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

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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 Boorgh 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
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 foraminiferal assemblages are characterized by a marked provincialism and differ from the Atlantic low-latitude assemblages starting from the Middle Miocene (laccarino et al., 2011; Lirer & laccarino, 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; laccarino 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 [laccarino 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 (laccarino et al., 2011).
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 *Rezhakia* 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 (40Ar/39Ar 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 lacustrine sedimentation continued up to the Late Miocene in the central NAFB (Kirschker et al., 2016).
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 foraminifer species *Globigerinoides bisphericus* and the calcareous nannofossil species *Helicosphaera amphiaperta* (Brozohaty, Cicha, Kovác, & 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]

Sub-basins of Paratethys Realm
1. Alpine-Carpathian Foredeep - western (a), central (b), and eastern (c),
2. Vienna,
3. Styrian,
4. Danube and Zala-Mura,
5. Southern Pannonian
6. Nógrád/South Slovakian, East Slovak (6a)
7. Transylvanian,
8. Polish-Ukrainian Carpathian Foredeep,
9. East Carpathian Foredeep and Getic,

Straits
A. Rhône strait,
B. Trans-Tethyan corridor,
C. Carasul strait.
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, Coriç, & 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 (Kovác 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-Karpatian sea remarkably follow the contours of the Mid-Hungarian Line, and spreading all over the Carpathian foredeep (Figures 3 and 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.

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 C5n.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 (Coriç & Rögli, 2004; Oszczykpo and Oszczykpo-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 (Coriç & Rögli, 2004; Hohenegger et al., 2009). Many other Badenian sedimentary successions contain the planktonic foraminifer Praeorbulina glomerosa glomerosa in their lower part (Kovác 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 suturealis (de Leeuw et al., 2013; Kovác et al., 2007; Rögli 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 Karpation 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.

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REFERENCES


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