Mediterranean is again through the Trans-Tethyan corridor in Slovenia (Figure 4c). This corridor is considered to have persisted throughout the entire Badenian stage and lasted until 12.7–12.6 Ma (Bartol et al., 2013). Tectonic subsidence of the Pannonian and Carpathian Foredeep region in the Middle Miocene was intrinsically related to subduction and slab roll-back processes in Central Europe (Horváth et al., 2006). Ongoing subsidence likely caused a progressive south-eastward transgression, ultimately flooding all the studied Central European basins. This transgression is diachronous throughout the Central Paratethys domain, depending on the regional tectonic setting. More accurate dating of the basal marine succession is needed to better comprehend the underlying dynamics.

4 | GEODYNAMICS VS. CLIMATE

To distinguish geodynamic from climatic causes is one of the most challenging and complex issues in modern Earth sciences. Sea-level lowering and tectonic uplift will both decrease the water exchange in marine gateways and may thus cause similar changes in depositional environment. The land-locked Paratethys basins were only connected to the open ocean via narrow gateways, and hydrological fluctuations have profound influences on environmental conditions, such as temperature, salinity and humidity (Karami, de Leeuw, Krijgsman, Meijer, & Wortel, 2011).

Despite being located close to tectonically active mountain regions such as the Alps, Dinarides and Carpathians, palaeoenvironmental changes in the Central Paratethys basins are commonly linked to third-order sea-level cycles and are generally correlated to the sea-level curve of Haq et al., (1988) and the sequence stratigraphic cycles of Hardenbol et al., (1998). In this context, the Ottnangian–Karpatian and Karpatian–Badenian boundaries are correlated to the Bur3 and Lan1/Bur5 lowstands, respectively (Figure 1a). In addition, the basal marine Badenian transgression is commonly correlated to the global sea-level cycle TB2.3.

Our data compilation demonstrates that marine sedimentation across the studied boundaries is mostly discontinuous, age data are scarce, and reliable biostratigraphic markers are limited, especially in the Early Miocene successions (Figure 3). The disintegration of the Ottnangian Sea is marked by significant tectonic activity in the Alpine region, and the re-flooding by the Karpatian Sea is strongly related to a shear-zone along the Mid-Hungarian Line. In most areas, the Badenian transgression (<15.2 Ma) is significantly younger than previously estimated (~16 Ma) and is strongly influenced by subduction-related processes in the Pannonian and Carpathian domain. We conclude that tectonic reorganization of the Central European basins is the dominant factor in the Early to early Middle Miocene time interval and that global sea-level fluctuations are of subordinate relevance for its palaeogeographic evolution.

ACKNOWLEDGEMENTS

This work was financially supported by the Netherlands Geosciences Foundation (ALW) and the Netherlands Organization for Scientific Research (NWO) through the VICI grant of WK. We thank Niccolò Baldassini, Agata Di Stefano, Elena Turco, Michal Kováč and Mathias Harzhauser for constructive stratigraphic discussions and/or feedback on our figures.

REFERENCES

Abdul Aziz, H., Böhme, M., Rocholl, A., Prieto, J., Wijbrans, J. R., Bachtadse, V., & Ulbig, A. (2010). Integrated stratigraphy and $^{40}Ar/^{39}Ar$ chronology of the early to middle Miocene Upper Freshwater Molasse in western Bavaria (Germany). *International Journal of Earth Sciences*, *99*, 1859–1886.

Abdul Aziz, H., Di Stefano, A., Foresi, L. M., Hilgen, F. J., Iaccarino, S. M., Kuiper, K. F., . . . Turco, E. (2008). Integrated stratigraphy and 40 Ar / 39 Ar chronology of early Middle Miocene sediments from DSDP Leg 42A, Site 372 (Western Mediterranean). *Palaeogeography Palaeoclimatology Palaeoecology*, *257*, 123–138.

Andreyeva-Grigorovič, A. S., Kováč, M., Halásová, E., & Hudáčková, N. (2001). Litho and biostratigraphy of the Lower and Middle Miocene sediments of the Vienna basin (NE part) on the basis of calcareous nannoplankton and foraminifers. *Scripta, Facultatis Scientiarum Naturalium Universitatis Masarykianae Brunensis*, *30*, 27–40.

Andreyeva-Grigorovič, A. S., Kulchytsky, Y. O., Gruzman, A. D., Lozynyak, P. Y., Petrashkevi, M. I., Portnyagina, L. O., . . . Shvareva, N. J. (1997). Regional Stratigraphic Scheme Of Neogene Formations Of The Central Paratethys In The Ukraine. *Geologica Carpathica*, *48*, 123–136.

Auer, J. (1996). *Biostratigraphische und Magnetostratigraphische Untersuchungen im Grenzbereich Unter- und Mittelmiozan (Karpatium/Badenium) Der Paratethys, Steirisches Becken, Steiermark, Osterreich, Ziegelei Aflenz/Wagna*.

Bartol, M., Mikuž, V., & Horvat, A. (2013). Palaeontological evidence of communication between the Central Paratethys and the Mediterranean in the late Badenian/early Serravalian. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *394*, 144–157.

Beldean, C., Filipescu, S., & Bălc, R. (2010). An Early Miocene biserial foraminiferal event in the Transylvanian Basin (Romania). *Geologica Carpathica*, *61*, 227–234.

Berger, J.-P., Reichenbacher, B., Becker, D., Grimm, M., Grimm, K., Picot, L., . . . Schaefer, A. (2005). Paleogeography of the Upper Rhine Graben (URG) and the Swiss Molasse Basin (SMB) from Eocene to Pliocene. *International Journal of Earth Sciences*, *94*, 697–710.

Berggren, W. A., Kent, D. V., Swisher, C. C., & Aubry, M.-P. (1995). A revised Cenozoic geochronology and chronostratigraphy. *SEPM Special Publication*, *54*, 129–212.

Blow, W. H. (1969). Late middle Eocene to Recent planktonic foraminiferal biostratigraphy. In P. Bronniman & R. R. Renz (Eds.), *Proceedings of the First International Conference on Planktonic Microfossils* (pp. 199–422). Geneva: Leiden (E.J. Brill).

Brzobohatý, R., Cicha, I., Kováč, M., & Rögl, F. (2003). *The Karpatian - a Lower Miocene stage of the Central Paratethys*. Brno: Masaryk University.

Ćorić, S., Harzhauser, M., Hohenegger, J., Mandic, O., Pervesler, P., Roetzel, R., . . . Zuschin, M. (2004). Stratigraphy and correlation of the Grund Formation in the Molasse Basin, northeastern Austria (Middle Miocene, Lower Badenian). *Geologica Carpathica*, *55*, 207–215.

Ćorić, S., Pavelić, D., Rögl, F., Mandic, O., & Vrabac, S. (2009). Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geologica Croatica*, *62*, 31–43.

Ćorić, S., & Rögl, F. (2004). Roggendorf-1 borehole, a keysection for Lower Badenian transgressions and the stratigraphic position of the Grund Formation (Molasse Basin, Lower Austria). *Geologica Carpathica*, *55*, 165–178.

Dank, V. (1988). Petroleum geology of the Pannonian basin, Hungary: an overview. In L. H. Royden & F. Horvath (Eds.), *The Pannonian Basin. A Study in Basin Evolution*. *AAPG Memoirs*, *45*, 319–331.

de Leeuw, A., Filipescu, S., Maţenco, L., Krijgsman, W., Kuiper, K., & Stoica, M. (2013). Paleomagnetic and chronostratigraphic constraints on the Middle to Late Miocene evolution of the Transylvanian Basin (Romania): Implications for Central Paratethys stratigraphy and emplacement of the Tisza-Dacia plate. *Global and Planetary Change*, *103*, 82–98.

de Leeuw, A., Mandic, O., Krijgsman, W., Kuiper, K., & Hrvatović, H. (2012). Paleomagnetic and geochronologic constraints on the geodynamic evolution of the Central Dinarides. *Tectonophysics*, *530–531*, 286–298.

de Leeuw, A., Mandic, O., Vranjković, A., Pavelić, D., Harzhauser, M., Krijgsman, W., & Kuiper, K. F. (2010). Chronology and integrated stratigraphy of the Miocene Sinj Basin (Dinaride Lake System, Croatia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *292*(1–2), 155–167.

Di Stefano, A., Baldassini, N., Maniscalco, R., Speranza, F., Maffione, M., Cascella, A., & Foresi, L. M. (2015). New bio-magnetostratigraphic data on the Miocene Moria section (Northern Apennines, Italy): connections between the Mediterranean region and the North Atlantic Ocean. *Newsletters on Stratigraphy*, *48*, 135–152.

Di Stefano, A., Foresi, L. M., Lirer, F., Iaccarino, S. M., Turco, E., Amore, F. O., . . . Abdul Aziz, H. (2008). Calcareous plankton high resolution bio–magnetostratigraphy for the Langhian of the Mediterranean area. *Revista Italiana Di Paleontologia E Stratigrafia*, *114*, 51–76.

Foresi, L. M., Verducci, M., Baldassini, N., Lirer, F., Mazzei, R., Salvatorini, G., & Da Prato, S. (2011). Integrated stratigraphy of St. Peter's Pool section (Malta): new age for the Upper Globigerina Limestone member and progress towards the Langhian GSSP. *Stratigraphy*, *8*(2–3), 125–143.

Géczy, B. (1973). Plate tectonics and paleogeography in the East-Mediterranean Mesozoic. *Acta Geologica Hungarica*, *17*, 421–428.

Grunert, P., Tzanova, A., Harzhauser, M., & Piller, W. E. (2014). Mid-Burdigalian Paratethyan alkenone record reveals link between orbital forcing, Antarctic ice-sheet dynamics and European climate at the verge to Miocene Climate Optimum. *Global and Planetary Change*, *123*, 36–43.

Haq, B. U., Hardenbol, J., & Vail, P. R. (1988). Mesozoic and Cenozoic chronostratigraphy and cycles of sea level changes. In C. K. Wilgus (Ed.), *Sea-level changes - an integrated approach*. *Society of Economic Paleontologists and Mineralogists, Special Publications*, *42*, 71–108.

Hardenbol, J., Thierry, J., Farley, M. B., Jacquin, T., de Graciansky, P., & Vail, P. R. (1998). Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. *SEPM Special Publication*, *60*, 3–13.

Harzhauser, M., & Mandic, O. (2008). Neogene lake systems of Central and South-Eastern Europe: Faunal diversity, gradients and interrelations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *260*(3–4), 417–434.

Harzhauser, M., & Piller, W. E. (2007). Benchmark data of a changing sea — Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *253*(1–2), 8–31.

Hilgen, F. J., Lourens, L. J., & Van Dam, J. A. (2012). The Neogene Period. In Gradstein, F.M., Ogg, J.G., Schmitz, M.D. and Ogg, G.M (Eds)., *The Geologic Time Scale 2012 Volume 2* (pp. 923–978). Elsevier: Amsterdam.

Hohenegger, J., Ćorić, S., & Wagreich, M. (2014). Timing of the Middle Miocene Badenian Stage of the Central Paratethys. *Geologica Carpathica*, *65*, 55–66.

Hohenegger, J., Rögl, F., Ćorić, S., Pervesler, P., Lirer, F., Roetzel, R., ... Stingl, K. (2009). The Styrian Basin : a key to the Middle Miocene (Bade- nian / Langhian) Central Paratethys transgressions. *Austrian Journal of Earth Sciences*, *102*, 102–132.

Horváth, F., Bada, G., Szafian, P., Tari, G., Adam, A., & Cloetingh, S. (2006). Formation and deformation of the Pannonian Basin: constraints from observational data. *Geological Society, London, Memoirs*, *32*, 191–206.

Hudson, S. M., Johnson, C. L., Efendiyeva, M. A., Rowe, H. D., Feyzullayev, A. A., & Aliyev, C. S. (2008). Stratigraphy and geochemical characterization of the Oligocene-Miocene Maikop series: Implications for the paleogeography of Eastern Azerbaijan. *Tectonophysics*, *451*(1–4), 40–55.

Iaccarino, S. (1985). Mediterranean Miocene and Pliocene planktonic foraminifera. In H.M. Bolli, J.B. Saunders & K. Perch-Nielsen (Eds.), *Plankton Stratigraphy* (pp. 283–314). Cambridge: Cambridge University Press.

Iaccarino, S. M., & Salvatorini, G. (1982). A framework of planktonic foraminifera biostratigraphy for early Miocene to Late Pliocene Mediterranean area. *Paleontologia Stratigrafica Ed Evoluzione*, *2*, 115–125.

Iaccarino, S.M., Premoli, Silva, I., Biolzi, M., Foresi, L.M., Lirer, F., Turco, E., & Petrizzo, M.R. (2007). Practical manual of Neogene planktonic Foraminifera. In: *International School on Planktonic Foraminifera (Neogene Planktonic Foraminifera)* M. Biolzi, S.M. Iaccarino, E. Turco, A. Checconi & R. Rettori, eds.) Tipografia Pontefelicino: Perugia.

Iaccarino, S. M., Stefano, A. Di, Foresi, L. M., Turco, E., Baldassini, N., Cascella, A., ... Parma, V. G. P. U. A. (2011). High-resolution integrated stratigraphy of the upper Burdigalian-lower Langhian in the Mediterranean : the Langhian historical stratotype and new candidate sections for defining its GSSP. *Stratigraphy*, *8*(1960), 199–215.

Kälin, D., & Kempf, O. (2009). High-resolution stratigraphy from the continental record of the Middle Miocene Northern Alpine Foreland Basin of Switzerland. *Neues Jahrbuch Für Geologie Und Paläontologie - Abhandlungen*, *254*, 177–235.

Karami, M. P., deLeeuw, A., Krijgsman, W., Meijer, P. T., & Wortel, M. J. R. (2011). The role of gateways in the evolution of temperature and salinity of semi-enclosed basins: An oceanic box model for the Miocene Mediterranean Sea and Paratethys. *Global and Planetary Change*, *79*, 73–88.

Kempf, O., Matter, A., Burbank, D. W., & Mange, M. (1999). Depositional and structural evolution of a foreland basin margin in a magnetostratigraphic framework: the eastern Swiss Molasse Basin. *International Journal of Earth Sciences*, *88*, 253–275.

Kirscher, U., Prieto, J., Bachtadse, V., Aziz, H. A., Doppler, G., Hagmaier, M., & Böhme, M. (2016). A biochronologic tie-point for the base of the Tortonian stage in European terrestrial settings: Magnetostratigraphy of the topmost Upper Freshwater Molasse sediments of the North Alpine Foreland Basin in Bavaria (Germany). *Newsletters on Stratigraphy*, *49*, 445–467.

Kollmann, K. (1965). Jungtertiär im steirischen Becken. *Mitteilungen Der Geologischen Gesellschaft in Wien*, *57*(2), 479–632. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Jungterti r+im+Steirischen+Becken#0

Kováč, M., Andreyeva-grigorovich, A., Bajraktarević, Z., Brzobohatý, R., Filipescu, S., Fodor, L., ... Studencka, B. (2007). Badenian evolution of the Central Paratethys Sea : paleogeography, climate and eustatic sea-level changes. *Geologica Carpathica*, *58*, 579–606.

Kováč, M., Baráth, I., Harzhauser, M., Hlavatý, I., & Hudáčková, N. (2004). Miocene depositional systems and sequence stratigraphy of the Vienna Basin Depositional systems and sequence stratigraphy. *Courier Forschungsinstitut Senckenberg*, *246*, 187–212.

Leeuw, A. De, Mandic, O., Krijgsman, W., Kuiper, K., & Hrvatovic, H. (2011). A chronostratigraphy for the Dinaride Lake System deposits of the Livno-Tomislavgrad Basin : the rise and fall of a long-lived lacustrine environment. *Stratigraphy*, *8*, 29–43.

Lirer, F., & Iaccarino, S. (2005). Integrated stratigraphy (cyclostratigraphy and biochronology) of late Middle Miocene deposits in the Mediterranean area and comparison with the North and Equatorial Atlantic Oceans: synthesis of the major results. *Terra Nova*, *17*, 338–349.

Lirer, F., & Iaccarino, S. (2011). Mediterranean Neogene historical stratotype sections and Global Stratotype Section and Points (GSSP): state of the art. *Annalen des Naturhistorischen Museums in Wien. Serie A für Mineralogie und Petrographie, Geologie und Paläontologie, Anthropologie und Prähistorie*, *113*, 67–144.

Lourens, L. J., Hilgen, F. J., Laskar, J., Shackleton, N. J., & Wilson, D. (2004). The Neogene period. In F. M. Gradstein, J. G. Ogg & A. G. Smith (Eds.), *A Geological Timescale 2004* (pp. 409–440). Cambridge: Cambridge University Press.

Mandic, O., de Leeuw, A., Bulić, J., Kuiper, K. F., Krijgsman, W., & Jurišić-Polšak, Z. (2012). Paleogeographic evolution of the Southern Pannonian Basin: 40Ar/39Ar age constraints on the Miocene continental series of Northern Croatia. *International Journal of Earth Sciences*, *101*, 1033–1046.

Martini, E. (1971). Standard Tertiary and Quaternary calcareous nannoplankton zonation. In A. Farinacci (Ed.), *Proceedings of the Second Planktonic Conference, Roma 1970* (pp. 739–785). Rome: Edizioni Tecnoscienza 2.

Márton, E., Tischler, M., Csontos, L., Fügenschuh, B., & Schmid, S. M. (2007). The contact zone between the ALCAPA and Tisza-Dacia mega-tectonic units of Northern Romania in the light of new paleomagnetic data. *Swiss Journal of Geosciences*, *100*, 109–124.

Marunteanu, M. (1999). Litho and biostratigraphy (calcareous nannoplankton) of the Miocene deposits from the Outer Moldavides. *Geologica Carpathica*, *50*(4), 313–324.

Marzocchi, A., Flecker, R., van Baak, C. G., Lunt, D., & Krijgsman, W. (2016). Mediterranean outflow pump: An alternative mechanism for the Lago-mare and the end of the Messinian Salinity Crisis. *Geology*, *44*, 523–526.

Oszczypko, N., & Oszczypko-Clowes, M. (2011). Stages of development in the Polish Carpathian Foredeep basin. *Central European Journal of Geosciences*, *4*, 138–162.

Palcu, D. V., Tulbure, M., Bartol, M., Kouwenhoven, T. J., & Krijgsman, W. (2015). The Badenian – Sarmatian Extinction Event in the Carpathian foredeep basin of Romania: Paleogeographic changes in the Paratethys domain. *Global and Planetary Change*, *133*, 346–358.

Pálfy, J., Mundil, R., Renne, P. R., Bernor, R. L., Kordos, L., & Gasparik, M. (2007). U-Pb and 40Ar/39Ar dating of the Miocene fossil track site at Ipolytarnóc (Hungary) and its implications. *Earth and Planetary Science Letters*, *258*(1–2), 160–174.

Papp, A., & Cicha, I. (1978). Definition der Zeiteinheit M - Badenian. In A. Papp, I. Cicha, & F. F. Steininger (Eds.), M4 - Badenien (Moravien, Wielicien, Kosovien). Chronostratigraphie und Neostratotypen, Miozän der Zentralen Paratethys. (pp. 47–48). Bratislava: Slowakische Akademie der Wissenschaften.

Pezelj, D., Mandic, O., & Ćorić, S. (2013). Paleoenvironmental dynamics in the southern Pannonian Basin during initial Middle Miocene marine flooding. *Geologica Carpathica*, *64*, 81–100.

Piller, W. E., Harzhauser, M., & Mandic, O. (2007). Miocene Central Paratethys stratigraphy – current status and future directions. *Stratigraphy*, *4*, 151–168.

Popescu, G. (1975). Date noi cu privire la biostratigrafia si corelarea Miocenului mediu din aria carpatica. *Dari de Seama Ale Sedintelor, Institutul de Geologie Si Geofizica: Stratigrafie*, *61*, 65–84.

Popov, S. V, Rögl, F., Rozanov, A. Y., Steininger, F. F., Shcherba, I. G., & Kováč, M. (2004). Lithological-Paleogeographic maps of Paratethys. *Courier Forschungsinstitut Senckenberg*, *250*, 1–46.

Popov, S. V., Shcherba, I. G., Ilyina, L. B., Nevesskaya, L. A., Paramonova, N. P., Khondkarian, S. O., & Magyar, I. (2006). Late Miocene to Pliocene palaeogeography of the Paratethys and its relation to the Mediterranean. *Palaeogeography Palaeoclimatology Palaeoecology*, *238* (1–4), 91–106.

Ramstein, G., Fluteau, F., Besse, J., & Joussaume, S. (1997). Effect of orogeny, plate motion and land–sea distribution on Eurasian climate change over the past 30 million years. *Nature*. *386*, 788–795. https://doi.org/10.1038/386788a0

Reichenbacher, B., Krijgsman, W., Lataster, Y., Pippèrr, M., Baak, C. G. C., Chang, L., ... Bachtadse, V. (2013). A new magnetostratigraphic framework for the Lower Miocene (Burdigalian/Ottnangian, Karpatian) in the North Alpine Foreland Basin. *Swiss Journal of Geosciences*, *106*, 309–334.

Roetzel, R., de Leeuw, A., Mandic, O., Márton, E., Nehyba, S., Kuiper, K. F., ... Wimmer-Frey, I. (2014). Lower Miocene (upper Burdigalian, Karpatian) volcanic ash-fall at the south-eastern margin of the Bohemian Massif in Austria – New evidence from 40Ar/39Ar-dating, palaeomagnetic, geochemical and mineralogical investigations. *Austrian Journal of Earth Sciences*, *107*, 2–22.

Rögl, F. (1999). Mediterranean and paratethys. Facts and hypotheses of an Oligocene to Miocene Paleogeography (short overview). *Geologica Carpathica*, *50*, 339–349.

Rögl, F., Ćorić, S., Daxner-Höck, H., Harzhauser, M., Mandic, O., Svábenická, L., & Zorn, I. (2003). Correlation of the Karpatian Stage. In R. Brzobohatý, I. Cicha, M. Kovác & F. Rögl (Eds.), *The Karpatian - a Lower Miocene Stage of the Central Paratethys* (pp. 32–37). Brno: Masaryk University.

Rögl, F., Spezzaferri, S., & Ćorić, S. (2002). Micropaleontology and biostratigraphy of the Karpatian-Badenian transition (Early-Middle Miocene boundary) in Austria (Central Paratethys). *Courier Forschungsinstitut Senckenberg*, *237*, 47–67.

Rybár, S., Halásová, E., Hudáčková, N., Kováč, M., Kováčová, M., Šarinová, K., & Šujan, M. (2015). Biostratigraphy, sedimentology and paleoenvironments of the northern Danube Basin: Ratkovce 1 well case study. *Geologica Carpathica*, *66*, 51–67.

Rybár, S., Kováč, M., Šarinová, K., Halásová, E., Hudačková, N., Šujan, M., ... Klučiar, T. (2016). Neogene changes in palaeogeography, palaeoenvironment and the provenance of sediment in the Northern Danube Basin Neogene changes in palaeogeography, palaeoenvironment and the provenance of sediment in the Northern Danube Basin. *Bulletin of Geosciences*, *91*, 367–398.

Sachsenhofer, R. F. (1994). Petroleum generation and migration in the Styrian Basin (Pannonian Basin system, Austria): an integrated geochemical and numerical modelling study. *Marine and Petroleum Geology*, *11*(6), 684–701.

Sant, K., Kirscher, U., Reichenbacher, B., Pippèrr, M., Jung, D., Doppler, G., & Krijgsman, W. (2017). Late Burdigalian sea retreat from the North Alpine Foreland Basin: New magnetostratigraphic age constraints. *Global and Planetary Change*, *152*, 38–50.

Schlunegger, F., Burbank, D. W., Matter, A., Engesser, B., & Mödden, C. (1996). Magnetostratigraphic calibration of the Oligocence to Middle Miocene (30-15 Ma) mammal biozones and depositional sequences of the Swiss Molasse Basin. *Eclogae Geologicae Helvetiae*, *89*, 753–788.

Selmeczi, I., Lantos, M., Bohn-Havas, M., Nagymarosy, A., & Szegő, É. (2012). Correlation of bio- and magnetostratigraphy of Badenian sequences from western and northern Hungary. *Geologica Carpathica*, *63*(3), 219–232.

Spezzaferri, S., Ćorić, S., & Stingl, K. (2009). Palaeoenvironmental reconstruction of the Karpatian-Badenian (Late Burdigalian-Early Langhian) transition in the Central Paratethys. A case study from the Wagna section (Austria). *Acta Geologica Polonica*, *4*, 523–544.

Székely, S. F., Beldean, C., Bindiu, R., Filipescu, S., & Săsăran, E. (2016). Palaeoenvironmental changes in the transylvanian basin during the early miocene revealed by the foraminifera assemblages. *Geological Quarterly*, *60*, 165–178.

ter Borgh, M., Vasiliev, I., Stoica, M., Knežević, S., Matenco, L., Krijgsman, W., Rundić, L. & Cloetingh, S. (2013). The isolation of the Pannonian basin (Central Paratethys): New constraints from magnetostratigraphy and biostratigraphy. *Global and Planetary Change*, *103*, 99–118.

Turco, E., Bambini, A. M., Foresi, L., Iaccarino, S., Lirer, F., Mazzei, R., & Salvatorini, G. (2002). Middle Miocene High-resolution calcareous plankton biostratigraphy at Site 926 (Leg 154, Equatorial Atlantic Ocean): paleoecological and paleobiogeographical implications. *Geobios Memoire Special*, *34*, 257–276.

Turco, E., Hüsing, S., Hilgen, F., Cascella, A., Gennari, R., Iaccarino, S. M., & Sagnotti, L. (2017). Astronomical tuning of the La Vedova section between 16.3 and 15.0 Ma. Implications for the origin of megabeds and the Langhian GSSP. *Newsletters on Stratigraphy*, *50*, 1–29.

Ustaszewski, K., Schmid, S.M., Fügenschuh, B., Tischler, M., Kissling, E. and Spakman, W., 2008. A map-view restoration of the alpine-carpathian-dinaridic system for the early miocene. *Swiss Journal of Geosciences*, *101*, 273–294.

van de Wal, R. S. W., de Boer, B., Lourens, L. J., Köhler, P., & Bintanja, R. (2011). Reconstruction of a continuous high-resolution CO2 record over the past 20 million years. *Climate of the Past*, *7*, 1459–1469.

Vass, D. (2002). The Origin and Disappearance of the Hungarian Paleogene Basins and the Short Term Lower Miocene Basins in the Northern Hungary and Southern Slovakia. *Bulletin de l'Academie Serbe Des Sciences et Des Arts*, *125*, 29–46.

Wade, B. S., Pearson, P. N., Berggren, W. A., & Pälike, H. (2011). Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth-Science Reviews*, *104*, 111–142.

Zachos, J. C., Dickens, G. R., & Zeebe, R. E. (2008). An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature*, *451*, 279–283.

Zuschin, M., Harzhauser, M., Hengst, B., Mandic, O., & Roetzel, R. (2014). Long-term ecosystem stability in an Early Miocene estuary. *Geology*, *42*, 7–10.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Data S1: Collected age details per sub-basin

How to cite this article: Sant K, Palcu DV, Mandic O, Krijgsman W. Changing seas in the Early–Middle Miocene of Central Europe: a Mediterranean approach to Paratethyan stratigraphy. *Terra Nova*. 2017;29:273–281. https://doi.org/10.1111/ter.12273