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A new magnetostratigraphic framework for the Lower Miocene (Burdigalian/Ottnangian, Karpatian) in the North Alpine Foreland Basin

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Abstract Oligocene–Miocene chronostratigraphic correlations within the Paratethys domain are still highly controversial. This study focuses on the late Early Miocene of the Swiss and S-German Molasse Basin (Late Burdigalian, Ottnangian–Karpatian). Previous studies have published different chronologies for this time interval that is represented by the biostratigraphically well constrained Upper Marine Molasse (OMM, lower and middle Ottnangian), Upper Brackish Molasse (OBM, Grimmelfingen and Kirchberg Formations, middle and upper Ottnangian to lower Karpatian, MN 4a–MN 4b) and Upper Freshwater Molasse (OSM, Karpatian–Badenian, MN 5). Here, we suggest a new chronostratigraphic framework, based on integrated magneto-litho-biostratigraphic studies on four sections and three boreholes. Our data indicate that the OBM comprises chrons 5D.1r and 5Dn (Grimmelfingen Fm), chron 5Cr (lower Kirchberg Fm) and the oldest part of chron 5Cn.3n (upper Kirchberg Fm). The OSM begins during chron 5Cn.3n, continues through 5Cn, and includes a long reversed segment that can be correlated to chron 5Br. The OMM-OSM transition was completed at 16.0 Ma in the Swiss Molasse Basin, while the OBM-OSM changeover ended at 16.6 Ma in the S-German Molasse Basin. As the lower Kirchberg Fm represents a facies of the Ottnangian, our data suggest that the Ottnangian–Karpatian boundary in the Molasse Basin is approximately at 16.8 Ma, close to the 5Cr–5Cn.3n magnetic reversal, and

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thus 0.4 Myr younger than the inferred age of 17.2 Ma used in recent Paratethys time scales. Notably, this would not be problematic for the Paratethys stratigraphy, because chron 5Cr is mainly represented by a sedimentation gap in the Central Paratethys. We also realise, however, that additional data is still required to definitely solve the age debate concerning this intriguing time interval in the North Alpine Foreland Basin. We dedicate this work to our dear friend and colleague Jean-Pierre Berger (8 July 1956–18 January 2012).

Keywords Paratethys · Molasse Basin · Upper Freshwater Molasse · Upper Brackish Molasse · Small mammal biostratigraphy · Otolith zones

1 Introduction

The Molasse Basin, which is part of the North Alpine Foreland Basin (NAFB), developed during the Late Eocene/Early Oligocene and belongs to the biogeographic entity of the Paratethys. It stretches from the Haute Savoy in France through Switzerland and Southern Germany to Austria and continues to the Carpathian Foredeep (e.g. Lihou and Allen 1996; Schlunegger et al. 1997; Kováč et al. 2004; Dellmour and Harzhauser 2012). The thickness of the Molasse sediments may comprise a few tens of metres in the distal areas, but can reach up to >4,000 m in the proximal regions, near to the Alps (e.g. Lemcke 1988). Sediments of the Molasse Basin mainly derive from the Alps and to a reduced extent from sources to the North (e.g. Kuhlemann and Kempf 2002).

The western part of the Molasse Basin, from France approximately up to the longitude of Munich (S-Germany), belongs to the Western Paratethys, while the eastwards adjacent area is part of the Central Paratethys (Seneš 1973: Fig. 2). The differentiation of Western and Central Paratethys mainly results from different environmental settings during the Late Oligocene and Early Miocene, when the area of the Western Paratethys was drained by a large river system (Lower Freshwater Molasse sedimentation), whereas marine conditions remained in the Central Paratethys (Lower Marine Molasse sedimentation) (e.g. Lemcke 1988).

Oligocene–Miocene chronostratigraphic correlations within the Paratethys domain and between the Paratethys and the Mediterranean are still highly controversial (Piller et al. 2007; Abdul Aziz et al. 2008, 2010; Kälin and Kempf 2009), mainly because the Paratethys fauna and flora include many endemic elements. For this reason, regional stratigraphic stages have been introduced for the Central and Eastern Paratethys (Cicha et al. 1967; Papp et al. 1973; Steininger et al. 1976). Their correlation with the Global Time Scale is mainly achieved by a combination of biostratigraphy, magnetostratigraphy, Ar/Ar dating, sequence stratigraphy, or cyclostratigraphy (e.g. Kempf et al. 1999; Piller et al. 2007; Frieling et al. 2009; Lirer et al. 2009; Krijgsman et al. 2010; Paulissen et al. 2011; Vasiliev et al. 2011; Grunert et al. 2013). The Paratethys sedimentary record, however, is often discontinuous, lithofacies can change considerably, and volcanic ashes or bentonites that provide radiometric ages are rare. Thus, relations to global climate changes or sea level variations are difficult to establish and several aspects of the chronostratigraphic, palaeoenvironmental and palaeogeographic evolution of the Paratethys remain ambiguous.

This study focuses on the late Early Miocene (Late Burdigalian, Central Paratethys stages Ottnangian and Karpatian) and early Middle Miocene (Early Langhian, early Badenian) in the Molasse Basin of Switzerland and S-Germany. The Molasse sediments of this time interval comprise the upper part of the Upper Marine Molasse, the Upper Brackish Molasse and the lower part of the Upper Freshwater Molasse (Fig. 1). The precise correlation of these sediments to the Global Time Scale (GTS) is highly debated because successions that are laterally equivalent according to biostratigraphy based on small mammals have been correlated differently to the GTS, reaching differences in age up to 0.8 Myr (Kälin and Kempf 2009; vs. Abdul Aziz et al. 2010; see here Fig. 1). Notably, both chronologies are supported by bentonite ages, either based on U/Pb (Swiss Molasse Basin, Gubler et al. 1992; Gubler 2009) or Ar/Ar ages (S-German Molasse Basin, Abdul Aziz et al. 2010).

The objective of this study is to test if a coherent magnetostratigraphic time framework can be achieved for the Molasse Basin of Switzerland and S-Germany. We carried out new integrated magneto-litho-biostratigraphic studies on several sections and boreholes in the Swiss and S-German Molasse Basin, and recalibrate the previously established magnetostratigraphic patterns of Kälin and Kempf (2009) and Abdul Aziz et al. (2010).

1.1 Geological setting

The sediments that were deposited in the Swiss and S-German parts of the Molasse Basin during the Ottnangian, Karpatian and early Badenian include, from bottom to top, the Upper Marine Molasse (OMM), Upper Brackish Molasse (OBM) and Upper Freshwater Molasse (OSM) (Lemcke 1988; Doppler and Schwerd 1996; Fig. 1). In the Swiss part of the basin, the OBM is not developed; time-equivalent deposits belong to the OMM (Kiderlen 1931; Büchi and Schlanke 1977; Kuhlemann and Kempf 2002). Note that here we use the German abbreviations OMM (Obere Meeresmolasse), OBM (Obere Brackwassermolasse) and OSM

(Obere Süßwassermolasse) to avoid confusion with the older (Oligocene) Molasse groups, usually abbreviated as UMM (Untere Meeresmolasse), UBM (Untere Brackwassermolasse) and USM (Untere Süßwassermolasse).

1.1.1 Early and middle Ottnangian (OMM)

During the Ottnangian, the Paratethys was connected with the western Mediterranean Tethys by a narrow seaway ("Burdigalian seaway"), during which a basin-wide transgression flooded the North Alpine Foreland Basin (Allen et al. 1985; Rögl 1998). Marine glauconitic sands and marls, often rich in foraminifers and other marine microfossils, represent the OMM deposits of this time interval (Wenger 1987; Grunert et al. 2010; Pippèrr 2011; Grunert et al. 2013). In the Swiss Molasse Basin, these marine sediments are termed St. Gallen Formation, their foraminiferal content is poor, the facies predominantly shallow to marginal marine (Berger 1985; Keller 1989). In the Molasse basin of S-Germany and Upper Austria, a lower and middle Ottnangian part of the OMM can be recognized based on benthic foraminifers; the lower Ottnangian OMM is characterized by predominantly deep neritic facies, while the middle Ottnangian OMM is regressive and mostly shallow-neritic to marginal marine (Wenger 1987; Rupp et al. 2008; Grunert et al. 2010; Pippèrr 2011). In the S-German Molasse Basin the lower Ottnangian OMM comprises the Untersimbacher Schichten, Neuhofen Fm and equivalent units, while the middle Ottnangian consists of the Glaukonitsande & Blättermergel and equivalent units (Wenger 1987; Heckeberg et al. 2010; Pippèrr 2011). In the Molasse Basin of Upper Austria, the Vöckla, Atzbach and Ottnang Formations represent the lower Ottnangian, while the Ried Fm and several other formations form the middle Ottnangian (Rupp et al. 2008; Grunert et al. 2010).

1.1.2 Middle and late Ottnangian (OMM/OBM)

The Swiss Molasse Basin remained marine during the middle and late Ottnangian and the corresponding sediments are those of the St. Gallen Formation (Berger 1985;

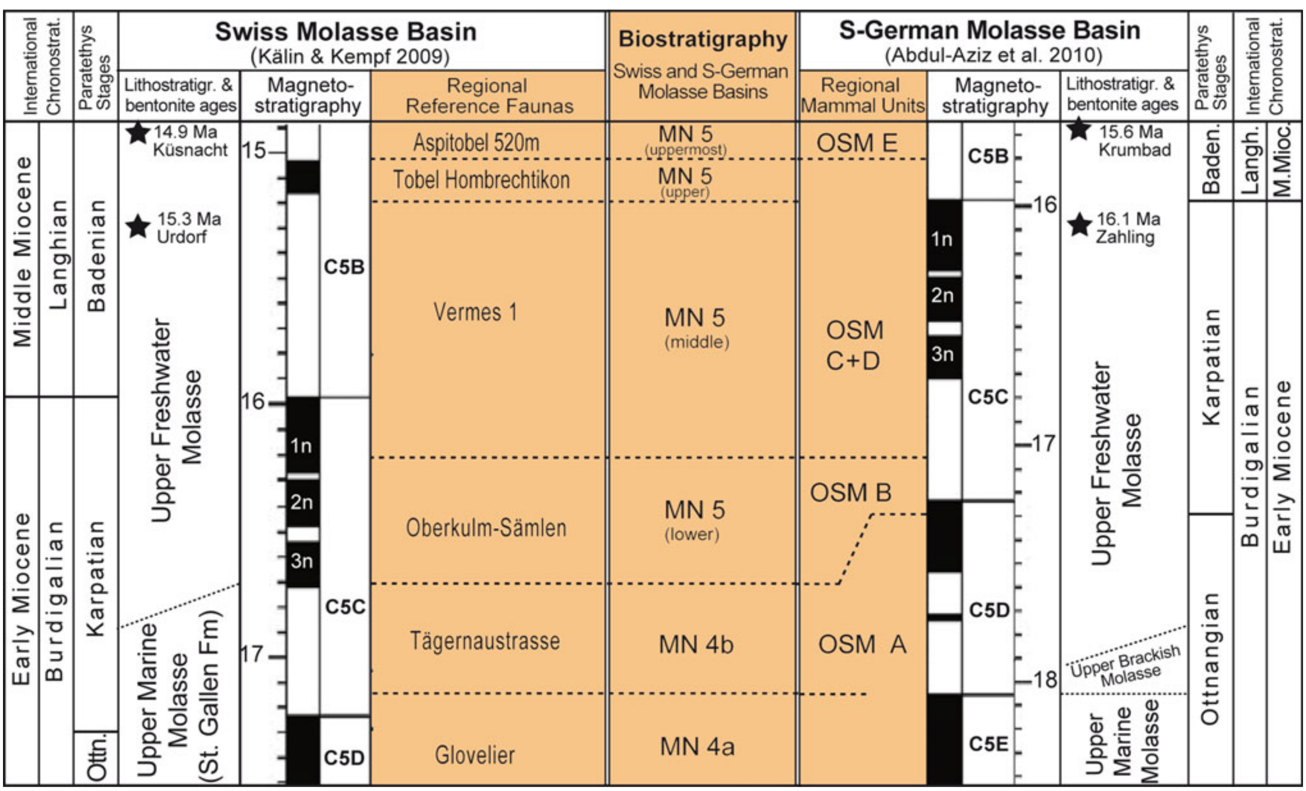

Fig. 1 Magnetostratigraphic and biostratigraphic framework in the Swiss and S-German Molasse Basin according to Kälin and Kempf (2009) (*left columns*) and Abdul Aziz et al. (2010) (*right columns*). Note the great difference between the Swiss and S-German Molasse Basin in the correlation of the magnetostratigraphic records to the Global Time Scale (GTS), despite the biostratigraphy (coloured) indicate similar ages for these deposits. Correlation between the small mammal chronology (MN units) and OSM units follows Kälin and Kempf (2009) and Abdul Aziz et al. (2010) (for a revision see Fig. 13). International chronostratigraphy according to the GTS of Lourens et al. (2004) and Gradstein et al. (2012). *Stars* indicate bentonite ages based on U/Pb (in Switzerland) and Ar/Ar (in S-Germany)

Keller 1989). The South-eastern German and Upper Austrian Molasse Basin stayed marine in the middle Ottnangian, while brackish conditions and the sediments of the Rzehakia Fm (Oncophora Beds) developed in the late Ottnangian. In contrast, the region of the South-western German Molasse Basin was affected by a regression in the course of the middle Ottnangian (Kiderlen 1931; Lemcke et al. 1953; Lemcke 1988). The regression resulted in the incision of the Graupensand-River that drained from ENE to WSW along the northwestern margin of the S-German Molasse Basin to the Molasse Sea in Switzerland (Moos 1926; Kiderlen 1931). The Graupensand-River eroded the underlying OMM and Lower Freshwater Molasse (USM), which resulted in the structure of the so-called Graupensandrinne (Kiderlen 1931; Doppler et al. 2005). Erosion was subsequently followed by accumulation and the deposition of the generally ~20 m thick Grimmelfingen Formation took place. The Grimmelfingen Fm consists of fine- to coarse-grained carbonate-free to -poor sands and gravelly layers (Graupensande); lydite pebbles and the heavy mineral spectrum indicate a source of these sands in the Bohemian Massiv and Frankenwald (Lemcke 1985). Fossils are exclusively known from the base of the Grimmelfingen Fm, where a layer with marine and brackish fossils occurs (Reichenbacher et al. 1998; Sach and Heizmann 2001). The well-preserved teeth of sharks as well as the composition of the shark fauna clearly indicate that this fossiliferous basal layer is autochthonous and not reworked from older OMM beds (Reichenbacher et al. 1998; Sach and Heizmann 2001). The Grimmelfingen Fm overlies discordantly the USM or, in the case that the USM is completely eroded, the Upper Jurassic (Kiderlen 1931; Schreiner 1976, 1978; Tipper et al. 2003). Kiderlen (1931), Lemcke (1988) and others interpreted the sedimentary structures of the Grimmelfingen Fm as fluvial, but Luterbacher et al. (1992) and Asprion and Aigner (2000) found evidence for an estuarine environment. It should be added that Tipper et al. (2003) argued that the Graupensandrinne resulted from submarine erosion and that the Grimmelfingen Fm is marine, but this hypothesis needs further investigation.

The usually up to 15 m thick Kirchberg Fm overlies the Grimmelfingen Fm without a discontinuity and probably represents a short-term transgression of the Swiss Molasse Sea (Kiderlen 1931; Büchi and Schlanke 1977; Lemcke 1988). The lithostratigraphic concept of the Kirchberg Fm, of which the type locality is Illerkirchberg, is based on Kranz (1904), and has been refined by Schlickum (1963), Reichenbacher (1989) and Doppler (2011). Accordingly, the fossil content represents a criterion for the recognition of the Kirchberg Fm, and for its subdivision in “lower Kirchberg Fm” and “upper Kirchberg Fm” (Fig. 2; see also Sect. 2.4).

The Grimmelfingen and Kirchberg Formations are generally summarized as Upper Brackish Molasse (OBM) (Doppler et al. 2005). If fossils are absent, the boundary between the Grimmelfingen Fm and Kirchberg Fm is not sharp and the identification of the Grimmelfingen Fm mainly relies on the occurrence of gravels, lydite and carbonate-free to -poor sands (Doppler 1989 and this study). The Grimmelfingen Fm is considered as middle Ottnangian; fossil mammals in the basal fossiliferous layer are indicative for the mammal unit MN 4a (Heizmann 1984; Reichenbacher et al. 1998; Sach and Heizmann 2001). The Kirchberg Fm is traditionally considered as upper Ottnangian and represents one of the faciostratotypes of the Rzehakia Formation in the Central Paratethys (Čtyroký et al. 1973a, b). The uppermost part of the Kirchberg Fm south of Oberkirchberg (site 18 according to Reichenbacher 1989) has yielded a single biostratigraphically valuable tooth of the small mammal *Megacricetodon* aff. *collongensis* that may correlate to mammal unit MN 4b or the local mammal unit OSM-A (Reichenbacher et al. 2004). Teeth of the same species from the locality Günzburg 2, positioned above the Kirchberg Fm in the lowermost OSM, provide additional support for the assignment of the Kirchberg Fm to MN 4b (Reichenbacher et al. 1998). In addition, the otolith zone OT-M4 (*Dapalis formosus* taxon-range zone) is characteristic for the entire Kirchberg Fm (Reichenbacher 1999; Reichenbacher et al. 2004).

1.1.3 Karpatian (OMM/OSM) and early Badenian (OSM)

OMM sedimentation continued until the early Karpatian in the Swiss Molasse Basin, whereas OSM sediments accumulated in the Molasse Basin of S-Germany and Upper Austria (Kuhlemann and Kempf 2002; Reichenbacher et al. 2005). The biostratigraphy is mainly based on the evolution of small mammals (Bolliger 1992, 1994; Heissig 1997; Böhme et al. 2001; Abdul Aziz et al. 2008; Kälin and Kempf 2009; Prieto et al. 2009). No OMM or OBM sediments with small mammal fossils indicative for a mammal unit younger than MN 4b are known from the Swiss and S-German Molasse Basin. This means that the Molasse Sea had totally disappeared from that area with the beginning of the mammal unit MN 5 (Fig. 1).

In the Swiss Molasse Basin, regional mammal zones named after characteristic taxa were introduced by Kälin and Kempf (2009), and in the S-German Molasse Basin regional biostratigraphic units or Assemblage Zones, termed OSM A to OSM F, were defined by Heissig (1997) and Böhme et al. (2001) (Fig. 1). Both regional mammal zonations have been correlated to a magnetostratigraphic framework and calibrated to radiometrically dated volcanic ash layers (bentonites) (Abdul Aziz et al. 2008, 2010; Kälin

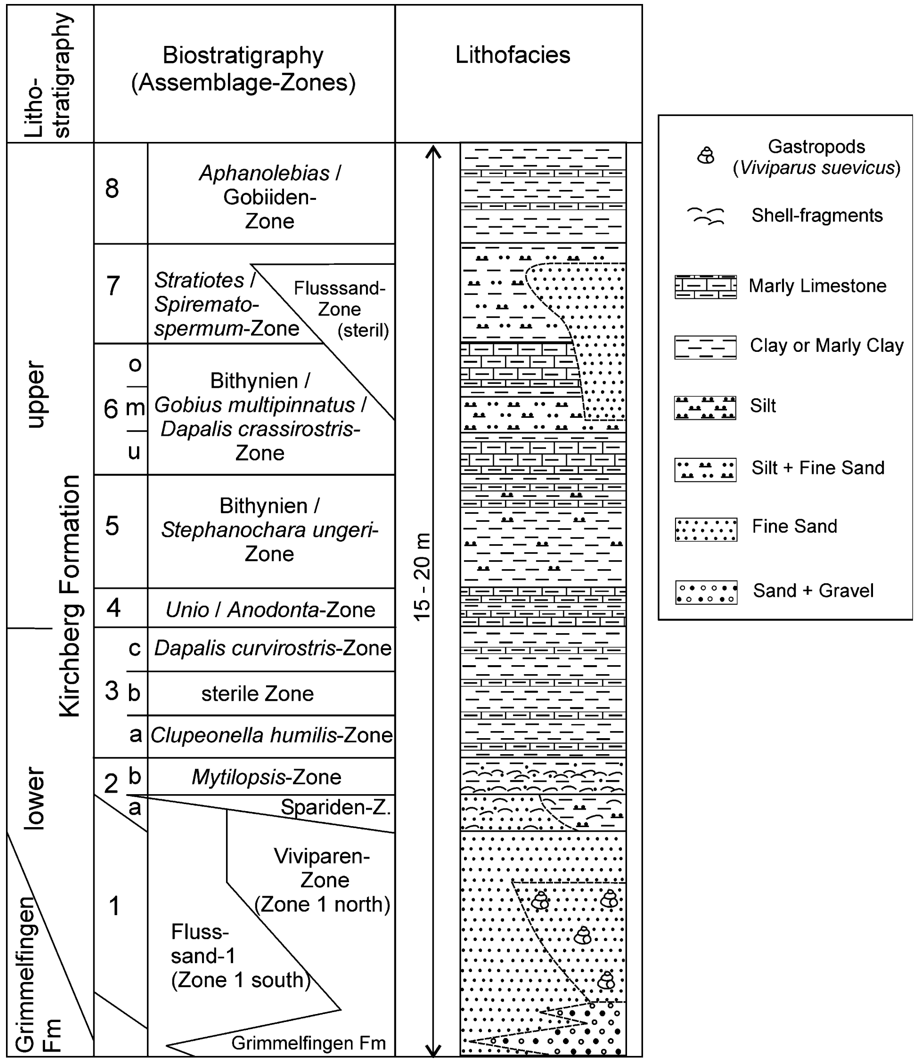

Fig. 2 Lithostratigraphy, biostratigraphy and lithofacies of the Kirchberg Formation at the type section Illerkirchberg. Assemblage-zones 1–8 refer to the biostratigraphic zonation of Reichenbacher (1989), which is based on typical assemblages of bivalves, gastropods, ostracods, charophytes and otoliths; subdivision in lower and upper Kirchberg Fm follows Doppler (2011)

and Kempf 2009). However, these studies imply that biostratigraphically equivalent sediments would be up to 0.8 Myr older in the S-German Molasse Basin in comparison to the Swiss Molasse Basin (Fig. 1).

2 Studied sites

Three sections in Switzerland (Mauensee, Schmiedrued-Dorfbach, Schmiedrued-Pfyffrüti), one in S-Germany (Illerkirchberg) and three cores of boreholes located in S-Germany (Hamlar 1, Druisheim, Gempfing) were studied (Fig. 3). All sections and boreholes straddle the transition interval from the OMM/OBM towards the OSM.

2.1 Section Mauensee (Swiss Molasse Basin)

The Mauensee section (47°10′N, 8°3.6′E) is located in the Molasse Basin of Central Switzerland at the eastern margin of the ancient Napf fan-delta (Fig. 3). It is about 70 m thick and represents one of the best continuously exposed outcrops of the upper part of the St. Gallen Fm (OMM) (Reichenbacher et al. 2005). A 7-m thick conglomerate layer and about 30 m of marine sandstones with some marly intercalations form the lower part of the section. This sequence is overlain by a lacustrine horizon consisting of a fossiliferous mudstone–limestone complex of about 3.7 m thickness that contains freshwater and terrestrial molluscs, otoliths, as well as teeth and bones of small mammals and other vertebrates. The lacustrine horizon can be correlated to the uppermost mammal unit MN 4b and otolith zone OT-M5a (Reichenbacher et al. 2005; Jost et al. 2006). Above the lacustrine horizon lies a thin conglomerate bed (bed 55) that is followed by a 24.5-m thick sequence of marine sandstones with some thin layers of gravels and boulders. The uppermost 5 m of the Mauensee section comprises dark brown marls, mudstones and sandstones

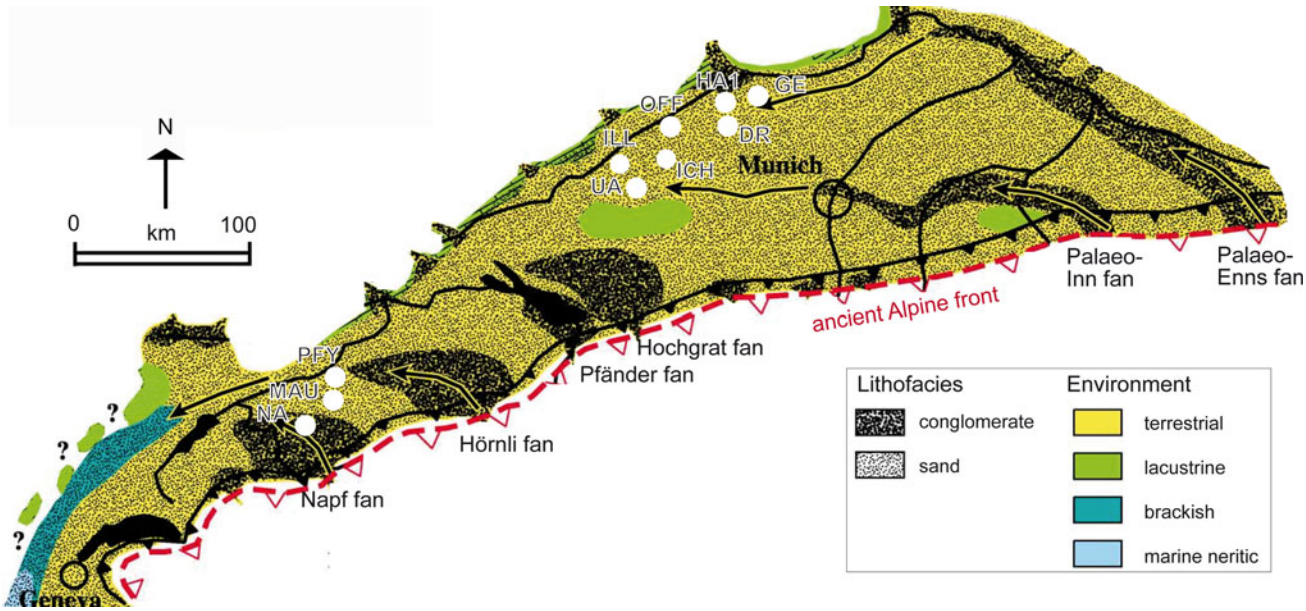

Fig. 3 Palaeogeographic situation at the time period of the Upper Freshwater Molasse (older part) and position of the sections that are important for this study. NA, Napf (Kälin and Kempf 2009); MAU, Mauensee (this study); PFY, Schmiedrued-Pfyffrüti and Schmiedrued-Dorfbach (this study); ILL, Illerkirchberg (this study); UA, Untereichen-Altenstadt (Abdul Aziz et al. 2010), ICH, Ichenhausen (Abdul Aziz et al. 2010), OFF, Offingen (Abdul Aziz et al. 2010), HA1, Hamlar 1 (this study); DR, Druisheim (this study); GE, Gempfing (this study). Map source: Kuhlemann and Kempf (2002)

with freshwater and terrestrial molluscs, representing the basal OSM.

2.2 Section Schmiedrued-Dorfbach (Swiss Molasse Basin)

The section (47°16.064′N, 8°6.499′E) is situated about 15 km to the north of the Mauensee section and located near to the section Schmiedrued-Pfyffrüti (Fig. 3). It exposes a succession of marine sandstones with an intercalated 4 m thick lacustrine horizon (Fig. 4), corresponding in lithofacies and fossil content to the lacustrine horizon of Mauensee (Reichenbacher et al. 2005; Jost et al. 2006). The small mammal fossils and otoliths of the lacustrine horizon are indicative of the uppermost mammal unit MN 4b and otolith zone OT-M5a (Reichenbacher et al. 2005; Graf et al. 2012).

2.3 Section Schmiedrued-Pfyffrüti (Swiss Molasse Basin)

The section Schmiedrued-Pfyffrüti (47°16.495′N, 8°7.021′E) is situated close to the Schmiedrued-Dorfbach section (Fig. 3). The entire section is about 100 m thick and comprises ~57 m marine sediments and ~43 m OSM (Fig. 4). The marine sediments can be correlated with the uppermost OMM of the Schmiedrued-Dorfbach and Mauensee sections by means of lithostratigraphy, i.e. presence of a 10 m thick conglomeratic layer ("Quarzitnagelfluh"), which is a marker horizon within the St. Gallen Fm (Reichenbacher et al. 2005; Graf et al. 2012). The base of the OSM succession at Schmiedrued-Pfyffrüti continues the lowermost OSM exposed in the Mauensee section and yielded three fossiliferous layers at the levels 618, 640, and 642 m (discovered by J. Jost) (see below).

2.4 Section Illerkirchberg (S-German Molasse Basin)

This section (48°19.509′N, 10°0.519′E) is located south of the city of Ulm (Fig. 3). It is the stratotype of the Kirchberg Fm (Strauch 1973) and exposes a fossiliferous, 15–20 m thick alternation of dark brown and grey marls, white or grey marly limestones, blackish organic clays, as well as beige, grey and green fine sands and silts (Kranz 1904; Schlickum 1963; Reichenbacher 1989). The Kirchberg Fm can be subdivided in eight assemblage zones based on typical co-occurrences of bivalves, gastropods, ostracods, charophytes or otoliths; the lower Kirchberg Fm is brackish-marine and comprises the Zones 1–3, and the upper Kirchberg Fm is brackish-lacustrine and includes the Zones 4–8 (Reichenbacher 1989). Based on the presence of otoliths of *Dapalis*, both the lower and upper Kirchberg Fm at Illerkirchberg are corresponding to the otolith zone OT-M4 (Reichenbacher 1999).

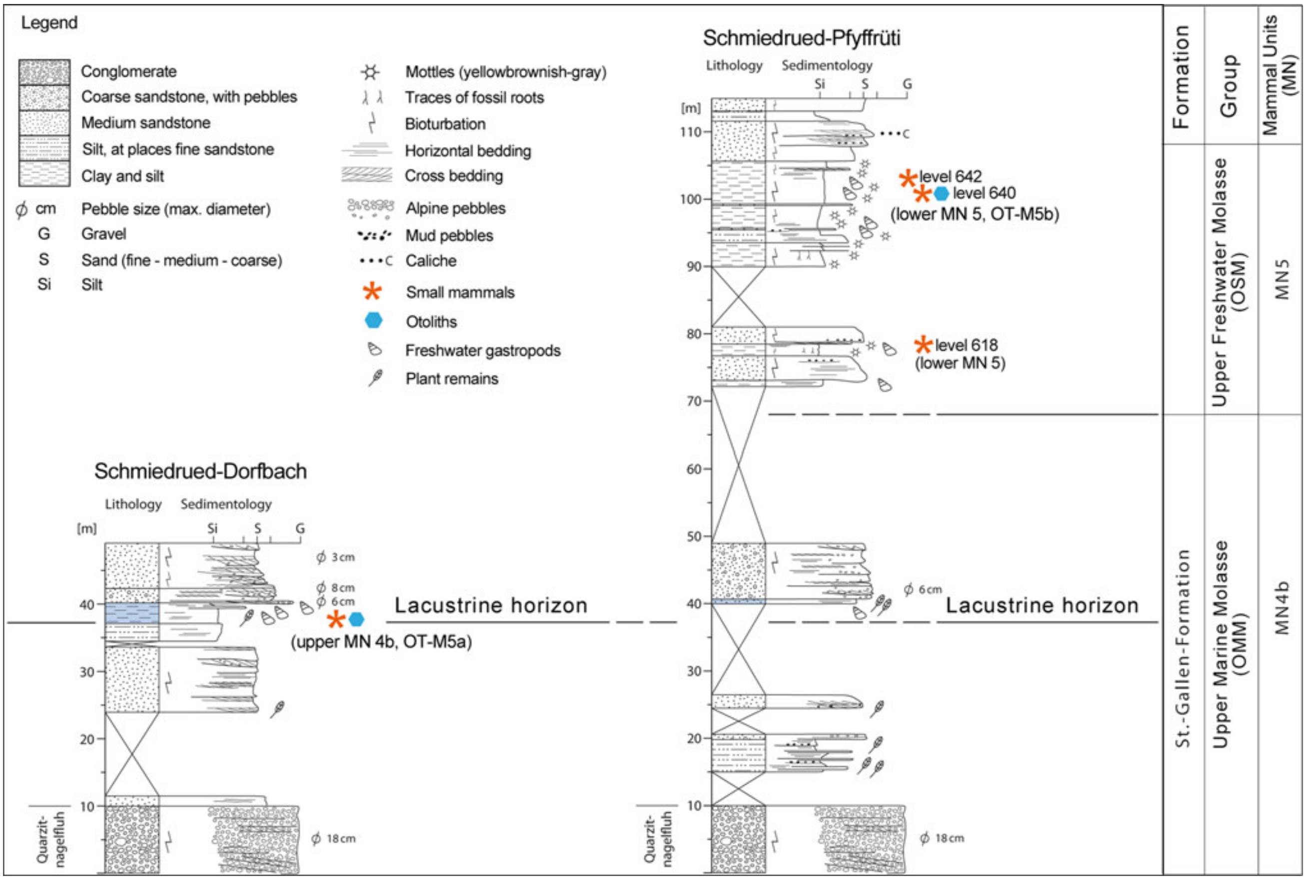

Fig. 4 Lithostratigraphy and lithofacies of the Schmiedrued-Dorfbach and Schmiedrued-Pfyffrüti sections. Modified from Graf et al. (2012)

2.5 Boreholes Hamlar 1, Druisheim and Gempfing

All drillings were conducted in the year 2011. The research drillings Hamlar 1 (48°41.33′N, 10°49.97′E) and Druisheim (48°38.26′N, 10°50.30′E) were located in the region of the river Lech mouth (Fig. 3), SE and SSE of the town of Donauwörth. The drilling of Gempfing (48°41.10′N, 10°59.65′E) was positioned SSW of Burgheim south of the Danube valley (Fig. 3). All cores are stored in the archive of the Bavarian Environment Agency (Landesamt für Umwelt) in Hof.

3 Methods

3.1 Micropalaeontology and biostratigraphy

Core and outcrop samples were processed by soaking in hydrogen peroxide solution for several hours, washing through 63, 200 and 400 µm mesh sieves, and drying at a temperature of 40 °C. Down to a grain size of 400 µm, microfossils were picked completely; smaller grain-sizes were picked from representative splits of the samples. Microfossils and small mammal teeth were identified to species level (as far as possible) and counted. Biostratigraphic interpretations rely on foraminifers and otoliths for core samples, and on teeth of the cricetid *Megacricetodon bavaricus* and otoliths for outcrop samples.

3.2 Magnetostratigraphic sampling

Magnetostratigraphic sampling focused on the fine-grained (clay-silt) intervals of the sections and cores of boreholes; sand and sandstones were generally omitted. The sections could only be sampled at irregular intervals because of difficult outcrop conditions (steep and heavily vegetated slopes). All samples were drilled using an electric drill powered by a generator and using water as coolant, two specimens per site were taken and measured. Since the cores of the three boreholes are taken without orientation, the magnetic inclination has been used for interpretation.

3.3 Paleomagnetic measurements

The natural remanent magnetization (NRM) of the Illerkirchberg section was measured on a vertically oriented 2G

Enterprises DC SQUID cryogenic magnetometer (noise level 10^{-12} Am^2) in a magnetically shielded room at the Niederlippach paleomagnetic laboratory of Ludwig-Maximilians-University Munich, Germany. All the other sections and cores were measured on a horizontally oriented 2G Enterprises DC SQUID cryogenic magnetometer (noise level 3×10^{-12} Am^2) in the paleomagnetic laboratory Fort Hoofddijk of the Utrecht University, The Netherlands. The initial magnetic susceptibility of the samples was measured on a Kappa bridge KLY-2. The characteristic remanent magnetization (ChRM) was determined by thermal (TH) demagnetization, using incremental heating steps of 20 and 30 °C, carried out in a laboratory-built shielded furnace. When available, a second sample was demagnetized using alternating field (AF) demagnetization. To monitor changes in the mineralogical composition, the bulk magnetic susceptibility was measured after each thermal step on a Minikappa KLF-3 (Geofyzika Brno). Induced Remanent Magnetisation (IRM) acquisition curves were constructed on selected samples to investigate the magnetic mineralogy using the IRM-fitting program of Kruiver et al. (2001). Demagnetization results were plotted on orthogonal vector diagrams (Zijderveld 1967) and ChRM directions were calculated using principle component analysis (PCA; Kirschvink 1980).

4 Results

4.1 Results of micropalaeontological and biostratigraphical analysis

For the already known biostratigraphy of the sections Mauensee, Schmiedrued-Dorfbach and Illerkirchberg see above (Sects. 2.1, 2.2, 2.4). As mentioned in Sect. 2.4, the Kirchberg Fm usually contains characteristic assemblages of macro- and microfossils. They allow to identify the Kirchberg Fm in the boreholes and to distinguish lower and upper Kirchberg Fm. The fossil assemblages used here for the recognition of the lower Kirchberg Fm comprise co-occurring marine-euryhaline and brackish species such as the bivalves *Rzehakia partschi*, *Cerastoderma socialis*, *Limnopagetia* sp., *Mytilopsis clavaeformis*, and *M. amygdaloides*; the gastropods *Viviparus suevicus*, *Nematurella convexula*, *N. zilchi*, and *Ctyrokya* spp.; the ostracods *Caspiolla kirchbergensis*, *Candona suevica* and *Mediocypris candonaeformis*, as well as otoliths of the herring-like *Clupeonella humilis* and *C. cornuta*, the ambassids *Dapalis formosus*, *D. curvirostratus*, and the goby *Gobius multipinnatus*, and also the teeth of sparid fishes. Shells and opercula of *Bithynia* spp. that co-occur with the ostracod *Mediocypris candonaeformis*, otoliths of *Gobius multipinnatus* and, more rarely, *Dapalis* spp. characterize the upper Kirchberg Fm, whereas other clearly brackish or marine-euryhaline species do not occur in this unit.

If fossils are absent or scarce, the boundaries Grimmelfingen Fm–lower Kirchberg Fm and upper Kirchberg Fm–OSM are difficult to draw. In these cases we identified the Grimmelfingen Fm based on the occurrence of sands that are carbonate-free to -poor, and recognized the upper boundary of the Kirchberg Fm using the last occurrence of brackish microfossils such as the ostracod *Mediocypris candonaeformis*.

4.1.1 Borehole Hamlar 1

Based on the micropalaeontological analyses of 57 samples combined with lithofacies criteria, the borehole Hamlar 1 can be subdivided as follows (Fig. 5):

8.05–53.5 m OSM
–57.90 m OBM: upper Kirchberg Fm
–70.2 m OBM: lower Kirchberg Fm
–90.65 m OBM: Grimmelfingen Fm
–99.00 m Lower Freshwater Molasse

The 20.45 m thick Grimmelfingen Fm consists of carbonate-free to carbonate-poor, fine to coarse-grained sands and fine gravelled sands. Macro- and microfossils are absent (Fig. 5). Above follow 9 m of fine sands, silts and marls that contain the characteristic fossil assemblages of the lower Kirchberg Fm, including *Mytilopsis clavaeformis*, *M. amygdaloides*, *Cerastoderma sociale*, *Nematurella* spp., and otoliths of *Clupeonella humilis*, *Dapalis formosus* and *Gobius multipinnatus*. The occurrence of *Dapalis* (abundantly present between 62.79–61.24 m) indicates a correlation with the otolith zone OT-M4. This sequence is overlain by a 3 m thick layer of marine, glauconitic sands, containing rare to abundant small-sized benthic foraminiferal assemblages, co-occurring with *Nematurella convexula*; planktonic foraminifers occur only sparsely. The low diversity of the foraminiferal assemblages, the predominance of *Ammonia* (and *Elphidium*) and the presence of the brackish water species *Nematurella convexula* clearly point to a marginal marine shallow environment with unfavourable conditions, such as decreased salinity or salinity fluctuations. The age of the sands is constrained by the presence of the benthic foraminifer *Pappina breviformis* (60.0–60.2 m), which has its first appearance in the middle Ottnangian (Cicha et al. 1998); thus the marine sands cannot be older than middle Ottnangian. Notably, these marine sands represent a particular facies of the lower Kirchberg Fm that had not been found elsewhere so far.

Above occurs a thin limestone bed (0.2 m) and silty to fine sandy sediments (4.2 m) that represent the upper Kirchberg Fm according to the microfossil content (Fig. 5). A continuous transition from the upper Kirchberg Fm to the OSM is indicated by the homogenous silty lithofacies.

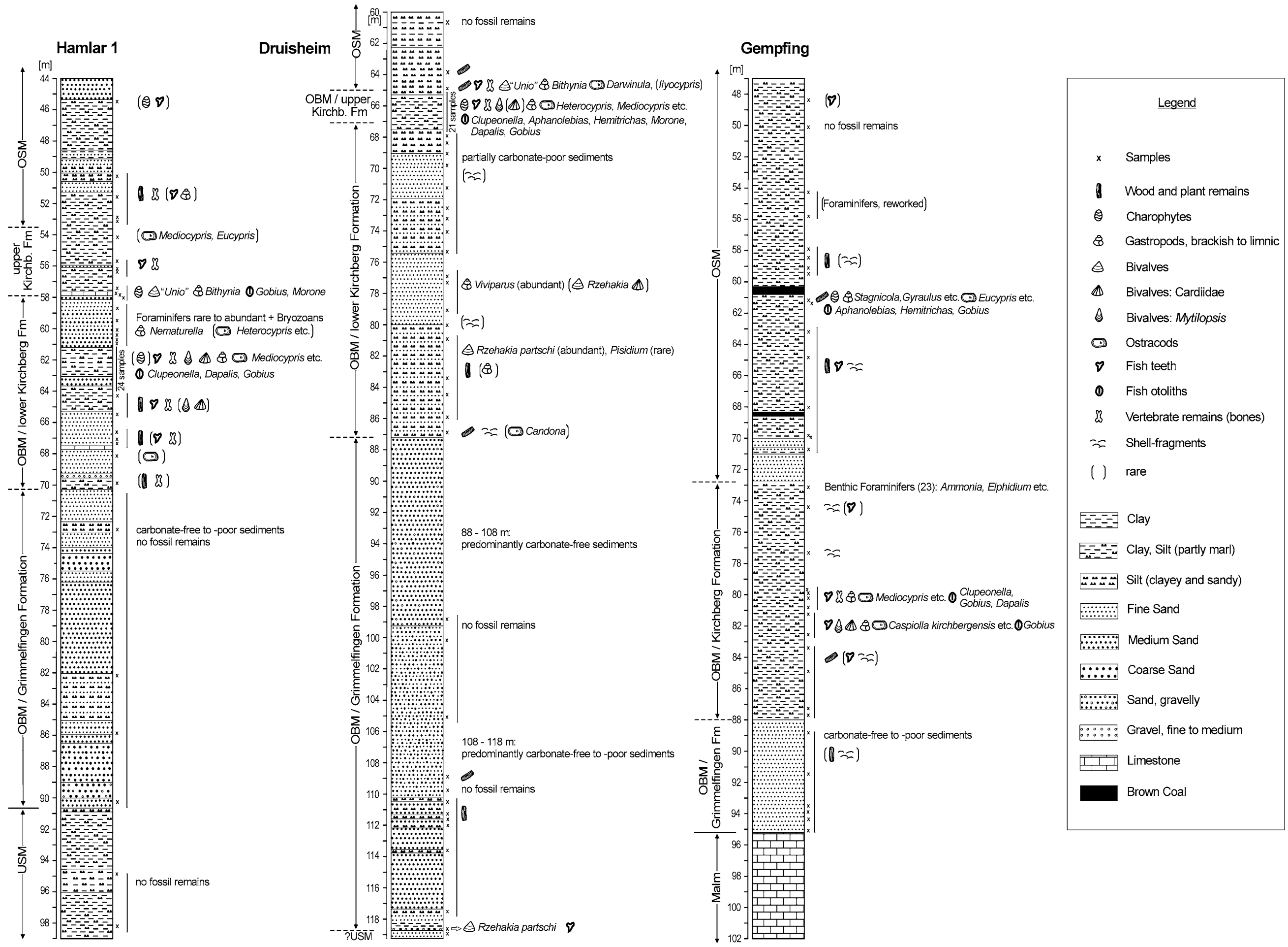

Fig. 5 Lithostratigraphy, lithology and fossil content of the studied boreholes

The boundary to the OSM was drawn based on the last occurrence of *Mediocypris candonaeformis* in sample 54.15–54.25 and the absence of brackish microfossils in the samples above.

4.1.2 Borehole Druisheim

Based on the micropalaeontological analyses of 56 samples combined with lithofacies criteria, the borehole Druisheim can be subdivided as follows (Fig. 5):

9.15–65.00 m OSM
–67.10 m OBM: upper Kirchberg Fm
–87.20 m OBM: lower Kirchberg Fm
–118.70 m OBM: Grimmelfingen Fm
–119.20 m ?Lower Freshwater Molasse

In Druisheim, the basal fossiliferous layer of the Grimmelfingen Fm is present (118.5–118.7 m) and contains abundant and well-preserved *Rzehakia partschi* and teeth of marine fishes (Sparidae) (Fig. 5). The Grimmelfingen Fm reaches a thickness of 31.50 m, the lithofacies is similar as described above for Hamlar 1 (with the exception that the basal fossiliferous layer is only present in Druisheim). The boundary Grimmelfingen Fm–Kirchberg Fm is drawn based on the appearance of *Candona* (86.85–87.0 m) and *R. partschi* (85.90–86.0 m). The sandy lowermost Kirchberg Fm (corresponding to Zone 1) comprises 19.6 m and contains several fossiliferous layers with *R. partschi*, *Viviparus suevicus* and teeth of marine fishes (Sparidae). Above follows an only 0.5 m thick marl that has yielded rich microfossil assemblages indicative for Zones 2 and 3 (lower Kirchberg Fm), with numerous otoliths of *Clupeonella humilis*, *Dapalis formosus*, *D. curvirostris* and *Gobius multipinnatus*; also the bivalve *Mytilopsis amygdaloides*, the gastropods *Nematurella convexula*, *N. zilchi* and *Ctyrokia conoidea* and among the ostracods *Mediocypris candonaeformis* are present (Fig. 5). Then follow 2.1 m marls that yielded, amongst others, otoliths of *G. multipinnatus*, the ostracod *M. candonaeformis* and numerous charophytes and freshwater gastropods; such an assemblage is characteristic for the upper Kirchberg Fm. One sample in the lower Kirchberg Fm (at 67.26–67.31 m) and one in the lowermost upper

Kirchberg Fm (at 66.57–66.15 m) yielded many well-preserved *Dapalis* otoliths and *Nematurella* spp. co-occurring with corroded and fragmented remains of the same taxa. The presence of *Dapalis* (67.57–66.15 m) indicates a correlation of both the lower and upper Kirchberg Fm with the otolith zone OT-M4.

The last occurrence of the ostracod *Mediocypris candonaeformis* was recorded at 65.17–65.22 m. A sample at 64.88–65.0 m yielded opercula of *Bithynia*, the ostracod *Darwinula stevensoni*, teeth of cyprinid fishes, but no clearly brackish fossils. No microfossils were found in the silts above. Accordingly the boundary to the OSM was drawn at 65.0 m.

4.1.3 Borehole Gempfing

Based on the micropalaeontological analyses of 35 samples combined with lithofacies criteria, the borehole Gempfing can be subdivided as follows (Fig. 5):

4.30–72.80 m OSM
–88.00 m OBM: Kirchberg Fm
–95.20 m OBM: Grimmelfingen Fm
–102.00 m Upper Jurassic

The 7.2 m thick Grimmelfingen Fm is composed of carbonate-poor fine sands, macro- and microfossils are absent. The boundary to the Kirchberg Fm was drawn based on a distinct increase in carbonate content at 88.0 m; in addition a few fragments of molluscs and ostracods (not determinable) have been found between 87.4 and 83.4 m (Fig. 5). From 82.65 up to 79.68, the sediments can be assigned to Zones 2 and 3 of the lower Kirchberg Fm based on the brackish microfossil assemblages, which are, however, not as abundant and diverse as seen in Hamlar 1 and Druisheim. *Clupeonella cornuta* and *Gobius multipinnatus* are dominant among the fish otoliths, but *Dapalis formosus* appears as well (79.68–79.88 m). This segment of the borehole Gempfing can be correlated to the otolith zone OT-M4. However, a separation lower/upper Kirchberg Fm is not possible at Gempfing. The last occurrence of *Clupeonella* otoliths (indicative for the lower Kirchberg Fm) is at 79.68 m, but the sandy silts between 79.5 and 73.23 m contain no or indeterminable fossil remains (Fig. 5). At 73.10–73.23 m, some well-preserved, probably autochthonous foraminifers occur, i.e. *Bolivina dilatata* (2 specimens), *Bulimina elongata* (1 spec.), *Elphidium matzenense* (1 spec.), *Protelphidium roemeri* (1 spec.), *Nonion commune* (3 spec.), and *Ammonia beccarii* s. l. (11 spec.). These foraminifers point to a shallow-marine environment. An interesting taxon is *Protelphidium roemeri*, because this species is restricted to the Eggenburgian and Ottnangian (Cicha et al. 1998). Based on the presence of these foraminifers and the lack of other microfossils we interpret the interval between 79.68 and 73.1 m as a facies of the Kirchberg Fm without further specification. We draw the boundary to the OSM at 72.8 based on the transition to sands (see Fig. 5) and the absence of brackish fossils or foraminifers. Samples from the OSM at 61.15–61.25 and 61.20–61.33 yielded a comparatively abundant microfossil assemblage with some freshwater gastropods (*Stagnicola*, *Gyraulus*), ostracods (*Eucypris*, *Heterocypris*, *Darwinula*) and otoliths (*Gobius* sp. juv., *Hemitrichas* cf. *martinii*, *Aphanolebias konradi*). The otolith assemblage is indicative for the otolith zone OT-M5a.

4.1.4 Schmiedrued-Pfyffrüti

Megacricetodon bavaricus has been found in the levels 618 and 640 m of this section, whereas no biostratigraphical useful small mammals were recovered from layer 642. Biostratigraphic age calibrations are possible based on the length and width of the lower first molars (m1) and upper first molars (M1) of this species (Table 1). The measurements show that the size values of the *M. bavaricus* molars from level 640 are clearly higher than those from level 618, but still considerably smaller than the values of faunas indicative for middle MN 5 such as Hüllistein and Vermes 1. *Keramidomys* is missing in both levels, but it is recorded from Oberkulm-Sämlen (reference locality for the *Keramidomys–Megacricetodon bavaricus* overlap zone), located some hundred meters nearby in a comparable lithostratigraphic position (Kälin and Kempf 2009). Thus both the levels 618 and 640 can be correlated with the *Keramidomys–Megacricetodon bavaricus* overlap zone and lower mammal unit MN 5 (see also Sect. 5).

The otolith fauna in level 640 is characterized by abundant otoliths of *Aphanolebias konradi*, whereas *Hemitrichas martinii* is lacking. This is indicative for the otolith zone OT-M5b (Reichenbacher 1999).

4.2 Rock magnetic results

Most IRM acquisition curves are fitted with either two or three components (Online Resource 1). The main part of the curve is commonly fitted using one or two components, which provide information on the origin and character of the magnetic carriers (Fig. 6). A small component categorized as “thermal activation” is commonly necessary to obtain the best mathematical fit, but does not represent a true magnetic carrier. The IRM fitting results indicate that the main magnetic mineral in the Molasse rocks is magnetite, although in some cases hematite is also present.

In the Mauensee section most samples contain magnetite of detrital origin and in some samples hematite is also present. Some samples show low dispersion parameter (DP) values of ~ 0.2, suggesting a biogenic origin. Samples from the Pfyffrüti section mostly show detrital

Table 1 Measurements of lower first molars (m1) and upper first molars (M1) of *Megacricetodon bavaricus* from Schmiedrued-Pfyffrüti

	m1, length	m1, width	M1, length	M1, width
Level 640 m	1.80 (n = 1)	1.08 (n = 1)	1.88 (±0.11) (n = 6)	1.24 (±0.03) (n = 6)
Level 618 m	1.69 (±0.07) (n = 5)	1.00 (±0.04) (n = 5)	1.72 (±0.10) (n = 7)	1.19 (±0.08) (n = 7)

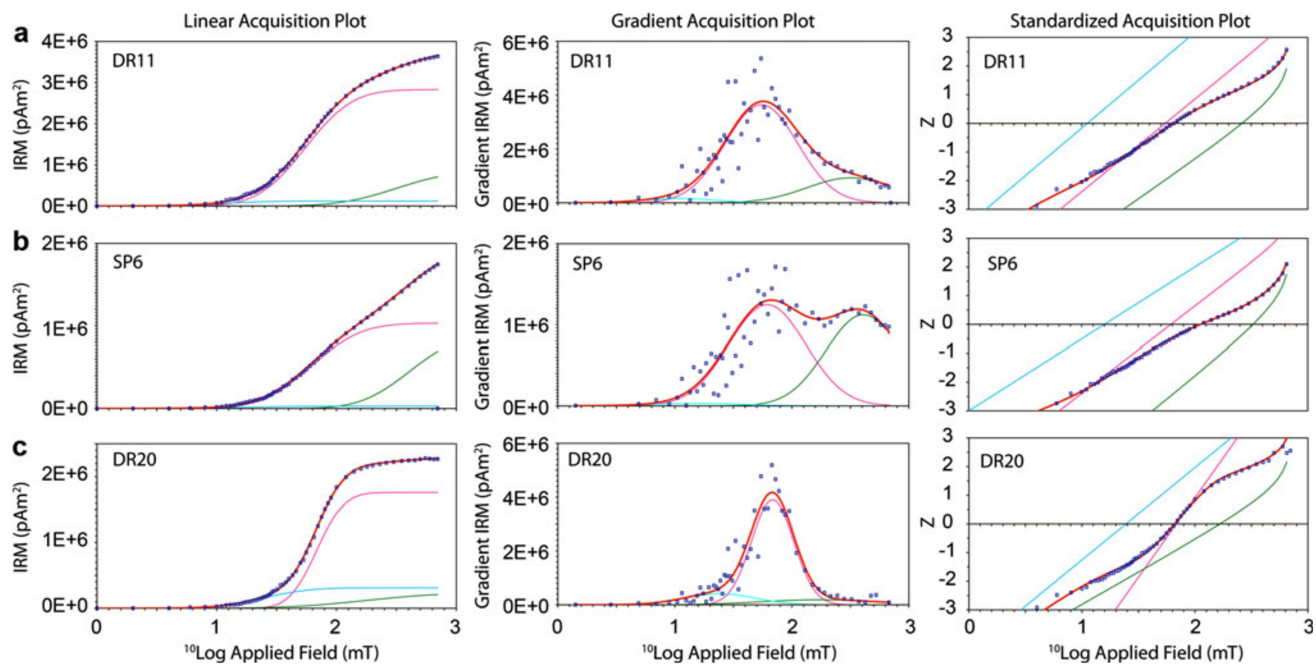

Fig. 6 Representative examples of the IRM component analysis (Kruiver et al. 2001). **a** Druisheim core: wide DP typical for detrital magnetite. **b** Pfyffrüti section: two components, detrital magnetite and hematite. **c** Druisheim core: narrow DP (0.2) typical for biogenic magnetite

magnetite in combination with detrital hematite. In the case of the Hamlar 1 core, the composition of the IRM signal is in all cases dominated by a relatively low coercivity mineral (magnetite) together with a higher coercivity mineral (hematite). DP values are between 0.3 and 0.4, indicating a detrital origin for both. The Druisheim core shows a similar distribution of DP values, however, one sample (DR20) has a rather small DP (0.2) suggesting a biogenic origin. IRM curves of the Gempfing core mainly indicate magnetite as the magnetic carrier. Some samples show low DP values of respectively 0.17 and 0.2, indicating a biogenic origin.

4.3 Demagnetization results

The ChRM directions were calculated using at least four temperature or field steps in the range 210–510 °C and 20–100 mT, respectively. The quality of the measurements and the line fitting were evaluated by visual inspection of Zijderveld diagrams (Fig. 7) and by calculating the maximum angular deviation (MAD). MAD values larger than 15° and/or samples with unconvincing ChRM directions were considered unreliable and are indicated with open circles in Figs. 8, 9 and 10. The declination and inclination results of all sections are plotted in stratigraphic order. For the unoriented Bavarian drill cores only inclination is plotted in stratigraphic order. Non-interpretable and intervals lacking data are represented by grey shaded areas in the polarity record.

The quality of the demagnetisation diagrams allowed a reliable interpretation of the paleomagnetic signal for most samples. Most samples have low NRM intensities, up to 13,000 μA/m. The Zijderveld diagrams of the thermally demagnetized samples reveal the presence of three magnetic components. A first viscous component is removed at 100 °C and a second normal oriented component is removed around 210 °C. The third component is interpreted as the characteristic remanent magnetization (ChRM). Two unblocking temperatures can be distinguished. The majority of the samples have unblocking temperatures between 420 and 510 °C, confirming that iron oxides are the main carrier of the ChRM. Zijderveld diagrams from AF demagnetized samples generally show that most of the NRM is removed at fields of 100 mT, indicating that magnetite is the main carrier of the magnetic signal.

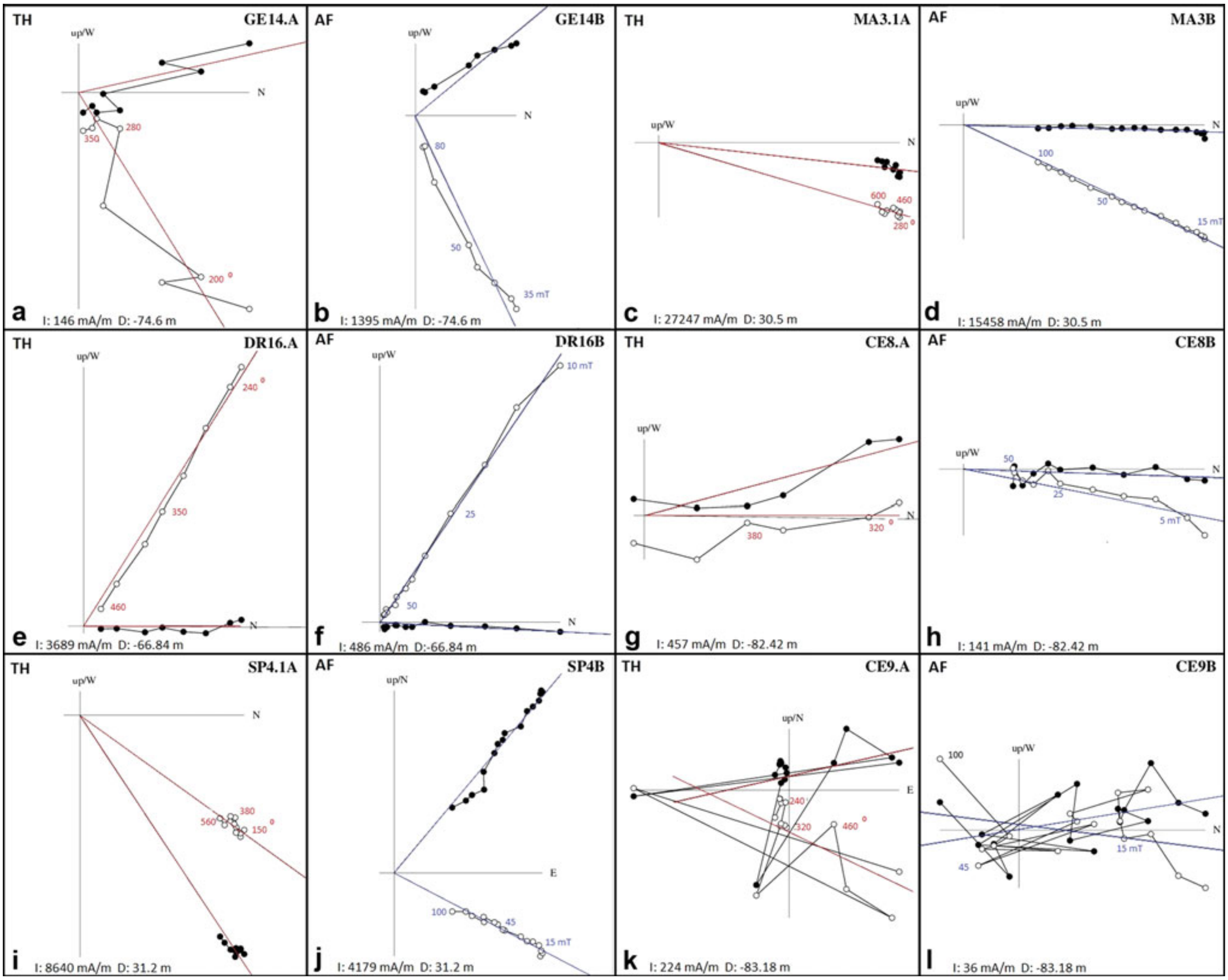

Fig. 7 Thermal (TH/*red*) and alternating field (AF/*blue*) demagnetization diagrams of characteristic samples. Values along the vectors are given in °C (TH) of mT (AF). I, intensity at 280° or at 35 mT; D, depth of sample. **a**–**b** *GE* Gempfing core. **c**–**d** *MA* Mauensee section. **e**–**f** *DR* Druisheim core. **g**–**h** *CE* Hamlar 1 core. **i**–**j** *SP* Schmiedrued-Pfyffrüti section. **k**–**l** *CE* Hamlar 1 core

4.3.1 Sections Mauensee and Schmiedrued-Dorfbach

In the case of the 72 m thick Mauensee section 18 samples were analysed (Fig. 8a). In addition, five levels were sampled at the lacustrine horizon at Schmiedrued-Dorfbach. The intensity ranged from low to medium values up to values of 25,000 μA/m. The samples from the biostratigraphically important lacustrine horizon at Mauensee (at 43 m, Fig. 8a) and Schmiedrued-Dorfbach (data not shown) both yielded normal polarity. Compared to the samples from the boreholes (see below), the samples from Mauensee had a large second magnetic component ranging between 100 and 500 °C (sometimes even as high as 600 °C). The quality inspections showed almost no samples with a poor or unreliable signal. All demagnetized samples show normal polarities.

4.3.2 Section Schmiedrued-Pfyffrüti

18 samples were analyzed for the 35 m thick OSM succession at the Pfyffrüti section. The base of the sampled OSM continues the top of the sampled OSM at the Mauensee section (see Sect. 2.3 for details of correlation). The NRM intensity differs heavily throughout the section between 100 and 6,000 μA/m. In addition, a single temperature interval that reveals the original signal in all the samples could not be defined properly. The analyses of the declination and inclination results reveal that a normal polarity interval is present at the base of this section, then follows a relatively long reversed interval (Fig. 8b).

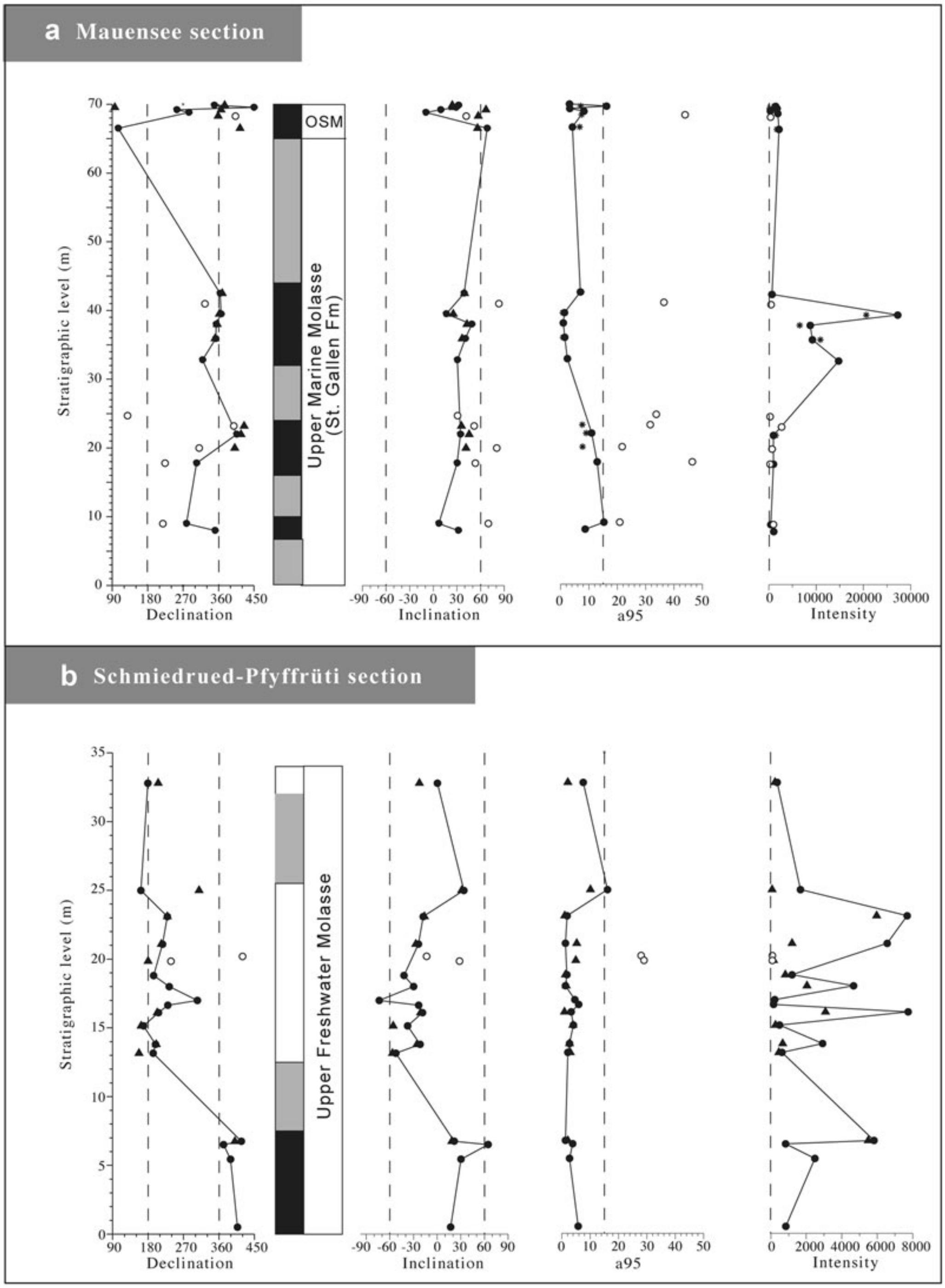

Fig. 8 Palaeomagnetic results of the Mauensee (**a**) and Schmiedrued-Pfyffrüti (**b**) sections. The *black dots* (*triangles*) in the declination, inclination and a95 records represent reliable ChRM directions after thermal (alternating field) demagnetisation, the *white dots* (*triangles*) uncertain directions. In the polarity columns, *black zones* indicate normal, *white zones* reversed and *gray shaded zones* undefined polarity

4.3.3 Section Illerkirchberg

The sampled section corresponds to profile no. 13 in Reichenbacher (1989) and includes layers of the Zones 3c–8 (see Fig. 2). A total number of 32 samples were taken and analysed for magnetostratigraphy. The resultant polarity record is dominantly normal with a reverse interval at the base of the section (Fig. 9). A single reversed sample is situated within the long normal interval.

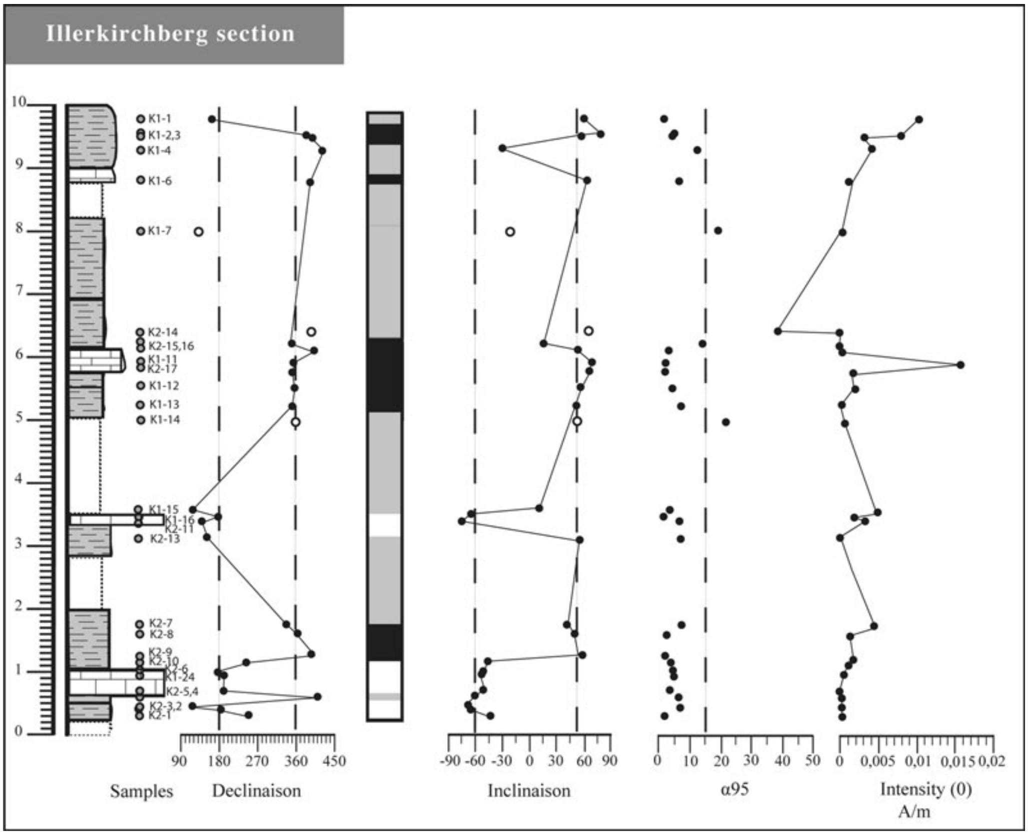

Fig. 9 Palaeomagnetic results of the Illerkirchberg section. For details see caption of Fig. 8

4.3.4 Borehole Hamlar 1

38 samples were drilled and 17 samples could be analysed. The NRM intensity differs heavily with values up to 3,000 µA/m. The Zijderveld diagrams show the original signal between 100 and 380 °C. The analysis of the inclination values reveals that a normal interval is present in the Grimmelfingen Fm, whereas the lower Kirchberg Fm is of reversed polarity (Fig. 10a).

4.3.5 Borehole Druisheim

38 samples were drilled and 21 samples could be analysed for magnetostratigraphy. The NRM intensity values are between 100 and 800 µA/m in most cases, but a few samples have a much larger value up to 5,000 µA/m. The Zijderveld diagrams mostly show three components of which the component between 100 and 380 °C represents the original signal. The signal at higher temperatures becomes more scattered and is interpreted as the formation of secondary magnetite. The analyses reveal a reversed polarity for the lowermost Grimmelfingen Fm, lower Kirchberg Fm and lower part of the upper Kirchberg Fm (Fig. 10b). The OSM dominantly has a normal polarity, but contains a short reversed interval in the upper part.

4.3.6 Borehole Gempfing

46 samples were drilled and 22 samples have been analysed for magnetostratigraphy. The NRM intensity values differ heavily from values of 200–9,000 µA/m. The analysis of the Zijderveld diagrams showed, in most cases, three components of which the first one is removed at about 100 °C. The second component represents the original signal of the sample and is removed around 380 °C. After that the signal becomes more scattered which is related to the formation of secondary magnetite. The data show that the lower segment of the Kirchberg Fm is of reversed polarity. A reversed to normal transition is recorded within the overlying segment of the Kirchberg Fm, the normal interval continues in the lower OSM. Then follow two relatively short reversed and normal polarity intervals (Fig. 10c).

5 Discussion

5.1 Biostratigraphic constraints based on small mammals and otoliths

The biostratigraphy of the here studied Molasse sediments is mainly based on the evolutionary lineage of the cricetid

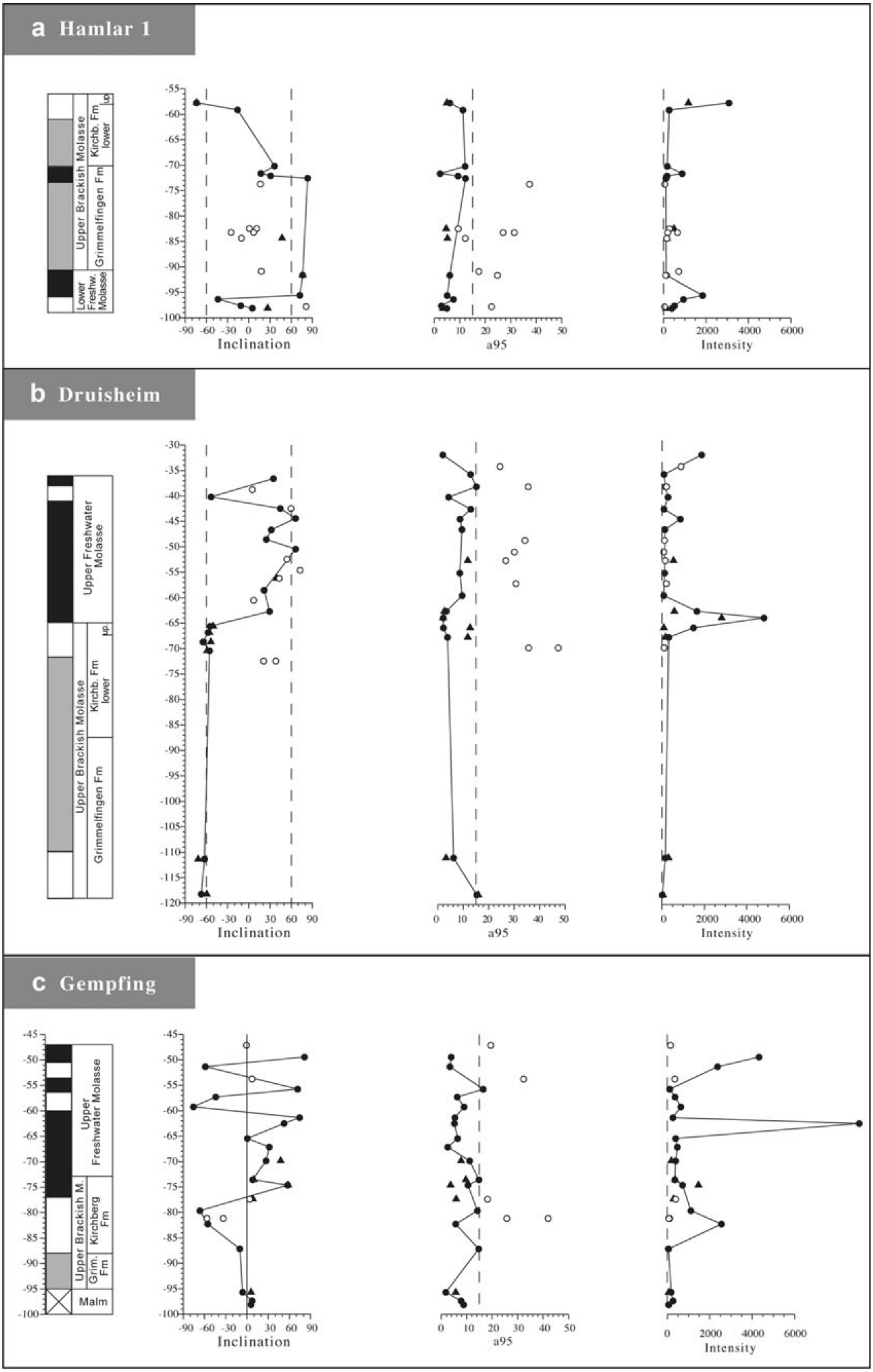

Fig. 10 Palaeomagnetic results of the three studied boreholes Hamlar 1 (**a**), Druisheim (**b**), and Gempfing (**c**). For details see caption of Fig. 8

Megacricetodon; the evolutionary stage of this species is indicated by the length of its lower first molar (Fig. 11). The clear size-evolution seen in this cricetid has been used for the local biozonations in Switzerland and S-Germany (Bolliger 1992, 1994; Heissig 1997; Böhme et al. 2001; Abdul Aziz et al. 2008, 2010; Kälin and Kempf 2009; Prieto et al. 2009). Kälin and Kempf (2009: Fig. 10) suggested a correlation of the local zonations between Switzerland and S-Germany, however, this correlation was based on the assumption that the definition of *Megacricetodon* aff. *bavaricus* (based on the size of its lower first molar) is the same in Switzerland and S-Germany. In the course of this study it became clear that the definition of *Megacricetodon* aff. *bavaricus* is not consistent between Switzerland and S-Germany. The improved correlation is indicated in Figs. 11 and 13.

In addition, otoliths are useful for the biostratigraphic interpretation of the Molasse sediments (Reichenbacher 1999). The here important otolith zones OT-M4 and OT-M5a, b are based on extinction events and soundly calibrated by small mammal data (Reichenbacher 1998, 1999; Reichenbacher et al. 2004, 2005). The extinction event of *Dapalis* defines the upper boundary of OT-M4. Later, the taxon *Hemitrichas* disappears (upper boundary of OT-M5a). These extinctions can be considered as almost isochronous, which is supported by the clear correlation between otolith zones and small mammal units (Reichenbacher et al. 2004, 2005; this study).

5.2 Chronostratigraphic correlation

5.2.1 OBM and lowermost OSM in S-Germany

Summary of polarity pattern. The cores of the boreholes Hamlar 1 and Druisheim provided polarity data of the Grimmelfingen Fm, while polarity data of the Kirchberg Fm are available from all three boreholes and the Illerkirchberg section (Figs. 9, 10 and 12). The data reveal that the lowermost segment of the Grimmelfingen Fm is reverse (Druisheim), while the uppermost part is normal (Hamlar); the polarity of the middle part is not known. The lower Kirchberg Fm is consistently reversed in Gempfing, Druisheim, Hamlar 1, and Illerkirchberg. Reversed polarity is also seen for the lowermost upper

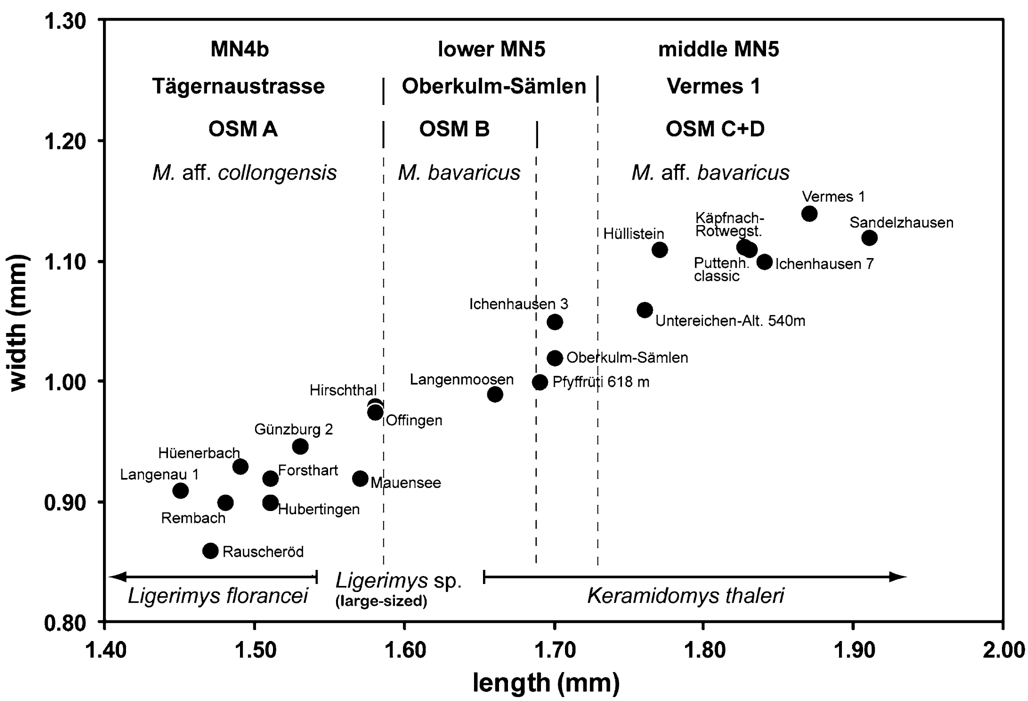

Fig. 11 Length–width diagram of the first lower molar (mean values) of cricetids representing the *Megacricetodon* evolutionary lineage from sites in the Swiss and S-German Molasse Basin. Note that the evolution of the lineage is mainly characterized by increase in molar length. The last occurrences of the eomyids *Ligerimys florancei* and *Ligerimys* sp. and the first occurrence of *Keramidomys thaleri* determine the "boundary" between the mammal units MN 4b and MN 5. Data for Günzburg 2 (n = 13) refer to measurements made by JP (this study) and data for Käpfnach-Rotwegstollen (n = 5) and Schmiedrued-Pfyffrütibach 618 m (n = 5) were conducted by DK (this study). Further small mammal data are from: Fahlbusch (1964) for Langenmoosen (n = 34); Wu (1982) for Puttenhausen classic (n = 17); Ziegler and Fahlbusch (1986) for Rauscheröd (n = 11), Rembach (n = 13), and Forsthart (n = 12); Reichenbacher et al. (2005) for Hubertingen (n = 8), Hüenerbach (n = 5), Mauensee (n = 6), Hirschthal (n = 7), Oberkulm-Sämlen (n = 19), Hüllistein (n = 24), Vermes 1 (n = 18); Wessels and Reumer (2009) for Sandelzhausen (n = 13); Abdul Aziz et al. (2010) for Langenau 1 (n = 12), Offingen 2 (n = 3), Ichenhausen 3 (n = 6), Untereichen-Altenstadt 540 m (n = 6), Ichenhausen 7 (n = 4)

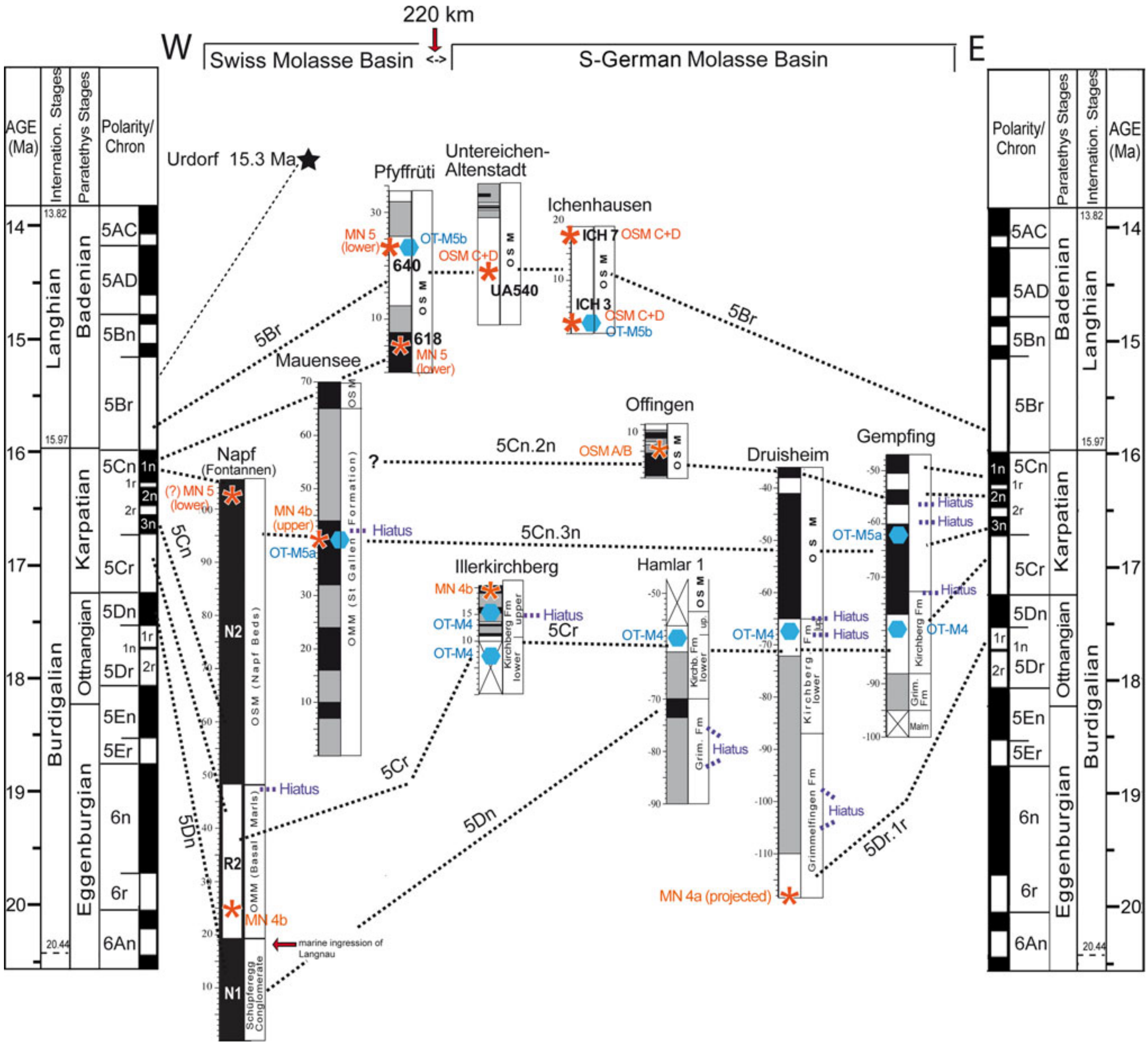

Fig. 12 Interpretation of the magnetostratigraphy of the Upper Marine Molasse (OMM), Upper Brackish Molasse (OBM), and Upper Freshwater Molasse (OSM) in the Swiss and S-German Molasse Basin; polarity pattern of the Napf section according to Kälin and Kempf (2009), polarity pattern of the sections Untereichen-Altenstadt, Ichenhausen and Offingen according to Abdul Aziz et al. (2010). *Black* normal polarity, *white* reversed polarity, *grey* no polarity data, *orange stars/orange lettering*, biostratigraphical data based on small mammal fossils; *blue hexagons/blue lettering*, biostratigraphical data based on otoliths. GTS according to Lourens et al. (2004) and Gradstein et al. (2012)

Kirchberg Fm in Druisheim and Illerkirchberg (note that in Gempfing the boundary between lower and upper Kirchberg Fm could not be determined due to the scarcity of microfossils). The remaining segment of the Kirchberg Fm appears normal at Gempfing and Illerkirchberg, with the exception of a short reversed segment at Illerkirchberg (K1-15, K1-16). This reversed signal corresponds to a hard limestone at the top of Zone 5; currently it is not possible to decide if it indicates a reliable chron or a cryptochron. The normal interval that begins within the upper Kirchberg Fm is most likely the same normal that appears in the lowermost OSM of Druisheim and Gempfing (see Fig. 12 and Sect. 5.2.3).

Possible hiatuses. Based on the co-occurrences of well-preserved and corroded microfossils in the Druisheim samples at 67.26–67.31 and 66.15–66.35 m, it is likely that small hiatuses combined with erosional events interrupted the sedimentation of the Kirchberg Fm. In addition, the normal polarity interval of the upper Kirchberg Fm is not developed at Druisheim. This indicates that the beginning of the OSM sedimentation caused erosion of the uppermost Kirchberg Fm (see Fig. 12).

Interpretation of polarity pattern. The type locality of the Kirchberg Fm is one of the faciostratotypes for the Rzehakia Fm (Čtyroký et al. 1973b). Accordingly, it is late Ottnangian in age. However, the late Ottnangian is characterized by the normal chron 5Dn in the GPTS (Fig. 12), whereas the Kirchberg Fm revealed a reversed chron. Two interpretations are possible: the Kirchberg Fm may correspond to chron 5Cr (early Karpatian) or chron 5Dr.1r (middle Ottnangian). In the first case, the polarity pattern of the Grimmelfingen Fm (that underlies the Kirchberg Fm) would indicate chrons 5Dn and 5Dr.1r (late to middle Ottnangian), while in the second case a correlation to chrons 5Dr.1n and 5Dr.2r (middle to early Ottnangian) would be plausible. Abdul Aziz et al. (2010) suggested the latter correlation based on the interpolation of polarity patterns derived from OSM sections in the S-German Molasse Basin (western Bavaria). However, we propose an alternative correlation and relate the Kirchberg Fm to chron 5Cr and the Grimmelfingen Fm to chrons 5Dn and 5Dr.1r. This correlation appears reasonable because it fits with previously published data of both the middle Ottnangian OMM in S-Germany and the lower Ottnangian OMM in Upper Austria (Pippèrr et al. 2007; Grunert et al. 2010). According to Pippèrr et al. (2007), the base of the middle Ottnangian can be constrained by means of Sr-isotope data, pointing to an age of 17.8 ± 0.3 Ma, and also by small mammal data and otoliths, indicating a correlation to the mammal unit MN 4a and otolith zone OT-M3. This leads to the assumption that the middle Ottnangian OMM was deposited during the time of chron 5Dr, which agrees perfectly with the results of Grunert et al. (2010). These authors studied the stratotype of the Central Paratethys regional stage Ottnangian, i.e. the section Ottnang-Schanze in the Molasse Basin of Upper Austria (see Rögl et al. 1973). The section exposes the uppermost part of the lower Ottnangian OMM and, based on a combination of bio- and magnetostratigraphy, can be related to chron 5Dr.2r and 17.95–18.056 Ma (Grunert et al. 2010). If we would follow the correlation of Abdul Aziz et al. (2010), the lower Grimmelfingen Fm and uppermost lower Ottnangian OMM would represent the same chron (5Dr.2r). This is unlikely because the sedimentation of the middle Ottnangian OMM (most likely during chron 5Dr) and the subsequent erosion event that is indicated by the structure of the Graupensandrinne happened before the deposition of the Grimmelfingen Fm (see Sect. 1.1.2), and no time would be left for their formation. In addition, the mammal faunas at the base of the Grimmelfingen Fm were correlated to MN 4a (Heizmann 1984; Reichenbacher et al. 1998), which also indicates the formation of these beds in the middle Ottnangian (see Pippèrr et al. 2007). Moreover, the Grimmelfingen Fm may represent a rather long time span because discontinuous sedimentation is likely for sediments of a fluvial-estuarine environment. Therefore we suggest correlating the Grimmelfingen Fm with chrons 5Dn and 5Dr.1r and the lower Kirchberg Fm as well as the lowermost part of the upper Kirchberg Fm with 5Cr. Accordingly, the normal polarity of the remaining upper Kirchberg Fm is corresponding to 5Cn.3n. This suggestion is additionally reinforced by the correlation of the polarity patterns of the uppermost OMM and lower OSM in the Swiss Molasse Basin in the studies of Kälin (1997), Kempf et al. (1999) and Kälin and Kempf (2009) (see Sect. 5.2.2).

5.2.2 *OMM in Switzerland/lowermost OSM in S-Germany*

Summary of polarity pattern. The Mauensee section has revealed normal polarity, but several segments could not be sampled either due to unsuitable lithofacies or outcrop conditions (Fig. 8a). Most important is the recognition of normal polarity for the lacustrine horizon, which is an important marker in terms of bio- and lithostratigraphy (see Sects. 2.2 and 2.3).

Possible hiatuses. A thin conglomerate above the lacustrine horizon points to a hiatus linked with erosion (Reichenbacher et al. 2005).

Interpretation of polarity patterns. The lacustrine horizon of Mauensee has yielded small mammals and otoliths that allow the identification of the uppermost mammal unit MN 4b and the otolith zone OT-M5a (Reichenbacher et al. 2005; Jost et al. 2006). The size evolution of the small mammal *Megacricetodon* aff. *collongensis* (see Fig. 11) clearly indicates that the lacustrine horizon of Mauensee is younger than the site Günzburg-2, which represents the lowermost OSM in S-Germany, just above the Kirchberg Fm in S-Germany (Reichenbacher et al. 1998). In addition, the appearance of otolith zone OT-M5 hints to a younger age of the lacustrine horizon of Mauensee in comparison to the Kirchberg Fm, which is characterized by otolith zone OT-M4. Therefore we suggest that the normal polarity of Mauensee belongs to the same normal chron that is seen in the lower OSM of the boreholes Druisheim and Gempfing. This assumption is strongly supported by the presence of the otolith zone OT-M5a not only in the lacustrine horizon of Mauensee, but also in the lower OSM at Gempfing (Fig. 12).

An interesting section that can be used for further comparison is the Fontannen section, which is located in the proximal area of the Napf fan in Switzerland (Fig. 3) and comprises about 900 m conglomerates with a few marly intercalations (Schlunegger et al. 1996; Kälin and Kempf 2009). Its magnetostratigraphy has been examined by Schlunegger et al. (1996) and was recalibrated in Kempf et al. (1997) and Kälin and Kempf (2009). The segment of the "Basal Marls" and the overlying lower part of the Napf Beds (illustrated here in Fig. 12) is important for the correlation of Mauensee. The Basal Marls were deposited shortly after a marine ingression, provided a reversed polarity (R2 in Schlunegger et al. 1996), and yielded small mammal faunas indicative for the mammal unit MN 4b (Kälin and Kempf 2009: Fig. 5A). The lowermost Napf Beds display normal polarity (N2 in Schlunegger et al. 1996) and contain the small mammal fauna of the locality Unter Spitz that is assigned with question mark to lower MN 5 (Kälin and Kempf 2009: Fig. 5A). Schlunegger et al. (1996) correlated the reversed Basal Marls of the Fontannen section to chron 5Cn.1r, but this correlation was based on the assumption that the small mammals in the Basal Marls should be assigned to the mammal unit MN 5 (rather than to MN 4b, as indicated in Kälin and Kempf 2009). Kempf et al. (1997) re-calibrated the polarity and mammal data of the Fontannen section and correlated R2 to chron 5Cr, and N2 to all chrons (normal and reversed) of 5Cn. This interpretation has been sustained in Kälin and Kempf (2009). In addition, Kälin and Kempf (2009) assumed that a hiatus is present within the Basal Marls, and that this hiatus is responsible for the comparatively short reversed segment (R2) in the Fontannen section. Furthermore, the authors found evidence for a second hiatus at the uppermost part of the N2 segment in the Fontannen section (not indicated in Fig. 12 because the N2 segment is not shown completely).

The small mammals of the lacustrine horizon of Mauensee indicate the mammal unit upper MN 4b and thus a slightly older age of the respective normal segment in comparison to the normal segment of the Fontannen section (that has revealed the small mammals of Unter Spitz, ?lower MN 5). Furthermore, the size evolution of *Megacricetodon* aff. *collongensis* shows that the Mauensee small mammals are younger than the small mammals from the Hüenerbach site in the (reversed) Basal Marls (Reichenbacher et al. 2005: Fig. 3; see here Fig. 11). As a result, the normal polarity of the lacustrine horizon at Mauensee most likely corresponds to the lower part of the N2 segment of the Fontannen section. Based on our assumption that this normal polarity interval is the same that is seen in the lowermost OSM of S-Germany (positioned above the reversed interval of the Kirchberg Fm that we correlate here with chron 5Cr), a correlation with chron 5Cn.3n is suggested, which is not in conflict with the interpretation of Kempf et al. (1997) and Kälin and Kempf (2009).

5.2.3 OSM in Switzerland and S-Germany

Summary of polarity pattern. The lowermost OSM of the studied Schmiedrued-Pfyffrüti section shows normal polarity, which compares well with the normal polarities of the lowermost OSM in the Mauensee section; then follows a transition to a relatively long reversed interval (Fig. 12). In the OSM of Druisheim a short reversed interval follows above the normal interval of the lowermost OSM, whereas two short reversed intervals follow above the normal interval in Gempfing (Fig. 12).

Possible hiatuses. The OSM of Pfyffrüti is most likely a continuous succession, which is indicated by the homogenous marly-silty-sandy lithofacies, often showing the typical orange mottles that are indicative for some pedogenetic overprint, and additionally supported by the superposition of two mammal sites that are similar in age (Graf et al. 2012; this study). At Druisheim, a hiatus at the base of the OSM is likely because the upper part of the Kirchberg Fm is missing (see above). The remaining OSM of Druisheim consists of a homogenous marly-silty lithofacies without any signs of reworking or abrupt changes in bedding or colour. Therefore we consider this part of the OSM of Druisheim as a continuous succession and not affected by hiatuses. A homogenous marly-silty lithofacies is also present in Gempfing, however abrupt changes in colour (but no reworking) may indicate a hiatus at the top of the long normal polarity interval (at 60 m) and another one at the top of the first short reversed interval (at 56.5 m).

Interpretation of polarity patterns. The previously studied sections Untereichen-Altenstadt (UA) and Ichenhausen (Ich) comprise a relatively long reversed interval and all have yielded small mammal data (sites Ich 3, Ich 7, UA 540; Abdul Aziz et al. 2010). As mentioned above, the evolutionary stage of *Megacricetodon bavaricus* is mainly indicated by the length of the lower first molar (Fig. 11). The sites Ich 3 and Pfyffrüti 618 revealed very similar molar lengths of this small mammal, while the molar lengths from the sites UA 540 and Ich 7 are larger (see Fig. 11). Accordingly, the OSM sections containing Ich 3 and Pfyffrüti can be interpreted as time-equivalents, while the overlying OSM (with UA 540 and Ich 7) is younger. It is important to mention that the up to 20-m thick OSM segment at Pfyffrüti, Ichenhausen and Untereichen-Altenstadt (that is continuously reversed polarized; see Fig. 12) displays a fine-grained marly and silty lithofacies with some pedogenetic overprint (Prieto et al. 2009; Abdul Aziz et al. 2010; Graf et al. 2012; this study). This indicates continuous sedimentation, no major gaps and low sedimentation rates. Thus, both lithofacies characters and clear evolution of *M. bavaricus* indicate that this reversed segment of the OSM represents a significant time span, which is in agreement with Abdul Aziz et al. (2010) (for Ichenhausen and Untereichen-Altenstadt). Abdul Aziz et al. (2010) suggested a correlation of this segment to chron 5Cr, which appeared to be supported by the Ar–Ar ages of the Zahling-2 (16.1 ± 0.2 Ma) and Krumbad bentonites

(15.6 ± 0.4) (Abdul Aziz et al. 2010: Fig. 14). However, the lithostratigraphic correlation of these bentonites is not unambiguous because they are not positioned in the magnetostratigraphically and biostratigraphically sampled sections, and, moreover, their ages might be too old as indicated by new analyses based on Ur-Pb ages (unpublished data of M. Böhme and A. Rocholl).

For further comparison, the distal Zürich profile (sensu Kälin and Kempf 2009) in the Swiss Molasse Basin is interesting. It includes a reversed segment that contains the small mammal site Käpfnach-Rotwegstollen (middle MN 5); a short normal chron follows a few metres above (Kälin and Kempf 2009: Fig. 5B). The *M. bavaricus* evolutionary stage at Käpfnach-Rotwegstollen is biostratigraphically close to Ich 7 (see Fig. 11). The correlation of the reversed segment (containing the mammal site Käpfnach-Rotwegstollen) to the top of chron 5Cr is apparently a mistake in the figure 6 of Kälin and Kempf (2009), because in the synthetic figure 8 of the same paper, the authors correlate the middle MN 5 to chrons 5Cn.1n and 5Br. This latter correlation is supported by lithostratigraphic data and radiometric (U–Pb) ages because the marker horizon “Meilen Limestone” appears about 60 m above the Käpfnach-Rotwegstollen site, and this limestone is known to occur about 50 m below the Urdorf bentonite (15.27 ± 0.12 Ma) (Kälin and Kempf 2009).

Here we suggest that the reversed interval of Pfyffrüti, Untereichen-Altenstadt, Ichenhausen and the Zürich profile discussed above can be correlated with chron 5Br (see Fig. 12). A younger age is unlikely because the Urdorf bentonite (15.27 ± 0.12 Ma) is known in superposition. It is also unlikely that the long time span that is apparently represented in these distal sections can be correlated with one of the short reversed chrons of 5Cn. Moreover, we consider it as unlikely that it represents chron 5Cr because this would cause serious problems for the known age constraints of the OMM (see Sect. 5.2.2).

Our interpretation, however, also results in an alternative correlation of the Offingen section, considered in Abdul Aziz et al. (2010) as representing chron 5Dn and a small segment of 5Cr. *Megacricetodon* from Offingen is transitional between mammal units OSM A and OSM B, clearly older than *Megacricetodon* from Pfyffrüti/level 618 m, but slightly younger than *Megacricetodon* from the lacustrine horizon at Mauensee (see Fig. 11). Therefore Offingen is parallelized here to the short chrons of 5Cn.2n and 5Cn.1r (Fig. 12).

The OSM at Druisheim and Gempfing is constrained by lithostratigraphic data because it overlies the Kirchberg Fm. The lithofacies indicates continuous sedimentation for Druisheim, but possible gaps at Gempfing. As a result, the short reversed interval at the top of the long normal interval in the OSM of Druisheim may refer to chron 5Cn.2r, and the two short reversed intervals at Gempfing may correspond to chron 5Cn.2r and 5Cn.1r.

5.3 Implications for Paratethys stratigraphy: the Ottnangian/Karpatian boundary

The most surprising aspect of our interpretation is that the Kirchberg Fm, traditionally considered as late Ottnangian in age, now correlates with the time interval of the early Karpatian (chron 5Cr; see Figs. 12, 13).

The previous assumption of late Ottnangian age for the Kirchberg Fm is mainly based on:

1. The type locality of the Kirchberg Fm (Illerkirchberg) was selected as a facio-stratotype of the Central Paratethys Rzehakia Fm based on a typical mollusc assemblage that is found in all successions of the Rzehakia Fm in the Central Paratethys, but not known from stratigraphically older or younger deposits; characteristic elements are *Rzehakia* spp., *Cerastoderma* spp., *Nematurella* spp. and others (Čtyroký et al. 1973a, b).
2. The Kirchberg Fm at the type locality and at several other locations in S-Germany yields a fish fauna that compares well (with several identical species) with those of the Rzehakia Fm in the Carpathian Foredeep (Ivancice, S-Moravia); characteristic taxa are *Dapalis formosus*, *Gobius multipinnatus*, *Morone* spp. (Weiler 1966; Martini 1983; Reichenbacher 1988, 1993). Stratigraphically important is the absence of any species of *Dapalis* from deposits younger than the Kirchberg Fm (Reichenbacher 1993, 1998; Böhme and Reichenbacher 2003; Jost et al. 2006).
3. The Kirchberg Fm shares the typical mollusc fauna with the Oncophora (Rzehakia) Beds in the Southeast German and the Upper Austrian Molasse Basin. These beds are positioned without unconformity above the middle Ottnangian segment of the OMM (Wittmann 1957; Schlickum 1964; Rupp and van Husen 2007). The OSM deposits directly above the Oncophora Beds in Rauscheröd, Rembach and Forsthart have yielded small mammals indicative for the mammal unit MN 4b (Ziegler and Fahlbusch 1986; see here Fig. 11), which at that time was considered to correlate with the late Ottnangian.

However, the precise stratigraphic equivalency of the different members of the Rzehakia Fm throughout the Central Paratethys is not well supported (Čtyroký et al. 1973a, b). Only in the South-eastern German and Upper Austrian Molasse Basin do the brackish deposits with the typical *Rzehakia* species concordantly overlie middle Ottnangian strata. In the Vienna Basin, no brackish facies and no *Rzehakia* appear above the marine Ottnangian (Kováč

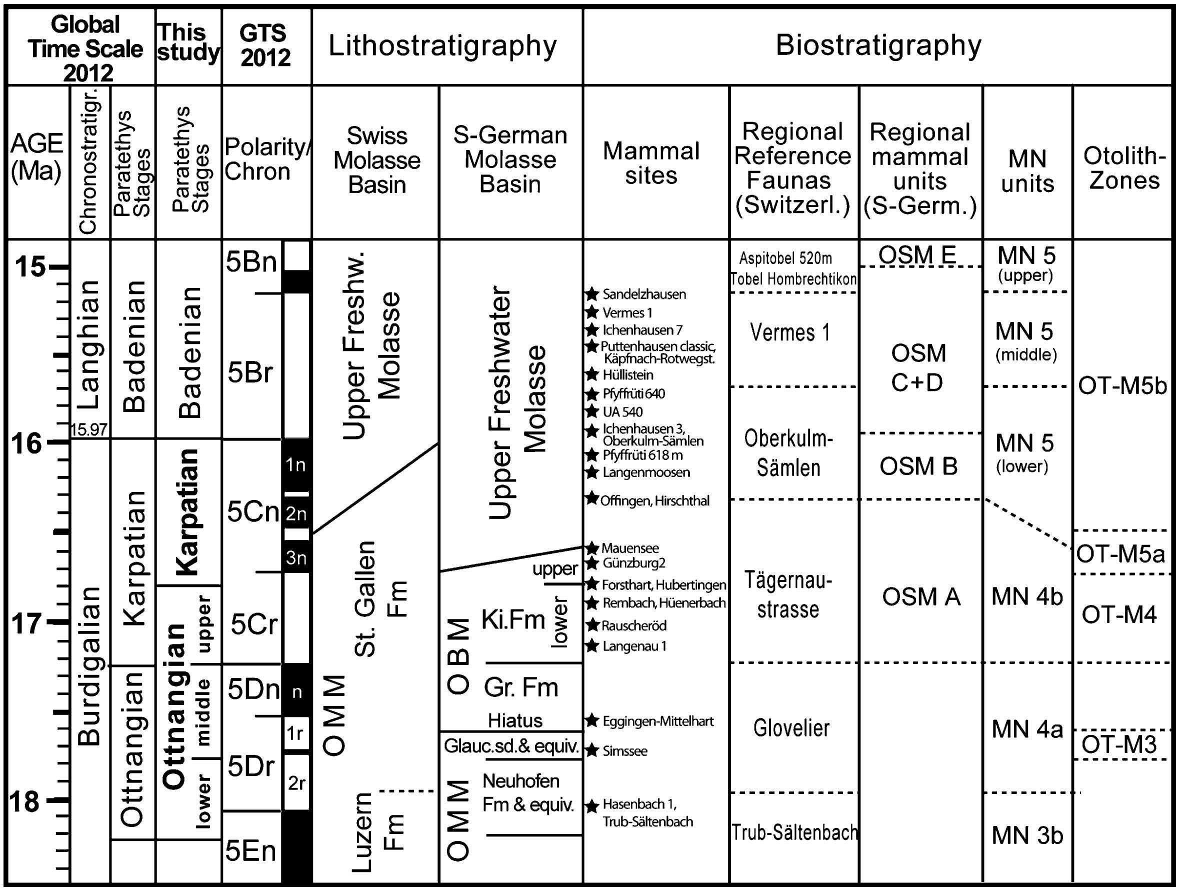

Fig. 13 New magnetostratigraphic framework and biostratigraphic correlation in the Swiss and S-German Molasse Basin and possible shift of the Ottnangian-Karpatian boundary (GTS according to Lourens et al. 2004; Gradstein et al. 2012). Note that the position of the MN4b/MN5 "boundary" varies, depending if it is set at the last occurrence of *Ligerimys* sp. or the last occurrence of *Ligerimys florancei* (see also Fig. 11). Note also that the correlation between the Swiss reference faunas and the OSM units is different from Kälin and Kempf (2009) (see Sect. 5.1. for details). OMM, Upper Marine Molasse; Glauc.sd., Glaukonitsande and Blättermergel; OBM, Upper Brackish Molasse; Gr.Fm, Grimmelfingen Formation; Ki. Fm, Kirchberg Formation. See Sect. 5.1 and captions of Figs. 1 and 11 for further references

et al. 2004). The faciostratotype Ivancice and other sections in the Carpathian Foredeep of southern Moravia are located above crystalline basement rocks, and in other areas of the Central Paratethys the Rzehakia Fm overlies Eggenburgian sediments (Čtyroký et al. 1973a, b). Thus it is possible that the facies characterized by *Rzehakia* and co-occuring molluscs such as *Nematurella* and *Limnopagetia* developed locally and indicate a brackish facies during the early/middle/late Ottnangian rather than a precise late Ottnangian age. Moreover, in those areas where the marine transgression of the Karpatian did not take place, such as in the S-German Molasse Basin or in the Slovak Neogene Basins, the facies characterized by *Rzehakia* may have extended until the Karpatian (Čtyroký et al. 1973a, b; Holcová 2003). Further evidence for this hypothesis is provided by the observation that the land snail *Cepaea silvana* (indicative for the post-Ottnangian period in S-Germany) appears in the uppermost Kirchberg Fm (Schlickum 1963; Reichenbacher 1989). In contrast, this species is lacking in the Oncophora Beds, where it is replaced by its ancestor *Cepaea brandti* (Schlickum 1964).

Notably, the previous speculations of a Karpatian age of the Kirchberg Fm refer exclusively to its uppermost part. The lower Kirchberg Fm (Zones 1–3) with its typical brackish mollusc and fish fauna clearly represent the character of other brackish Ottnangian faunas in the Central Paratethys, regardless whether they are early, middle or late Ottnangian in age. Also the foraminifers found in the Kirchberg Fm of Gempfing clearly support an age that it not younger than Ottnangian (see Sect. 4.1.3). Therefore it is possible that the Ottnangian-Karpatian boundary should be drawn at the top of the lower Kirchberg Fm and in the uppermost part of the 5Cr chron, at c. 16.8 Ma (Fig. 13). However, the current state of knowledge only allows suggesting that such a shift in the boundary might be necessary in the future, when new data are available.

5.4 Implications for Paratethys stratigraphy: The Karpatian

Following the original definition by Cicha et al. (1967), the (1) Karpatian is a time span of the Miocene between the terminal beds of the Helvetian [Ottnangian] and the global first appearance of the Orbulines [*Praeorbulina*], (2) the Karpatian overlies at its stratotype [at Slup in the Carpathian Foredeep] the brackish Rzehakia Beds, (3) the Karpatian mollusc, foraminiferal, ostracod and otolith fauna is different from those of the Burdigalian-Helvetian [Eggenburgian-Ottnangian] and includes mostly species that are also typical for younger Miocene strata (see also Cicha and Rögl 2003). In addition, Cicha and Rögl (2003) state that the benthic foraminifer *Uvigerina graciliformis* appears at the base of the Karpatian. However, this foraminifer only occurs in deep-marine facies, but lower Karpatian sediments of deep-neritic facies are not known (see also Rögl et al. 2003).

In the Carpathian Foredeep, in the Vienna Basin, and in the easternmost Austrian Molasse Basin the Karpatian is linked with a new transgression from the Mediterranean Sea via the "Trans Dinaride Corridor" somewhere in Slovenia or northern Croatia and is characterized by new elements in the marine fauna (Kováč et al. 2003). In contrast, no marine Karpatian is present in the S-German and Upper Austrian Molasse Basin (Doppler et al. 2005; Rupp and van Husen 2007; Kälin and Kempf 2009).

A conspicuous characteristic of the Karpatian transgression is that it usually appears above a hiatus so that no boundary stratotype can be identified for its lower boundary (Cicha and Rögl 2003; Rögl et al. 2003). In addition, records of marine "lower Karpatian" sediments are not unambiguously supported. For example, the "lower Karpatian" successions from the Vienna Basin (Kováč et al. 2004) are not supported by biostratigraphy data and could also represent the Ottnangian. Furthermore, there is no complete magnetostratigraphic record from the Paratethys area of the chron 5Cr, corresponding to the "lower Karpatian"; only the borehole Nosislav-3 (Carpathian Foredeep) probably includes the upper part of this chron (Rögl et al. 2003). The lack of a complete record of chron 5Cr was thought to result from a large hiatus at the Ottnangian/Karpatian boundary and in the lower Karpatian due to the tectonic reorganisations (Kováč et al. 2003, 2004; Rögl et al. 2003). Consequently, a future position of the Ottnangian/Karpatian boundary at 16.8 Ma (instead of at 17.2 Ma) would not be problematic. In this case, the time span of the upper Ottnangian, mainly represented by the Kirchberg Fm, would just fill (at least partially) the assumed sedimentation gap within the chron 5Cr.

6 Conclusions

The herein suggested alternative magnetostratigraphic correlation indicates that the lower Kirchberg Fm and lowermost part of the upper Kirchberg Fm can be correlated to chron 5Cr, which represents the early Karpatian in the current Global Time Scale (Fig. 13). The lower Kirchberg Fm (Zones 1–3) is characterized by faunal elements that are typical for the Ottnangian. Consequently, our results implicate that the Ottnangian-Karpatian boundary in the Molasse Basin should be drawn at the top of the lower Kirchberg Fm and thus in the uppermost part of chron 5C, at circa 16.8 Ma (Fig. 13). This would result in a considerably shorter time span of the Karpatian, i.e. lasting from 16.0 to 16.8 Ma rather than from 16.0 to 17.2 Ma, and the duration of the lower Karpatian hiatus would be shorter than previously assumed. However, further studies are necessary in order to test our alternative correlation and it is not our intention to re-define here this shift of the upper Ottnangian based on the present state of knowledge.

According to our new interpretation, the OMM-OSM changeover was completed at circa 16.0 Ma in the Swiss Molasse Basin, while the OBM-OSM transition ended at 16.6 Ma in the S-German Molasse Basin (Fig. 13). Due to the fluvial dominated sedimentation regime of the OSM, the contact of the OSM base can be erosive both in the Swiss and S-German Molasse Basin. The normal polarity of the lower OSM in S-Germany and the upper Kirchberg Fm correlates best to chron 5Cn.3n. Accordingly, the relatively long reversed intervals of Pfyffrüti, Untereichen-Altenstadt and Ichenhausen, which have revealed comparable biostratigrapic ages, correspond to chron 5Br.

The here suggested correlation is different from a previous correlation presented in Abdul Aziz et al. (2010). If we would apply this correlation to our new data the normal segments of Pfyffrüti and Mauensee would correspond to chron 5Dn (late Ottnangian), the Kirchberg Fm would represent chron 5D.1r, and the Grimmelfingen Fm chrons 5Dr.1n and 5Dr.2r. We consider this as unlikely because previous biostratigraphic studies do not support such "old" ages. Eventually, our new correlation is not in conflict with the magnetostratigraphic framework of the OSM and upper OMM presented in Kälin and Kempf (2009); the main difference refers to the upper boundary of the regional reference fauna Oberkulm-Sämlen and lower MN 5, respectively, which is now 0.5 Myr younger and positioned at 15.7 Ma (Fig. 13).

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