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A biochronologic tie-point for the base of the Tortonian stage in European terrestrial settings: Magnetostratigraphy of the topmost Upper Freshwater Molasse sediments of the North Alpine Foreland Basin in Bavaria (Germany)

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With 8 figures and 2 tables

Abstract. Chronostratigraphic correlation and dating of terrestrial, especially mammal bearing, sediments of the European Neogene are still problematic and highly debated. In particular, absolute ages for important vertebrate assemblages are often not available making correlation during the continental Miocene across Europe so ambiguous. Here we present a detailed magnetostratigraphic study on a paleontological key section of the Middle to Late Miocene transition in the North Alpine Foreland Basin (NAFB) in Bavaria (Hammerschmiede) and a neighboring drill core, which has a total length of 150.4 m and includes, stratigraphically, the fossil site. We identify three complete normal polarity intervals, which have been correlated based on biochronologic constraints to chrons C5An.1n, C5r.2n and C5r.2r-1n. At least two major hiatuses probably occurred within the interjacent reversed chrons, for which geological indications are present and might be relatable to isochronic features in the Vienna basin. Inferred upper limits of the accumulation rate vary between 10 and 30 cm/kyr. This correlation determines the age of the Hammerschmiede vertebrate level HAM 5 to be about 11.62 Ma, making it an ideal biochronologic tie-point for the base of the Tortonian and Pannonian stages in terrestrial settings. Additionally, we date the youngest freshwater molasse lithostratigraphic unit of the Bavarian part of the NAFB, the *Obere Serie*, to between 13.8 and 11.1 Ma. Following our correlation, the lack of hipparion horses in the Bavarian part of the NAFB has stratigraphic rather than ecologic reasons and the '*Hipparion* datum' seems to be a single bio-event at 11.1 Ma in Western Eurasia.

Key words. Magnetostratigraphy, Miocene, North Alpine Foreland Basin, Hipparion-datum event

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1. Introduction

Chronostratigraphy of continental sediments is complicated because global chronostratigraphic stage boundaries are usually defined in marine settings (Gradstein et al. 2012). It is therefore important to provide a robust continental biostratigraphy with range-zones that are either geochronologically dated or stratigraphically correlated to marine sediments. Since the latter is rarely feasible, independent dating methods have to be applied. For a long time it was assumed that the Middle-to-Late Miocene boundary, e.g., the base of the Tortonian stage (11.625 Ma, Hüsing et al. 2007), coincides with the immigration of hipparionin horses from North America into Eurasia (Bernor et al. 1988). However, it is becoming more evident that the '*Hipparion* datum' actually postdates the base of the Tortonian (Sen 1990, Garcés et al. 2003) by about 400 kyrs and is now estimated at 11.2 Ma (Vasiliev et al. 2011). As a consequence, the Middle-to-Late Miocene boundary can no longer be defined by terrestrial fossils. To better characterize this boundary in European continental settings a reference locality with a geochronologic age nearest the base of the Tortonian is needed. Unfortunately, in the Spanish Calatayud-Montalbán Basin, where the fossil vertebrate record is dense during the Middle and Late Miocene (Van Dam et al. 2014), no fossils are recorded between 11.85 and 11.4 Ma. The North Alpine Foreland Basin (NAFB), however, provides potentially suitable candidates for a continental reference locality for the base of the Tortonian. The youngest molasse sediments in the western part of the basin (Switzerland) have been dated based on apatite fission track to 11.5 ± 0.3 Ma (Rahn and Selbekk 2007). At the eastern rim of the basin (Upper Austria), the youngest molasse sediments can be found in the Hausruck area, where the mammalian fauna (Thenius 1952, Daxner-Höck 2004) biochronologically points to about 9 Ma. In the central part of the NAFB (Bavaria), where several fossil localities (e.g., Kaufbeuren area: Markt Rettenbach, Dehm 1934, Hammerschmiede, Mayr and Fahlbusch 1975, Hillenloh, Prieto and Rummel 2009, Munich area: Oberföhring, Unterföhring, Aumeister, Großlappen, Ingolstädter Straße 166, Stromer 1938, Klein 1939) are known for this time period, dating is so far lacking. However, using biochronological arguments, Prieto et al. (2011) assume that the vertebrate locality Hammerschmiede (Mayr and Fahlbusch 1975) is slightly older than 11.5 Ma. More recently, Van den Hoek Ostende et al. (accepted) redefined the age constraints to be slightly older than 11.3 Ma, which therefore almost coincides with the base of the Tortonian.

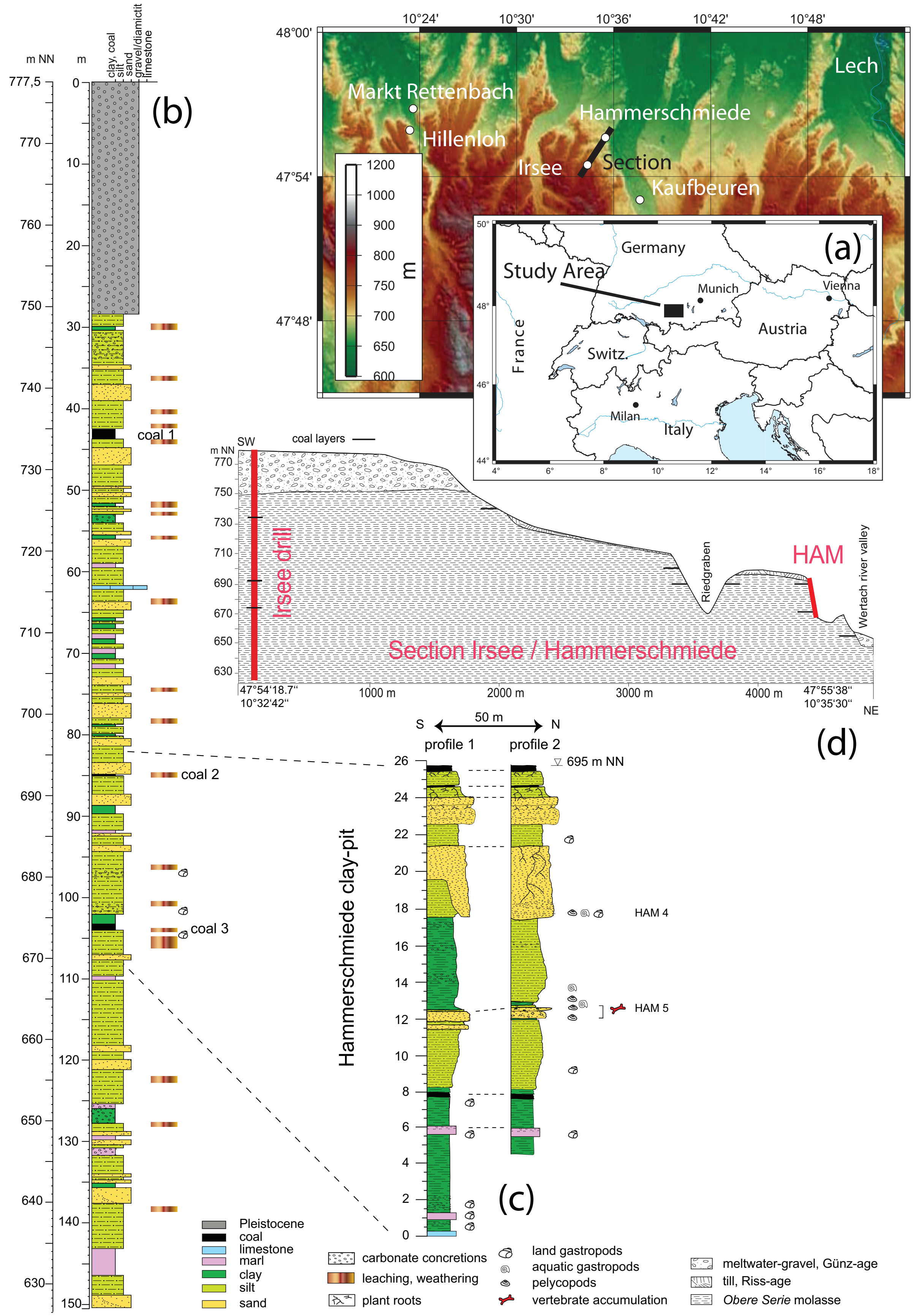
Here we apply a magnetostratigraphic approach to date the youngest molasse sediments of the NAFB in Bavaria, exposed in the area of Kaufbeuren. In addition, magnetostratigraphic results are presented from a research core which was drilled near Hammerschmiede with a stratigraphical overlap allowing for lateral correlation to the sections of Markt Rettenbach and Hillenloh.

2. Geological overview and setting of the study area

The facies distribution, stratigraphy, sedimentology, and general structure of the North Alpine Foreland Basin (NAFB), which comprises Oligocene and Miocene molasse sediments, has been studied in great detail (e.g., Lemke et al. 1953, Schlunegger et al. 2002, Kuhlemann and Kempf 2002, Doppler et al. 2005). At the same time, molasse sediments became more and more important for climatic reconstructions based on a huge amount of paleontological findings (e.g., Böhme 2003). Chronologic dating for these sequences, however, has been problematic for a long time. In recent years precise chronological integration based on magnetostratigraphy and Ar-Ar dating was largely improved for the Early to Middle Miocene Upper Freshwater Molasse (UFM = OSM in german literature) sediments in Bavaria and Switzerland (Schlunegger et al. 1996, Kempf et al. 1997, 1999, Abdul Aziz et al. 2008, 2010, Reichenbacher et al. 2013). In contrast, chronology of the younger parts of the UFM is still largely speculative.

In western Bavaria, the UFM in the northern part of the basin is lithostratigraphically subdivided into four

Fig. 1. (a) Map of Central Europe together with topographic map of the study area with the location of the Irsee drill core and the Hammerschmiede section. (b+c) Geological profiles with organic rich layers ('coal layers'). (b) Lithological column of the drill core labeled with topographic (left) and height below surface of the drill core (right). The latter is used as reference in all following figures. (c) Two profiles from the Hammerschmiede (HAM) section, which are 50 m apart, with stratigraphic height above ground are shown. The correlation with Irsee (dotted lines) is based on the topographic height. Magnetostratigraphic samples were taken from profile 1, the paleontological sites HAM 5 and HAM 4 are situated in profile 2. (d) Cross section ranging from the Irsee drill core to the Hammerschmiede section, which is also marked with a black line in (a).



(a)
(b)
(c)
(d)
Markt Rettenbach
Hillenloh
Hammerschmiede
Section
Irsee
Kaufbeuren
Lech
48°00'
47°54'
47°48'
10°24'
10°30'
10°36'
10°42'
10°48'
m
Germany
Study Area
Munich
Vienna
Austria
France
Switz.
Milan
Italy
m NN
m
clay, coal
silt
sand
gravel/diamictit
limestone
coal 1
coal 2
coal 3
SW
coal layers
Irsee drill
Riedgraben
HAM
Wertach river valley
Section Irsee / Hammerschmiede
47°54'18.7"
10°32'42"
1000 m
2000 m
3000 m
4000 m
47°55'38"
10°35'30"
NE
S
50 m
N
profile 1
profile 2
695 m NN
Hammerschmiede clay-pit
HAM 4
HAM 5
Pleistocene
coal
limestone
marl
clay
silt
sand
carbonate concretions
leaching, weathering
plant roots
land gastropods
aquatic gastropods
pelycopods
vertebrate accumulation
meltwater-gravel, Günz-age
till, Riss-age
Obere Serie molasse

units (Doppler 1989, Doppler et al. 2005); in stratigraphically ascending order: *Limnische Untere Serie* (lacustrine to swampy facies; thickness ~ 80 m), *Fluviatile Untere Serie* (sandy fluvial facies), *Geröllsandserie* (gravelly fluvial facies; both fluvial dominated units together ~ 150 m in thickness), and *Obere Serie* (sandy fluvial facies; thickness up to 300 m in the southern parts of the basin). In these southern parts (e.g. near Kaufbeuren) the *Untere Serie* is replaced by the *Obere Bunte Mergelserie* (variegate marls up to 400 m thick). The youngest stratigraphic unit *Obere Serie* is characterized by mostly carbonatic fine-grained sediments like marl and fine sand, which can occasionally contain thin lignitic horizons (Doppler 1989).

The clay pit of Hammerschmiede and the research drill site at Irsee are situated in the eastern Allgäu region (southwestern Bavaria) several kilometers northwest of the town of Kaufbeuren (Fig. 1). Situated at the foot of the hillside at the western margin of the Wertach valley, the Hammerschmiede section uncovers 25.7 m of the *Obere Serie*. Additionally, two seams of inferior quality lignite crop out in the clay pit. From the slopes of the Riedgraben, a nearby smaller tributary valley, near-surface mining for further coal seams was carried out till 1947. There is no observable dip of the outcropping strata. The adjacent ridge with the village and monastery of Irsee culminates some 100 m higher than the base of the Hammerschmiede pit, so that the youngest molasse sediments, covered by Pleistocene tills and gravels, can be expected there.

The Irsee drilling was carried out in 2011 at the plateau nearly 2 km W of the parish church of Irsee and 4.3 km southwest of the Hammerschmiede clay pit (Fig. 1). The upper 58 m have been drilled by percussion coring and downcore by the rotary coring technique. The bore-hole reached its final depth at 150.5 m and is stored in the drill-core storage of the Geoscience department (University of Tübingen). The top of the drill core is about 80 m above the surface of the pit and given its total depth it includes all of the Hammerschmiede section (Fig. 1).

3. Paleomagnetic sampling and methods

3.1 Irsee

For magnetostratigraphy at least one sample each meter of the Irsee drill core was taken using a battery driven drill. The sampled specimens have a diameter and length of about 1 inch and the top of the cores was marked. By this the direction of the magnetization in each sample yields the magnetic inclination during sedimentation. The resulting declination will be arbitrary due to the drilling technique, where the azimuth of each core meter is not known. In total 156 samples were obtained for magnetostratigraphic analysis and subjected to stepwise thermal cleaning using a Schonstedt furnace. The magnetization was measured at each step using a cryogenic SQUID magnetometer (2-G) in a shielded room at the University of Munich. Directional data were calculated using a least squares approach (Kirschvink 1980) based on at least four consecutive demagnetization steps.

For investigating the paleoclimate parameters another 118 specimens (diameter 1 inch, length ~ 2 cm) were taken for measuring rock magnetic parameters throughout the sections. In a first step, the magnetic susceptibility (MS) was measured on all samples. Subsequently, all samples were demagnetized in a 90 mT alternating field (AF) and afterwards an anhysteretic remanent magnetization (ARM) was imparted between 90 and 10 mT in a 100 μT d.c. bias field. Subsequently, 55 representative samples were stepwise demagnetized using field strengths up to 90 mT to investigate the spectrum of the ARMs. Both values of ARM and MS were mass normalized. AF demagnetization and the imparting of ARMs were performed with the automated system of the incorporated 2-G cryogenic SQUID magnetometer at the University of Munich (Wack and Gilder 2012).

For determination of the magnetic carrier within the sampled material, which is responsible for the NRM, representative samples were taken from all different lithologies and segments of the Irsee drill core. On six samples orthogonal isothermal remanent magnetizations (IRMs) were imparted using fields of 2.3 T, 0.40 T and 0.12 T, respectively, which were then stepwise thermally demagnetized, following the method of Lowrie (1990). Ten samples were measured with a variable field translation balance (VFTB, Krása et al. 2007), which included the acquisition of IRM, hysteresis loops, backfield curves and thermomagnetic measurements with a bias field of various strengths.

3.2 Hammerschmiede

Samples for magnetostratigraphy were obtained along the ~ 26 m thick outcrop 'profile 1', situated about 50 meters south of the fossil excavation (named 'profile 2' in Fig. 1).

A total of 43 oriented samples were drilled at the outcrop of Hammerschmiede with a portable battery driven drill with a diameter of 1 inch and a length of ~5 cm. Orientation was obtained using a standard magnetic compass (Brunton). Thermal demagnetization experiments, ARM acquisition, ARM demagnetization and rock-magnetic parameters were performed following the algorithms described above. Paleoclimate parameters and rock-magnetic measurements were performed using ARM and subsequent AF demagnetization on 30 and 5 samples, respectively.

4. Results

4.1 Lithologic description of the Irsee drill-core

Pleistocene gravels and diamicts cover the upper 28.4 m of the scientific drill-core. The thickness of the Pleistocene cover reduces the accessible molasse sediments to 122 m. The section overlying the Hammerschmiede pit is only about 50 m thick.

About 75% of the molasse core consists of fine-grained, mostly silty, but also sandy or clayey marls of dominantly grey colour, indicating the lithostratigraphic unit *Obere Serie* (Doppler 1989). Layers containing quartz pebbles, which would allow a classification to the older unit *Geröllsandserie* are lacking till the base of the borehole. Solid pedogenic carbonate concretions but also soft calcitic precipitates occur throughout the core and in deeper parts of it single strata of marls are more or less cemented. The marly facies is interrupted by nearly 20 decalcified clayey to silty horizons representing the remains of former, weathered surfaces. These strata are often characterized by increased organic content (blackish, more or less humic layers), culminating in three small lignite seams at 42.35–42.50 m, 43.60–43.90 m and 84.87–85.12 m depth. Remains of macro-fossils are very rare in the core. Shells of gastropods were only be observed at depths of 96.52–98.78 m, 101.37–102.07 m and 103.32–103.98 m, always located beneath humic horizons.

About 25% of the molasse sequence is represented by sands or sandy silts without a clayey fraction. These layers rarely extend over more than two meters in thickness and generally show a tendency to intermix with fine-grained sands and silts. A grain size of medium sand is hardly reached. Calcitic cement coagulates in parts the sands.

Despite of the largely horizontal bedding, which is marked by noticeable grain size differences, the layers are mostly massive and lamination could not be observed very often. At least 20 accumulation cycles, each finished by weathering, decalcification and mostly enrichment of organic matter subdivide the 122 m long molasse sequence of the borehole (Fig. 1). The top of each cycle may represent a paleosol.

The depositional environment of most of these sediments seems to be an extensive floodplain. Sandstones related to river channels could not be identified confidently in the core while pedogenic features point to frequent interruptions of sedimentation.

4.2 Sedimentologic description of the Hammerschmiede section

The 25.7 m thick section is best exposed at the southern end of the present-day (2012–2015) clay pit (Fig. 2). The sedimentary succession can be traced over 150 m in a northern direction. The horizontally bedded sediments are principally bright-grey in color, carbonatic and fine-grained (clay to fine sand fractions) and show distinct pedogenic overprints. Seven marker beds can be traced over the whole distance (correlated with dashed lines in Fig. 1): three lignite (or lignitic) horizons, three sand horizons and one marlstone. The approximately 0.45 m thick homogenous silty-clayey marlstone in the basal part of the northern profile contains well-preserved land gastropods (*Triptychia*, Helicoidea/*Pseudochloritis*?; Fig. 2F and G) while in the upper 20 cm abundant pedogenic carbonate concretions are present. The up to 10 mm thick concretions are matrix-supported and therefore most probably in-situ. One and a half meters above this carbonate-rich horizon a 20 cm thick blackish lignite horizon appears, which overlays about 70 cm of yellowish and brownish mottled dark-grey clay, rich in clay cutanes and some land gastropods (Helicoidea/*Pseudochloritis*?). The lignite is platy in texture, partly xylitic and can be horizontally replaced by carbonatic peat clay. This 2.2 m thick succession can be interpreted as a complete calcic paleosol, where the marlstone represents the Bk-horizon, the mottled clay the Bt-horizon, and the lignite the A-horizon. Between the lower and the upper lignite horizons three horizontally continuous bodies of fine-sand occur. The lower one is 1.05 m thick, greenish-grey in color, contains iron-hydroxide stains, and shows no bedding structures. The granulometry varies from fine-sandy silt (lower 25 cm) to silty fine-sand (upper 60 cm). The


A
B
C
D
E
F
G

middle sand horizon is 2.80 m thick in the southern part of the clay pit and develops up to a 4 meter deep channel towards the north, where it has an erosional base (Fig. 2B). The grey-blue to greyish silty fine-sand is rich in mica and contains iron-hydroxide stains. In shallower parts of the channel sand-filled burrows of Ephemeroptera larvae can be found at the top of the underlying clay. The deepest parts of the channel show well-developed small-scale cross bedding structures and trough cross stratification (Fig. 2C). Reworked pedogenic carbonate concretions, pieces of wood, fragmented land gastropods, and few aquatic and terrestrial vertebrate bones can be found as channel-lag. From the trough cross stratified sands of this channel a well-preserved autochthonous aquatic mollusc fauna (named HAM 4) has been described (Schneider and Prieto 2011). The upper part of the channel shows well preserved fossil roots, which are up to 3 cm thick (Fig. 2C). The root system can be traced at least to a depth of 2.80 m. The upper sand horizon is 1.40 m thick and consists of grey silty fine-sand showing iron-hydroxide stains. This horizon is divided by a 20 cm thick pedogenic bed 0.70 m above its base. The pedogenic bed consists of mottled clayey and sandy silt and shows small-scaled fossil roots. In the lower part of the sand horizon, 30 cm above its base, a layer containing reworked pedogenic carbonates and up to 3 cm diameter clay pebbles occurs.

The top of the presently exposed sedimentary succession in the Hammerschmiede outcrop is marked by a 35 cm thick lignite horizon (Fig. 2E). The basal 25 cm show a platy texture and rarely contain xylit. The upper 10 cm are blackish carbonatic organic clay rather than lignite. The lignite overlays about 10 cm of sandy and clayey silt, which is free of carbonate and is grey-greenish and rusty-yellowish mottled. Below that, a 40 cm thick rooted silt horizon occurs which contains abundant fine-dispersed, powdery, whitish soft carbonate. Therefore, this 0.85 m thick topmost succession can be interpreted as an immature calcic paleosol. Directly below this soil a second, but shallower, calcic paleosol is developed. Its A-horizon is a 7 cm thick blackish carbonatic peat clay, which overlays 5 cm of thick grey clay (Bt-horizon) and an 8 cm thick whitish clay horizon with abundant powdery (soft) carbonate (Bk-horizon) and some land snail fossils. The rooting system of this paleosol reaches about 50 cm below the base of A-horizon.

In addition to the three complete preserved paleosols described, several truncated paleosols, lacking completely or partly the organic-rich A-horizon, occur especially in the middle part of the section (between the two lower sand horizons). These paleosols are characterized by up to 0.60 m thick grey green-yellowish mottled clayey marls containing matrix-supported pedogenic carbonate concretions. Thin A-horizons (or remnants of them) can be preserved. In addition, two less-developed calcic paleosols, where A-horizons are lacking and the nodule-bearing calcic horizons are clay-rich (Btk-horizons), constitute the basal 4 meters of the succession in the southern profile.

The lower sand horizon in the northern profile turns out to be the most important paleontological layer (named HAM 5), because it provides the majority of vertebrate fossils from Hammerschmiede. Its base is found at 681 m above sea-level (a.s.l.) and consists of 0.30 m of grey and fine-sandy marl containing double-valved unionids (*Margaritifera flabellata*) and extremely abundant component-supported pedogenic carbonate concretions with an average diameter of 10 mm and rarely up to 40 mm (Fig. 2C). This horizon is followed by 0.20 m of carbonate cemented fine-to-medium grained sand. Besides double-valved unionids this horizon contains reworked caliche pebbles (marlstones with 10 mm diameter pedogenic carbonate concretions). The next 0.15 m up-section is similar to the basal horizon, but the component-supported pedogenic carbonate concretions are usually only 1 mm in diameter. In addition, a trough-shaped fine-to-medium grained sand body occurs, which contains beside marlstone pebbles up to 35 mm diameter well-rounded quartz pebbles. Above this horizon, 0.20 m of grey-

Fig. 2. Hammerschmiede clay-pit. A – View over the outcrop in eastern direction in 2014 (detail of picture corresponds to 250 m). White arrow indicates the approximate position of excavations in the early 70's by Helmut Mayr. B – Deepest, channelized part of the middle sand horizon (visible maximum thickness of sand ~ 2 m). C – Close-up of the channel from B showing cross bedding structures and trough cross stratification (length of hammer blade 22 cm; black arrow indicate limonitizied tree roots). D – Component-supported pedogenic carbonate concretions at the base of the vertebrate-bearing channel HAM 5 (white scale 10 mm). E – Upper lignite horizon (length of hammer blade 22 cm). Notice the fine-dispersed (whitish powdery) soft carbonate below the lignite. F – Land gastropod (Helicoidea/*Pseudochloritis*?) from the marl at stratigraphic meter 5.9. G – Land gastropod (*Triptychia*) from the same horizon as F.

Table 1 Fossil vertebrate taxa from the Hammerschmiede level HAM 5.

Ordnung	Familie	Taxon
Esociformes	Esocidae	*Esox* sp.
Siluriformes	Siluridae	*Silurus* nov. sp.
Cypriniformes	Cyprinidae	*Tinca* sp.
		Palaeoleuciscus sp.
		Leuciscus sp.
	Cobitidae	*Cobitis* sp.
Perciformes	Gobiidae	*Gobius* sp.
	Percidae	*Perca* sp.
Urodela	Proteidae	*Mioproteus* sp.
	Cryptobranchidae	*Andrias scheuchzeri*
		Urodela indet.
	Salamandridae	*Triturus roehrsi*
		Triturus aff. *montadoni*
Anura	Discoglossidae	*Latonia gigantea*
	Palaeobatrachidae	*Palaeobatrachus* sp.
	Hylidae	*Hyla* sp.
	Bufonidae	*Bufo* sp.
	Ranidae	*Pelophylax* sp.
	Pelobatidae	*Eopelobates* sp.
Choristodera		*Lazarussuchus* sp.
Chelonia	Trionychidae	*Trionyx* sp.
	Chelydridae	*Chelydropsis* sp.
	Emydidae	*Clemmydopsis* sp.
	Testudinidae	*Testudo* sp.
Aves		Aves indet.
Squamata	Amphisbaenidae	Amphisbaenidae indet.
	Lacertidae	*Lacerta* sp. 1
		Lacerta sp. 2
	Scincidae	*Chalcides* sp.
	Anguidae	*Pseudopus pannonicus*
		Ophisaurus sp.
	Colubridae	Colubrinae sp. 1
		Colubrinae sp. 2
		Natricinae sp. 1
		Natricinae sp. 2
Eulipotyphla	Erinaceidae	*Galerix exilis*
	Cordylidae	*Metacordylodon schlosseri*
	Plesiosoricidae	*Plesiosorex schaffneri*
	Talpidae	*Gehardstorchia quinquecuspidata*
	Dimylidae	*Plesiodimylus johanni*
	Soricidae	*Crusafontina exulta*
		Paenelimnoecus crouzeli
		Paenesorex sp.
		Dinosorex nov. sp.
Chiroptera		Chiroptera div. sp.
Primates	Pliopithecidae	Pliopithecidae indet.
Carnivora	Amphicyonidae	*Amphicyon* sp.
	Ursidae	cf. *Kretzoiarctos beatrix*
	Mustelidae	*Proputorius pusillus*
		Proputorius sansaniensis
		Eomellivora sp.
	Felidae	*Pseudaelurus quadridentatus*
Proboscidea	Gomphotheriidae	*Gomphotherium* sp.
	Deinotheriidae	*Deinotherium* sp.
Perissodactyla	Rhinocerotidae	*Hoploaceratherium belvederense*
	Chalicotheriidae	*Anisodon grande*
	Equidae	*Sinohippus* sp.
Artiodactyla	Suidae	*Listriodon splendens*
		Parachleuastochoerus steinheimensis
	Tragulidae	*Dorcatherium naui*
	Moschidae	Moschidae indet.
	Cervidae	*Euprox furcatus*
		Muntiacini indet.
	Bovidae	*Miotragocerus monacensis*
		Boselaphinae indet.
Lagomorpha	Ochotonidae	*Prolagus oeningensis*
		Eurolagus fontannesi
Rodentia	Sciuridae	*Spermophilinus bredai*
		Albanensia grimmi
	Castoridae	*Euroxenomys minutus*
		Chalicomys jaegeri
	Gliridae	*Microdyromys complicatus*
		Muscardinus hispanicus
		Glirulus conjunctus
		Eliomys reductus
		Eliomys assimils
		Myoglis meini
	Eomyidae	*Eomyops catalaunicus*
		Keramidomys sp.
	Cricetidae	*Democricetodon* nov. sp.
		Collimys hiri
		Megacricetodon minutus
		Microtocricetus molassicus
		Eumyarion latior
	Anomalomyidae	*Anomalomys gaudryi*

green silty clay occurs, containing flaser bedded fine-sand laminae, few reworked pedogenic carbonate concretions (up to 8 mm in diameter) and very few up to 40 mm diameter quartz pebbles. This layer also contains abundant fluvial bivalves (*Sphaerium*, *Pisidium*, *Margaritifera*) and terrestrial gastropods. Above the described 0.85 m sand body a one meter thick greenish-rusty mottled sandy clay to silty fine-sand is present showing a coarsening-upward trend. Small fluvial bivalves (*Sphaerium* vel *Pisidium*) are common, in addition to terrestrial (Helicoidea/*Pseudochloritis*?) and small aquatic gastropods (*Planorbis*, *Boryshtenia* vel

Bithynia). However, nearly all molluscs from the vertebrate-bearing sand body are badly preserved due to partial leaching of their carbonate shells.

4.3 Paleontology of the Hammerschmiede vertebrate bearing sands

The above described sand body of the lower sand horizon (HAM 5) contains abundant vertebrate remains, especially in its lowermost 0.60 m. This sand body likely corresponds to the fossil horizon (HAM 1) excavated by Helmut Mayr 200 m to the east of the present excavation at 680 m a.s.l. in the early 70's (Mayr and Fahlbusch 1975).

New paleontological excavations have been conducted from 2011 to 2015 by the University of Tübingen, which provided over 500 catalogued field-specimens. The majority of finds are isolated bones and teeth. Complete mammalian mandibles are rare and only single finds represent partly articulated skeletons. Bones and teeth are usually black in color. Brownish colored bones come from the upper part of the sand body and differ from the black ones by better fossilization but usually higher fragmentation. Some brownish and very few blackish bone fragments are abraded, probably indicating longer fluvial transport. Many of the black bones show a poor fossilization (very soft when moist), but are complete or largely complete, indicating fluvial transport over a short distance and rapid burial of carcasses (in the case of articulation). To recover small-size vertebrates, about 500 kg of sediments have been screen-washed, yielding several thousands of bones and teeth.

The taxonomic composition of the fauna HAM 5 is exceptional and all major groups of vertebrates are preserved (e.g. fishes, amphibians, reptiles, birds, mammals). So far, 85 taxa have been recognized, belonging to 55 vertebrate families (Table 1), which ren-

Table 2 Mammal faunal lists of Hillenloh, Hammerschmiede level HAM 4 and Markt Rettenbach according to Stromer (1930), Dehm (1934), Fahlbusch (1975), Bolliger (1996), Prieto and Rummel (2009), Prieto et al. (2014) and unpublished results.

	Order	Family	Taxon
Hillenloh	Eulipotyphla	Cordylidae	?*Metacordylodon* sp.
		Dimylidae	*Plesiodimylus* sp.
		Soricidae	*Crusafontina* sp.
	Proboscidea	Deinotheriidae	*Deinotherium* sp.
	Lagomorpha	Ochotonidae	indet.
	Rodentia	Cricetidae	*Collimys dobosi*
			Megacricetodon minutus
			Microtocricetus molassicus
		Anomalomyidae	*Anomalomys* cf. *rudabanyensis*
Hammerschmiede 4	Perciformes	Percidae	indet.
	Urodela	Cryptobranchidae	*Andrias scheuchzeri*
	Chelonia	Chelydridae	*Chelydropsis* sp.
		Emydidae	*Clemmydopsis* sp.
	Carnivora	Mustelidae	cf. *Potamotherium* sp.
	Perissodactyla	Rhinocerotidae	*Aceratherium* sp.
	Artiodactyla		Ruminantia indet.
	Rodentia	Castoridae	*Euroxenomys minutus*
			Chalicomys jaegeri
Markt Rettenbach	Proboscidea	Deinotheriidae	*Deinotherium* sp.
	Perissodactyla	Rhinocerotidae	*Aceratherium* sp.
	Artiodactyla	Suidae	*Listriodon splendens*
			Parachleuastochoerus steinheimenensis
		Bovidae	indet.
	Rodentia	Eomyidae	*Keramidomys mohleri*

der the Hammerschmiede (HAM 5) locality one of the most taxonomically diverse Late Miocene vertebrate localities on a global scale.

The channel-lag of the middle sand horizon (HAM 4) provides only few, mostly aquatic vertebrate taxa (Table 2), but, at present, less attention has been paid to this layer.

4.4 Rock magnetic results

Generally, it was difficult to extract meaningful rock-magnetic results from the magnetically weak sediments. After subtraction of a paramagnetic signal, hysteresis loops only vaguely suggest a low coercivity ferromagnetic mineral (Fig. 3h). However, thermomagnetic experiments with low and high bias fields of ~40 and ~600 mT, respectively, were successful in achieving interpretable results for various stratigraphic positions throughout the drill core (Fig. 3a–f), as well as from different materials (Fig. 3: silt (d), clay (a), marl (f) and sand (e)). The heating cycles of all samples, together with the occasional occurrence of one low temperature phase at ~100 °C, show similar features: (1) a first high temperature phase, which loses its intensity before 600 °C and (2) a second phase, where all the intensity is lost shortly before 700 °C. The second phase is weak and sometimes not recognizable. Only in one sample a third Curie temperature can be

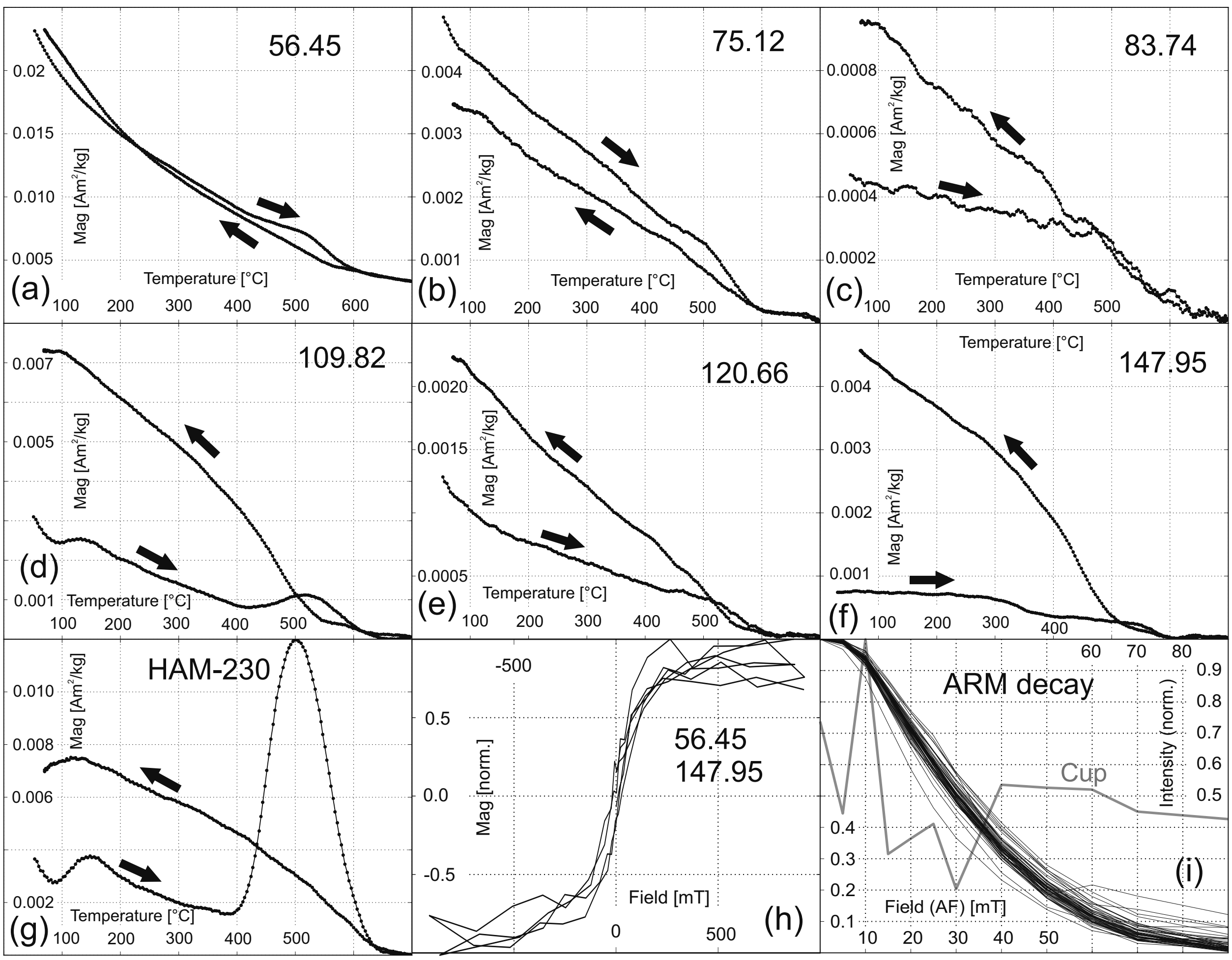


Fig. 3. Rock magnetic results of representative samples from the Irsee drill core and the Hammerschmiede section. (a–g) show thermomagnetic curves where arrows indicate the heating and cooling cycles. (a) is not corrected for paramagnetic contributions, whereas (b–g) are corrected for it. (h) shows two hysteresis loops of samples from the Irsee drill core. (i) shows the intensity during alternating field (AF) demagnetization of the previously imparted ARM (see text for details). Light grey curve indicates the result of the procedure of an empty cup for comparison. Sample name of Irsee correlates to the position below surface.

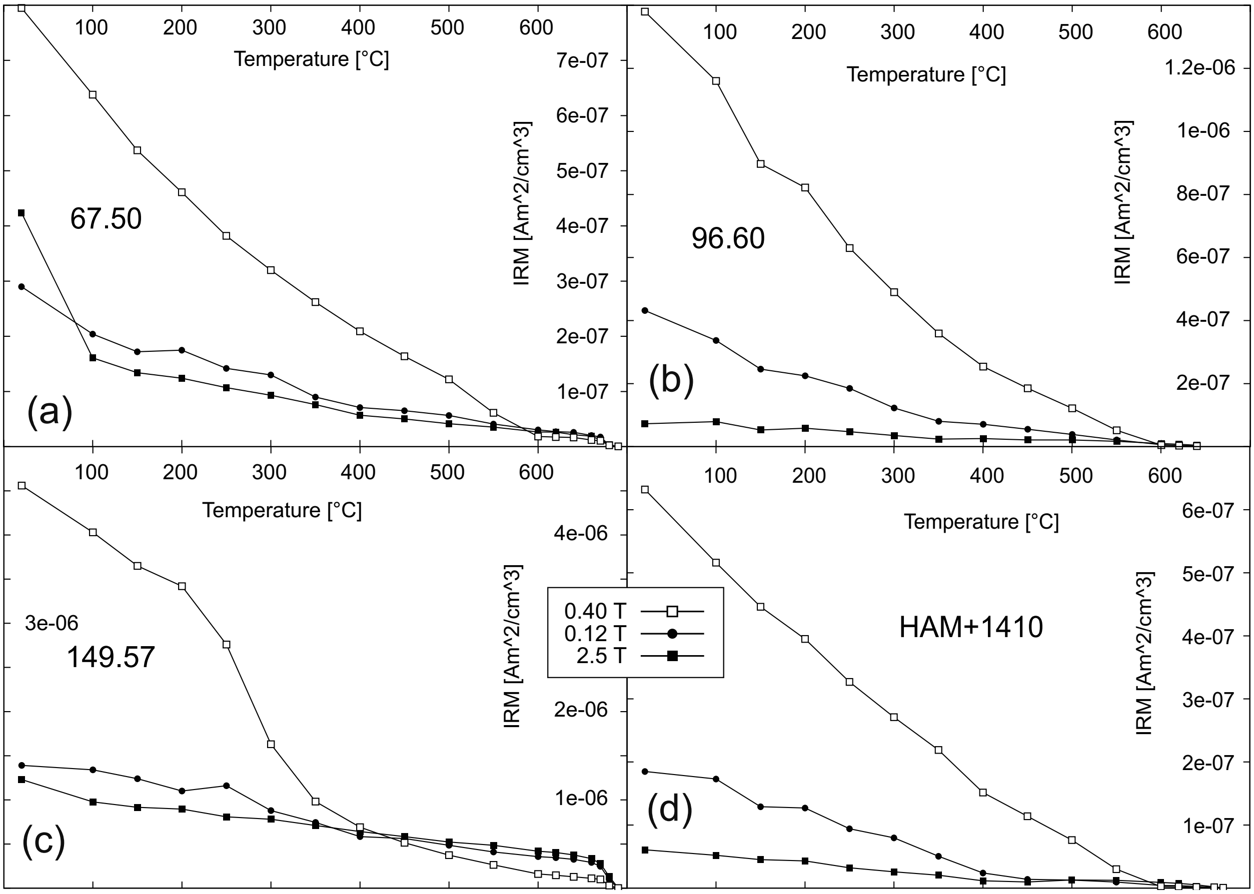


Fig. 4. Results of stepwise thermal demagnetization of a composite three axis isothermal remanent magnetization (IRM) with fields of 0.12, 0.40 and 2.5 T (Lowrie 1990) of four representative samples of each section. (a–c) show samples from the Irsee drill core, where the sample name corresponds to the stratigraphic position below surface. (d) shows the result of a sample from the Hammerschmiede section.

identified with a drop towards ~350 °C (Fig. 3f). Especially in the lower part of the drill core, the intensity increased after the cooling cycle. Additionally, one sample shows a clear indication of the formation of magnetite (Fig. 3d), which suggests that paramagnetic clay minerals are transformed (e.g., Hirt and Gehring 1991, Pan et al. 2005, Kirscher et al. 2011).

Samples from the Hammerschmiede outcrop show the formation of magnetite in an exaggerated form (Fig. 3g) probably due to the generally weaker magnetic signal of these samples.

AF demagnetization of the imparted ARM was used as another tool to characterize the magnetic mineral content. Inspection of 55 AF spectra of the ARM of samples from the Irsee core (45 samples) and the Hammerschmiede outcrop (7 samples), which were both normalized by the maximal value, show a narrow distribution with a well-defined medium destruction field (MDF, Fig. 3i).

Thermal demagnetization of a composite three axis IRM (Lowrie 1990) yields, in general, the same results as the thermomagnetic curves. Most dominant are a medium coercivity phase (0.4 T), which is removed before 600 °C, and the high temperature phase, which was activated up to 2.5 T. This is visible in two samples (Fig. 4a, c) but is not recognizable in the other two experiments. Only at the bottom of the drill core a strong medium coercivity phase (0.4 T) is present, which vanishes at ~350 °C.

4.5 Paleomagnetic results

4.5.1 Demagnetization results

Despite the weak magnetic signal, 53 % of all samples (Irsee and Hammerschmiede) show stable demagnetization behavior with a clear trend of the characteristic component towards the origin of the projection plane (Fig. 5a–q). These were therefore classified as quali-

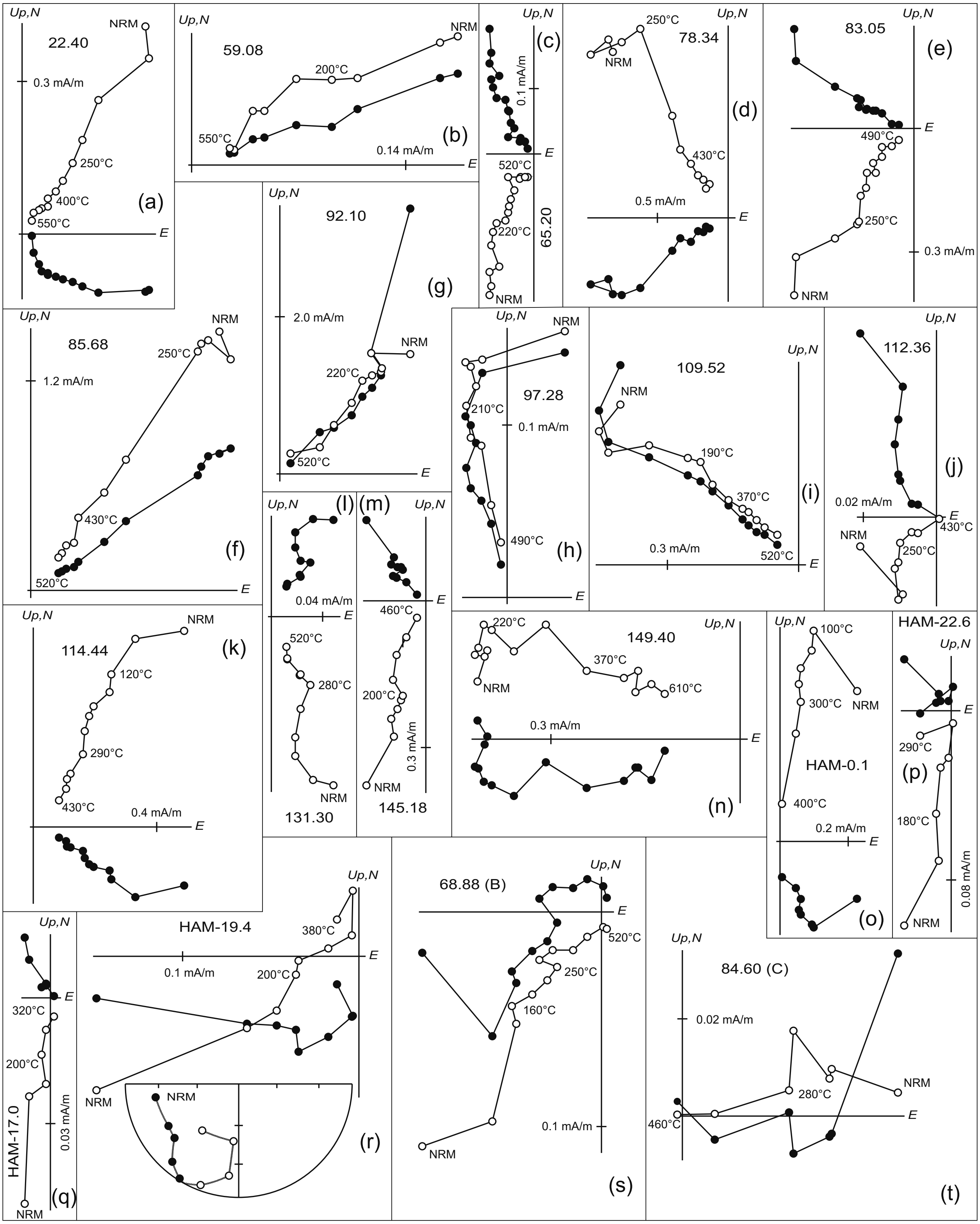


Fig. 5. Results of stepwise thermal demagnetization experiments on orthogonal vector endpoint diagrams (Zijderveld 1967) of representative samples from the Irsee drill core (a–n, s+t) and the Hammerschmiede section (o–r). Open (closed) symbols indicate projections onto the vertical (horizontal) plane. Sample name of Irsee samples represent stratigraphic position below surface. (s+t) show representative results of samples classified B and C with a normal and reversed polarity, respectively. Sample names of Hammerschmiede samples correspond to stratigraphic height, compare Fig. 1).

ty 'A'. The samples from the Irsee drill core show an additional low temperature component (LTC) between 100 and ~200–250 °C (Fig. 5). After removal of the LTC a high temperature component (HTC) can be observed, which is present up to ~550 °C. Sometimes, due to the weakness of the signal, the magnetization is already removed after ~400–450 °C (Fig. 5k, j).

Samples from the outcrop at Hammerschmiede show, on average, an even weaker magnetic intensity (Fig. 5). The HTC is present in these samples up to 300–400 °C. Two samples from Hammerschmiede were analyzed using remagnetization great circles to identify the reversed polarity (Fig. 5r). Demagnetization data of 34 % of all the samples show a less clear trend that is not pointing towards the origin of the projection plane but still with a clear positive or negative inclination. These samples were classified as quality 'B' (Fig. 5s). Finally, 4 % of the samples show quite unstable demagnetization behavior and were therefore classified 'C' (Fig. 5t). The remaining 9 % of all samples show chaotic and unresolvable demagnetization characteristics and were therefore excluded from further investigation and are not included in the figures.

A secondary overprint caused by the drilling procedure, which would lead to steep inclinations close to ± 90°, cannot be observed (Fig. 6a). The weak signal of

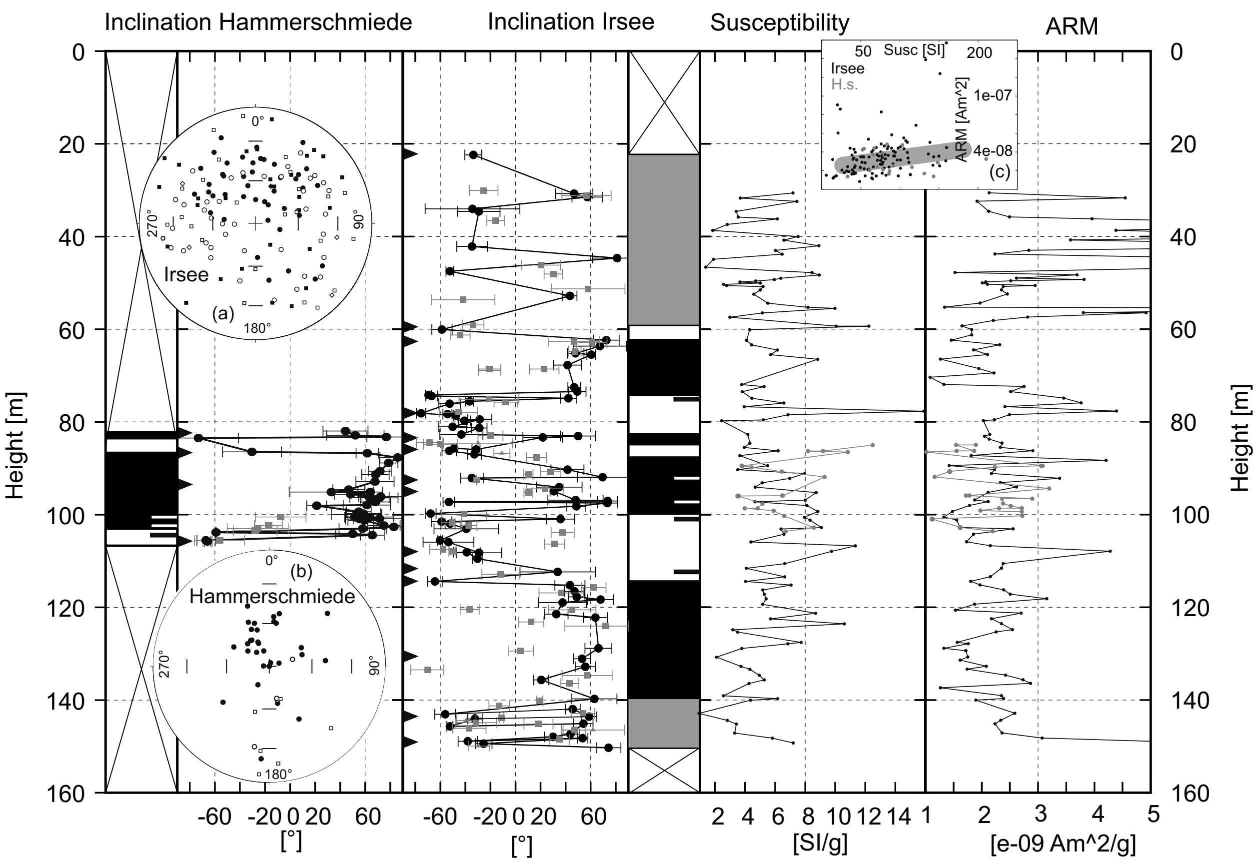


Fig. 6. Magnetostratigraphic results of the two sections Irsee and Hammerschmiede (left) with according interpretation of the magnetic polarity, where black (white) corresponds to normal (reverse) polarity and grey indicates zones of undetermined polarity. Stratigraphic position is given in meters according to the drill core below surface. The position of Hammerschmiede is based on the topographic relation to the Irsee drillcore surface. Black arrows indicate position of representative demagnetization diagrams (Fig. 5). X-errorbars represent α_{95} error interval of the principal component analysis of the demagnetization experiments (Kirschvink 1980). Data circles, squares and triangles represent quality A, B and C data. Two graphs on the right show the mass normalized records of susceptibility and anhysteretic remanent magnetization (ARM) of Irsee (black) and Hammerschmiede (grey) on the right. Also shown are the stereographic projections of sample mean directions from the Irsee drill core (a) and the Hammerschmiede section (b). Open (closed) symbols indicate projection on the lower (upper) hemisphere. Circles, squares and diamonds represent quality A, B and C results, respectively. (c) ARM versus susceptibility (King et al. 1983).

the Hammerschmiede samples yield quite a diverse distribution, but a normal polarity of ~360° declination and a reversed polarity close to 180° declination can be observed (Fig. 6b). Inclinations of the Irsee samples of quality 'A' yield a positive mean inclination value of 48.4° with an error of 14.2°, quality 'B' yield 35.7° ± 18.1° and quality 'C', 30.3° ± 20.2° for 82, 53 and 6 samples respectively. All directional results of the Hammerschmiede samples yield a mean direction of D = 345.5°, I = 71.9°, k = 5.3 and an α_{95} of 10.1°.

4.5.2 Magnetostratigraphic results

The resulting inclination values have been plotted versus the stratigraphic height (Fig. 6), where the heights of the Hammerschmiede section were transferred into the Irsee reference frame, which resulted in a position between 82 and 108 m (Fig. 1). The Hammerschmiede section yields four different polarity intervals, two normal ones and two reversed intervals. The Irsee drill core has five pronounced polarity intervals, three normal and two reversed. Below the Pleistocene cover of 28 m, an interval of 30 m was drilled using a percussion coring technique, at which the drilled material got decompressed before it was put into wooden boxes. Additionally, the demagnetization results did not show coherent results, and therefore the magnetic signal of this interval was interpreted as unreliable. The lowermost 10 m show a very chaotic and highly fluctuating signal (Fig. 6) and are therefore also treated as an unreliable part. In the whole sequence there are several single samples with an opposing inclination compared to the surrounding samples, which is not uncommon in Miocene sections (Abdul Aziz et al. 2000, Krijgsman and Kent 2004). Only between 82 and 84 m are there two short normal and reversed polarity intervals (Fig. 6).

Comparing the polarity pattern of the Irsee core and the Hammerschmiede section yields, in principle, the same results (Fig. 6). Exact comparison of the drill core and the section, however, shows that the long normal polarity interval at Hammerschmiede is slightly (~4 m) longer. Also, small layers enriched in organic matter (named coal layers in Fig. 1) cannot be precisely correlated (Figs. 1 and 6).

4.5.3 Paleoclimatic results

MS and ARM were both normalized with their corresponding weight and plotted versus height (Fig. 6). Additionally, the two parameters were plotted against each other to illustrate eventual significant climatic changes or trends within the section (e.g., Banerjee et al. 1981). It turns out that both parameters are linearly dependent except for very few outliers (Fig. 6c). Samples from both sites behave similarly. The MS and ARM records also do not indicate overall trends or distinct features but suggest cyclicity.

5. Implications and discussion

5.1 Rock magnetism

The rock magnetic experiments are in agreement with the presence of magnetite as the magnetic carrier of the characteristic remanence (ChRM) in all the sampled material. This is further confirmed by the demagnetization results of a three axis IRM (Fig. 4d), which is especially important for the samples from Hammerschmiede, where the thermomagnetic curves are obscured by the formation of new magnetite. Although hematite is present in various amounts, it is of minor importance as indicated by the weak magnetic signal. The hematite might cause, however, the occasional demagnetization trends, which are not directed towards the origin of the projection plane. A separate directional phase carried by the hematite phase could not be identified.

There is some evidence of the low temperature mineral goethite and the iron-sulfide greigite (Fig. 3b, d, f). The AF spectrum of the ARM (Fig. 3i) and the thermal demagnetization results, which show a narrow MDF range and no large change in direction at ~350 °C (Fig. 5), argue against an extensive occurrence and important contribution of these minerals to the ChRM.

5.2 Magnetostratigraphy

The huge variety of paleontological findings from layer HAM 5 between stratigraphic meters 11.5 and 12.5 of the Hammerschmiede section (Fig. 1) constrains its biochronologic age to slightly older than 11.3 Ma (Prieto et al. 2011, Van den Hoek Ostende et al., accepted, see further discussions in chapter 5.4). Therefore, we correlate the oldest normal polarity interval of the drill-core to magneto-chron C5An.1n (all magnetic polarity chrons are based on the recent compilation of the Neogene timescale of Hilgen et al. 2012), and the middle normal polarity interval (corresponding to the main normal interval of Hammerschmiede) to C5r.2n (Fig. 7). The slightly longer normal polarity interval of the Hammerschmiede section might be caused by small lateral variations in accumulation rate.

We propose that the youngest normal polarity interval at the Irsee drill core can be correlated to C5r.2r-1n, which was first described by Schneider (1995) in ODP Leg 138 Site 845 and also identified in other sections (e.g., Abdul Aziz et al. 2000, Hüsing et al. 2007, Paulissen et al. 2011, Fig. 7). Assuming a constant rate of accumulation within each polarity interval, our interpretation would need two phases with a significant decrease in accumulation rate (Fig. 7), which seems highly unlikely taking into account that no major change in depositional style took place. On the contrary, an extensive erosion channel (middle sand horizon) observed in the Hammerschmiede claypit at the beginning of the short reversed polarity interval suggests the presence of hiatuses. Therefore we suggest that not one but two phases of enhanced erosion took place, one during the erosion by the channel at Hammerschmiede (erosion phase 2/EP2 in Fig. 7) and the other during the older reversed polarity interval (EP1 in Fig. 7). Identification of erosion at the drill core is impossible due to the small scale of observation. We note here that this is probably a quite crude approach, which definitely contains some amount of uncertainty due to the approximated assumption of constant accumulation rates. We describe the average accumulation rate of the preserved stratigraphic sections and assume that they are constant. The preserved section depends on the available accommodation space over a specific period of time and is a function of subsidence (including compaction) rather than sedimentation rate only. Therefore, the accumulation rate cannot exactly be identified with the actual sedimentation rate. However, our approach still represents the best estimate and, keeping in mind the drawbacks, can be used as valuable constraint.

This interpretation would indicate that the oldest sediments at the Hammerschmiede section have an age of 11.667 Ma and therefore, using a proposed average

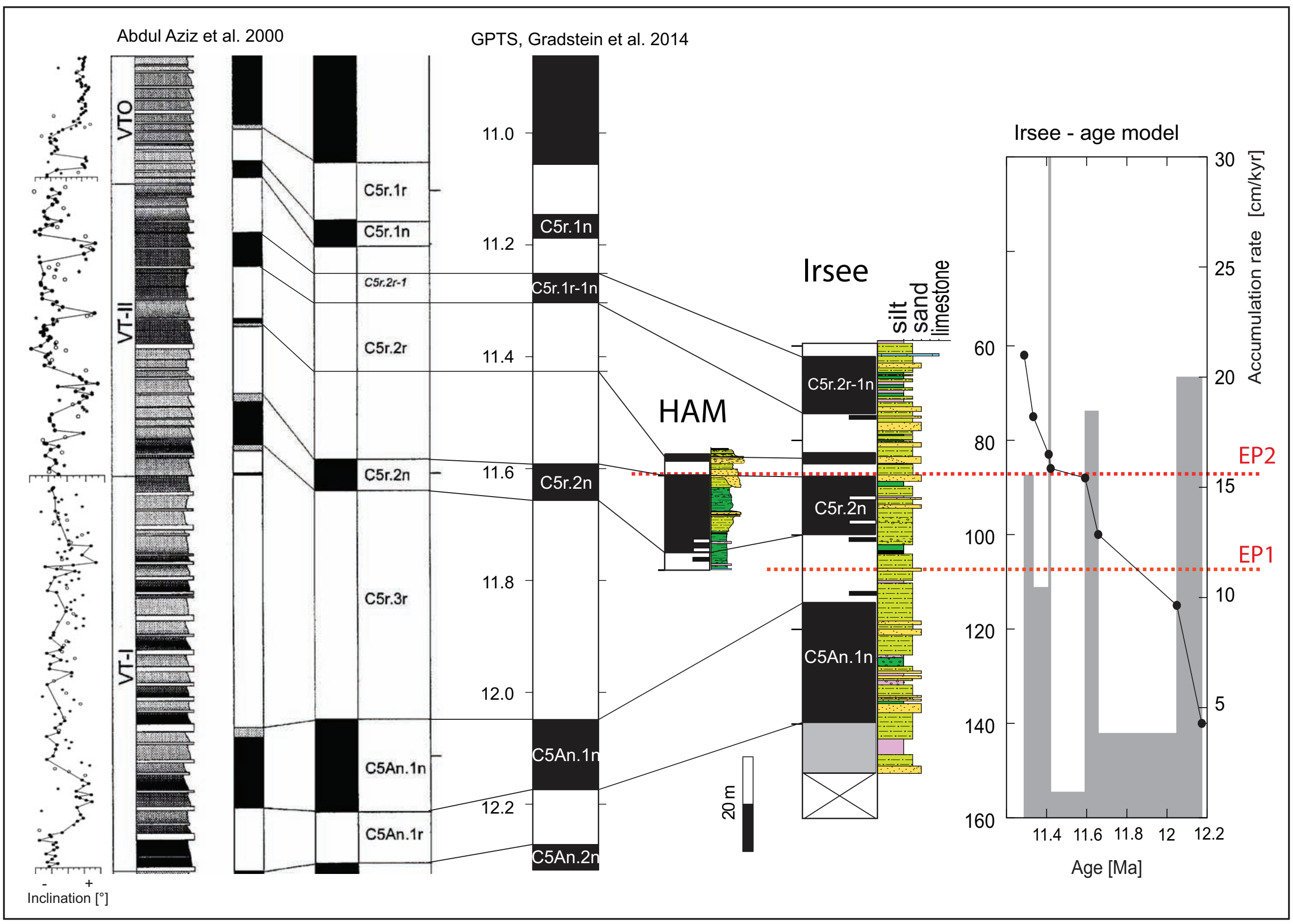


Fig. 7. Proposed final age correlation of the resulting inclination of samples from the Irsee drill core and the Hammerschmiede section with the global polarity time-scale (GPTS) of Hilgen et al. 2012. Also shown are the results of the Orera composite section of the same time interval (Abdul Aziz et al. 2000). On the right the resulting accumulation rate is plotted using the fixed reversal points (see text for detailed description). Red dotted lines indicate suggested positions of the two hiatuses: EP1,2 – erosion phases 1 and 2. Lithological columns are also shown, for description see Figure 1.

accumulation rate of about 26 cm/kyr during C5r.2n, constrains the age of the vertebrate site HAM 5 (between 11.5 and 12.5 m) to 11.622–11.618 Ma. It has to be pointed out that the 65 kyr long chron C5r.2n is about 4 m thicker in the Hammerschmiede section than in the Irsee drill core (~ 12 m versus ~ 16 m). This might be related to slightly different accumulation rates (~ 26 cm/kyr versus ~ 19 cm/kyr) or to small scale erosion in the Irsee region. Even if the four meters represent erroneous paleomagnetic results of samples from the Hammerschmiede section at the base of C5r.2n, this would only result in an older age for HAM 5 of a few kyrs.

We note that our interpretation suggests that the age of the main fossil vertebrate horizon at the Hammerschmiede section shortly succeeds the base of the Tortonian stage by less than a precession cycle. The youngest point which was reliably recorded by paleomagnetic data in the Irsee drill core is the end of chron C5r.2r-1n at 11.289 Ma. We can speculate that if the accumulation rate was more or less similar (about 15 cm/kyr) after that point, the youngest part of the molasse sediments present at Irsee are about 11.09 Ma old (at 30 m below surface).

The two major and/or possibly numerous additional small erosion hiatuses left significant time gaps in the sediments of the *Obere Serie*. Assuming a rather constant accumulation rate of 15 cm/kyr during the lower 60 meters of the well, we estimate that the time gap produced by the older major hiatus might be as long as 300 kyrs during Chron C5r.3r. The time gap of the younger hiatus, clearly visible by the thick erosion channel in the Hammerschmiede outcrop, occurred during the early part of Chron C5r.2r and can be estimated to be about 150 kyrs (11.59 to 11.44 Ma), which also represents the maximum, and respective minimum, age for fossils from the channel-lag accumulation HAM 4. Again, it must be noted that accumulation was most probably not constant and that the two proposed major phases of erosion are only end members. Therefore the presented interpretation and the suggested accumulation rates only serve as constraints to the real values. Accumulation rates as proposed by our model, in the range of 10–30 cm/kyr, however, seem reasonable compared to other studies of the Bavarian Molasse sediments (e.g., Frieling 2009), whereas very low rates of less than 5 cm/kyr seem unlikely.

Finally, we might have underestimated the actual average accumulation rate in the lowermost part of the section. The initiation of chron C5An.1n might have happened earlier compared to our interpretation. This has no effect, however, on our main outcomes, but would indicate further changes in average accumulation rates in the lower part of the drill core.

5.3 General stratigraphy

By using the temporal correlation of the Irsee drill core we can suggest ages of other important fossil bearing sites of the *Obere Serie* in the Kaufbeuren area, namely Markt Rettenbach (12.8 km WNW of the drill location) and Hillenloh (12.1 km WNW the drill location). Both former clay pits are not longer available for magnetostratigraphic sampling, but it might be possible to correlate them to the Irsee drill core using their absolute topographic height (660 m above sea-level and 695–707 m above sea-level respectively) assuming horizontality and negligible dipping of the sediment beds. Taking into account the presence of erosional features, this approach is only a vague constraint and serves as a best achievable age estimate for these inaccessible outcrops. The resulting inferred age for Markt Rettenbach is 12.06 Ma and for Hillenloh between 11.30 and 11.41 Ma.

We identified two major stratigraphic gaps, interpreted as erosional hiatuses in the Irsee drill. The older one can be correlated to the upper Sarmatian and has eroded about 45 m of sediment (time gap of 300 kyrs), whereas the younger erosion of about 27 m of sediment took place in the earliest Pannonian (about 150 kyrs gap between 11.59 and 11.44 Ma). The younger erosional hiatus may possibly have an equivalent in the *Obere Serie* around Munich (Klein 1939, Fuss et al. 2015), where fine-grained clastics (so called ‘Flinz’; containing the mammalian faunas of Aumeister, Oberföhring, Unterföhring and Großlappen) are eroded by gravel sands (‘Oberer Schweißsand’, containing the mammal fauna from Ingolstädter Str. 166). In addition, erosion and redeposition of upper Sarmatian and earliest Pannonian molluscs by the paleo-Danube during the early Pannonian has been documented by Harzhauser et al. (2011) on the Mistelbach block in the northwestern Vienna Basin. Furthermore, similar intense erosion in the stratigraphic position of our older stratigraphic gap has been described from the central Vienna Basin (Spannberg 21 well), where a time gap of 180–210 kyrs is documented at the top of the upper Sarmatian (Paulissen et al. 2011). The concentration of erosional events around the Serravallian-Tortonian transition along the northern Alpine margin may be related to both eustatic lowstand of the Ser4/Tor1 sequence-boundary documented in the Vienna basin (Paulissen et al. 2011) and regional eastern Alpine uplift (Neyba and Roetzel 2004).

5.4 Biostratigraphy

The large mammal fauna of Hammerschmiede (HAM 5) is rich (20 taxa) and can best be compared to the fauna of Hollabrunn (formerly Ober-Hollabrunn) in Lower Austria (Sickenberg 1928, Pia and Sickenberg 1934, Van der Made et al. 2014, Fuss et al. 2015), to which it shares about half of all taxa. Most importantly, both localities share *Pseudaelurus, Listriodon splendens*, *Parachleuastochoerus steinheimensis*, *Dorcatherium naui*, and *Miotragocerus monacensis*. Except the later species, all these taxa represent a common and very typical association in late Middle Miocene assemblages (e.g. the early upper Sarmatian locality Gratkorn in the Styrian Basin, Gross et al. 2014). A significant difference of both Hammerschmiede and Hollabrunn to earlier assemblages is the presence of the comparatively large-size boselaphine bovid *M. monacensis* (Fuss et al. 2015), whereas bovids are represented in Gratkorn by a small-size *Tethytragus* sp. (Aiglstorfer et al. 2014). *M. monacensis* first occurs in the later part of the Upper Ervilia zone of Atzgersdorf/Mauer (Fuss et al. 2015), between 12.0 and 11.9 Ma. Two very interesting components in the Hammerschmiede large-mammal fauna represent a large-size anchitheriin horse (*Sinohippus* sp., browsing forest horse) and an ailuropodin bear (cf. *Kretzoiarctos beatrix*, giant panda). Both taxa link Hammerschmiede to the 11.87 Ma old Spanish site Nombrevilla 2 (Salesa et al. 2004, Abella et al. 2012, Van Dam et al. 2014), confirming the conclusion that, despite the chronostratigraphic position of Hammerschmiede at the base of the Tortonian, and respectively the Pannonian, their large-mammal fauna is essentially of late Middle Miocene age.

Hammerschmiede (and the contemporary faunas of Hollabrunn, Oberföhring, Unterföhring, Aumeister; Fig. 8) may indeed represent the last European mammal fauna with Middle Miocene character, because in slightly younger deposits correlated to the *Mytilopsis ornitopsis* zone (11.5 to 11.4 Ma; Vienna Basin, Pannon B of Papp 1951) many Middle Miocene large-mammal lineages are replaced by new immigrants.

The large mammal results have strong support from small mammals. The presence of the microtoid rodent *Microtocricetus molassicus* allows us to affirm that Hammerschmiede is younger than Gratkorn, but also than most of the late Sarmatian s.str. localities from central Europe. The first occurrence of this species in Hungary occurs in Felsőtárkány 3/8 and 3/10. Hír and Kókay (2010) conclude that the deposits range from the latest part of the Sarmatian to Pannon A/B (ca. 11.2–11.7 Ma). This is in good agreement with the minimum age of Hammerschmiede as proposed by Prieto et al. (2011) and Van den Hoek Ostende et al. (accepted), and fixes a maximum age for the first occurrence of *Microtocricetus molassicus* in central Europe.

Similar to Hammerschmiede, the calculated ages for Markt Rettenbach and Hillenloh are in good agreement with their respective mammalian fauna (Table 2).

For Markt Rettenbach, the coexistence of both suids *Listriodon splendens* and *Parachleuastochoerus steinheimensis* together with an undetermined bovid, distinctly smaller than *Miotragocerus monacensis*, resembles the locality Gratkorn (van der Made et al. 2014, Aiglstorfer et al. 2014) dated to between 12.2 and 12.0 Ma (Gross et al. 2014) and is unlike Hammerschmiede (Fuss et al. 2015). Furthermore, the eomyid *Keramidomys mohleri*, known from both Anwil and Kleineisenbach (Fahlbusch 1975) and possibly from Gratkorn (Prieto et al. 2014), is not present in sediments younger than 12 Ma.

For Hillenloh, the presence of the anomalomyid rodent *Anomalomys* cf. *rudabanyensis* (Bolliger 1996) suggests a correlation with the Pannonian (Harzhauser et al. 2011). This agrees with Prieto and Rummel (2009), who proposed for Hillenloh a younger age than Hammerschmiede, based on tooth-size differences between populations of the cricetid rodent *Collimys*. The three magnetostratigraphic dated localities from the *Obere Serie* in the Kaufbeuren area enable a stratigraphic correlation to chronostratigraphic dated mammal localities from the Central and Eastern Paratethys, and especially to localities without chrono- or magnetostratigraphic control (Fig. 8). Thereby, the magnetostratigraphic age of the Hammerschmiede fossiliferous level of 11.62 Ma provides an ideal tie-point not only for the base of the Tortonian (11.625 Ma, Hüsing et al. 2007), but also for the coeval base of the Central Paratethys regional stage Pannonian (11.63 ± 0.04 Ma, Ter Borgh et al. 2013).

Based on our chronology, Markt Rettenbach correlates to the Upper Ervilia zone, between the mammalian levels of Gratkorn (Styrian Basin) and Atzgersdorf/Mauer (Vienna Basin). The localities from the Munich area, namely Aumeister, Oberföhring, and Unterföhring, do not significantly differ, biochronologically, from HAM 5, whereas Großlappen is stratigraphically slightly older (Fig. 4 in Fuss et al. 2015). The youngest locality Hillenloh can be correlated to the top of the *Mytilopsis ornithopsis* zone. It is slightly older than Mataschen (Styrian Basin, Chron C5r.2r-1n; Gross et al. 2011) and comparable to Bullendorf (Vienna Basin) and both Sopron and Diósd-1 (Eisenstadt–Sopron Basin). The correlation of Ingolstädter Str. 166 (Munich area) is uncertain and based only on the observed erosional hiatus between this locality and the stratigraphic lower fine-clastics of Aumeister, Oberföhring, and Unterföhring (Fuss et al. 2015). However, the large mammal fauna of Ingolstädter Str. 166 (Stromer 1938) shows, with *Hoploaceratherium belvederense*, a typical Late Miocene rhino species (Heissig 1996).

The oldest *Hippotherium* remains in Central Europe appear in delta plain sediments of the paleo-Danube (Hollabrunn–Mistelbach Formation) in the northwestern Vienna Basin in localities correlated to the *Mytilopsis hoernesi* zone (e.g., Gaiselberg, Mariathal, Atzelsdorf, Zapfe 1949; Woodborn 2009) and dated to between 11.2 and 11.1 Ma (Harzhauser et al. 2007). In Eastern Europe, putative older hipparionin horses are claimed from the middle Bessarabian (Vangengeim et al. 2006) in association with a small-mammal fauna (e.g., with the presence of murids in Buzhor-1), which are clearly more modern than that from the Hollabrunn–Mistelbach Formation. However, the distinctly most ancient *Hippotherium* in the Eastern Paratethys is documented in the Gritsiv locality (western Ukraine). The geology and biostratigraphy of the Gritsiv outcrop, which is situated at the most northern geographic extent of lower and middle Bessarabian transgressions (Pevzner and Vangengeim 1993) is described in Vasilyan et al. (2013, see also Korotkevich et al. 1985 and Topachevski et al. 1996). The vertebrate fauna is derived from clay-filled karstic surfaces intercalated between lower Bessarabian algal reef carbonate (with *Sarmatimactra vitaliana*) and middle Bessarabian silts and marls (with *Podolimactra podolica*). This sea-level lowstand, during which karstification occurs, can be easily correlated on the basis of *Sarmatimactra vitaliana* (the index fossil for the late upper Sarmatian and lower Bessarabian) to Ser4/Tor1 sequence boundary. The clays and the overlying middle Bessarabian sediments show an inverse magnetic polarity (Korotkevich et al. 1985), which can be correlated to Chron C5r (Vasilyev et al. 2013). We propose here a more precise correlation to Chron C5r.1r (11.146–11.056 Ma), which is not only the minimum age for Gritsiv, but also matches its geographic position at the northernmost margin of the middle Bessarabian transgression during the TB3.1 cycle (Fig. 8). This correlation suggests that the *Hippotherium* immigration ('*Hipparion* datum event') was essentially an isochronic bioevent in Western Eurasia, occurring at

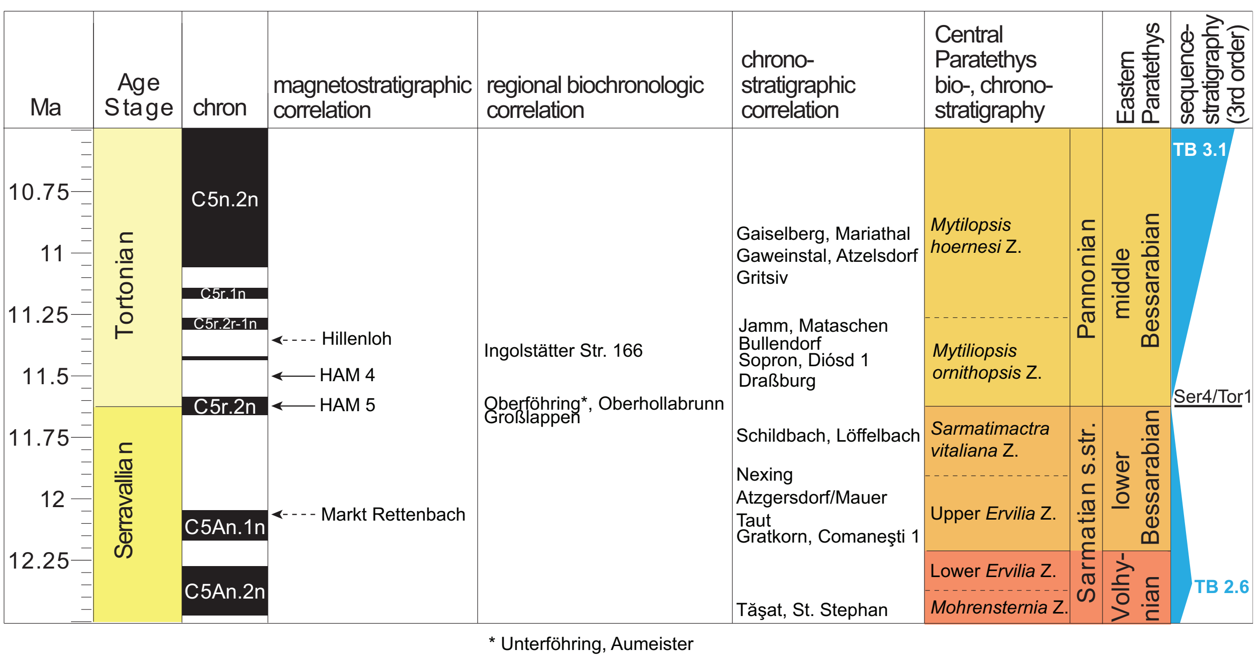


Fig. 8. Stratigraphic correlation of Middle to Late Miocene mammal localities from Central and Eastern Europe (see text for further explanations).

11.1 Ma in the Eastern and Central Paratethys and the Valles Penedes (Garcés et al. 1997). Another implication of this correlation is that the lower–middle Bessarabian boundary corresponds to the Serravallian–Tortonian boundary (Fig. 8), just as the Volhynian–Bessarabian boundary of the Eastern Paratethys correlates to the lower–upper Sarmatian boundary in the Central Paratethys (in agreement with mollusc biostratigraphy and contrary to Hilgen et al. 2012).

5.5 Paleoclimate

Both the MS and ARM records indicate cyclicity (Fig. 6), which might be related to climatic cycles. To improve the age correlation or infer global climate shifts and/or orbital cycles in the Molasse basin, however, the signal is not sufficient or distinct enough and the observed and suggested non continuous sedimentation infers too many uncertainties to suitably utilize the signals. These records might still hold as a starting point for comparison of other paleoclimatic parameters.

Proxy-based paleohumidity data for the Hammerschmiede outcrop can be inferred from pedologic and paleontologic climofunctions. The relationship between mean annual precipitation (MAP) and the depth of the soil carbonate horizon in non-vertisol soils, established for moderately mature calcic soils in alluvial fans and riverine plains (Retallack 1994, 2005, Sheldon and Tabor 2009), can be applied to the calcic paleosol developed between profiles meters 5.8 and 8.0 (Fig. 1; the two topmost paleosols are too immature) with an estimated age of 11.64 Ma. Applying Retallacks (2005) equation and a depth of 170 cm will result in a MAP of 858 ± 147 mm for this soil. Furthermore, Böhme et al. (2008) published precipitation estimates for the vertebrate faunal horizons HAM 1, 2, and 3 (old excavations), based on climofunctions for the eco-physiologic diversity of amphibians and reptiles (Böhme et al. 2006), resulting in 974 ± 256 mm, 1008 ± 257 mm, and 1196 ± 263 mm MAPs respectively. However, the exact correlation of these three vertebrate samples to our profiles remains speculative and only HAM 1 can be correlated to HAM 5 with some reservations.

These absolute values (both soil-derived and herpetofaunal-derived) are higher than during the Late Sarmatian of the Central Paratethys area (Böhme and Vasilyan 2014), but still up to 32 % lower than the present-day precipitation in the Kaufbeuren area (1241 mm, Deutscher Wetterdienst). In combination with warmer than present-day temperatures (Böhme and Vasilyan 2014) this would imply a significant seasonal water stress for the ecosystem (potential evaporation exceeds precipitation), which is also indicated by the abundant pedogenic carbonate concretions.

6. Conclusions

A magnetostratigraphic study has been carried out on a drill core near the village Irsee and on the mammal bearing section of Hammerschmiede. ChRMs were identified in 91 % of the sampled material as being carried by magnetite. The resulting polarity pattern of the drill core has three long normal polarity intervals and two reversed ones (Fig. 6). Topographic correlation of the Hammerschmiede section and Irsee drill core yields in general similar polarity patterns. We correlate the normal polarity intervals with C5An1n, C5r.2n of Hilgen et al. (2012) and C5r.2r-1n (Schneider 1995) in decreasing age, which documents for the first time the Middle to Late Miocene boundary in the NAFB with a precise magnetostratigraphic age constraint.

Inspecting the average accumulation rate, knowing that an actual constant sediment accumulation is highly unlikely in the studied sections, suggests some main phases of erosion between ~ 11.41 and ~ 11.59 Ma and between 11.66 and 12.05 Ma. There is evidence of enhanced erosion at ~ 11.5 Ma in the form of an erosion channel at the Hammerschmiede section.

There might be a relationship between proposed hiatuses present in the Irsee drill core sediments and more or less isochronous sediment cessation events in the Vienna Basin. To identify this as a more global feature, however, more detailed data would be necessary.

Additionally, we calculate the youngest UFM sediments in the Bavarian part of the NAFB to be ~ 11.09 Ma old. We therefore constrain the age of the 122 m long UFM core from Irsee to 12.2 to 11.1 Ma (late Sarmatian to Pannonian C). A total of 450 kyrs seems not to be present in the Irsee drill core, which would suggest that only 60 % of time is represented in the *Obere Serie* stratigraphy of the Kaufbeuren area. Assuming constant accumulation rates and/or similar stratigraphic representation for the up to 300 m thick lithostratigraphic unit *Obere Serie* (sensu Doppler 1989) would place the initiation of their deposition, or the *Geröllsandserie* – *Obere Serie* transition at 13.8 Ma, contemporaneous with the Middle Miocene global climate transition at the onset of the Badenian salinity crisis (De Leeuw et al. 2010) and the Langhian–Serravallian boundary. It has further been shown here that coal layers enriched in organic matter have little spatial coverage and therefore cannot be used as regional stratigraphic markers.

Our results put crucial constraints on a straightforward mammal biostratigraphy of Central Europe and allocate the Hammerschmiede fossiliferous level HAM 5 as a continental chronostratigraphic tie-point for the base of the Tortonian stage and respectively the Pannonian regional stage. We define the age of HAM 5 to be within the normal polarity chron C5r.2n (11.592–11.657 Ma). Assuming a rather constant accumulation within chron C5r.2n would put the age of HAM 5 at 11.62 Ma, just slightly younger than the base of the Tortonian. The only partly studied Hammerschmiede fauna includes 85 taxa from 55 vertebrate families so far, highlighting this locality as one of the taxonomically most diverse Late Miocene vertebrate localities on a global scale.

Furthermore, by lateral correlations we suggest ages of the nearby mammal localities Markt Rettenbach of 12.06 Ma and Hillenloh of 11.30–10.41 Ma, which are consistent with biochronologic data. It also appears that the lack of hipparionin horse fossils in the Bavarian part of the NAFB has a chronologic, rather than ecologic reason. According to our chronology and discussions the '*Hipparion* datum' was a bioevent in western Eurasia at 11.1 Ma, synchronous in the Ukraine, Austria, and Spain.

Finally, the late Sarmatian and early Pannonian climate in the NAFB seems to be cyclic and less humid than today (as proposed by Harzhauser et al. 2007, for the Central Paratethys), thereby providing a significant water stress for continental ecosystems.

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