

A numerically calibrated reference level (MP28) for the terrestrial mammal-based biozonation of the European Upper Oligocene

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Abstract The fauna of the Enspel (Westerwald) and the neighbouring Kärlich (Neuwied basin) fossil deposits correspond to the Upper Oligocene Mammal Paleogene (MP) reference level 28 and 28–30, respectively. Basaltic flows and a trachyte tuff terminating and predating the fossil deposit sedimentation allow to numerically calibrate the MP reference levels by radioisotope dating. Laser fusion $^{40}\text{Ar}/^{39}\text{Ar}$ step heating on volcanic feldspars yield a time interval of 24.9–24.5 Ma for reference level MP28 at Enspel and a maximum age of 25.5 Ma for the time interval MP28–MP30 at Kärlich. Interpolation between the time intervals determined for the Enspel reference level MP28 and the age of the global Oligocene/Miocene boundary of 24.0 ± 0.1 Ma taken from literature results in time intervals of 24.5–24.2 Ma and 24.2–23.9 Ma for the younger reference levels MP29 and MP30, respectively. These intervals of ≤ 0.4 m.y. for MP reference levels of the latest Oligocene are short

relative to older Oligocene MP reference levels 21–27 between 34 and 25 Ma. Since subdivision into MP reference levels essentially is based on assemblages of mammal taxa and on evolutionary changes in tooth morphology of mammals short MP time intervals during the latest Oligocene indicate a rapid evolutionary change relative to the early Oligocene.

Keywords Oligocene · $^{40}\text{Ar}/^{39}\text{Ar}$ dating · Mammal Paleogene (MP) reference level · Numerical calibration · Evolutionary change

Introduction

In the terrestrial environs of Europe, the Paleocene, Eocene and Oligocene biostratigraphically represent 30 Mammal Paleogene (MP) reference levels (e.g., Russel et al. 1982; Brunet and Vianey-Liaud 1987). Regarding the Oligocene, MP21 is the oldest reference level forming the base and MP30 is the youngest forming the top of the Oligocene. The definition of the relative age succession of mammal fossils and the subdivision into MP levels mainly is based on evolutionary changes in tooth morphology of rodents and artiodactyls, respectively.

Dating of mammal fossil deposits is crucial to understanding mammal evolution. However, dating especially of terrestrial deposits is difficult. Provided that there is a mammal based biostratigraphic zonation, a current dating approach is to correlate the local magnetic polarity stratigraphy related to the mammal deposit layers with the global polarity time scale (GPTS). This approach can be difficult, for example, if there are no distinct marker-type layers of known age

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connecting the local and global magnetic polarity chronostratigraphic systems. If the mammal deposit origin is related to a volcanic event, the mammal deposition age can be derived precisely by dating of suitable volcanic products using radioisotope methods, for example the $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique. However, mammal fossil deposits genetically associated with volcanism are rare. With the exception of the Middle Eocene reference levels MP11 (Mertz et al. 2000) and MP13 (Mertz and Renne 2005) representing the European Land Mammal Age (ELMA) Geiseltalian, no Paleogene $^{40}\text{Ar}/^{39}\text{Ar}$ data are available for the numerical calibration of the origin of fossil deposits. In this paper, we present $^{40}\text{Ar}/^{39}\text{Ar}$ data on volcanic rocks closely predating or terminating the sedimentation of the Upper Oligocene fossil deposits Enspel (Westerwald) and Kärlich clay mine (Neuwied basin). Aim is to provide numerically calibrated tie points for the terrestrial mammal based biozonation of the European Upper Oligocene.

Geological and biostratigraphic setting

Enspel/Westerwald

The Enspel fossil deposit (Topographic Map 1:25,000 Sheet 5313 Bad Marienberg; R 34 2181 H 56 0933) is located on Mount Stöffel in the west of the Westerwald volcanic field (Fig. 1), which is part of the Cenozoic Central European volcanic province. Neighbouring volcanic fields of Cenozoic age are Siebengebirge, Vogelsberg and Eifel. Lehmann (1930) gives a detailed petrographic description of the Mount Stöffel basaltic rocks. Based on major element data from Lehmann (1930) the Mount Stöffel volcanism in the total alkali

versus silica (TAS) classification (Le Maitre et al. 1989) represents basaltic to basanitic compositions. The fossil deposit is covered by a ca. 100 m thick basaltic flow. Mining of the flow exposed fossil-bearing black pelite deposited in a former isolated lake during the Late Oligocene. Graben-type, maar-type or caldera-type origins of the lake basin have been discussed (e.g., Felder et al. 1998; Pirrung 1998; Pirrung et al. 2001). Drilling in the lake sediments close to the assumed basin center recovered 137 m of lacustrine sediments comprising black pelite interstratification, 90 m of pyroclastic rocks and 24 m of Devonian host rock sediments (Felder et al. 1998). At 214–220 m depth fragmented basalt was drilled. Vesicles, sediment inclusions as well as fritting of sediments underlying the basalt indicate that the basalt represents a flow predating lake sedimentation. The lithozone division of the drill core appears to correspond to different stages known from maar genesis and tephra fall out of episodic volcanic eruptions. The Enspel flora indicates a temperate warm climate with an average annual temperature of ca. 15°C (Köhler 1998). The fauna record found in the lake sediments consists of insects, fish, tadpoles, frogs, salamanders, reptiles, birds and mammals. Stratigraphically most relevant is the occurrence of particularly well-preserved eomyid teeth of *Eomys quercyi* (Storch et al. 1996; Engesser and Storch 1999). *Eomys quercyi* is a species typical for MP28 (Brunet and Vianey-Liaud 1987). Eomyidae is an extinct family of rodents with representatives capable of gliding locomotion (Storch et al. 1996).

Kärlich clay mine/Neuwied basin

The Kärlich clay mine (Topographic Map 1:25,000 Sheet 5610 Bassenheim R 26 0478 H 55 8425) is located in the Neuwied basin (Fig. 1), a ca. 30 km wide E-striking depression which developed during the Cenozoic (e.g., Bibus 1983). A detailed description of the Neuwied basin stratigraphy exposed at the Kärlich clay mine is given by, e.g., Frechen (1976) or Boenigk and Frechen (2001). Relevant for our purpose is the Upper Oligocene sequence which is formed by three rock units each up to several meters thick. The sequence starts with a blue-coloured limnic clay (“Blauton”) deposited mainly in the central part of the Neuwied basin (e.g., Meyer and Stets 1996). The blue-coloured clay is overlain by trachyte tuff and then by the so-called “Knubb” forming the top of the Upper Oligocene sequence. The Knubb essentially represents re-deposited trachyte tuff at its base followed by younger sandy clay as well as fine sand with layers containing isolated bones and teeth from fish,

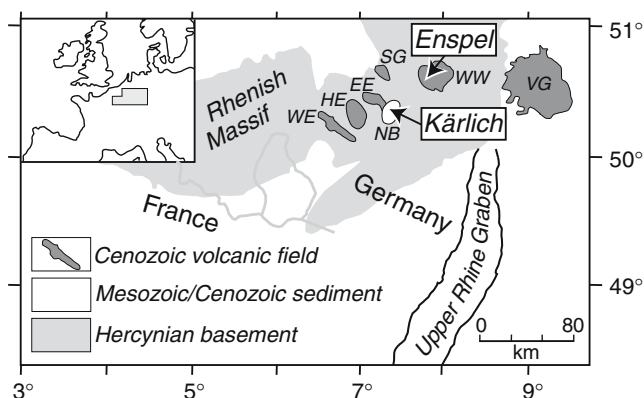


Fig. 1 Geological overview with Kärlich clay mine and Enspel fossil deposits (VG Vogelsberg, WW Westerwald, SG Siebengebirge, EE East Eifel, HE Hocheifel, WE Westeifel, NB Neuwied basin)

amphibians, reptils, birds, and mammals (Heizmann and Mörs 1994). The occurrence of rodents of the genus *Archaeomys* indicates that the Knubb fauna represents Mammal Paleogene reference level MP25–MP30. However, Heizmann and Mörs (1994) concluded that the Knubb *Archaeomys* is a progressive genus since its teeth have no more synclinales developed (Mödden 1993) and therefore most likely represents MP28–MP30. Assigning the Kärlich Knubb mammal fauna to reference level MP28–MP30 currently appears to be the best approach. However, it can not be excluded that MP27 is the oldest Kärlich Knubb reference because the upper molars of *Archaeomys* lose their syncline II in late stages of wear and therefore look similar to upper molars from MP28 (Mödden 1993).

Sampling

For the isotope dating of the Enspel mammal fauna, the upper basaltic flow was sampled at the site of the mining company “Adrian Basalt Co KG” at 425 m above sea level (sample basalt 002) representing a time mark on top of the taphocoenosis. As an older time mark the drilled lower flow (sample basalt 217.75–217.45 m depth) was used.

For the Knubb fauna dating, the trachyte tuff was sampled from a drill core drilled in 1998 by the Geological Survey of the State of Rheinland-Pfalz at the site Rübenacher Höhe (R 33 9631 H 55 8454) located ca. 2 km southeast of the Kärlich clay mine. The drilling recovered the same Upper Oligocene sequence as at the Kärlich clay mine, although in the drill core Knubb sediments and the blue-coloured clay are less thick compared to the Kärlich clay mine profile (Hofmann et al. 2003). Trachyte tuff from the drill core was sampled at a depth of 27.0–27.1 m for establishing a numerical maximum age for the Knubb MP28–MP30 time interval. The trachyte tuff from the Rübenacher Höhe instead of that from the Kärlich clay mine was used for isotope dating because the drilled trachyte tuff is less altered.

Analytical methods

After crushing and grain size fractionation of basalt hand specimen from the Enspel upper and lower flows, respectively, ground mass grains of 200–315 μm size consisting of essentially plagioclase and subordinate sanidine have been produced by magnetic, density and hand-picking procedures. Sanidine crystals of

500–1,000 μm grain size were hand-picked from the trachyte tuff. Thin section investigations show that the ground mass and sanidine crystals are barely affected by alteration and therefore are regarded to be suitable for dating purposes.

For $^{40}\text{Ar}/^{39}\text{Ar}$ dating, basalt groundmass and trachyte tuff sanidine grains were loaded in Al disks and neutron-irradiated in the Cd-shielded port of the TRIGA reactor at Oregon State University. After irradiation the Enspel groundmass multi-grain separates and Rübenacher Höhe sanidine single crystals were incrementally heated by a CO_2 laser (Renne et al. 1997) and their Ar isotope compositions were analyzed using a Mass Analyzer Products 215–50 gas source mass spectrometer. Mass discrimination was determined by analyses of atmospheric Ar from an on-line pipette. Irradiation parameter (“J values”, dimensionless) were determined from single crystal laser fusion analyses of Fish Canyon sanidine (using an age of 28.02 Ma reported by Renne et al. 1998), which was irradiated together with the Enspel and Rübenacher Höhe samples. Corrections applied for interfering nucleogenic isotopes of Ar are those given by Renne et al. (1998). Analytical errors are given on 1σ and do not include error contributions related to decay constants, the age of the irradiation standard, or isotopic abundances of K. Age calculations are based on IUGS constants (Steiger and Jäger 1977).

Analytical results

Both feldspar samples from the Enspel upper and lower flows yield $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra with well defined plateaus at 24.56 ± 0.04 Ma (Lab# 32568-01) and 24.79 ± 0.05 Ma (Lab# 32571-01) comprising ca. 70 and 80% of the total ^{39}Ar degassing, respectively (Fig. 2). During the low-temperature degassing comprising < 5% of the total ^{39}Ar , the apparent step ages are younger than the plateau ages most probably because of radiogenic ^{40}Ar loss caused by minor alteration. Measured K/Ca ratios in the range of ca. 1–3 show that the mineral separation process applied effectively led to considerable enrichment of sanidine, which in the original rock appears in the order of magnitude of < 1%. Two $^{40}\text{Ar}/^{39}\text{Ar}$ analyses on trachyte tuff single sanidine crystals yield age spectra with plateaus at 25.49 ± 0.03 Ma (Lab# 32566-01) and 25.47 ± 0.04 Ma (Lab# 32566-02), respectively, comprising > 97% of the total ^{39}Ar degassing in both cases (Fig. 2). Both $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages are identical within analytical errors indicating a trachyte tuff age of 25.48 ± 0.04 Ma.

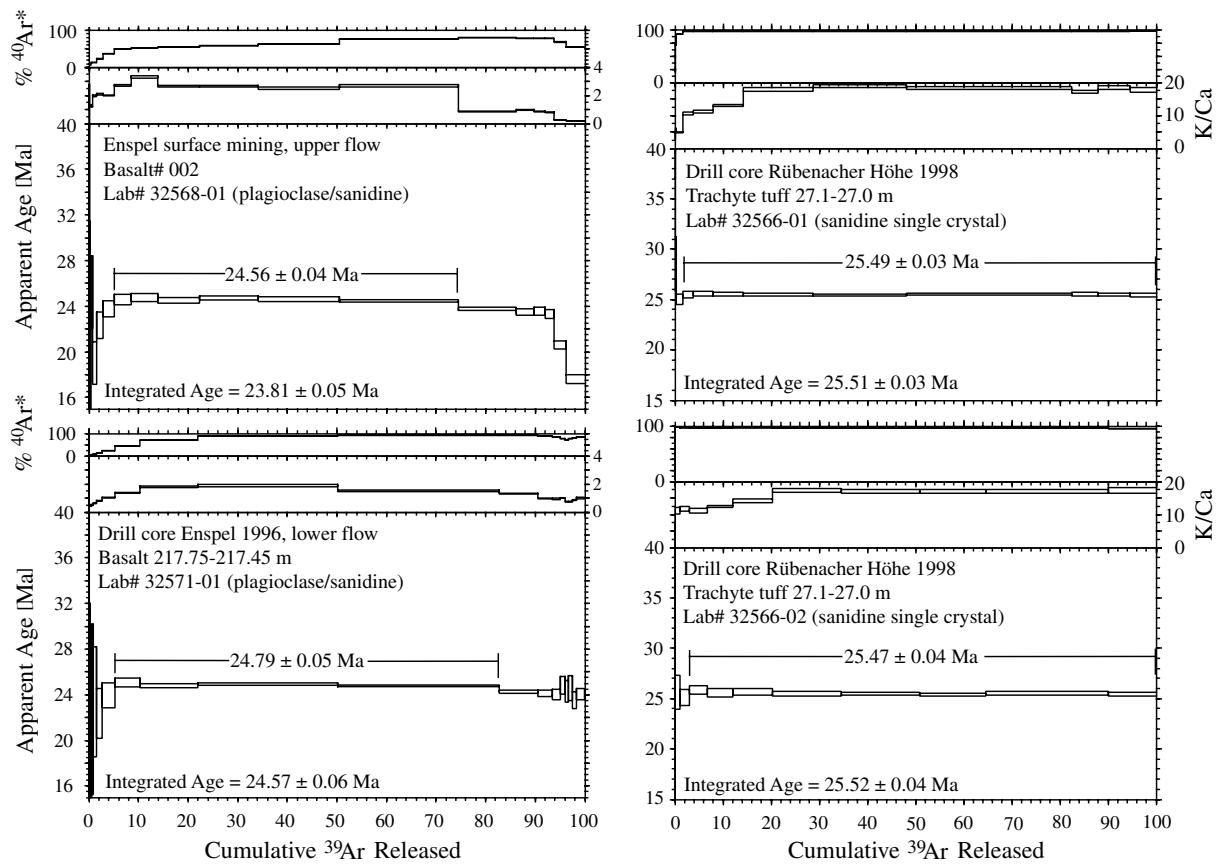


Fig. 2 $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of feldspar multi-grain separates from volcanic flows predating and terminating the lacustrine sedimentation of the Enspel fossil deposit (*left*) and of sanidine

single crystals from trachyte tuff underlying the Kärlich clay mine deposit. Analytical errors are 1σ

Summarizing, the reproducibility of our $^{40}\text{Ar}/^{39}\text{Ar}$ results and flat plateau-type age spectra of the samples measured indicate that their Ar isotope systems are not significantly disturbed regarding the age information. In addition, considering the high Ar-retentivity of sanidine with a high activation energy for Ar up to > 200 kJ/mol (e.g., Baadsgaard et al. 1961) we conclude that our $^{40}\text{Ar}/^{39}\text{Ar}$ ages are geologically meaningful. Thus, the plateau ages from Enspel and Kärlich/Rügenacher Höhe samples define basalt lava and trachyte tuff extrusion events.

Discussion

Ages of Enspel and Kärlich clay mine “Knubb” sedimentation

In order to determine the age of Enspel reference level MP28, the time span of lacustrine sedimentation has to be defined because the black pelite interstratifications formed during aquatic sedimentation contain the

eomyids relevant for the MP28 correlation. The dated flows provide a close age bracket for the Enspel lacustrine sediments, which are older than 24.56 ± 0.04 Ma and younger than 24.79 ± 0.05 Ma. Paleomorphology reconstructions indicate that the upper basalt flow ran into a lake basin at least several tens of meters deep (Pirrung 1998). Also, the drill core sediments do not show indications of alluviation (Felder et al. 1998). Therefore, we interpret the age of the upper flow as a discrete time mark for the termination of lacustrine sedimentation. There is a hiatus between the onset of lacustrine sedimentation at ca. 140 m depth of the drill core and the lower flow, represented by ca. 75 m of pyroclastic rocks deposited during the initial lake basin development. However, the time span for deposition of some tens of meters of pyroclastic rocks in the early phases of volcanologically triggered basin formation such as in maar-type or caldera-type craters is negligible in terms of geologically relevant time scales (e.g., Cas and Wright 1995). Thus, we consider the age of the lower flow as representing the onset of a period of ca. 300 k.y. of lacustrine

sedimentation. This results in a theoretical value for average annual sedimentation of about 0.47 mm, although the application of this rate might be questionable. Debris flows and landslides reconstructed from drill core petrography (Felder et al. 1998) indicate that sedimentation to a relevant extent was episodic rather than continuous. However, it is not clear whether the Enspel lacustrine sedimentation exclusively comprises MP28 or whether the older sediment succession possibly in addition represents younger MP27. Also, it is unclear whether the uppermost sediments represent youngest MP28. In order to account for this uncertainty we consider a geological error of + 0.1 m.y. for the younger and ± 0.1 m.y. for the older numerical interval brackets. Summarizing, we suggest a time interval between 24.9 and 24.5 Ma for reference level MP28 in Enspel.

The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 25.48 ± 0.04 Ma from trachyte tuff sanidines of the Rübenacher Höhe drill core represents a maximum age for the Mammal Paleogene reference levels MP28–MP30 related to the Knubb sedimentation. Since MP30 represents the latest Oligocene the time interval for the Knubb sediment deposition lies in between 25.5 Ma and the age of the Oligocene/Miocene boundary. Conventional K–Ar dating on sanidine sampled directly from the Kärlich clay mine trachyte tuff (Lippolt 1961) yields an age of 23.4 ± 0.6 Ma (pre-1980 published ages are recalculated to IUGS constants given in Steiger and Jäger 1977). The discrepancy of ca. 2 m.y. between $^{40}\text{Ar}/^{39}\text{Ar}$ and K–Ar ages could be caused by a methodical problem of conventional K–Ar dating possibly related to incomplete degassing of the sanidines measured (e.g., McDougall et al. 1980).

Westerwald and Neuwied basin Upper Oligocene volcanism

Conventional K–Ar total rock dating on Westerwald basalt occurrences from Marienberg and Kackenberger Stein located a few km to the northeast of Mount Stöffel yield 26.2 ± 1.5 Ma and 22.7 ± 2.5 Ma, respectively (Lippolt and Todt 1978). Tertiary total rock separates from Central European volcanic fields are known to be sensitive to disturbances of their K–Ar isotopic system by excess Ar (Rittmann and Lippolt 1998) and Ar loss (Müller-Sohnius et al. 1989). However, at least the Marienberg total rock age appears to be geologically significant because a plagioclase-enriched separate from this occurrence yield an age of 24.8 ± 2.3 Ma concordant with the total rock age within analytical error (Lippolt and Todt 1978).

The effusion of the Enspel volcanic flows during the time span 24.9–24.5 Ma overlap in age with both the Marienberg and Kackenberger Stein volcanic events, together forming a relevant volcanic phase in the western part of the Westerwald.

For the Neuwied basin trachyte tuff an origin from the trachyte volcanism either of the Siebengebirge or the Westerwald volcanic fields (Fig. 1) is discussed (e.g., Frechen 1976). The evaluation whether the Westerwald trachyte volcanism represents the source of the trachyte tuff deposited in the Neuwied basin using a possible temporal relation is difficult on the basis of the available data. Although conventional K–Ar total rock ages on Westerwald trachytes yield an age range from 22.8 ± 0.8 to 25.7 ± 0.8 Ma (Lippolt and Todt 1978) corresponding in age to the Rübenacher Höhe trachyte tuff, as mentioned above conventional K–Ar ages on total rock separates can be affected by distortions of the Ar isotope system. Therefore, it is not clear whether these ages are geologically significant.

Conventional K–Ar ages of sanidines from trachyte tuff occurrences ($n = 16$) of the Siebengebirge region with one exception vary between 22.5 ± 0.5 and 23.9 ± 0.5 Ma (Todt and Lippolt 1980) and are younger than the $^{40}\text{Ar}/^{39}\text{Ar}$ single crystal sanidine age of 25.48 ± 0.04 Ma for the Rübenacher Höhe trachyte tuff. In contrast, $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages on sanidine single crystals ($n = 6$) from Siebengebirge-related trachyte tuff indicate different phases of episodic volcanic activity within a short period from 25.46 to 25.30 Ma (Mertz et al., unpublished data) contemporaneous with the Rübenacher Höhe trachyte tuff pyroclastic event considering analytical errors. In addition, conventional K–Ar measurements on sanidines from Siebengebirge trachytes ($n = 6$) yield ages between 25.2 ± 0.6 and 26.4 ± 0.8 Ma (Todt and Lippolt 1980) covering the trachyte tuff $^{40}\text{Ar}/^{39}\text{Ar}$ age range. On the basis of the age concordance between Siebengebirge trachyte K–Ar and trachyte tuff $^{40}\text{Ar}/^{39}\text{Ar}$ as well as Rübenacher Höhe trachyte tuff $^{40}\text{Ar}/^{39}\text{Ar}$ ages coupled with undisturbed plateau-type $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of our measured sanidine single crystals we conclude that the Neuwied basin trachyte tuff represents an early phase of the Siebengebirge trachyte tuff production which occurred over a time interval of 0.2 m.y. from 25.5 to 25.3 Ma. Also, the systematically younger conventional K–Ar ages of the trachyte tuff relative to the trachytes are possibly related to a methodical problem of conventional K–Ar sanidine dating and are regarded as not being geologically meaningful.

Oligocene/Miocene boundary and time intervals of Late Oligocene Mammal Paleogene reference levels

Figure 3 shows a time scale indicating the relation between the global Oligocene/Miocene boundary as well as the Enspel MP28 and Kärlich Knubb MP28–MP30 time intervals established by our $^{40}\text{Ar}/^{39}\text{Ar}$ data. A global stratotype section and point (GSSP) for the Oligocene/Miocene boundary has been established at the Chron 6Cn.2n/r boundary in the Lemme-Carrosio section, NE Italy (Steininger et al. 1997). Based on seafloor spreading geomagnetic polarity stratigraphy and the time scale of Harland et al. (1990), Cande and Kent (1992, 1995) gave an age of 23.8 ± 1.0 Ma for the Oligocene/Miocene boundary. Shackleton et al. (1999, 2000) derived an astronomically calibrated age of 22.9 ± 0.1 Ma and tuning of ODP site 926 to the La2003 obliquity solution resulted in an age for the base of the Miocene of 23.03 Ma (Lourens et al. 2004). By integrating biostratigraphy and magnetic polarity

stratigraphy with ages from $^{40}\text{Ar}/^{39}\text{Ar}$ measurements and $^{87}\text{Sr}/^{86}\text{Sr}$ chronostratigraphy, Wilson et al. (2002) assigned an age of 24.0 ± 0.1 Ma to the Oligocene/Miocene boundary. This date matches well the age established by seafloor geomagnetic polarity, however, it is ca. 1 m.y. older than the astronomically calibrated age. Wilson et al. (2002) attributed this discrepancy to the possibility that Shackleton et al. (1999, 2000) observed three 400 k.y. eccentricity cycles or a 1.2 m.y. modulation of obliquity amplitude too young in their astronomical calibration. In this case, considering given uncertainties, all three boundary ages suggested are indistinguishable. Because of the integrated approach we find the numerical definition of the Oligocene/Miocene boundary of Wilson et al. (2002) most suitable. Interpolation between the boundary age of 24.0 ± 0.1 Ma and an interval of 24.9–24.5 Ma for MP28 yields intervals of 24.5–24.2 Ma for MP29 and 24.2–23.9 Ma for MP30. Considering an age of 23.8 Ma for the Oligocene/Miocene boundary the MP28 and MP29 intervals stay the same whereas MP30 extends from 24.2–23.8 Ma.

As a maximum age of the time interval MP28–MP30, the Rübenacher Höhe $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine plateau age of 25.5 Ma confirms the results on the Late Oligocene MP reference level calibration derived from the Enspel $^{40}\text{Ar}/^{39}\text{Ar}$ data by an independent location. The hiatus of 0.6 m.y. between the maximum age of the Knubb mammal fauna and the Enspel MP28 interval could represent the time of trachyte tuff redeposition occurring prior to the Knubb sedimentation and later than the trachyte tuff volcanism. In addition, it can not be excluded that the Neuwied basin trachyte tuff sequence originally consisted of further pyroclastic flows younger than the dated 25.5 Ma trachyte tuff which either had been eroded or not been deposited in the Kärlich clay mine/Rübenacher Höhe region. Another plausible explanation of the 0.6 m.y. hiatus is the possibility that the Knubb sedimentation not only represents reference levels MP28–MP30 but in addition part of MP27.

Comparison between magnetostratigraphy-derived ages and $^{40}\text{Ar}/^{39}\text{Ar}$ results

For different locations of the northern alpine Lower Freshwater Molasse Engesser and Mödden (1997) using data of Schlunegger et al. (1996) derived ages for Late Oligocene MP levels by correlating the local magnetic polarity stratigraphy with the GPTS. Four out of six reference fauna of reference levels 28–30 dated match the time intervals we suggested considering a geological uncertainty of ± 0.1 Ma as discussed,

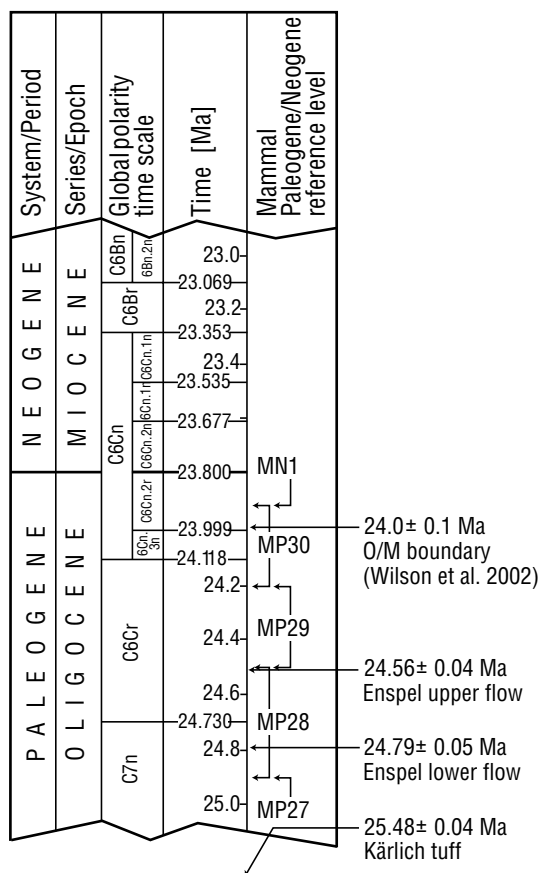


Fig. 3 Chronostratigraphy, magnetostratigraphy and geochronology at the base of the Miocene as presented by Steininger et al. (1997) from the global stratotype section and point (GSSP) as well as suggested Late Oligocene time intervals of reference levels MP28–MP30 derived from $^{40}\text{Ar}/^{39}\text{Ar}$ dating

independently whether 23.8 Ma (e.g., Steininger et al. 1997) or 24.0 Ma (Wilson et al. 2002) is used for the base of polarity chron C6Cn.2n at the Oligocene/Miocene boundary. However, the reference fauna Rickenbach (MP29, 6Cr) and Fornant 7 (MP28, 7n.2n) appear to be too old up to ca. 0.2–0.5 Ma, respectively, in the magnetostratigraphy time scale. This discrepancy could be caused by the problem of exact timing of reference localities within a polarity chron.

Evolution rate

$^{40}\text{Ar}/^{39}\text{Ar}$ -derived time intervals of 0.4 m.y. or possibly shorter for the Late Oligocene reference levels MP28–MP30 can not be applied to older MP levels. For example, intervals of Middle Eocene MP reference levels derived from $^{40}\text{Ar}/^{39}\text{Ar}$ dating appear to be on the order of 1 m.y. (Mertz and Renne 2005). Also, considering an age of 10 m.y. from 34 to 24 Ma for the Oligocene (Berggren et al. 1995), an average interval of 0.4 m.y. does not match the remaining older Oligocene MP reference levels of 21–27. Their average time intervals should be longer by a factor of three compared to the younger Oligocene MP reference levels. Based on a comparison between magnetostratigraphy data and ages derived by evolutionary lineages, Legendre and L  veque (1997) found such relatively long MP time intervals for the pre-25 Ma Oligocene.

The determination of the relative age succession of fossil deposits together with their subdivision into MP levels is essentially based on evolutionary changes in mammalian tooth morphology and on assemblages of different mammalian taxa. Short MP intervals in the Late Oligocene indicate rapid evolutionary change of the mammalian stratigraphic key genera, especially *Archaeomys* and *Issiodoromys* (BiochroM'97 1997).

Two major factors which could influence the evolution rate in the Late Oligocene are volcanism and climate change. Besides its regional importance for Westerwald and Siebengebirge, volcanism of Late Oligocene age has also been active in further Central (Fig. 1) or East European intraplate volcanic fields such as Rh  n, Oberpfalz, Bohemia, Lausitz and Lower Silecia or has accompanied rifting processes in Central or Southwest Europe as for example in the Rhine and Eger graben regions, the Massif Central or the Valencia trough (Todt and Lippolt 1975, 1980; Lippolt et al. 1975; Lippolt 1978; Lippolt and Fuhrmann 1982; Marti et al. 1992; Michon and Merle 2001). Usually, discrete catastrophic events such as extremely high magma production rates of 10 km³/year or more during a short period of few hundred k.y., are discussed as a

major cause for global mass extinction, as for example the eruptions of the Siberian (Renne and Basu 1991) or Central Atlantic magmatic province (Marzoli et al. 1999) flood basalts at the end of the Permian or Triassic, respectively. However, there is no comparable catastrophic volcanism active a few m.y. prior to or contemporaneous with the Oligocene/Miocene boundary. Instead, pre-24 Ma volcanism in Europe is characterized by a high frequency of volcanic eruptions during a relatively long time span of some m.y. and occurring within a relatively large area with a radius of ca. 1,000 km. In addition, a strong decrease in $\delta^{18}\text{O}$ signatures of deep-sea foraminifera during the Late Oligocene reflects a massive warming trend starting at ca. 27 Ma, which was interrupted by a short severe glaciation event (Mi-1 Glaciation) close to the Oligocene/Miocene boundary (e.g., Zachos et al. 2001). It is unclear whether there is a relationship between volcanism and climate change between ca. 27 and 24 Ma, however, both factors are known to trigger acceleration in evolutionary change substantially.

Conclusions

Step-heating $^{40}\text{Ar}/^{39}\text{Ar}$ dating via laser on feldspar multi-grain separates from volcanic flows terminating and predating the Enspel fossil deposit sedimentation and on sanidine single crystals from trachyte tuff underlying the K  rlich clay mine fossil deposit sediments yield a time interval of 24.9–24.5 Ma for reference level MP28 and a maximum age of 25.5 Ma for the time interval MP28–MP30.

Well defined $^{40}\text{Ar}/^{39}\text{Ar}$ plateau comprising up to 97% of the total ^{39}Ar degassing indicate that our experimentally derived data are geologically meaningful.

By interpolation between the $^{40}\text{Ar}/^{39}\text{Ar}$ age of the Enspel reference level MP28 and the age of the global Oligocene/Miocene boundary of 24.0 ± 0.1 Ma taken from literature, we suggest time intervals between 24.5–24.2 Ma and 24.2–23.9 Ma for the reference levels MP29 and MP30, respectively.

Short intervals ≤ 0.4 m.y. for MP reference levels 28–30 indicate a phase of rapid evolutionary change relative to longer intervals of older Oligocene MP reference levels 21–27 comprising the time span 34–25 Ma.

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