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Timing of the Middle Miocene Badenian Stage of the Central Paratethys

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Abstract: A new and precisely defined chronometric subdivision of the Badenian (Middle Miocene, regional stage of Central Paratethys) is proposed. This uses global events, mainly geomagnetic polarity reversals as correlated chronometric boundaries, supported by climatic and sea-level changes in addition to isotope events and biostratigraphic data. The Karpatian/Badenian boundary lies at 16.303 Ma, at the top of Chron C5Cn.2n, which is near the base of the *Praeorbulina sicana* Lowest-occurrence Zone (LOZ). The Badenian/Sarmatian boundary is placed at the top of polarity Chron C5Ar.2n, thus at 12.829 Ma. In relation to three sea level cycles TB 2.3, TB 2.4 and TB 2.5 and astronomically confirmed data, the Badenian can be divided into three parts of nearly equivalent duration. The Early Badenian as newly defined here ranges from 16.303 to 15.032 Ma (top of polarity Chron C5Bn.2n). The younger boundary correlates roughly to the base of the planktonic foraminifera *Orbulina suturalis* LOZ at 15.10 Ma, the HO (Highest Occurrence) of the nannofossil *Helicosphaera ampliaperta* at 14.91 Ma (NN4/NN5 boundary) and the Lan2/Ser1 sequence boundary at 14.80 Ma. The subsequent Mid Badenian ranges from 15.032 Ma to 13.82 Ma; the latter datum correlates with the base of the Serravallian, characterized by a strong global cooling event reflected in the oxygen isotope event Mi3b. The main part of cycle TB 2.4 falls into the Mid Badenian, which can be subdivided by a short cooling event at 14.24 Ma during the Middle Miocene Climate Transition (14.70 to 13.82 Ma). The HCO (Highest common occurrence) of the nannofossil *Helicosphaera waltrans* at 14.357 Ma supports this division, also seen in the tropical plankton Zones M6 *Orbulina suturalis* LOZ and M7 *Fohsella peripheroacuta* LOZ that correspond roughly to the lower and upper Lagenidae zones in the Vienna Basin, respectively. The Late Badenian is delimited in time at the base to 13.82 Ma by the Langhian/Serravallian boundary and at the top by the top of polarity Chron C5Ar.2n at 12.829 Ma. The Mediterranean Langhian/Serravallian boundary can be equated with the Mid/Late Badenian boundary at 13.82 Ma. However, the Karpatian/Badenian boundary at 16.303 Ma, a significant event easily recognizable in biostratigraphy, paleoclimate evolution and sequence stratigraphy, cannot be equated with the proposed global Burdigalian/Langhian, and thus Early/Middle Miocene boundary, at 15.974 Ma.

Key words: Middle Miocene, Badenian, Paratethys, magnetostratigraphy, biostratigraphy, paleoclimate, sequence stratigraphy.

Introduction

In the last decade much work has been done in the Badenian (e.g. Kováč et al. 2004, 2007; Harzhauser & Piller 2007; Piller et al. 2007), the first regional stage of the Middle Miocene in the Central Paratethys (Cicha & Seneš 1968; Papp et al. 1968). However, despite numerous publications, the timing of the Badenian, its division into substages and their ages remain vague.

On the basis of wells in the type area of the Badenian, the Vienna Basin, Grill (1943) subdivided the Badenian, at that time erroneously equalized with the Mediterranean Tortonian stage, into 4 zones, renamed by Papp & Turnovsky (1953) as the basal "Lageniden Zone", the "Sandschaler Zone" (agglutinated foraminifera zone), the "*Bulimina*/*Bolivina* Zone" and the uppermost zone of impoverished faunas; by definition, this was established as a regional ecostratigraphic zonation. Utilizing the evolution of the benthic foraminifer *Uvigerina*, Papp & Turnovsky (1953) divided the "Lageniden Zone" into lower and upper parts. This division was perpetuated in the description of the Badenian stage by Papp et al. (1978a), leading to the erection of three Badenian substages: Moravian (Lagenidae zone), Wielician (agglutinated foraminifera zone) and Kosovian (*Bulimina*/*Bolivina* zone and the zone of impoverished faunas) in the Central Paratethys (Papp et al. 1978b). The Moravian was thought to represent the lowermost part of the Badenian, including the Badenian stratotype (Hohenegger & Wagreich 2012). The overlying Wielician is characterized by widespread evaporites in both the Carpathian Foredeep (Peryt 2006) and the Transylvanian Basin (Krézsek & Filipescu 2005), followed by the pronounced marine transgression of the Kosovian. The Badenian was correlated with the Langhian and the lower part of the Serravallian by Papp et al. (1978c), whereas the *Bulimina*/*Bolivina* zone and the Kosovian were equated to the lower Serravallian (Papp et al. 1978c).

Using the Neogene time-scale of Lourens et al. (2004a) and Hilgen et al. (2012), the duration and limits of the Badenian substages were linked to the Mediterranean global stages (Piller et al. 2007). In these attempts, the Karpatian/Badenian boundary was equated with the Burdigalian/Langhian boundary at 15.97 Ma (Strauss et al. 2006; Piller et al. 2007). This date was criticized by Rögl et al. (2007a,b), who put the boundary at 16.303 Ma, the FAD (First Appearance Date) of the foraminifer *Praeorbulina sicana*. The Wielician/Kosovian boundary was equated with the Langhian/Serravallian boundary at ca. 13.65 Ma (Piller et al. 2007), based on the ages constraints available before the Serravallian GSSP was erected (Hilgen et al. 2009). The Badenian/Sarmatian boundary, placed at 12.7 Ma by Harzhauser & Piller (2004) and Piller et al. (2007), was based on a correlation with sequence stratigraphy and the glacio-eustatic isotope event MSi-3 of Abreu & Haddad (1998). In contrast, Lirer et al. (2009) used astronomical data to suggest an age of 13.32 Ma for this boundary. The Moravian/Wielician boundary could not be constrained with similar precision, but was approximated to a stratigraphic level just after the Lan2/Ser1 sequence boundary at 14.2 Ma, connected to a significant global sea-level drop (Strauss et al. 2006) or a more regional, tectonically influenced sea-level lowstand (Rögl et al. 2007a).

The creation of the Serravallian GSSP at 13.82 Ma (Hilgen et al. 2009), the search for the GSSP of the Langhian stage, suggested to lie at the top of the polarity Chron C5Cn.1n at 15.974 Ma (Lourens et al. 2004a,b; Hilgen et al. 2012), and recently published data mainly from the Vienna Basin (e.g. Kováč et al. 2007; Hohenegger et al. 2011; Hohenegger & Wagreich 2012), the Styrian Basin (e.g. Schreilechner & Sachsenhofer 2007; Hohenegger et al. 2009; Spezzaferri et al. 2009) and the Transylvanian Basin (e.g. de Leeuw et al. 2012) make it necessary to reconsider the ages, delimitations and subdivisions of the Badenian.

In the following, the Badenian is chronometrically divided into ages based on astronomically tuned geomagnetic polarity reversals, paleoclimatic events, biozones and sea-level changes. This time frame could be the basis for reconsidering the chronostratigraphic substages and their boundary stratotypes.

Methods

In principle, existing data were used for a new "chronometric" (geochronological) subdivision of the Badenian into ages defined by multistratigraphic methods. Consequently, we use Early, Mid and Late for the chronometric subdivision of the Badenian (see recent discussions in Gradstein et al. 2012, and Zalasiewicz et al. 2013). Timing and subdivision rely primarily on magnetostratigraphy supported by biostratigraphic markers. Magnetostratigraphy dates are preferred because of their global synchronicity and stable and high-resolution dating, based on the Astronomically Tuned Neogene Time Scale (ATNTS, see Lourens et al. 2004a,b; Ogg 2012; Gradstein et al. 2012). Numerical ages from geochronology and astrochronology are considered, where appropriate, to obtain an improved time frame of geochronological ages for the proposed subdivisions of the Badenian.

Sequence stratigraphy and isotope stratigraphy (oxygen isotope excursions) are used as secondary correlation tools. In contrast to former compilations (e.g. Piller et al. 2007; Rögl et al. 2007a), sequence stratigraphy is not used here as the basis for the proposed subdivisions, because of problems in exact timing, especially for unconformities that encompass considerable time gaps at sequence boundaries. They are used, however, as additional means of correlation and calibration, both to regional and global 3rd-order cycles.

Sequence stratigraphy correlations are based principally on three sea-level cycles (TB 2.3, TB 2.4 and TB 2.5; Haq et al. 1988) recognized in the time interval between the late Burdigalian and the late Serravallian, which coincide with the Badenian in a broad sense. The sequences in Hardenbol et al. (1998) concerning the Middle Miocene are based on seismic data from the Pannonian Basin. Newer investigations of global sea-level variation using drill-cores from the New Jersey and Delaware coastal plains, also detected three sequences in the interval between 16 Ma and 13 Ma (Miller et al. 2005a,b; Kominz et al. 2008). These correlate strongly with sequences TB 2.3, TB 2.4 and slightly less well with TB 2.5 in the Paratethys, possibly marking the three Badenian cycles and sequences in seismic sections (e.g. Strauss et al. 2006; Schreilechner & Sachsenhofer 2007). The sequence boundaries of Hardenbol et al. (1998) have to be newly calibrated due to the recently refined timing of the Neogene (Hilgen et al. 2012; Anthonissen & Ogg 2012); as a result, they have not been used directly as geochronological constraints in our new subdivision of the Badenian based on biostratigraphy and magnetostratigraphy data from classic areas such as the Vienna Basin.

New Badenian chronometry and subdivision

The Badenian was defined as the first regional stage of the Middle Miocene in the Central Paratethys by Papp et al. (1978a), based on the work of Cicha & Seneš (1968) and Papp et al. (1968). A threefold division of the Badenian was suggested and defined by Papp et al. (1978a), including three stratotypes: (1) Lower Badenian–Moravian, (2) Middle Badenian–Wielician and (3) Upper Badenian–Kosovian. We redefine this subdivision for the Lower Badenian, where considerable shortcomings have been reported in recent years (e.g. Hohenegger et al. 2009). This new subdivision also differs from the recent compilations of Krijgsman & Piller (in Hilgen et al. 2012).

Karpatian/Badenian boundary

Papp & Cicha (1978) defined the base of the Badenian stage at the first occurrence of the planktonic foraminifer *Praeorbulina*, which we largely follow here. Since the FAD of *Praeorbulina sicana* was regarded by Cita & Blow (1969) as the base of the Langhian, thus determining the Lower/Middle Miocene boundary, the Karpatian/Badenian boundary was equated with the Burdigalian/Langhian boundary. Berggren et al. (1995) discussed the FAD of *P. glomerosa* sensu stricto at 16.1 Ma as a possible Langhian boundary marker, due to the diffuse onset of *P. sicana* at the type locality (Fornaciari et al. 1997). In terms of nannofossil zonations, the base of the Badenian was originally correlated to nannoplankton Zone NN5 by Papp et al. (1978c), and, more recently, placed in the uppermost NN4 (e.g. Kováč et al. 2004; Rögl et al. 2007a,b; Piller et al. 2007; Hohenegger et al. 2009).

Depending on different time calibrations of the *Praeorbulina* lineage, the Karpatian/Badenian boundary, as determined by the beginning of that lineage, was either set at

16.4 Ma (Ćorić et al. 2004) following the FAD of *P. sicana* in Berggren et al. (1995) or 16.303 Ma (Rögl et al. 2007a,b; Harzhauser & Piller 2007), or at 16.27 Ma (Hohenegger et al. 2009) according to the FAD of *P. glomerosa* given in Lourens et al. (2004b).

Both boundaries differ strongly in age from the Burdigalian/Langhian boundary, namely the base of the Langhian, recently proposed at 15.974 Ma, which is the top of polarity Chron C5Cn.1n (Lourens et al. 2004a; Hilgen et al. 2012). This proposal was put forward because the onset of the extremely rare, but highly variable index fossil *Praeorbulina sicana* (Jenkins et al. 1981; Rio et al. 1997) is blurred in almost all sections to be considered for the Langhian GSSP (Turco et al. 2009). Although the top of polarity Chron C5Cn.1n is a distinct boundary in magnetostratigraphy, its calibration by biostratigraphic markers is problematic if the *Globigerinoides–Praeorbulina* lineage is not taken into consideration. Using calcareous nannofossils, the HCO (Highest Common Occurrence) of *Helicosphaera ampliaperta* and the beginning of the Paracme Zone of *Sphenolitus heteromorphus* have been proposed as biostratigraphic markers approximating the proposed polarity chron boundary (Iaccarino et al. 2009). Both nannofossil markers are not very useful, because these events are based on abundance peaks that may differ strongly between regions, due to environmental differences. Moreover, the HO (Highest Occurrence) of *H. ampliaperta* at astronomically calibrated 14.91 Ma (Shackleton et al. 1999) defines the boundary between NN4/NN5 (Martini 1971) and can better be used for the division of the Langhian into an earlier and later part. The abundance peak of *H. ampliaperta* at 15.899 ± 0.024 Ma is in fact close to the proposed boundary, but this peak is inconsistent because it is ecologically controlled as demonstrated by the broad confidence intervals (Abdul Aziz et al. 2008). The much narrower confidence limits for the base of the Paracme Zone of *Sphenolitus heteromorphus* at 15.949 ± 0.005 Ma (Abdul Aziz et al. 2008) could be a better signal, but this zone, defined by the lack of plankton, is very strongly controlled by paleoecology and is thus of questionable value, especially when comparing different regions and oceans. For example, a large gap in the distribution of *S. heteromorphus*, comparable to a paracme zone, can be detected in the continuous section of the Badenian stratotype belonging to the upper Lagenidae zone (Ćorić & Hohenegger 2008).

To clarify the position of the base of the Badenian in relation to the Burdigalian/Langhian boundary, more continuous transitions from the Karpatian to the Badenian have been investigated. So far, such transitions are not known from outcrops in the Central Paratethys, where unconformities due to tectonic movements ("Styrian Tectonic Phase"; Stille 1924; Rögl et al. 2007b) between Karpatian and Badenian sediments occurred (see also Rögl et al. 2002). However, investigations of wells in the Alpine Foredeep (Ćorić & Rögl 2004) and in the Styrian Basin (Hohenegger et al. 2009) documented the presence of significant intervals of sediment between the latest Karpatian and the base of the lower Lagenidae zone as the (former) inferred base of the Badenian. These sediments represent the time interval between ca. 16.3 Ma (Hohenegger et al. 2009) and at least 15.5 Ma, a considerable time span that has so far been largely missed in Badenian chronostratigraphy. This interval correlates with the upper part of nannoplankton Zone NN4. In wells of the Alpine-Carpathian Foredeep the boundary between the Karpatian/Badenian is documented by unconformities with conglomerates at the base of the overlying successions (Ćorić & Rögl 2004), and by an angular unconformity in 2D seismic data from the eastern Styrian Basin (Schreilechner & Sachsenhofer 2007).

Looking at the Styrian Basin in more detail (Fig. 1a,b), this lowermost Badenian, which represents the time interval between the late Karpatian and the (former) lower Badenian, is documented in three outcrop sections: the former brickyard at Wagna (Fig. 2), the Retznei quarry and the former sand pit at Katzengraben (Hohenegger et al. 2009; Spezzaferri et al. 2009). A closer look at the Wagna section brings significant arguments on the here newly defined Early Badenian (Hohenegger et al. 2011) and, thus, the new beginning of the Badenian.

In the upper part of the Wagna section, the lowermost Badenian is represented by an 8 m thick section (Fig. 2). Detailed sedimentological, magnetostratigraphic, biostratigraphic (Hohenegger et al. 2009) and paleoenvironmental investigations (Spezzaferri et al. 2009) documented different phases in the transgression of the Badenian Sea. A significant unconformity between silty sediments of the (Karpatian)

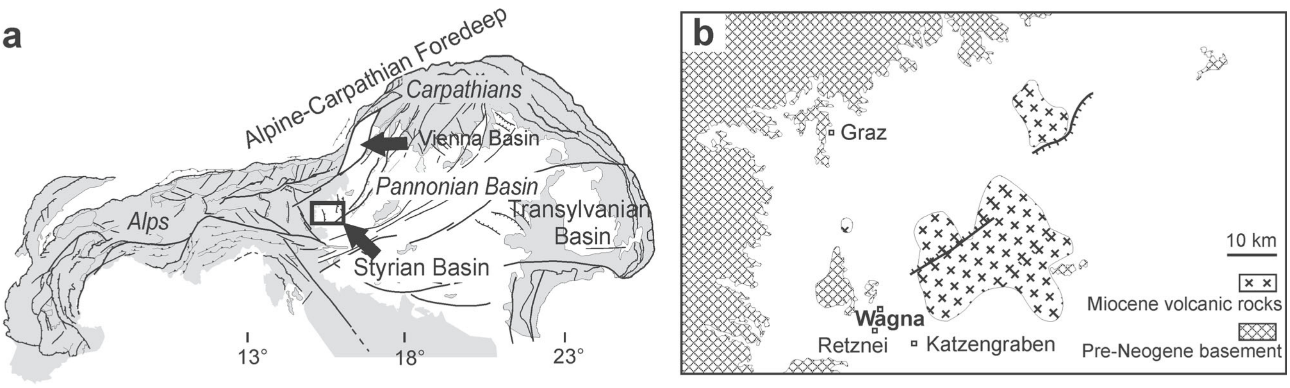

Fig. 1. a — Basins of the Central Paratethys mentioned in the text (modified from Hohenegger & Wagreich 2012). **b** — Styrian Basin with the location of Wagna, Retznei, Katzengraben (modified from Hohenegger et al. 2009).

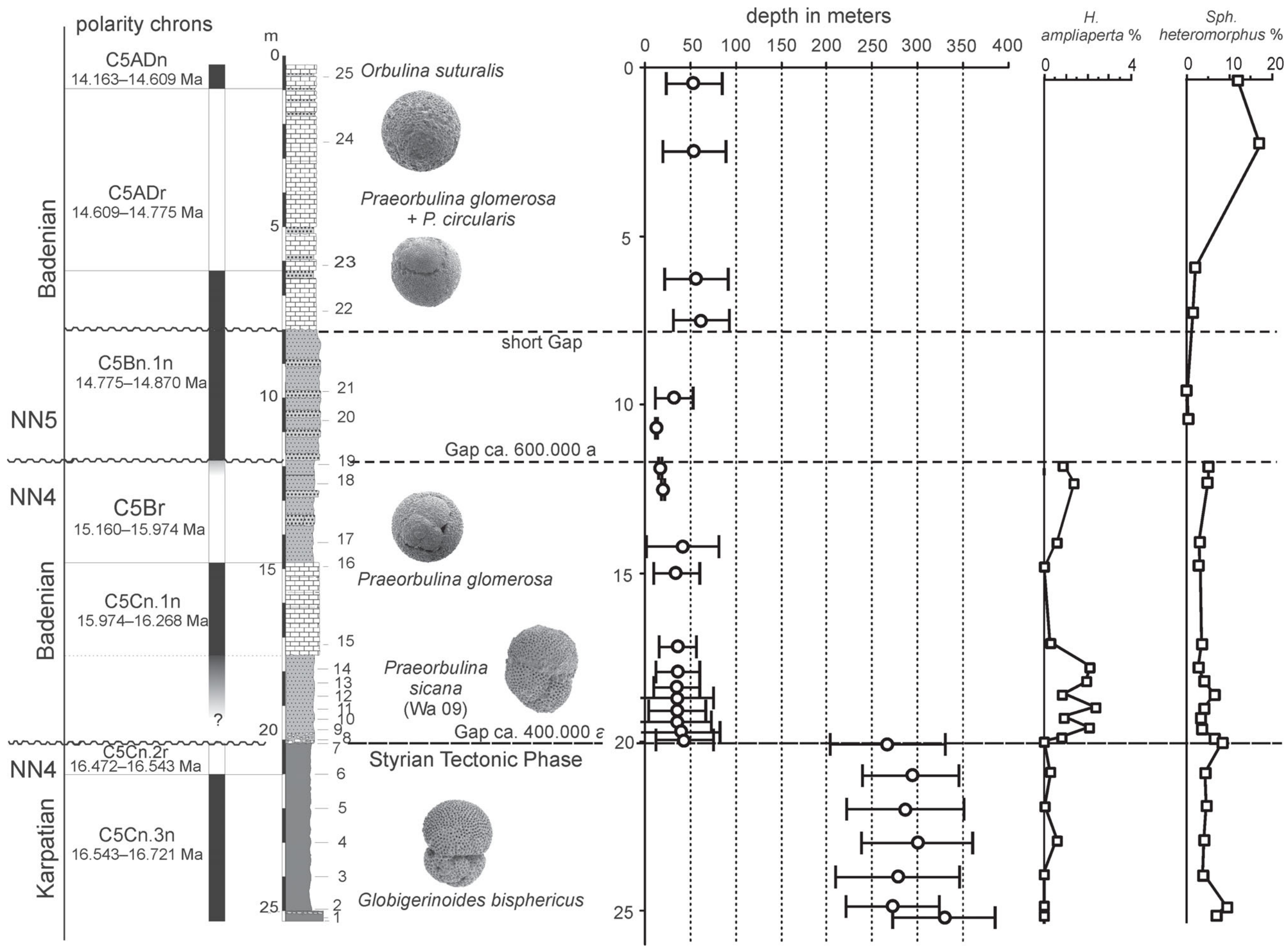

Fig. 2. Wagna, old brickyard, section 3. Interpreted stratigraphy, based on paleomagnetics, lithology, foraminiferal plankton (Hohenegger et al. 2009) and nannoplankton percentages, combined with depth estimations by benthic foraminifera using the method of Hohenegger (2004).

"Steirischer Schlier" and marly sand with small pebbles at the base of the overlying (Badenian) sequence could be linked with the Styrian tectonic phase (Rögl et al. 2007b). While the Steirischer Schlier biostratigraphically belongs to the Karpatian according to the planktonic foraminifer *Globigerina ottnangiensis* and the benthic foraminifera *Uvigerina graciliformis* and *Pappina primiformis* (Hohenegger et al. 2009), the overlying marly sand is characterized by *Praeorbulina sicana* found close to the base of the section part, and by a brackish water influence (Spezzaferri et al. 2009). Depth estimations based on depth ranges of benthic foraminifera (Hohenegger 2004) strengthened the evidence for the occurrence of a phase of tectonic uplift, from depths around 300 m in the Karpatian to 40 m in the following section interval (Fig. 2). This shift is contemporaneous with a climate change (Hohenegger et al. 2009), in the form of a significant warming, as documented in the calcareous nannoplankton (see Fig. 2 and Spezzaferri et al. 2009), and the instantaneous drop in oxygen and carbon isotope values (Latal & Piller 2003). This indicates tectonic movements and a coeval climate/paleoenvironmental change.

Dating of the section following this uplift is based on magnetostratigraphy, in combination with biostratigraphic markers (Fig. 2). The section between the two unconformities at 20.5 m and 13.8 m shows a more or less continuous sedimentation, seen in marly fine sand, interrupted by the growth of a coral bank. The estimated paleowater-depth varies between 10 m and 40 m. The NN4 index fossil *H. ampliaperta* is common throughout this part of the section except in the coral bank (which provides a striking example for the problems and chronostratigraphic misuse of an ecologically controlled, regionally restricted Paracme Zone).

The polarity reversal event, from normal to reverse, at 15 m is delimited by two biostratigraphic markers. First, the reversal falls within nannoplankton Zone NN4 (Martini 1971), which ends at 14.91 Ma; second, the reversal must be younger than 16.38 Ma because the occurrence of *Praeorbulina sicana* indicates the beginning of plankton Zone M5 (zonation according to Wade et al. 2011). Therefore, only two chron boundaries come into consideration: C5Cn.1n/C5Br at 15.974 Ma, which has recently regarded as the Burdigalian/Langhian, and thus the Early/Middle Miocene boundary (see above), and C5Bn.2n/C5Bn.1r at 15.032 Ma (Hilgen et al. 2012).

The first alternative seems to be more appropriate considering 3rd order sequences established in the Pannonian Basin (Hardenbol et al. 1998; Vakarcs et al. 1998), because the in-

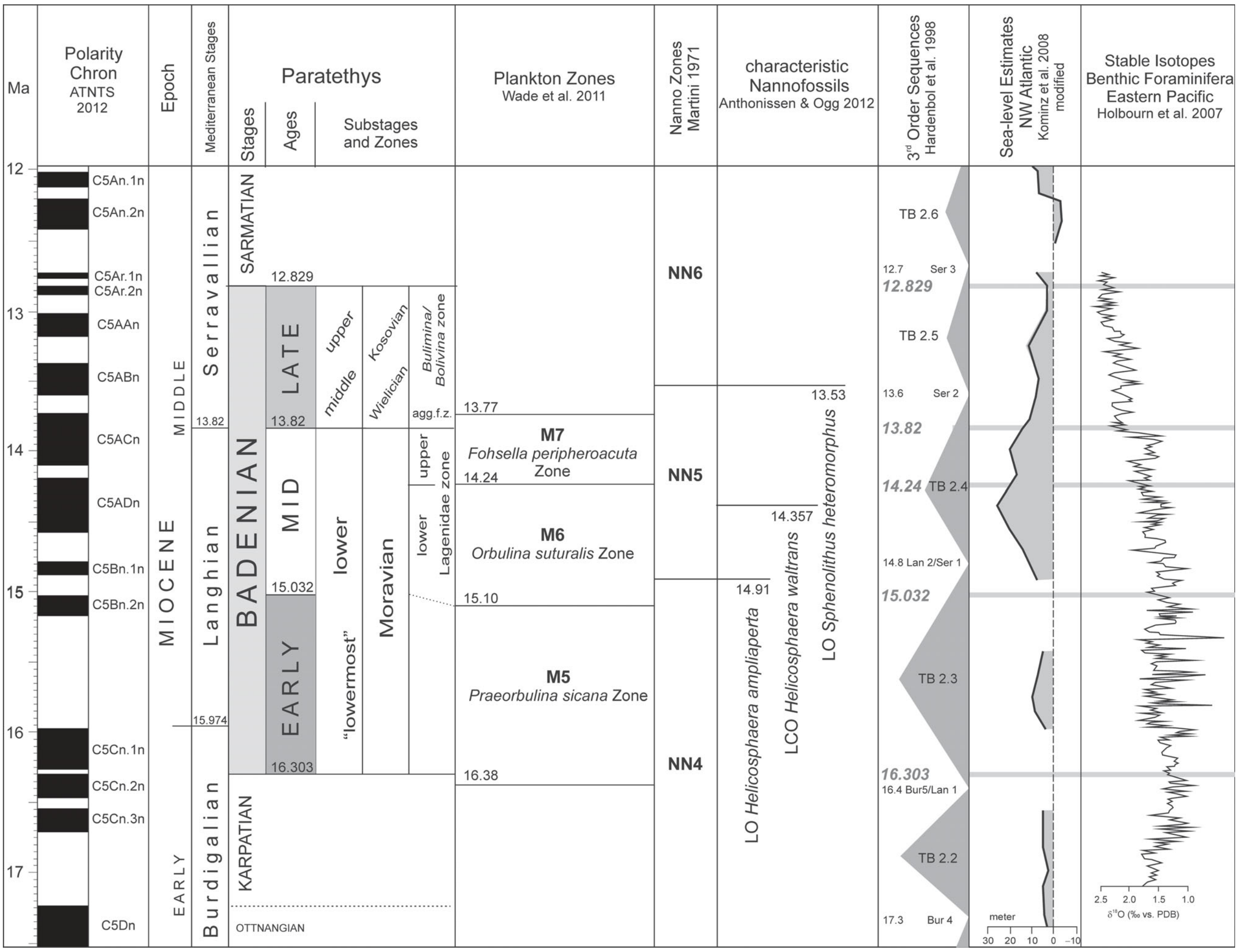

Fig. 3. Timing of the Badenian based on magnetostratigraphy, foraminiferal plankton and nannoplankton stratigraphy, 3rd order sequences, sea-level changes in the NW Atlantic and stable oxygen isotopes in the eastern tropical Pacific.

terval in question, from 16.40 Ma to 14.80 Ma, is represented by the single TB 2.3 sea-level cycle (Haq et al. 1988) starting with the Bur5/Lan1 sequence boundary. Accepting the first hypothesis, then the C5Cn.1n/C5Br boundary falls exactly within the transgressive phase of this sequence (Fig. 3). This is confirmed by paleodepth estimates within the Wagna section (Fig. 2), where the end of the Transgressive Systems Tract and the beginning of the Highstand Systems Tract (HST) is represented by the only preserved shallow-water sediments between two significant unconformities (=sequence boundaries), deposited just after the maximum flooding surface (Fig. 2). In the second alternative, the presence of these shallow water sediments (around 15.032 Ma) is difficult to explain in a sequence stratigraphy context, because it would be positioned near the end of the Falling Stage Systems Tract of the TB 2.3 cycle (Fig. 3), and thus in the strongest erosional phase as represented by the unconformity. In addition, there is no indication for tectonic subsidence at that time that could explain landward extension of shallow-marine sediments in a Lowstand Systems Tract.

If the Karpatian/Badenian boundary were correlated with the proposed Burdigalian/Langhian boundary at 15.974 Ma, then it is recognizable in the Wagna section only by paleomagnetic data, because the contemporaneous sedimentary change from coral limestone to fine sand disappears laterally within a few meters (compare Fig. 4 in Hohenegger et al. 2009). In contrast, the beginning of cycle TB 2.3 (Haq et al. 1988), at around 16.4 Ma (Hardenbol et al. 1998), forms a suitable and easily correlated boundary between the Karpatian and Badenian stages. This date marks the beginning of the "Middle Miocene Climate Optimum" (Fig. 3; Holbourn et al. 2007) and is correlated with the base of the foraminiferal plankton Zone M5, the lowest occurrence of *Praeorbulina sicana* (Wade et al. 2011). In addition to this definition based on sequence stratigraphy, paleoclimate and biostratigraphy, the Styrian tectonic phase documented by a strong uplift and the subsequent deepening led to the first Badenian transgression (Hohenegger et al. 2009). Therefore, we place the Karpatian/Badenian boundary at 16.303 Ma, the top of C5Cn.2n (ATNTS 2012, Hilgen et al. 2012) near the beginning of the *Praeorbulina* lineage (16.38 Ma; Wade et al. 2011; Anthonissen & Ogg 2012); this confirms the original definition by Papp & Cicha (1978). This boundary definition and age, as defined by magnetostratigraphy, was also used by Kováč et al.

(2007), Harzhauser & Piller (2007), Oszczypko & Oszczypko-Clowes (2012) and Hohenegger & Wagreich (2012).

Thus the ecologically, climatologically and tectonically well defined Karpatian/Badenian boundary does not correlate with the proposed Burdigalian/Langhian boundary, defined by the top of polarity Chron C5Cn.1n at 15.974 Ma (Lourens et al. 2004a; Hilgen et al. 2012); the latter does not show a significant ecological, environmental and climate signal (Fig. 3). This proposed Burdigalian/Langhian boundary does not justify a clear differentiation between Early and Middle Miocene, which should be documented in strong climate changes reflected in the macro- and microfauna (Harzhauser & Piller 2007).

Badenian/Sarmatian boundary

The end of the Badenian, the start of the Sarmatian, as defined by a major turnover in faunal elements (e.g. Harzhauser & Piller 2004), is extremely controversial in its timing, which ranges in the Central Paratethys from an astronomically dated 13.32 Ma (Lirer et al. 2009) to 12.7 Ma (Harzhauser & Piller 2004; Piller et al 2007; Paulissen et al. 2011). Restricted connections to the open oceans are correlated to sea-level lowstands such as the glacio-eustatic isotope event MSi-3 (Abreu & Haddad 1998) at 12.7 (Piller et al. 2007). The benthic foraminiferal $\delta^{18}O$ Mi4 event was also suggested as a possible Badenian/Sarmatian boundary and tentatively recalibrated to 12.8 Ma by Turco et al. (2001; 13.00 Ma of Westerhold et al. 2005) following Lourens & Hilgen (1997).

Paulissen et al. (2011) used well data in the central part of the Vienna Basin to tentatively correlate the Badenian/Sarmatian boundary (at 12.7 Ma) to the top of C5An.1n, but indicated poor resolution and difficulties in a reliable correlation in the Badenian up to the boundary interval. De Leeuw et al. (2012) dated the boundary in the Transylvanian Basin at 12.80 Ma, within C5Ar.2r. However, their uncertainty interval ranges from 12.68 to 12.84 Ma, including the tops of C5Ar.1n, C5Ar.2r and C5Ar.2n of ATNTS (Lourens et al. 2004a; Ogg 2012). Selmeczi et al. (2012) investigating wells from Western and Northern Hungary by magnetostratigraphy and biostratigraphy reinforced the estimation by Lirer et al. (2009) placing the boundary at 13.15 Ma.

To find appropriate boundaries, correlations between sequence cycles, magnetostratigraphy and biostratigraphic data are necessary. The largest part of the Late Badenian can be correlated with the third sea-level cycle (TB 2.5 after Haq et al. 1988) that must be calibrated to newer time scales. To overcome these problems, and in accordance with our previous approach, we use a magnetostratigraphic definition as a synchronous event for the base of the Sarmatian around the 12.7–12.8 Ma datum suggested by several previous authors. We suggest placing the Badenian/Sarmatian boundary at 12.829 Ma, which is the top of polarity Chron C5Ar.2n (Ogg 2012). This datum is near to the suggested boundary age of previous studies (Piller et al. 2007; De Leeuw et al. 2012, 2013), correlates well with the Mi4 dating in Turco et al. (2001) and follows the lowest sea-level stand in the NW Atlantic (Kominz et al. 2008), approximating the Ser3 sequence boundary of Hardenbol et al. (1998) at ca. 12.7 Ma (Fig. 3; 12.72 Ma according to TS Creator Vers. 6.1, http://www.tscreator.org).

Early Badenian

The beginning of the Early Badenian, here dated at 16.303 Ma, corresponds roughly to the base of foraminiferal plankton Zone M5, the *Praeorbulina sicana* LOZ (Wade et al. 2011; Anthonissen & Ogg 2012). The Bur5/Lan1 sequence boundary estimated at ca. 16.4 Ma (Hardenbol et al. 1998, TS Creator Vers. 6.1, http://www.tscreator.org) is close to this limit (Fig. 3).

The end of the Early Badenian corresponds to the top of polarity Chron C5Bn.2n at 15.032 Ma (Lourens et al. 2004b). We chose this age because it best approximates the base of plankton Zone M6, the *Orbulina suturalis* LOZ (Wade et al. 2011) at 15.10 Ma, the calcareous nannoplankton boundary NN4/NN5 (Martini 1971; Anthonissen & Ogg 2012) positioned at 14.91 Ma, and to the Lan2/Ser1 sequence boundary at ca. 14.8 Ma (Hardenbol et al. 1998). The newly defined Early Badenian therefore has a duration of 1.271 million years.

From a sequence stratigraphical viewpoint, the Early Badenian is represented by sea-level cycle TB 2.3 (Haq et al. 1988) (Fig. 3). According to the revised planktonic foraminiferal biostratigraphy calibrated by geomagnetic polarity and the astronomical time scale, the Early Badenian corresponds to the Subzone M5b, the *Praeorbulina sicana* Lowest Occurrence Zone between 16.38 (Anthonissen & Ogg 2012) and 15.10 Ma (Wade et al. 2011; Anthonissen & Ogg 2012). Paleoclimatically, the Early Badenian for the most part coincides with the "Middle Miocene Climate Optimum" (Phase 1 in Holbourn et al. 2007; for Central Paratethys paleoclimate records — see — e.g. Harzhauser & Piller 2007; Harzhauser et al. 2011) starting with an increase in temperature at 16.5 Ma and keeping constant temperatures until 14.7 Ma (Shevenell et al. 2004; Holbourn et al. 2004, 2007; Fig. 3).

Sediments of this first Badenian sea-level cycle are difficult to identify in outcrops and were commonly strongly eroded away due to the Styrian tectonic phase, before the more significant Mid Badenian transgression. Where the sediments are preserved in the shallower areas of the Styrian Basin, the sequence boundary Lan2/Ser1 is easily recognized by strong erosion (Rögl et al. 2002). Nevertheless, the Early Badenian time is represented in deeper parts of the Styrian Basin by subsurface sediments found as 250 to 750 m thick drill sections in the Western Styrian Basin (Hohenegger et al. 2009) and as the first Badenian sequence in 2D seismic data from the Eastern Styrian Basin (Schreilechner & Sachsenhofer 2007). Karpatian and Early Badenian sediments are largely uniform in wells of the Styrian Basin, both indicating deeper marine sedimentation, but they are separated by an unconformity that reflects the Styrian Tectonic Phase in deeper parts of the Styrian Basin. The upper limit of the first Badenian cycle is documented as a sequence boundary in the Styrian Basin with continuous and conformable deeper water sedimentation (Schreilechner & Sachsenhofer 2007).

In the Austrian part of the Alpine-Carpathian Foredeep, the first Badenian transgression, coupled with the Styrian Tectonic Phase, is documented in deep wells such as Roggendorf-1 by basal transgressive conglomerates below the Grund Formation (Ćorić & Rögl 2004). Subsurface sediments show a 90 m thick clastic sequence of Early Badenian age that overlies the silty-marly Laa Formation of Karpatian age (Ćorić & Rögl 2004). This section is unconformably followed by basal conglomerates with fine sediments of the Grund Formation of Mid Badenian age. The upper limit of the first Badenian cycle is marked by a clastic influence and the interval includes the sudden disappearance of *H. ampliaperta* (top of NN4).

Analogous to this succession, the 200 m thick Iváň Formation, a submarine canyon fill in the Moravian part of the Alpine-Carpathian Foredeep, unconformably overlies the Karpatian Laa Formation (Nový Přerov Member). The canyon fill shows a similar sequence of basal clastic sediments overlain by clays, dated as 16.5–16.3 Ma (Dellmour & Harzhauser 2012). This member is separated from the overlying Mid Badenian sediments by an unconformity (Adámek et al. 2003) and is regarded as Early Badenian (according to our definition) in contrast to Dellmour & Harzhauser (2012). The basal siliciclastic sediments underlying the Grund Formation in the Carpathian Foredeep of Moravia represent the Early Badenian according to the nannoflora (Švábenická 2002; Tomanová-Petrová & Švábenická 2007).

In the inner part of the Polish Carpathian Foredeep, Karpatian alluvial fans are overlain by the Dębowiec conglomerates, deposited during the first Badenian transgression, passing upwards into dark, clayey-sandy sediments of the Skawina Formation (Oszczypko & Oszczypko-Clowes 2012). *Praeorbulina glomerosa* indicates that the lower part of these up to 1000 m thick sediments belong to the Early Badenian, while the Mid-Badenian transgression, indicated by *O. suturalis* in the upper part of the Skawina Formation, fills the outer part of the Carpathian Foredeep with the upper Skawina Formation and the Baranów Beds (Oszczypko & Oszczypko-Clowes 2012).

In the north-western Transylvanian Basin, the Karpatian fan deltas and their overlying erosional surfaces are overlain in the shallower-water parts of the basin by conglomerates and thence by fine siliciclastic deposits containing the index fossil *P. glomerosa*. In the deeper-water parts of the basin, the fine siliciclastics of Early Badenian age directly overlie the basement (Krézsek & Filipescu 2005). This Early Badenian transgression is defined by Krézsek & Filipescu (2005) as TST1 in the sequence stratigraphy. This is followed by the second Badenian transgression (TST2) after HST1 and LST2 initiating the newly defined Mid Badenian, with *O. suturalis* marking its beginning. De Leeuw et al. (2012) dated this event in the Transylvanian Basin as older than the Dej Tuff Complex; that is, older than 14.38 Ma, consistent with our geochronological correlations.

Mid Badenian

We propose that the beginning of the Mid Badenian be fixed at 15.032 Ma, at the top of polarity Chron C5Bn.2n (Lourens et al. 2004b; Ogg 2012). This is slightly above the base of plankton Zone M6, the *Orbulina suturalis* LOZ (Wade et al. 2011).

According to the orbitally-based time calibration of the Badenian stratotype at its type locality (Baden Sooss), the interval between 13.982 Ma and 13.964 Ma (Hohenegger & Wagreich 2012) belongs to the upper Lagenidae zone, and hence the end of the Mid Badenian has to be younger. The next significant event is the climatically controlled Langhian/Serravallian boundary at 13.82 Ma (Hilgen et al. 2009), within the upper part of magnetochron C5ACn. Therefore, the Mid Badenian as defined here spans the time interval between 15.032 and 13.82 Ma, with a duration of 1.212 million years (Fig. 3).

There is a clear climatic transition from the "Middle Miocene Climate Optimum" lasting until 14.7 Ma (Phase I in Holbourn et al. 2007) to the subsequent "Middle Miocene Climate Transition" (Phase II) between 14.7 and 13.82 Ma, characterizing the main part of the Lagenidae zone, and is thus Mid Badenian in age. The world-wide extreme temperature decrease at 13.82 Ma led to lower, continuously decreasing temperatures in the following Phase III, termed "Icehouse" by Holbourn et al. (2007), and a significant global sea-level drop which also affected the Paratethys (e.g. de Leeuw et al. 2010).

The strong transgression of the Paratethys Sea, characterized by the appearance of the planktonic foraminifera *Praeorbulina circularis* and *Orbulina suturalis* together with the nannoplankton *Helicosphaera waltrans*, *Sphenolithus heteromorphus* and the absence of *H. ampliaperta*, was formerly believed to be the first Badenian transgression (Rögl et al. 2002). According to the LO (lowest occurrence) of *O. suturalis* at 15.10 Ma (Wade et al. 2011) and the HO of *H. ampliaperta* at 14.91 Ma (Lourens et al. 2004b), this transgression must lie close to the base of Zone NN5 (Fig. 3). It marks the onset of sea-level cycle TB 2.4 (Haq et al. 1988) starting with the Lan2/Ser1 sequence boundary, estimated by Hardenbol et al. (1998) to lie at 14.8 Ma. The TB 2.4 cycle ends with the Ser2 boundary, dated to around 13.6 Ma (Hardenbol et al. 1998; 13.54 Ma according to TS Creator Vers. 6.1, http://www.tscreator.org). Thus cycle TB 2.4 mostly represents the former "lower" Badenian, but now the Mid Badenian according to our subdivision (see also Piller et al. 2007). This Mid Badenian is subdivided in the Vienna Basin into the lower and upper Lagenidae zones (Fig. 3).

The division of the Mid Badenian based on benthic foraminifera in the Vienna Basin reflects ecological changes leading from a "warm water" fauna (lower Lagenidae zone) to a "slightly cooler but still warm water" fauna (upper Lagenidae zone) (Hohenegger et al. 2008). Thus the boundary between the lower and upper Lagenidae zones reflects an event in the climate transition curve. An important biostratigraphic signal is the HCO of the nannoplankton *Helicosphaera waltrans* at 14.357±0.004 Ma (Abdul Aziz et al. 2008). $^{40}Ar/^{39}Ar$ sanidine dating of a tuff sample from the Styrian Basin containing *H. waltrans* (Handler et al. 2006) gave an age of 14.390.12 Ma, confirming that the upper limit of the lower Lagenidae zone in the Vienna Basin containing *H. waltrans* must be younger than, but close to this date (Fig. 3).

Stable oxygen isotopes from the southern ocean show an initial strong positive excursion between 14.2 and 14.3 Ma in plankton and benthic foraminifera, as well as a pronounced $\delta^{13}C$ carbon maximum (CM5) at 14.24 Ma (Shevenell et al. 2004). This short, intense cooling event (MSi-1 of Abreu & Haddad 1998) could have been responsible for the global environmental change around 14.24 Ma, which in the Paratethys is seen in the disappearance of *H. waltrans* (characterizing possibly the LO of this species) and the change in the composition of the benthic foraminiferal fauna from the lower to the upper Lagenidae zone (Fig. 3). Strauss et al. (2006) recognized a sequence boundary in the upper Lagenidae zone (upper part according to Rögl et al. 2007b) in the southern Vienna Basin on top of their first Badenian cycle. This sequence boundary may be either of a more regional nature (Rögl et al. 2007b) or may be related to a smaller sea-level drop around 14.2 as recorded by, for example, Kominz et al. (2008).

Furthermore, the base of the tropical plankton Zone M7, the *Fohsella peripheroacuta* Lowest-occurrence Zone is also positioned at 14.24 (Anthonissen & Ogg 2012) or 14.23 Ma (Wade et al. 2011). The lack of the index fossil *F. peripheroacuta,* characteristic of tropical environments in the upper Lagenidae zone is in accordance with the slightly cooler water during this time interval.

Because the environmental change at 14.24 Ma is seen globally in the foraminiferal plankton zonation, both Lagenidae zones restricted to the Vienna Basin can be directly correlated with the tropical plankton Zones M6 and M7 (Wade et al. 2011). Thus, we conclude that the lower Lagenidae zone of the Vienna Basin corresponds largely to Zone M6 *Orbulina suturalis* Lowest-occurrence Zone from 15.10–14.24/14.23 Ma, where the index form is represented in the Central Paratethys. The subsequent M7 *Fohsella peripheroacuta* Lowest-occurrence Zone from 14.24/14.23–13.77/13.74 Ma (Wade et al. 2011; Anthonissen & Ogg 2012) corresponds in large part to the upper Lagenidae zone, but so far there is no evidence for this tropical index fossil in the whole Paratethys. Nevertheless, both zones can be alternatively used to subdivide the Mid Badenian rather than the informal division into lower and upper Lagenidae zone that is only valid for the Vienna Basin (Fig. 3).

Late Badenian

The younger part of the Badenian was subdivided by Papp et al. (1978a,b) into two substages; the Wielician (formerly regarded as "middle" Badenian, agglutinated foraminifera zone) and the Kosovian ("upper" Badenian, *Bulimina/Bolivina*-zone and the uppermost zone of impoverished faunas). The timing of these substages is difficult because tectonic uplift geographically separated the Carpathian Foredeep and Transylvanian Basin from the Vienna and Pannonian Basins (e.g. Rögl 1998).

Attribution of the Badenian stratotype from 13.982 to 13.964 Ma (Hohenegger & Wagreich 2012) to the Mid Badenian as newly defined here indicates that the age of the Mid/Late Badenian boundary must be younger than 13.964 Ma. The next younger pronounced and dated global event thus comprises the Langhian/Serravallian boundary at 13.82 Ma. The GSSP of the Serravallian marks an intense climatic change, with a strong drop in temperatures (Hilgen et al. 2009).

Given our dating of the Badenian/Sarmatian boundary at 12.829 Ma, the Late Badenian extended from 13.82 to 12.829 Ma, so that it lasted ca. 991 thousand years. The Wielician substage characterized by evaporites within the Carpathian Foredeep and the Transylvanian Basin (e.g. Peryt et al. 1997; Andreyeva-Grigorovich et al. 2003, 2008; Oszczypko et al. 2006; Peryt 2006; de Leeuw et al. 2010; Peryt & Gedl 2010; Filipescu & de Leeuw 2011; de Leeuw et al. 2012) corresponds to a subunit of the Late Badenian, separating it from the fully marine Kosovian starting diachronously from ca. 13.1 (Śliwiński et al. 2012) to ca. 13.6 Ma based on sea-level cycles (Fig. 3, Hardenbol et al. 1998; 13.54 Ma according to TS Creator Vers. 6.1, http://www.tscreator.org).

Conclusion

Investigations of the Karpatian and Badenian in the classic areas of the Austrian Alpine Foredeep and the Styrian Basin resulted in the detection of a large interval between the uppermost Karpatian and the base of the lower Lagenidae zone (the former base of the Badenian), the latter correlated with the NN4/NN5 boundary at 14.91 Ma. Detailed integrated stratigraphical investigations in the Styrian Basin shows a clear paleoenvironmental change documented by shallow benthic foraminifera, stable isotopes and the occurrence of the planktonic foraminifer *Praeorbulina sicana* together with the marked change in nannofossil composition at ca. 16.3 Ma. This change was caused by a significant Alpine tectonic event named the Styrian Tectonic Phase. On the basis of this and of magnetostratigraphic correlations, we conclude that the base of the Badenian should be placed at 16.303 Ma and does not coincide with the Burdigalian/Langhian boundary at 15.974 Ma. The interval between 16.303 and 15.032 Ma, named the Early Badenian, corresponds largely to the 3rd order sea-level cycle TB 2.3 (Haq et al. 1988).

The lower Lagenidae zone of the newly defined Mid Badenian belonging to the NN5 Zone starts at 15.032 Ma, which is the top of polarity Chron C5Bn.2n, and is terminated at 14.24 Ma due to the short cooling event in the Middle Miocene climate transition curve (Fig. 3). The stratotype of the Badenian stage in the southern Vienna Basin, belonging to the upper Lagenidae zone, has recently been calibrated by cross-correlating geophysical and geochemical variables with the mid-summer insolation curve (Hohenegger & Wagreich 2012). This resulted in an age between –13.982 (+0.003/–0.002) Ma and –13.964 (+0.003/–0.002) Ma for the stratotype section.

The significant $\delta^{18}O$ increase at 13.82 Ma, determined as the Langhian/Serravallian boundary, can be linked with the end of the Mid Badenian and beginning of the Late Badenian. The Badenian/Sarmatian boundary, possibly reflecting a sequence boundary finishing cycle TB 2.5 is placed at the top of polarity Chron C5Ar2n at 12.829 Ma.

The new chronometric division into an Early, Mid and Late Badenian correlates with the global 3rd order sequences

TB 2.3, TB 2.4 and particularly well with TB 2.5, with durations that are in the order of 1 million years each. The boundaries between these ages are either magnetostratigraphically or climatically, and thus astronomically, fixed, with good support from biostratigraphic markers. The informal division of the Badenian into the lower and upper Lagenidae Zone, the *Spiroplectammina* Zone and the *Bulimina/Bolivina* Zone, restricted to the Vienna Basin, can be correlated to the global plankton *Praeorbulina sicana* Zone marking the Early Badenian, *Orbulina suturalis* and *Fohsella peripheroacuta* Zone marking the Mid Badenian, and *Velapertina indigena* marking the Late Badenian in the Central Paratethys.

Finally, the new subdivision of the Badenian correlates with the paleoclimatic evolution of the Middle Miocene, where the Early Badenian approximately corresponds to the "Middle Miocene Climate Optimum". The Mid Badenian is characterized by the "Middle Miocene Climate Transition" and the Late Badenian is governed by the initial part of the "Middle Miocene Icehouse" reflecting the restarting of Antarctic glaciation.

The proposed new chronometric timing of the Badenian makes reconsideration of the chronostratigraphic substages necessary, because the holostratotypes of all substages do not contain the basal boundaries (Papp et al. 1978a). The basal Moravian spanning both the Early and Mid Badenian in time should be restricted to the latter by redefinition based on a new boundary stratotype, while the Early Badenian becomes open for the definition of a new substage necessarily determined by a boundary stratotype. The Wagna section (Fig. 2) cannot be used as a boundary stratotype because it lacks a continuous transition from the Karpatian into the Badenian. Redefinition and chronometric timing of the Late Badenian substages Wielician and Kosovian is also essential for establishing boundary stratotypes based on isochronous events.

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