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Contents

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The early Late Miocene hominid locality Hammerschmiede (Bavaria, Southern Germany) – excavation, stratigraphy, and taphonomic insights

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Abstract

The early Late Miocene fossil site of Hammerschmiede has been known for over half a century, but prior research primarily focused on taxonomy. Excavations by the University of Tübingen since 2011, with enhanced documentation and excavation techniques from 2017 onwards, have significantly increased both the quantity and quality of fossil finds, enabling detailed spatial and taphonomic analyses. The sedimentary sequence of the Upper Series lithostratigraphic unit at Hammerschmiede dips gently northward (<1°), linking it structurally to the Inclined Foreland Molasse. The site features seven fossil-bearing strata dated to between 11.62 and 11.56 Ma at the base of the Tortonian, respectively Pannonian stages. Current excavations are focusing on two fossil-rich fluvial deposits (HAM4, HAM5), representing distinct environments: a dynamic meandering river (HAM4) and a smaller, more stable rivulet (HAM5). Differences in vertebrate assemblages, microfossil distributions, and charcoal abundance suggest distinct ecological and environmental conditions between the two levels, reflecting variations in vegetation, fire regimes, and habitat structure. The HAM4 river was probably surrounded by a fire-prone, relatively sparse tree vegetation, providing some open space in the riparian landscape. In contrast, the HAM5 rivulet, which harbours both syntopic great apes *Danuvius guggenmosi* and *Buronius manfredschmidi*, may have flown through a more densely vegetated habitat. Both watercourses are characterised by organisms indicating clean and well-oxygenated waters (e. g., unionid mussels, salmonid fishes, giant salamanders), but geochemical data reveal redox-driven mineral alterations of fossil bones and plant remains. This was probably caused by a strong redox boundary at the sediment-water interface, induced by muddy bedload sediments, which are generally very fine-grained and range from silty clay (HAM5) to silty fine sand (HAM4). Lithic components coarser than sand are practically absent in the Hammerschmiede sequence. Observations of the exposed channel structures, supplemented by multiple orientation measurements on elongated objects and by taphonomic observations on possible individual skeletal strewnfields, uncover a meandering flow direction of the HAM4 river from southwest towards northeast and for the HAM5 rivulet from south to north. Biostratinomic studies further reveal complex bone accumulation patterns influenced by bone properties, flow dynamics, sediment composition, and biological activity. Skeletal strewnfields, including remains of mammals, birds, and turtles, suggest carcasses were introduced episodically, with some partial decomposition before fluvial transport. The HAM4 river experienced significant discharge fluctuations, affecting bone sorting and preservation. In contrast, the HAM5 rivulet exhibited lower turbulence and better-preserved skeletal associations.

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The exceptionally high biodiversity of Hammerschmiede, including currently 151 vertebrate species among which 86 are mammalian taxa, suggests a resource- and nutrient-rich ecosystem. This site may therefore provide a rare opportunity to study Late Miocene biodiversity at high temporal resolution. The well-documented stratigraphy allows α-diversity reconstructions at a resolution down to centuries, bridging the temporal gap between fossil and extant ecosystems. Additionally, the site preserves a geodiversity archive of climatic and ecological signals across multiple timescales. These findings underscore the importance of high-resolution excavation and documentation techniques in palaeontological research.

Keywords

Miocene, taphonomy, Hammerschmiede, meandering river, excavation techniques

1 Introduction

During the Late Mesozoic (mid-Cretaceous), the convergent movement of the African-Adriatic (Apulian) and European plates initiated extensive tectonic processes that led to the formation of the Alpine mountain ranges – an event known as the Alpine (Alpide) orogeny (Schwerd et al. 1996). Throughout the Cenozoic, the progressive and intensifying continental collision resulted in the accumulation of predominantly continental deposits within an orogenic wedge, which gradually advanced northward into the European Plate. As the growing mountain range underwent crustal thickening, the added mass caused it to "sink" into the earth's lithosphere and underlying mantle due to density compensation. At the same time, the peripheral lithosphere to the north experienced flexural bending. The depth and width of the resulting foreland basin were governed by the flexural rigidity of the lithosphere (Schwerd et al. 1996). In the case of the North Alpine Foreland Basin – also referred to as the Molasse Basin (from the German *Molassebecken*, itself derived from the French term *molasse*, meaning "very soft") – this basin extends more than 1000 km east to west, spanning France, Switzerland, Germany, and Austria along the entire Alpine front (Schwerd et al. 1996). The basin reaches a width of up to 130 km, with its primary phase of subsidence occurring between the Late Eocene and Late Miocene (Lemcke 1988, Schwerd et al. 1996, Kuhlemann et al. 2002, Doppler et al. 2005, Kuhlemann 2007).

The basin structure functions as a sediment trap, continuously accumulating material throughout its evolution. These sediments primarily consist of erosional products and debris from the rising Alps to the south but also include material from the Bohemian Massif to the north. This ongoing sediment accumulation further contributed to the basin's subsidence.

Due to significant variations in basin depth, sediment sources, and water supply, the deposited sequences show substantial differences across the entire foreland basin. The basin is deepest near the southern orogenic front and gradually rises at a low angle toward the north, resulting in sediment thicknesses of up to 5000 metres in the southernmost areas (Schwerd et al. 1996). A borehole near Opfenbach (Bavaria, Allgäu region), 65 km southwest of Hammerschmiede, documented 3650 metres of Molasse sediments (Lemcke 1988; Fig. 1.0.1).

The sedimentary record of the North Alpine Foreland Basin can be divided into four major sedimentary phases, which are characteristic of southern Germany and the Allgäu region in particular (Steininger et al. 1989, Schwerd et al. 1996, Scholz 2016). Depending on the degree of basin subsidence and global sea level fluctuations, marine transgressions of the Paratethys Ocean periodically flooded the foreland basin (Schwerd et al. 1996, Scholz 2016).

The oldest sediments in the Molasse Basin date back to the latest Eocene and belong to the Lower Marine Molasse (*Untere Meeresmolasse*, UMM; latest Eocene – earliest Oligocene) (Schwerd et al. 1996, Doppler et al. 2005, Scholz 2016, van der Boon et al. 2018). These are followed by terrestrial fluvial sand, silt, clay, and marl deposits, forming the Lower Freshwater Molasse (*Untere Süßwassermolasse*, USM; Early Oligocene – Early Miocene). Another marine transgression then led to the deposition of the Upper Marine Molasse (*Obere Meeresmolasse*, OMM; Early Miocene). The final major phase consists of terrestrial, predominantly fluvial deposits of the Upper Freshwater Molasse (*Obere Süßwassermolasse*, OSM; late Early Miocene – Late Miocene).

Ongoing Alpine tectonic activity from the south (Austroalpine nappes; *Alpine Decken*, Fig. 1.0.1) resulted in the overthrusting of the lowermost Molasse sediments (*Überfahrene Molasse*). In the southernmost region, parts of these deposits were folded and steeply

In addition to transport processes, sedimentation primarily considers the depositional state – the moment when a component can no longer be transported and becomes incorporated into the sediment. Retention on the riverbed is influenced by bottom friction, adhesion, and the weight, density, and surface properties (e. g., contact area) of the components (Voorhies 1969, Behrensmeyer 1975). Ultimately, the flow energy must not exceed the forces anchoring the component to the substrate to ensure permanent deposition.

During the intermediate phase between transport and final deposition, objects can undergo orientation adjustments. For example, elongated elements may align with the flow direction due to an anchor effect created by an asymmetrical shape or a heavier end. Alternatively, those objects may roll perpendicular to the flow (Lyman 1994). The statistical evaluation of the orientation of elongated objects within a deposit can thus provide critical insights into the flow direction and velocity of the depositing current (Müller 1963, Lyman 1994).

One effective method for analysing such orientations is the use of rose diagrams or line-direction histograms, which illustrate the alignment and length distribution of elongated components such as bones or wood fragments (Kreuzer 1988, Lyman 1994). Following Frison & Todd (1986), these diagrams can distinguish between random and non-random orientations of long-axis elements. An asymmetry in the diagram is interpreted as a non-random, flow-influenced positioning of components (Frison & Todd 1986, Lyman 1994).

Previously little considered, research is now increasingly including taphonomic observations and ecological conclusions that are unfolding the overall picture of the early Late Miocene Hammerschmiede ecosystems (e. g., Böhme et al. 2019a, Mayr et al. 2020a, 2020b, 2022, Lechner & Böhme 2022, 2023, Konidaris et al. 2023). However, the circumstances of the fossil site itself were only dealt with superficially. There is little information on the constantly changing and optimising field methods and documentation techniques, which so far have generated an extremely extensive pool of metadata that can be used to obtain further information on fossil habitats and shed light on the genesis of the fossil site itself. The present study aims at presenting and discussing initial results of taphonomic observations alongside a methodological overview. It provides insights into documentation techniques, spatial distribution, and potential contexts of finds and sites, sedimentological findings, and biostratinomic observations. Given the extensive data available, many topics are illustrated through case studies, offering an exemplary overview of the dataset, which is expected to yield even more insights in the future.

2 Excavation and documentation methods

2.1 Excavation techniques and historical review

While excavations in the early days (2011–2015) were carried out over short periods of a few days or weeks with only a small number of participants, constant methodological and technical optimisation has led to a steady increase in the number and quality of finds. Digging is mostly done with shovels, spades, hand shovels, boning knives or spatula tools, and for delicate work scalpels and dissecting needles are used. Fortunately, the rough work is carried out by workers from the clay mining company using large construction machines to remove the several-metres-thick overlying sediments, while the final exposure of the fossil layer is accomplished independently with a small excavator.

Stable finds are removed directly from the field and washed. Brittle or fragile objects are stabilised on the site with superglues of different viscosities. Usually, the moist matrix sediments prevent the adhesive from binding the matrix too strongly with the bone. More complex finds are recovered in a plaster jacket and prepared in the laboratory. Since 2021, more challenging finds have been examined by micro-CT scanner before preparation to facilitate the subsequent procedure.

2.2 Wet sieving

In 2016, clay mining in the pit reached the areas of HAM5 that had been exposed for the first time over a large area. In a large-scale securing operation, about 23 tonnes of the fossil layer were extracted with an excavator and stored in a nearby small shed in front of the pit. At this time, there was no other way to protect the fossil-bearing strata in situ, especially to prevent the potential loss of *Danuvius* specimens (Böhme et al. 2019a). This pile of material (called "Schlämmhaufen" in the German documentation) (Fig. 2.2.1 a) was processed by screen washing since 2016 in parallel to excavations in the clay pit itself until it was completed in the 2019 excavation year and finally yielded 6 additional specimens of *Danuvius* which could thus be saved from destruction.

The first construction used for screen washing is typical for palaeontological excavations, the material was wet sieved into three grain sizes (>5 mm, >1 mm, >0.6 mm) by stacked sieves with a direct water con-

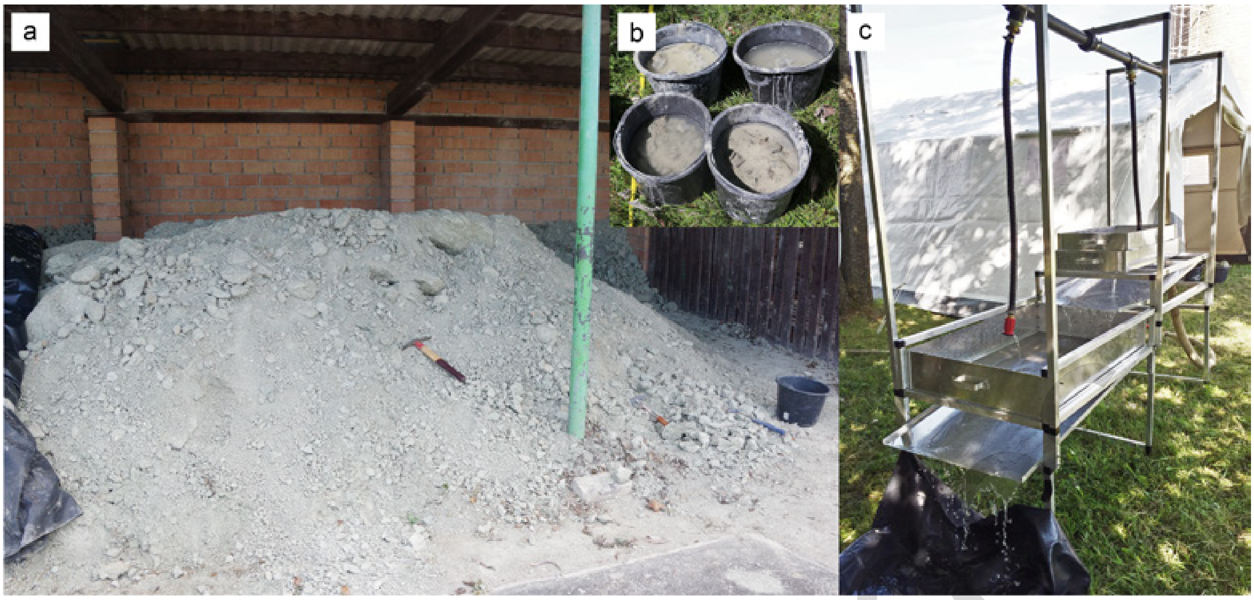


Figure 2.2.1. Overview of the first screen washing installation (August 2016) for the processing of the fossil sediments from the early Late Miocene Hammerschmiede site and the local stratigraphic level HAM5. (a) A pile of secured and stored sediments from the fossil-bearing layer HAM5 in 2016, approximately 23 tonnes. (b) The sediments were inspected for fossils, carefully coarsely crushed, and soaked with water in buckets for about 30 minutes. (c) The soaked material was screen washed and sieved into three grain sizes (>5 mm, >1 mm, >0.6 mm) using a stacked sieve screen wash construction and water from the nearby hydrant.

nection to the nearby hydrant. This work was done a few hundred metres in front of the clay pit area near a small stream into which the waste water could be discharged. At this time excavations were taking place only in HAM5. The dried clayey material from HAM5 was carefully coarsely crushed and soaked with water in buckets for about 30 minutes. At this stage, about 60 buckets of clayey mud of 10 kg each could be processed in one day (Fig. 2.2.1 b–c). The coarsest fraction had already been searched for fossils in the field. The medium grain size was transported completely and the smallest grain size in a representative sample in bags to Tübingen for further processing and picking in the laboratory (see section 2.3 Processing of the wet sieve residue).

The extreme effort to cope with the large amounts of material and finally the possibility of examining all excavation tailings for small fossils led the co-author TSL to design and construct a more optimised screening device in 2019. Based on existing designs used in industrial gold mining in North America, for example, the type selection fell on a portable sieve trommel washing system or rotational sieving system, short "Rosie" (Fig. 2.2.2). Rosie includes a horizontally rotating screen trommel with an adjustable angle, into which wet material is fed from a prewashing section. The trommel is powered by a chain drive from a windshield wiper motor, running on a 12 V car battery supported by solar panels, and rotates at a few revolutions per minute. The material is continuously washed from above by a spray bar, while the coarser fraction moves steadily toward the drum outlet due to the slight inclination. Various sieve mesh sizes are arranged along the drum sections, enabling the sorting of grain sizes and targeted removal from fine to coarse fractions. Because the particles are not thrown around as some might assume, but are slowly transported in the water film of the rotating system, hardly any damage is caused to the fossils by the washing process. In this way, more than 450 buckets per day could be processed of the clay material of HAM5 and considerably larger quantities of the sand material of HAM4 which does not need to be pre-soaked. Rosie sorts the residuals into a grain size of 1–5 mm and >5 mm. The latter is now sorted out on site in the old screen wash plant, while the former grain size is packed in bags and transported to Tübingen for further processing in the laboratory. With the completion of processing of the material from HAM5 stored outside the claypit, Rosie was directly installed and used at the excavation areas for the first time in 2020 (Fig. 2.2.2 a). The water required for this is fed to the system via around 750 metres of type B fire hose. The wastewater exits the pit via a settling basin and the site's integrated drainage system, from where it is conveyed to the nearest stream. Since 2020, all tailings have been screened for small fossils, and with the certainty of discovering all the little things, the excavation speed was increased to a higher efficiency.

subdivided into measured objects, those that were already discovered in situ and spatially documented on site, and isolated finds ("Lesefunde", Rosie specimens), those that were only registered in the wet sieving or from the collection boxes of the individual excavators afterwards. The numbers of the corresponding excavation years can be taken from Table 1. Note that geospatial measurements of finds have only taken place from the 2017 field season onwards. All numbers from previous years correspond to the numbers registered in the field book. It should also be noted that an extremely large number of microfossils are only archived in collection boxes or are still waiting for further processing, so that the actual number of finds is significantly higher.

3 Geology and stratigraphy of the clay pit Hammerschmiede

The actively mined Hammerschmiede clay pit exposes up to 27 metres of Miocene fluvio-alluvial sediments, supplemented by two major lignite seams – one near the top and one close to the base of the profile. Alluvial deposits include clays, silty clays, sands, marls, and silty marlstones. The sedimentary succession and its stratigraphic correlation in the north–south direction have been described by Kirscher et al. (2016). Due to the progression of the working area in the western direction during the last 10 years, the succession can now be better understood three-dimensionally

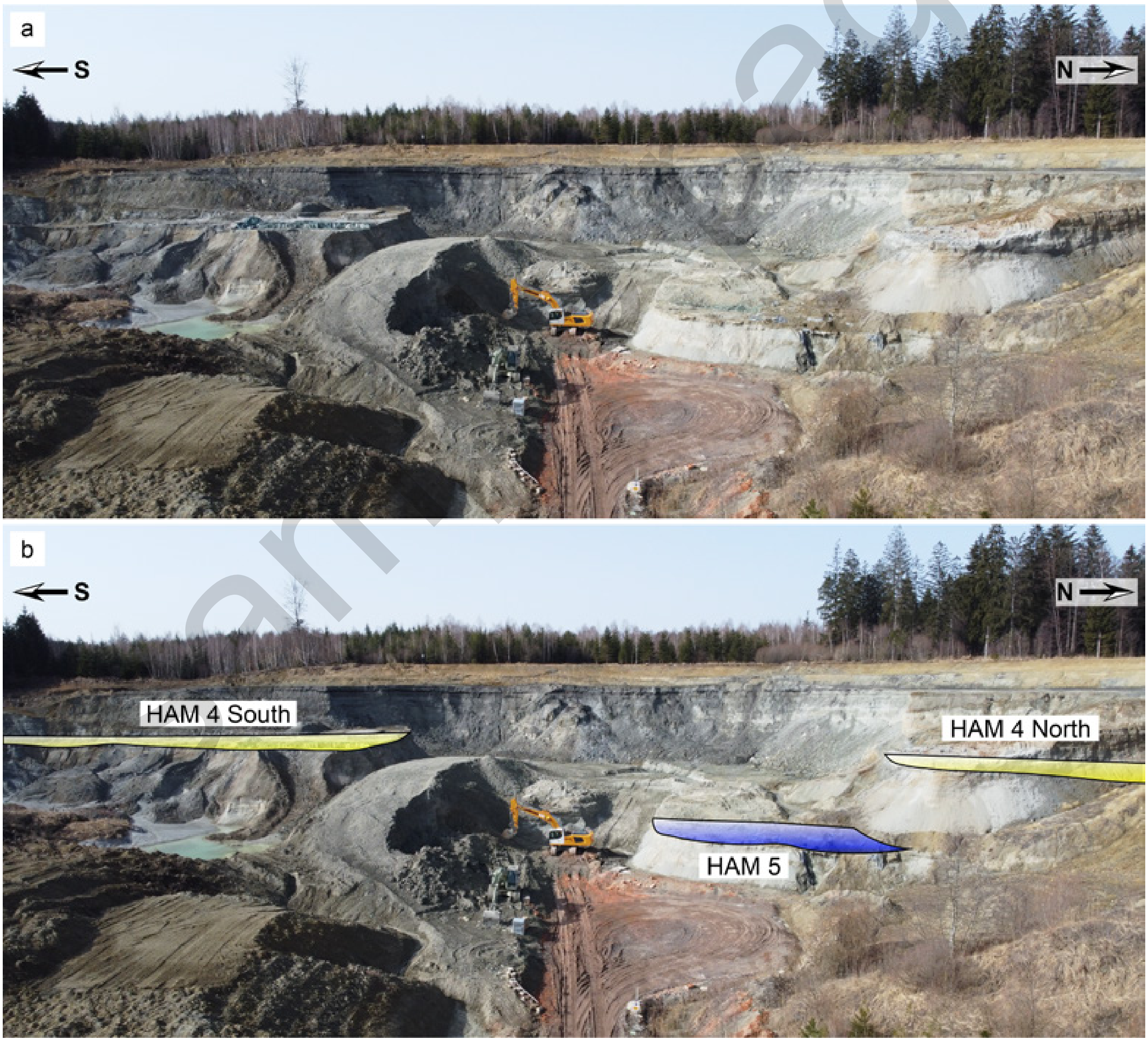


Figure 3.0.1. Overview of the Hammerschmiede clay pit, showing the approximate positions of the local stratigraphic levels HAM5 and HAM4 (February 2021). (a) Drone image from the east, in the direction of active clay mining. (b) Indicated areas of the local stratigraphic levels HAM5 (blue) and HAM4 (yellow). "HAM4 South" and "HAM4 North" correspond to the same channel HAM4, which artificially was interrupted in the central pit area due to mining activities. Image width approximately 150 metres.

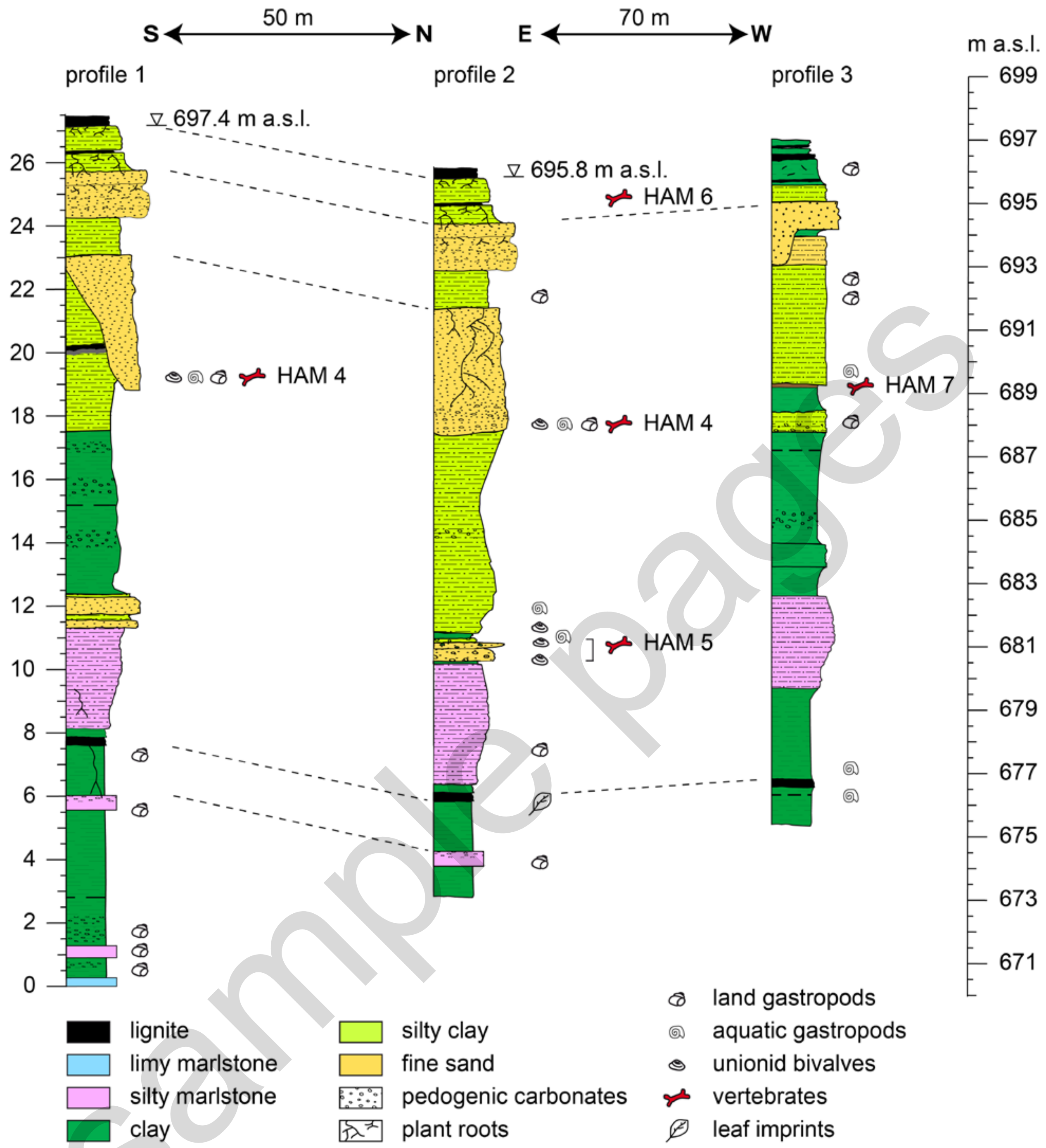


Figure 3.0.2. Lithological logs of three sections from the early Late Miocene Hammerschmiede section. Profile 1 marks the southernmost section of the clay pit. Profile 2 is located approximately 50 metres to the north of profile 1. Both profiles were exposed from 2011 till 2015 and are described in Kirscher et al. (2016), but are now lost due to clay mining. Profile 3 lies 70 metres to the west of the second profile and has been exposed since 2021. Fossil-bearing layers HAM4, HAM5, and HAM7 are marked in the profiles, and the supposed location of the historical find layer HAM6 from the end of the 1970s is noted. Note that the colour codes do not correspond to Fig. 3.0.3. The figure is updated and supplemented based on Kirscher et al. (2016: fig. 1c).

Lemcke 1988, Doppler et al. 2005, Scholz 2016). The tilt to the north was initiated by overthrusting of advancing Alpine nappes and the resulting folding and uplift of the Folded Molasse (= Subalpine or Imbricated Molasse), located more than 20 km south of Hammerschmiede.

3.1 Fossiliferous horizons of Hammerschmiede

The numbering of the local fossiliferous layers corresponds to their chronological order of discovery, not their stratigraphy (Figs 3.0.2, 3.0.3). The local stratigraphic levels HAM1, HAM2, and HAM3 are known from previous collections at Hammerschmiede (Mayr & Fahlbusch 1975, Fahlbusch & Mayr 1975, Fahlbusch 1975, Prieto & Rummel 2009, Prieto 2012), but only HAM1 was described by Mayr & Fahlbusch (1975). This site was found by Helmut Mayr (Munich, Germany) in May 1973 in the northern part of the pit at that time (eastern edge of the present-day pit). The fossiliferous horizon was a 0.5 m thick greenish-grey marl, rich in freshwater gastropods (*Bithynia*). According to our yearlong knowledge of the outcrop conditions, such a layer occurred only once in the succession between 690 and 691 m a. s. l. (Fig. 3.0.3). The unpublished horizons HAM2 and HAM3 have been found by Helmut Mayr in 1980. According to his statements to the co-author MB in the year 2000, the HAM2 level was situated five metres above HAM1 and a major sand package. Hence, we correlate HAM2 directly above the last crevasse splay sand between 695 and 696 m a. s. l. The HAM3 level was identified by Helmut Mayr above HAM2 on top of the succession. According to the discoverer's recollection, it represents a "sandy-marly channel filling with coal fragments, around 10 m above HAM1". A fluvial environment of this horizon seems indeed possible, given the freshwater molluscs (*Margaritifera*, *Spherium*, *Pisidium*, *Borysthenia*, *Segmentina*, *Gyraulus*, two species of *Bithynia*) described or mentioned by Schneider & Prieto (2011). However, sandy channel fills with coal fragments do not exist in the present-day Hammerschmiede section. A possible solution would be that HAM3 correlates with a now-removed south–north directed channel, which cut and eroded the upper seam eastwards from the present-day outcrop. In this case, the topographic correlation of the HAM3 level would be around the level of 697 m a. s. l., but stratigraphically younger than the upper lignite seam.

The fossiliferous horizons HAM4 and HAM5 were discovered consecutively by the co-author MB together with Jerome Prieto (Munich, Germany) in 2008. During the late 1970s and early 1980s, the private collectors Sigulf Guggenmos (Dösingen, Germany) and Manfred Schmid (Marktoberdorf, Germany) discovered another spatially delimited fossil horizon (Gregor 1982), classified after 2008 as HAM6. Based on photographs, notes, and memories made by both private collectors, it was possible to identify the stratigraphic position of this site, which is no longer accessible today. HAM6 was positioned at the top of the profile at the time of discovery, below the presently exposed upper coal seam above the channel HAM4 and below glacial till (S. Guggenmos pers. comm. 2017 and 2018, M. Schmid pers. comm. 2022; see photo in Konidaris et al. 2023: fig. 3). According to a profile drawn by Sigulf Guggenmos in the early 1980ies the about one-metre thick grey clay containing the partial skeleton of *Tetralophodon longirostris* and other mammals, was positioned directly above a 20 cm thick grey mica-rich fine sand and below about one metre of brownish to greyish clay. This information matches with a stratigraphic position directly above the highest (mica-rich) crevasse-splay sheet, between 695–696 m a. s. l.. Thus, the stratigraphic positions of HAM2 and HAM6 are identical.

In August 2019 another fossil stratum – HAM7 – was discovered by the two authors of this study. This horizon emerged westward of the erosional channel HAM4 with the progression of mining. HAM7 can be traced in the east–west direction for about 40 metres (Fig. 3.0.3) and is represented by two facies: 1) a 10 cm thick dark-brown organic-rich layer with a high abundance of disarticulate fish bones and teeth in addition to finds of small beavers (*Euroxenomys minutus*), snapping turtles (*Chelydropsis* sp.), charophyte gyrogonites, and molluscs belonging to the genera *Planorbarius*, *Planorbis*, and *Bithynia*. This brownish lacustrine facies is overlying dark-grey clays with sharp contact (Fig. 3.0.3). The 2) facies is found as a direct west- and northward continuation of the lacustrine dark-brown clays. It represents a 10 cm thick layer of mud containing very abundant clasts of clay, autochthonous pedogenic carbonates, and fossils characterizing non-aquatic environments (rhino teeth and *Testudo* carapace fragments). This terrestrial facies of HAM7 is developed only above mica-rich sands of a crevasse-splay tongue. This lens-shaped sand body is at maximum 60 cm thick and pinches out rapidly after 20 metres. So, the HAM7 horizon is related to a crevasse event. The damming of the sand body created a lake lateral to it (HAM7 lacustrine facies) and established terrestrial conditions above the groundwater table on top of the sand body (HAM7 terrestrial facies). Both facies underly the lacustrine clays correlated with HAM1.

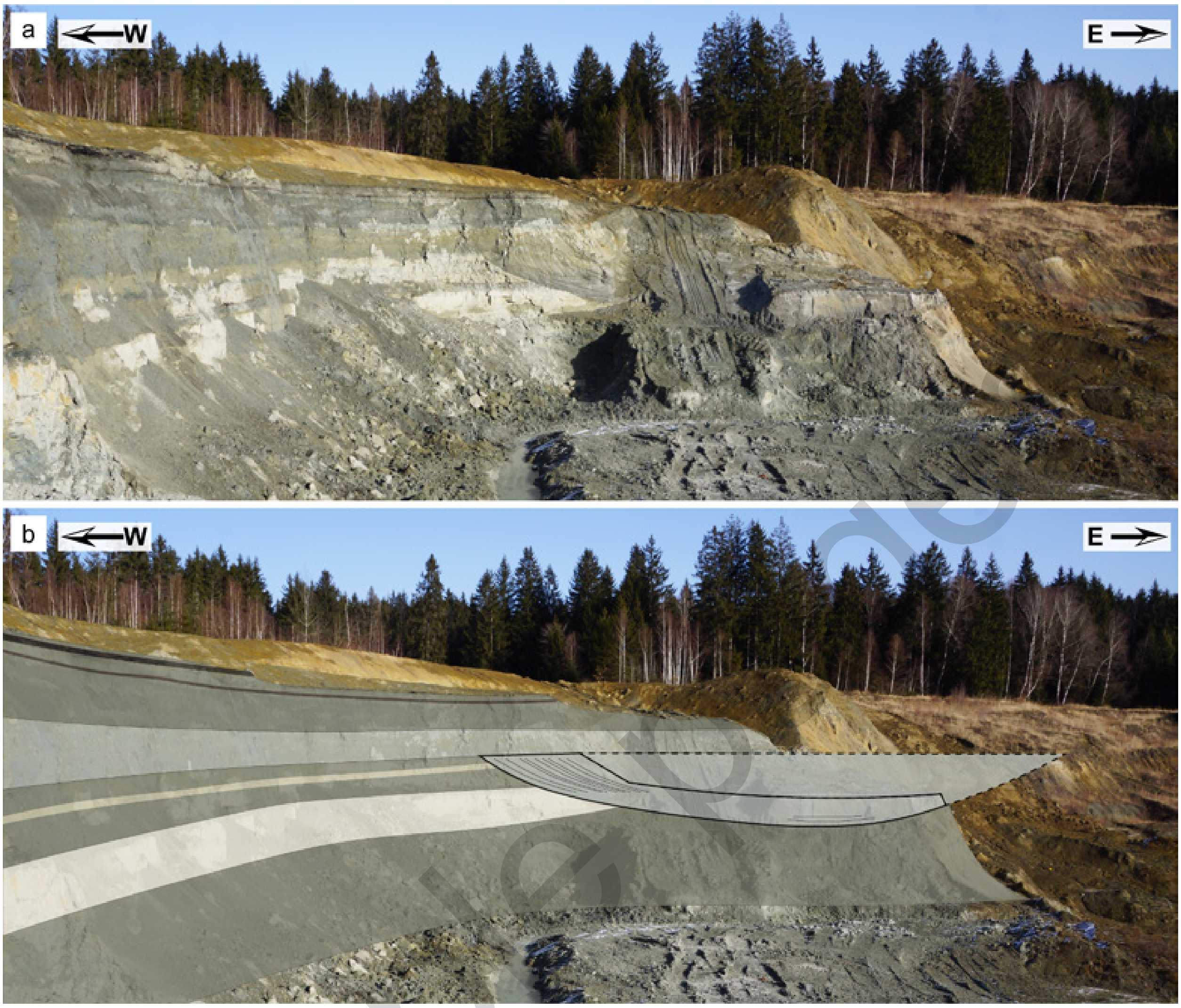


Figure 3.2.1. View of the northern wall of the Hammerschmiede clay pit in January 2020 (a) and with a sketch overlay (b). The stratigraphic hiatus between the ochre-coloured glacial till deposits of Pleistocene age at the top of the profile and the underlying early late Miocene deposits is clearly visible. The Miocene sediments are characterised by clays, silty clays, and sands (grey, green to bluish green), and one of the lignite seams (black) can be observed at the top of the pictured profile. Brighter colours indicate clay-rich strata, which dry out more quickly on the surface than the darker, sandier, and partly water-bearing levels. The erosive channel base structure represents the level and excavation area HAM4 North. HAM5 is located at the lower right edge at the base of the pit wall. Reconstructed channel width (b) as an approximate scale corresponds to about 50 metres.

3.2 The channel HAM4

The transverse section of the channel structure HAM4 is about 50 m wide and 4 m thick (Fig. 3.2.1). It preserves the main sedimentary features characterizing laterally accreting meandering rivers (Allen 1965): channel lag, lower and upper point bar deposits, and channel-fill (Fig. 3.2.2). The up to 3 m thick upper point bar and channel-fill sediments are non-fossiliferous and are removed before excavation.

For the investigation of the HAM4 channel internal mesoscale structure, two exemplary profile sections were chosen in the largest contiguously excavated area HAM4 South (2019–2023) (location of the profiles in the excavation area, see Fig. 3.2.3). Profiles were compiled transversely (Profile P1, Fig. 3.2.4) and parallel to the palaeo-flow direction approximately oriented from south to north (Profile P2, Fig. 3.2.5) of the HAM4 channel, using objects larger than 2 cm across a 4 m wide accumulation zone.

Medium and larger-sized vertebrate fossils (>2 cm) are concentrated in up to four inclined packages, interpreted as laterally accreting lower point bar units and associated channel lag deposits. Inclination occurs along the palaeo-flow direction with dip angles 2–3° (Profile P2, Fig. 3.2.5) and perpendicular to the palaeo-flow direction with dip angles 4–10° (Profile P1, Fig. 3.2.4), whereby dip angles increase with bar migration. This pattern indicates both downstream accretion

4 Palaeontology – faunal list of the Hammerschmiede

A first comprehensive faunal summary was provided by Kirscher et al. (2016) which was subsequently updated by Böhme et al. (2019a). With each excavation season, the Hammerschmiede site yields additional new species, necessitating updates to the previously published lists as well as additions and corrections. Some vertebrate species are completely new to science. Others are already known from other sites. Many taxonomic groups have not yet been extensively studied, but it is clear that the fauna is characterised by remarkable richness. To date, a total of 169 taxa can be recorded in the faunal list of Hammerschmiede (HAM1–6) (see Tab. 2). An overview of the major taxonomic groups comprises 15 molluscs (3 Bivalvia and 12 Gastropoda), 4 arthropods (crayfish, mayfly, skin beetle, termite), 11 fishes, 13 amphibians, 25 reptiles (1 Choristodera, 9 Chelonia, 15 Squamata), 15 birds, 86 mammals (15 Eulipotyphla, 1 Chiroptera, 2 Primates, 28 Carnivora, 2 Proboscidea, 5 Perissodactyla, 7 Artiodactyla, 2 Lagomorpha, and 24 Rodentia).

Table 2. Faunal list of the Hammerschmiede locality and the local stratigraphic levels HAM5, HAM4, HAM6, and HAM1–3 (combined). For species marked with *, Hammerschmiede is the type locality of the holotypes. Updated and supplemented with new expertise based on Kirscher et al. (2016), Table 1 and Böhme et al. (2019a), Supplementary Table 1.

Order	Family	Taxon	HAM 5	HAM 4	HAM 6	HAM 1–3
Unionida	Margaritiferidae	*Margaritifera (Pseudunio) flabellata*	X	X		X
Sphaeriida	Sphaeriidae	*Sphaerium (Amesoda) rivicola*	X			X
		Pisidium (Pisidium) amnicum	X	X		X
Architaenioglossa	Bithyniidae	*Bithynia* sp. 1	sp.	sp.		X
		Bithynia sp. 2				X
Heterobranchia	Valvatidae	*Borysthenia* sp.				X
Hygrophila	Planorbidae	*Segmentina* sp.				X
		Gyraulus sp.	?	?		X
		Planorbarius sp.		X		
Ellobiida	Carichiidae	*Carychium* sp.				X
Stylommatophora	Strobilopsidae	*Strobilops* sp.				X
	Filholidae	*Triptychia* sp.		X		X
	Helicidae	*Cepaea* sp.	X	X		
	Elonidae	*Tropidomphalus* sp.	X	X		
	Limacidae	*Limax* sp.	X	X		X
Decapoda	Potamidae	*Potamon* sp.			X	
Coleoptera	Dermestidae	gen. et sp. indet.		X		
Ephemoptera	incertae sedis	ichnosp. *Rhizocorallium jenense*		X		
Blattodea	Archotermopsidae	cf. *Microcarpolithes hexagonalis*	X	X		
Esociformes	Esocidae	*Esox* cf. *lepidotus*	X	X		X
Siluriformes	Siluridae	*Silurus* cf. *joergi*	X	X	X	X
Cypriniformes	Cyprinidae	*Tinca* sp.	X	X		X
		Gobio sp.		X		
		Leuciscus sp.	X	X		X
		Luciobarbus sp.	X	X		
	Cobitidae	*Cobitis* sp.	X	X		X
Perciformes	Gobiidae	*Gobius* sp.	X	X		X
	Percidae	*Perca* sp. 1	X	X		indet.
		Perca sp. 2	X	X		
Salmoniformes	Salmonidae	*Hucho hucho*	X	X		
Urodela	Proteidae	*Mioproteus* sp.	X	X	X	X
	Cryptobranchidae	*Andrias scheuchzeri*	X	X		X
	Scapherpetontidae	gen. et sp. indet.	X	X		X
	Batrachosauroididae	gen. et sp. indet.	X	X		X
	Salamandridae	*Chelotriton* sp.	X	X	X	X
		Triturus roehrsi	sp.	sp.		X
		Triturus aff. *montandoni*				X

Order	**Family**	**Taxon**	**HAM 5**	**HAM 4**	**HAM 6**	**HAM 1–3**
Rodentia (continued)	Sciuridae	*Miopetaurista* sp.	X	?		
	Castoridae	*Euroxenomys minutus*	X	X		X
		Steneofiber depereti	X	X		X
	Gliridae	*Microdyromys complicatus*	X			
		Muscardinus hispanicus	X	X		X
		Muscardinus sp.	X	X		
		Bransatoglis sp.	X			
		Glirulus conjunctus	X	?		X
		Eliomys reductus	sp.			X
		Eliomys assimilis				X
		Myoglis meini	X	X		X
	Eomyidae	*Eomyops catalaunicus*	X			X
		Keramidomys sp.	X			
	Cricetidae	*Democricetodon* n. sp.	X	X		X
		Collimys hiri	X	X		X
		Megacricetodon minutus	X	X		X
		*Microtocricetus molassicus**	X	X		X
		Eumyarion latior	X	X		
		Cricetodontini gen. et sp. indet.		X		
	Platacanthomyidae	*Neocometes* sp.		X		
	Anomalomyidae	*Anomalomys gaudryi*	X	X	X	X

5 Taphonomy

5.1 Area of excavation and documentation

The excavations were always clearly structured and documented separately according to their respective stratigraphic position in the profile. The local stratigraphic levels HAM5 and HAM4 should be regarded as separate sites representing different time periods and are treated here sequentially.

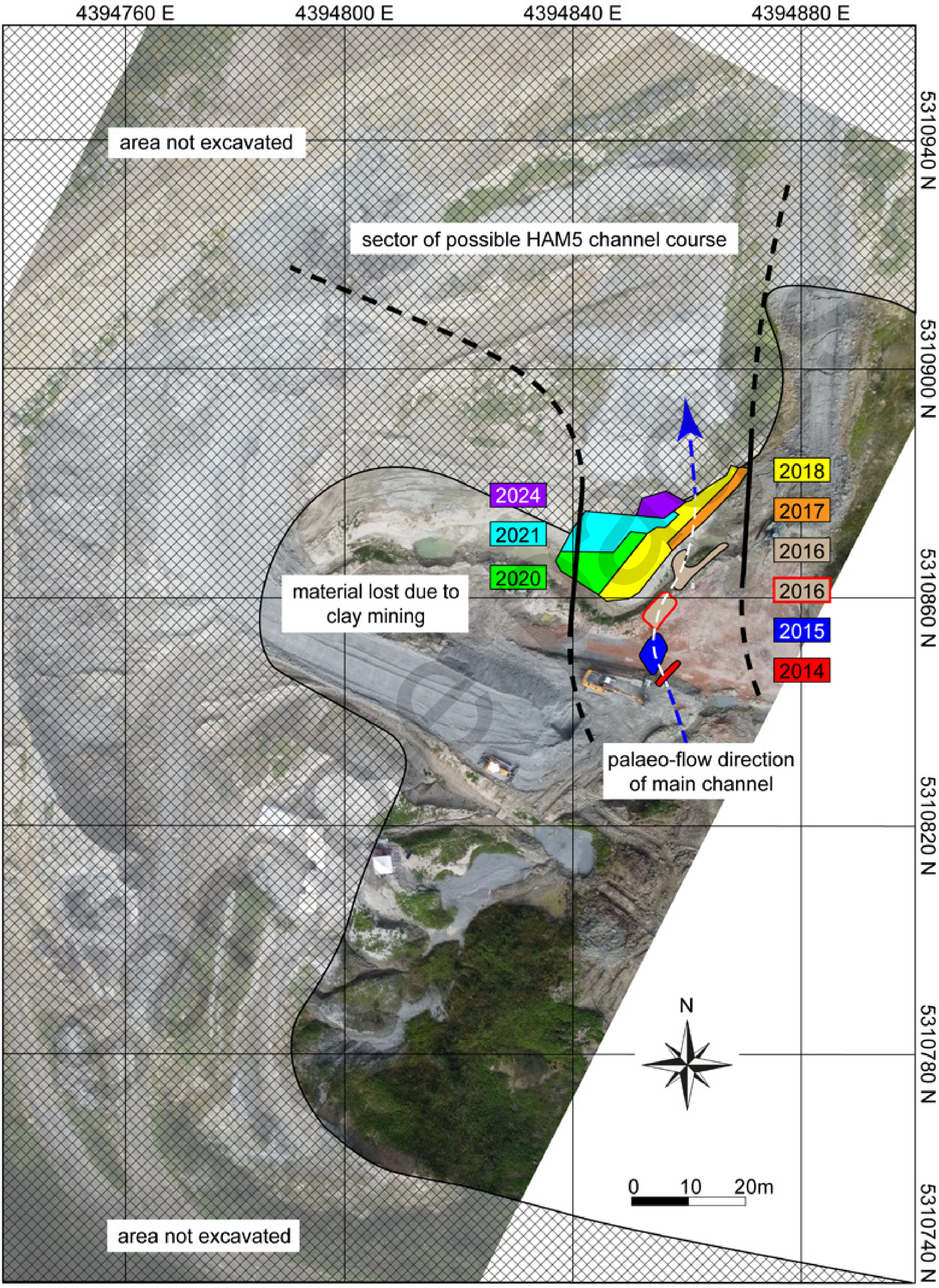
5.1.1 HAM5

In the years 2011 to 2015, no extensive excavations could take place. The exposure conditions of HAM5 were located on the steep slope of the active clay mining level, allowing only smaller-scale excavations to be carried out. In the excavation year 2016, a larger HAM5 area was exposed for the first time due to mining, as the overlying sediment was now removed. Here, for the first time, it was possible to excavate over three weeks and to work on an area of approximately 10 m^2. The finds from this period can only be estimated within the excavation area by the chronological sequence of finds. Even before the 2016 summer excavation season, a significant portion of HAM5 would have been lost to clay mining, as mining of the deeper layers was now to take place. Here, approximately 23 tonnes of the find layer was recovered on May 17, 2016, with an excavator and stored for later processing. In the subsequent excavation, HAM5 was explored in a further section with a corresponding gap in areas from previous years and also only rough localisation of finds. Only from 2017 onwards was it possible to begin a coherent excavation of HAM5, which also links up with a gap to previous areas (Fig. 5.1.1.1). Starting in 2017, finds and features were spatially surveyed, and exact find positions can now be placed in relation to each other. This was followed by excavations in 2017 (40 m^2), 2018 (100 m^2), 2020 (50 m^2), 2021 (100 m^2), 2022 (2 m^2), and 2024 (37 m^2). No excavations took place at HAM5 in 2019 and 2023.

Currently, the overlying strata of HAM4 North are blocking further progress, so that the documentation of the overlying HAM4 is necessary as preliminary work in order to continue HAM5 excavations. For the excavated areas and years 2017–2018, 2020–2022, and 2024 see Fig. 5.1.1.2, and for corresponding channel base morphology at the sections see Fig. 5.1.1.3.

5.1.2 HAM4

The local stratigraphic level HAM4 was already visible in the slope since the beginning of current research efforts in 2008. Due to its location in the middle of the mining slope, there was no possibility to realise larger


4394760 E
4394800 E
4394840 E
4394880 E
5310940 N
5310900 N
5310860 N
5310820 N
5310780 N
5310740 N
area not excavated
sector of possible HAM5 channel course
2024
2021
2020
material lost due to clay mining
2018
2017
2016
2016
2015
2014
palaeo-flow direction of main channel
N
0
10
20m
area not excavated

◄ **Figure 5.1.1.1.** Top view of the Hammerschmiede clay pit (drone image, September 2022) including the excavation areas within the local stratigraphic level HAM5 at the early Late Miocene Hammerschmiede locality. The areas of 2017, 2018, 2020, 2021, and 2024 mark contiguously excavated and spatially documented areas. The areas of 2014, 2015, and 2016 correspond to approximate estimates. The red encircled 2016 polygon indicates an area that was under threat of destruction from mining activity. Sediments of this section have been removed, stored (approximately 23 tonnes), and separately processed over the following years. Thick black lines indicate the channel course based on outcrop observations. Dashed thick lines indicate the presumed course from the south and a possible area of the course to the north (secured by laterally delimiting outcrops). The thick blue and white dashed lines indicate the course of the deepest incised main channel of HAM5. Unexcavated areas are shaded and other areas at this elevation have been lost due to clay mining. Coordinates correspond to Gauss-Krüger Zone 4 grid in metres. Grid spacing equals 40 metres.

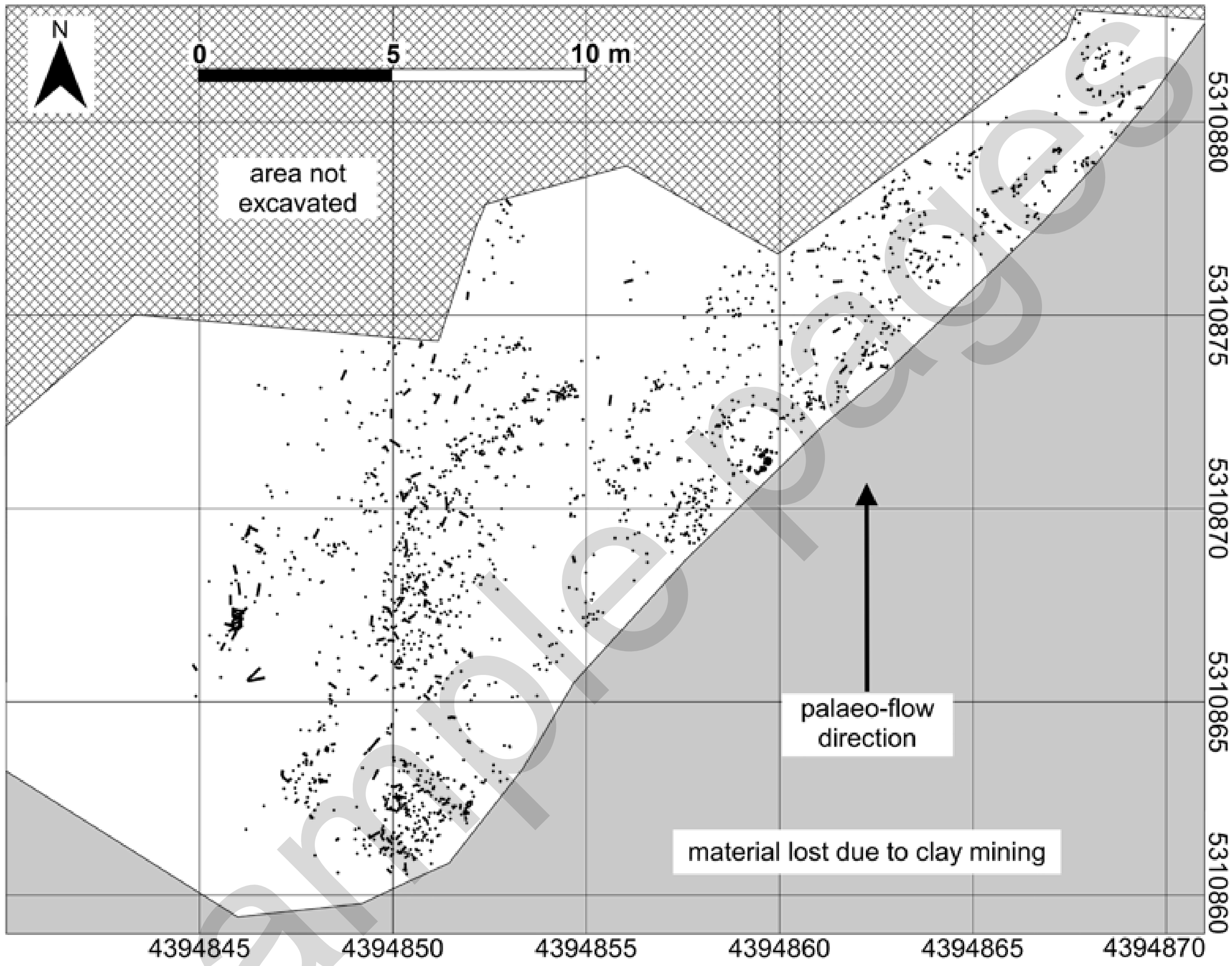


Figure 5.1.1.2. Detailed map of find distributions in the area of the local stratigraphic level HAM5 at the early Late Miocene Hammerschmiede site. The white polygon frames fully excavated areas of the years 2017, 2018, 2020, 2021, 2022, and 2024 (no excavations took place in 2019 and 2023). Black dots mark excavated and measured isolated finds (mostly bones). Black lines represent elongated bones including length and orientation. The black arrow indicates the presumed palaeo-flow direction of the watercourse. The grey area has been lost due to clay mining, and the shaded area includes unexcavated areas. Coordinates correspond to Gauss-Krüger Zone 4 grid in metres. Grid spacing equals 5 metres.

excavations until 2017. Until then, only single finds could be recovered from the slope. Only a change in the mining strategy of the pit operator (the pit became too deep, as the sediment thickness increased in the mining direction) with the creation of a mining floor in the stratigraphic level of HAM4, made it possible there to excavate over a wide area (Fig. 5.1.2.1).

After the intended end of the excavations in 2017, the extreme density of finds in HAM4, which was about to be mined, was recognised. The first finds were so promising that a new excavation campaign was carried out for a further 3 weeks in the autumn of the same year and continued in the same area in the spring of 2018. Until the following excavation period, the clay mining was so extensive that our work could only continue with a sufficiently large gap to the adjacent areas in the south, middle, and north. Until the temporary protection granted from spring 2020 and the final pro-

Figure 5.6.2.1. Different preservation conditions between the local stratigraphic levels HAM5 and HAM4 at the early Late Miocene Hammerschmiede site. (a–b) Two humeri of the antelope species *Miotragocerus monacensis* from the two different local stratigraphic levels HAM4 (a) and HAM5 (b) in lateral (a1, b2) and cranial (a2, b1) views. Note that the joints of the two bones shown indicate a humerus of nearly the same size. While the HAM4 humerus (a) is preserved almost intact in 3D, the HAM5 humerus diaphysis has undergone extreme medio-lateral compression resulting in significant lengthening (proximo-distal and cranio-caudal) while the distal joint itself is well-preserved. (a) SNSB-BSPG 2020 XCIV-7776; (b) SNSB-BSPG 2020 XCV-480. Scale bar equals 10 mm.

the workers and palaeontologists themselves, who of course may have caused damage to the finds in the form of mechanical fractures and displacements. The very sandy and silt-rich deposits of HAM4 show significantly less susceptibility to these contemporary pressures. Bones were recovered only a few centimetres below the excavator trackway, which left the internal cavity of the shaft intact. In most cases, any compressive damage that occurs affects the bottom sides of bones, which have collapsed. This is possibly caused by an historical ground failure of the surrounding sediments due to most probably very high lithostatic overburden pressures during diagenesis, as fragments are stabilised by mineralisation (Fig. 5.6.2.2).

5.8.4 Case study IV: HAM4 – *Dorcatherium naui*

The tragulid *Dorcatherium naui* is among the most abundant large mammal remains found in the Hammerschmiede deposits. Since finds of *Dorcatherium* are scattered almost everywhere, it is particularly difficult to reconstruct single individuals by strewnfields. In the southernmost excavation area (2019) within the very small proximity of a little more than one square metre at least 53 bones have been unearthed that are all anatomically assigned to the tragulid species *Dorcatherium naui* (Fig. 5.8.4.1).

The western section consists of various bones of the left and right hind limbs (without pelvic bones), and the eastern section yields 20 ribs (eleven right, nine left) from an extremely small spot (Fig. 5.8.4.2). In the entire area one thoracic vertebra and four cervical vertebrae (including axis but no atlas) were found. Between the closely adjacent find areas of the hind limbs and the ribs an excellent preserved skull of an adult female *Dorcatherium naui* was recovered (Hartung & Böhme 2022). Furthermore, a hemimandible was excavated in very close proximity to the main accumulations, which matches the dental wear and state of the cranium and occludes perfectly with the maxillary tooth row.

The monospecific accumulation of bones of *Dorcatherium naui* and the low density of finds in the vicinity of this enrichment spot, the anatomically correct arrangement (no perfect articulation) of many bones and skeletal regions, the perfect fit of pedal joints and the absence of duplicate skeletal elements leads to the conclusion that all of these bones belong to a single individual.

The present case is the first observation of a special taphonomic phenomenon in the Hammerschmiede deposits. The classical theory assumes that sedimentation or transport of bones is controlled by their physical properties, and especially by the density and shape of the bones (Voorhies 1969, Behrensmeyer 1975, Hanson 1980, Behrensmeyer 1988). According to this model, ribs and vertebrae are the "lightest" elements, which are transported the fastest and farthest away from the initial point a carcass enters the fluvial system. In this case study, ribs from both sides of the thorax appear to have remained at their initial location, along with the skull and some limb bones, while the thoracic vertebrae are largely absent, suggesting they were transported elsewhere. This biostratinomic observation is somehow similar to the situation of the juvenile *Propotamochoerus* described above, and we favour a similar explanation. A decisively different parameter to the classical observation models is that the Ham-

Figure 5.8.4.1. Reconstruction of the skeleton of *Dorcatherium naui* (Artiodactyla, Tragulidae) from the early Late Miocene Hammerschmiede fossil site and the local stratigraphic level HAM4. The skeleton was digitally assembled from 53 bones, which presumably belong to one individual. Bones belonging to the skeleton find, which are only present on one body side, were mirrored. Supplemented elements in white. Scapula, for *Dorcatherium* from Hammerschmiede unknown at the time of reconstruction, is supplemented from living artiodactyles (black). The front legs do not belong to this individual but were added from finds from the Hammerschmiede. Scale bar equals approximately 10 cm. Reconstruction created by C. Kyriakouli.

to flow in a helical motion must also be considered. Nevertheless, the fundamental assumption remains that the lateral dispersion of transported elements increases with distance.

5.9 Biogenic bone modifications and possible producers

A large number of the recovered bone finds from Hammerschmiede show possible traces of biogenic (animal or plant / algae / bacterial) modification. The following is an overview of the traces found in the Hammerschmiede material and an assignment to a possible producer. Traces are mainly found on disarticulated, isolated specimens and have not yet been recognised on bones belonging to skeletal strewnfields of single vertebrate individuals. Related or associated finds possibly have not been available to the modifiers (temporally, spatially), which could possibly imply that the better-preserved skeletal find complexes arrived at the site rather late, shortly before the final sediment cover.

Splinter bones: A significant amount of bone finds show mechanical breakage and fracturing or splintering into smaller parts and fragments (Fig. 5.9.1). Many of these splinters and bone shaft pieces show carnivorous tooth marks (puncture marks) in addition to fracture patterns possibly resulting from chewing (Fernández-Jalvo & Andrews 2016, Arnold 2022). The way the bones are fragmented indicates that they were manipulated mechanically in a “fresh” state (e. g., Fernández-Jalvo & Andrews 2016). Many bone shaft splinters collected as isolated finds can be assigned in terms of size to the long bones of bovids, tragulids, cervids, or suids. The majority of these bone shaft fragments show typical splinter fractures and tooth marks possibly produced by larger carnivores. Since larger felids and barbourofelids possessed relatively slender canines and likely did not employ them for bone-crushing, it is improbable that they produced the observed fracture patterns. However, it cannot be excluded that they – or other feliforms – may have caused some damage using their carnassials, although their bone-processing capabilities are generally considered less efficient compared to those of hyaenas, amphicyonids, or large mustelids such as *Eomellivora*, which are more likely candidates for marrow scavenging. While there are Pleistocene sites such as Untermassfeld (Germany) where carnivore taxa could be clearly linked to specific bone modification patterns (e. g., Arnold 2022), the diversity of large carnivores present at Hammerschmiede – combined with the current lack of detailed taphonomic data on many of these taxa – precludes definitive taxonomic attribution at this stage. Overall, the angled fragmentation patterns with curved cleavage are quite similar to regurgitated and chewed bones from modern hyaenas as shown by Fernández-Jalvo & Andrews (2016).

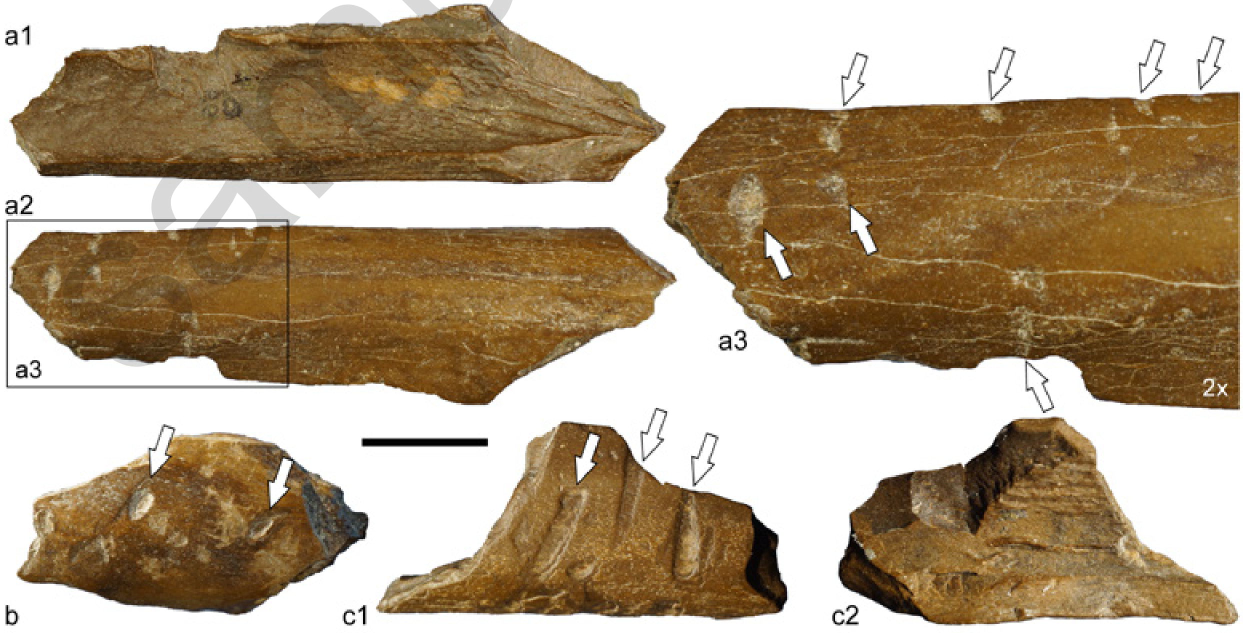


Figure 5.9.1. Bone splinters with tooth marks from the early Late Miocene Hammerschmiede deposits and the local stratigraphic levels HAM5 and HAM4. (a–c) Bone fragments most probably resembling diaphysis fragments of the antelope *Miotragocerus monacensis* showing surface pits (a2–3, b) and linear striations (b, c1) possibly produced by carnivore chewing. White arrows mark particularly conspicuous pits or linear striations. (a) GPIT/MA/19653; (b) GPIT/MA/19654; (c) GPIT/MA /16452. Scale bar equals 10 mm (a1–2, b, c) or 5 mm (a3).

6 Conclusion and outlook

The Hammerschmiede locality, known to science for over half a century, initially attracted attention primarily due to its taxonomic richness. Since the beginning of systematic excavations by the University of Tübingen in 2011 – and particularly with the implementation of advanced documentation and excavation methods from 2017 onwards – the quantity and quality of recovered fossils have significantly increased. These advances enhance spatial analyses and allow for deeper insights into sedimentary and biostratinomic processes.The sedimentary sequence of the Upper Series lithostratigraphic unit at Hammerschmiede exhibits a gentle northward dip of 0.5°–0.85°, indicating affiliation with the Inclined Foreland Molasse and the southern wing of the North Alpine Molasse Basin, which is tilted due to uplift of the Subalpine Molasse.

Seven fossil-bearing strata (HAM1–HAM7), chronologically dated to between 11.62 and 11.56 Ma, have been identified. While four of them represent historical outcrops (HAM1–3, 6), three (HAM4, 5, 7) remain accessible today, with ongoing excavations focusing on HAM4 and HAM5. The sedimentary facies within the 27 m thick exposed strata suggest a lower section composed predominantly of terrigenous floodplain deposits (containing the HAM5 level) and an upper section shaped by a dynamic meandering river system (HAM4), with associated channels, crevasse splays, and floodplain lakes (HAM1, 7).

The HAM4 channel displays a sinuous course from southwest to northeast, corroborated by both macro- and microscale flow direction analyses. These include orientations of elongated elements such as bones and wood, as well as the alignment of mass accumulations of freshwater pearl mussels. Taphonomic observations, including inferred strewnfields of individual skeletons, further support this reconstruction. Sedimentary structures in the HAM4 channel reveal a lateral and downflow accreting meandering river with four fining-upward point bar units. Fossil vertebrates, molluscs, and wood fragments are concentrated in middle to fine sands of the corresponding channel lag and the large-scale trough cross-stratified lower bar sediments. Cut-bank erosion is documented from mud clasts and reworked terrestrial gastropods and pedogenic carbonates, which are accumulated in the channel lag. The finer-grained inclined bedded sand with small-scale trough cross-stratifications of the upper bar facies contains no or very rare fossils and has been removed before excavation. The channels infill contains practically no pebble- or cobble-sized lithic clasts, suggesting that the source region of the HAM4 river was not the Alpine Orogen, but instead, its origin was intrabasinal, similar to today's nearby rivers Mindel and Günz. Further studies on heavy mineral assemblages should be conducted to test this hypothesis. The reconstructed dimensions of the HAM4 channel suggest that at bankfull stage, the river was up to 50 m wide and 4 m deep, while at low discharge, it narrowed to only 15 m in width and 1 m in depth.

Several skeletal strewnfields were detected at different excavation areas within lower bar deposits of HAM4, e. g., a suid, a tragulid, two antelopes, and avian remains. Furthermore, articulated finds of turtle shells and a bird leg (*Allgoviachen tortonica*, Mayr et al. 2022) were made. Several anatomically arranged skeletal elements indicate that at least connected parts (e. g., by ligaments) of carcasses were introduced to the fluvial system. This suggests partial carcass dehydration during the decomposition out of reach of scavengers and subsequent transportation and deposition of these elements by the river, potentially at higher discharge. The bone content within the channel lags is, similar to HAM5 (see below), very heterogeneous and mixed. Elements of assumed strewnfields of individuals are exceptions and most likely represent carcasses that were inserted late before the final burial.

The local stratigraphic level HAM5 most likely represented a smaller watercourse, more in the size of a rivulet and rather stable in place. The exact flow behaviour of the small HAM5 channel could not be clearly reconstructed due to the small extent of the available documented excavation area. Nevertheless, a slightly meandering course is suggested due to field investigations. The HAM5 flow direction towards the north is mainly estimated based on sedimentological evidence. The numerous reconstructed skeletal strewnfields of presumed single vertebrate individuals clearly indicate that a flow direction from south to north can be regarded as definite.

The HAM5 shows a main erosive channel depression, which was successively filled by two generations of fining upward sequences including basal channel lag deposits and on-top vegetation markers (roots) indicating slight temporal separations. These two channel fillings mostly enriched osteological specimens in channel lag deposits. Taxonomic, osteological, and preservative heterogeneity of the found material shows a strong intermixing and accumulation of objects from the closer but also more distant regions over a certain time, as many specimens are placed incoherently next to each other. Evidence that carcasses from the immediate vicinity washed into the HAM5 channel is provided by the reconstruction of a bony strewnfield representing a male individual of the great ape *Danuvius guggenmosi*. This discovery, as well as other skeletal strewnfields, prove that those carcasses were introduced into the area at a fairly late stage, shortly before the final burial, and thus repre-

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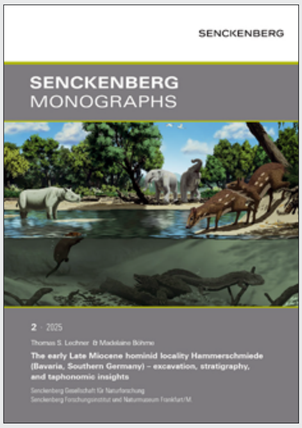

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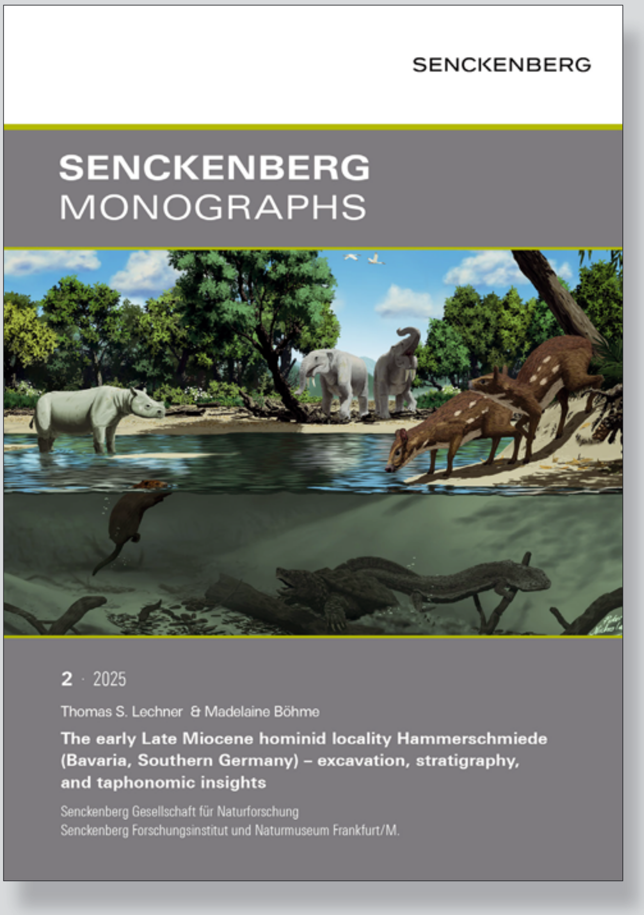

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Palaeoart reconstruction of the HAM4 channel (early Late Miocene, Hammerschmiede). Aquatic fauna includes *Silurus* (catfish), *Andrias* (giant salamander), *Chelydropsis* (snapping turtle), *Margaritifera* (freshwater pearl mussel), and *Euroxenomys* (dwarf beaver). Terrestrial mammals shown are *Dorcatherium* (tragulid), *Hoploaceratherium* (rhinoceros), and *Deinotherium* (shovel-tusked elephant). Vegetation is a hypothetical interpretation. Illustration: Peter Nickolaus

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