

# The late Middle Miocene (Sarmatian s.str.) fossil site Gratkorn – the first decade of research, geology, stratigraphy and vertebrate fauna

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**Abstract** This article summarises the history of research, the geological background and the stratigraphy of the Gratkorn locality (SE Austria). Since its discovery in 2005, 65 vertebrate taxa, comprising fishes, amphibians, reptiles, birds, and small and large mammals have been documented, as well as a variety of plant and invertebrate fossils. Due to its origin from a rapidly accumulated floodplain paleosol, time-averaging is low and the taphocoenose reflects well the original vertebrate community. The Gratkorn site is dated by integrated stratigraphy, but independent from vertebrate biochronology, to about 12.2–12.0 Ma (late Middle Miocene). Thus, it probably yields the most diverse, systematically excavated vertebrate fauna of that age in Europe and is an extremely important benchmark for a vertebrate-based, continental biostratigraphy of the Central Paratethyan realm and beyond.

**Keywords** Late Middle Miocene · Sarmatian s.str · Central Paratethys · Vertebrate fauna · Styria/Austria · Stratigraphy

## Introduction

In 2004, an intensive era of research started in the Gratkorn clay pit due to geological mapping (initiated by H.W. Flügel), which resulted in the discovery of this exceptional vertebrate locality. The mined clay deposit of the Gratkorn pit has yielded plentiful plant and invertebrate fossils. However, vertebrate findings, originating from a paleosol at the base of the pit, are of particular interest. An earlier overview has already emphasised the extreme importance of the Gratkorn vertebrate fauna and the Gratkorn site (Gross et al. 2011a). This is mainly because:

- a) It is well dated to about 12.2–12.0 Ma (late Middle Miocene; early late Sarmatian sensu regional Central Paratethyan stages corresponding to the Late Serravallian; Piller et al. 2007). Especially in the Central Paratethyan realm, well-dated and quantitative as well as qualitative rich vertebrate localities of that age are quite rare due to large-scale erosion of upper Sarmatian strata (e.g. Sabol and Holec 2002; Sacchi and Horvath 2002; Harzhauser and Piller 2004; Hír 2004; Kováč et al. 2004, 2008; Nargolwalla et al. 2006; Schreilechner and Sachsenhofer 2007; Venczel and Ştiucă 2008; Daxner-Höck and Göhlich 2009).
- b) At Gratkorn, all major vertebrate groups are represented (fishes, amphibians, reptiles, birds, mammals). The bulk derives from a quite rapidly accumulated floodplain paleosol. Despite several pre- and post-burial modifications, the taphocoenose reflects the original vertebrate community rather well.

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Dedicated to Helmut W. Flügel for his 90th birthday

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This article is a contribution to the special issue “The Sarmatian vertebrate locality Gratkorn, Styrian Basin”

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Thus, Gratkorn significantly widens our knowledge of late Middle Miocene terrestrial ecosystems in a manifold way (palaeoecology, vertebrate biostratigraphy, palaeobiogeography), a time when remarkable palaeogeographic, palaeoclimatic and in turn palaeobiotic changes reshaped Central Europe (e.g. isolation of the Central Paratethys from the world oceans and the formation of the Sarmatian Sea, and a drop of mean annual temperature and pronounced seasonality and aridity of climate; Böhme 2003; Mosbrugger et al. 2005; Jiménez-Moreno et al. 2005; Piller and Harzhauser 2005; Kováč et al. 2006; Costeur et al. 2007; Erdei et al. 2007; Böhme et al. 2008, 2011).

New or additional results since the overview of Gross et al. (2011a) concerning vertebrate taxonomy, palaeoecology, taphonomy and biochronological implication of vertebrates can be found in: Aiglstorfer et al. (2014a, b, c, d, this issue), Angelone et al. (2014, this issue), Böhme and Vasilyan (2014, this issue), Göhlich and Gross (2014, this issue), Havlik et al. (2014, this issue), Prieto et al. (2014a, b, this issue), and Van der Made et al. (2014). Further studies on, e.g. palaeopedology, trace fossils, insect, isopod, plants and carnivore remains are subjects of upcoming works.

### Geographical setting and the “first” decade of research at Gratkorn

The locality Gratkorn is situated in south-eastern Austria (federal state of Styria) about 700 m east of the market town of Gratkorn (15°20'56"E, 47°08'14"N; ~10 km NNW Graz; Figs. 1, 2). Actually, this outcrop is named St. Stefan clay pit (Gross 2008). Since “St. Stefan” or “St. Stephan” is a common name in Austria and frequently linked in vertebrate palaeontology with the early Sarmatian *Dryopithecus*-site “St. Stefan im Lavanttal” (Carinthia; Mottl 1957), we decided to use “Gratkorn” as the site name in order to avoid confusion.

For many decades, clay has been mined in the area of Gratkorn/St. Stefan. In the 1850s, the first notes about fossil plants in the area of St. Stefan were already being published (Unger 1850, 1852; Gross 1999). Nevertheless, except for the hints of leaf and freshwater gastropod remains in Flügel (1997), no further findings were recorded following Ungers' publication during the following ~150 years.

It was in summer 2004, when, in the course of geological mapping (Gross et al. 2007a; Flügel et al. 2011), the strata of the pit were sectioned and sampled for micropalaeontological purposes (note: during that time, the vertebrate-bearing paleosol was covered by debris flow deposits in the north as well as by the clay deposit in the south). Based on the microfossil content (ostracods), it soon became clear that the mined pelites represented limnic sediments of (Middle–Late) Miocene age. Since deposits as well as aquatic biota from the hinterland of the Middle Miocene Paratethyan Sea and the Late Miocene Lake Pannon are rare (Gross 2008), Gratkorn

rapidly turned into an important palaeontological site (e.g. field trips, annual meeting of the Paläontologische Gesellschaft in Graz 2005).

The high content of macro-plant remains of the pelites stimulated palaeobotanical sampling in May 2005 and gave the first biostratigraphical hints of a late Middle Miocene age (Meller and Gross 2006; Fig. 3a, b). During this fieldwork, the remarkably abundant occurrence of freshwater crabs was discovered (Klaus and Gross 2010).

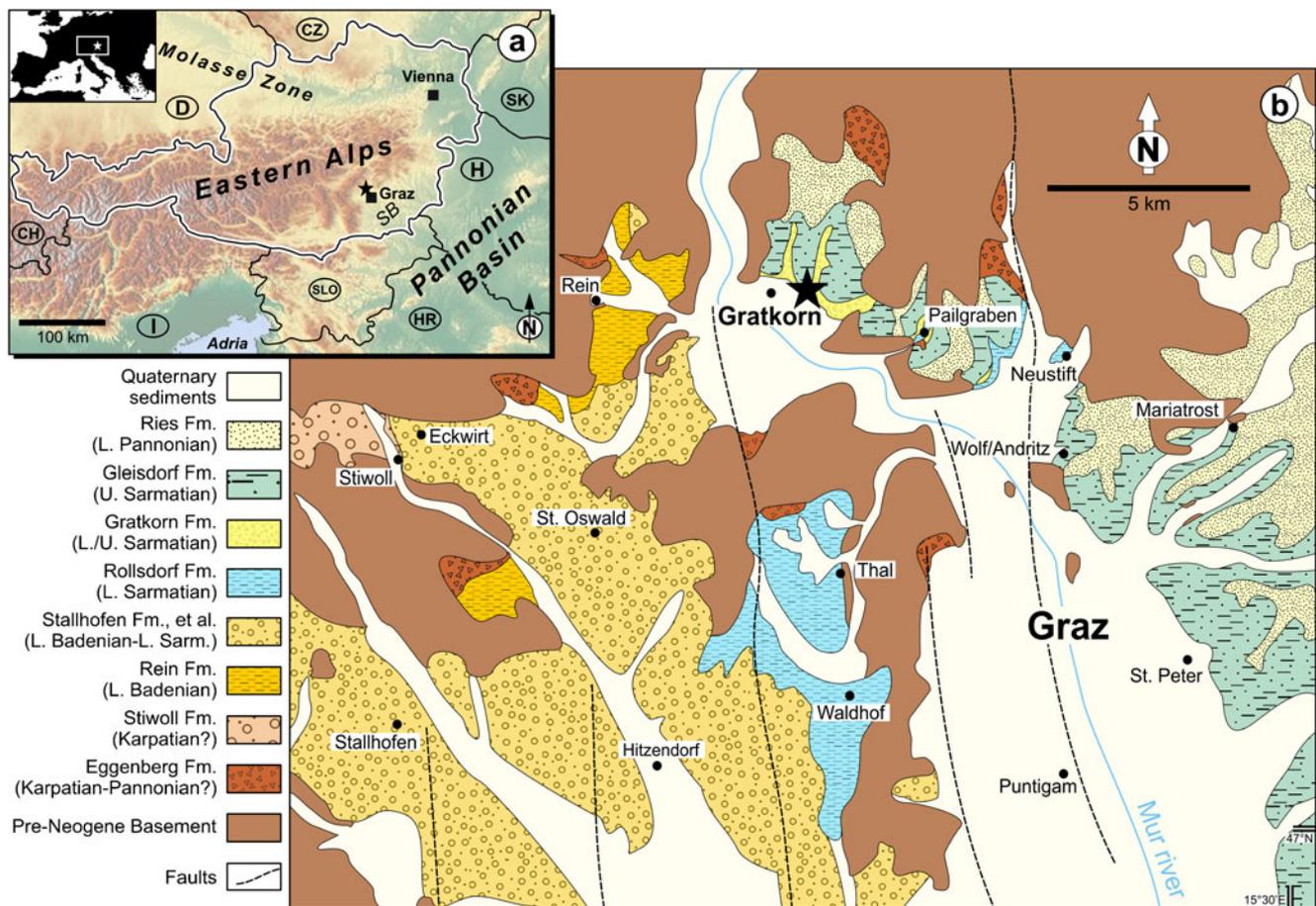
Later, the mining situation changed and parts of the paleosol became exposed, which led to the discovery of the first vertebrate remains at the beginning of July 2005. Due to mining activities, only heavily fractured teeth and larger bones were collected from the surface (note: among these findings are the teeth of the “second” deinotheres as well as the only fragment of a palaeomerycid; Aiglstorfer et al. 2014a, b, this issue). As only scattered vertebrate fossils emerged in, e.g. a joint inspection by G. Daxner-Höck and M.G. in July 2005, further excavations seemed unpromising (note: the paleosol was still largely covered by the clay deposit and other mining dumps as well as, later, by water; Fig. 3c). Nonetheless, the first bulk samples of the paleosol yielded abundant gastropod remains.

It took until March 2006, when roughly associated ribs and teeth of a deinotheres (Aiglstorfer et al. 2014a, this issue) were found, for the first systematic excavations to be initiated by the small team of the Joanneum (M.G., preparator N. Winkler and 2–4 freelancers). This campaign lasted until summer 2006 and was continued in summer 2007 (Fig. 3d–f). Meanwhile, H. Binder, G. Daxner-Höck, U. Göhlich, M. Harzhauser and P. Tempfer offered preliminary determination for the vertebrates as well as for the mollusc fauna. In particular, the latter emphasised a late Middle Miocene (Sarmatian s.str.) age for the Gratkorn paleosol (Harzhauser et al. 2008).

In May and September 2007, M.B. and Jérôme Prieto visited Gratkorn (Fig. 4a), studied already collected material and took additional bulk samples. This was the starting point for the current cooperation of Universalmuseum Joanneum–Eberhard Karls Universität Tübingen–Ludwig Maximilians Universität München, followed by annual joint excavations with German students since 2008 (Fig. 4a–d). Results from these as well as from earlier fieldwork have been previously published in Daxner-Höck (2010), Prieto et al. (2010a, b, 2012) and Gross et al. (2011a).

### Geological setting and stratigraphy

The Gratkorn pit is situated in the eastern part of the Gratkorn Basin, which belongs to a series of embayments and satellite basins along the northern margin of the Styrian Basin (Fig. 1). The basin itself is roughly encircled by carbonates of Paleozoic age (Flügel and Hubmann 2000; Flügel et al. 2011).



**Fig. 1** Location of the Gratkorn clay pit. **a** Its setting at the south-eastern margin of the Alps and northern periphery of the Styrian Basin, respectively; **b** simplified geological map of the surroundings of Graz based on

Kollmann (1965), Ebner (1983), Riepler (1988), Gross et al. (2007a), and Flügel et al. (2011), faults after Kröll et al. (1988; L Lower, U Upper)

Although outcrops as well as index fossils are rare, a correlation with the stratigraphical framework of the Styrian Basin (e.g. Kollmann 1965; Ebner and Sachsenhofer 1991; Harzhauser and Piller 2004; Schreilechner and Sachsenhofer 2007) has been achieved during recent years (Gross et al. 2007a, b, 2011a, b; Harzhauser et al. 2008).

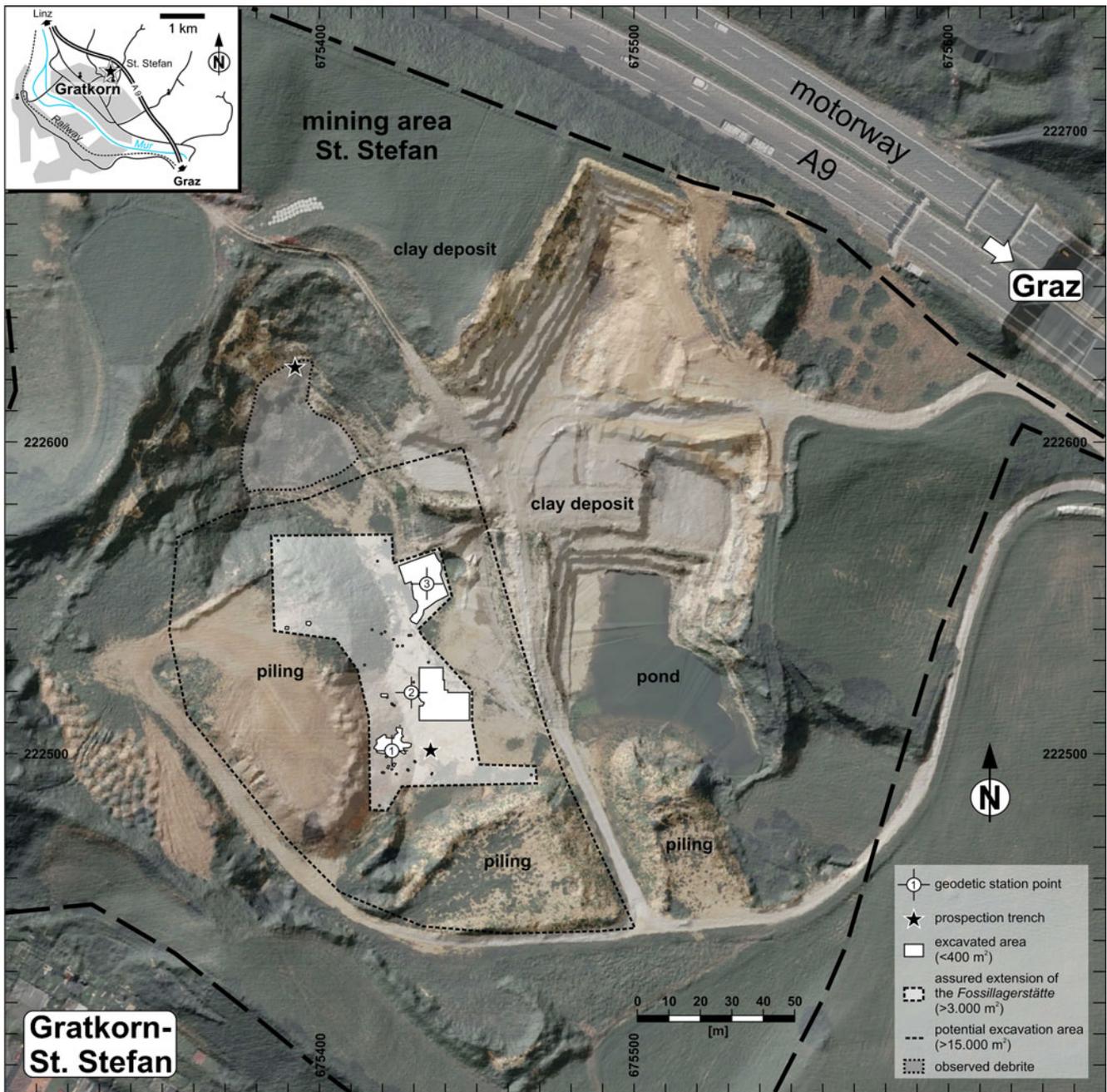
#### Litho- and biostratigraphy

In the eastern Gratkorn Basin, more than 20- to 30-m-thick, polymict coarse gravels/conglomerates with a sandy or pelitic matrix form the lowermost part of the exposed basin fill (Hilber 1893; Clar 1933, 1938; Ebner 1983; Winkler-Hermaden 1957; Flügel 1997; Gross et al. 2007a). Occasionally, horizontally or cross-bedded fine- to medium-grained gravels and sands are intercalated; locally, paleosol formation can be observed (e.g. at the base of the Gratkorn pit = the vertebrate-bearing horizon; Figs. 1, 5). These strata are termed the Gratkorn Formation (Flügel et al. 2011; compare Gross et al. 2007a) and interpreted as deposits of a braided river

system, partly influenced by distal alluvial fans (Gross et al. 2011a; compare, e.g. Hilber 1913; Winkler-Hermaden 1957).

The Gratkorn Fm. is overlain by up to 25-m-thick, massive or laminated, frequently plant-bearing, largely limnic pelites (Peterstal Member/Gleisdorf Formation; e.g. clay deposit at the Gratkorn site). Alternations of gravel-sand-pelite follow above (Lustbühel Member/Gleisdorf Fm.), and are topped by fluvial, quartz-dominated gravels/conglomerates with rare sandy and pelitic intercalations (Ries Formation; early Late Miocene/Pannonian; Kollmann 1965; Flügel 1997; Gross et al. 2007a; Flügel et al. 2011). Heterochronous talus deposits of late Early to early Late Miocene age (matrix-supported breccias and red earth; Eggenberg Formation; Flügel 1997; Flügel et al. 2011) occur, attached to the Paleozoic basement in the north-eastern Gratkorn Basin (e.g. Clar 1935; Flügel 1975).

The Gratkorn Fm. can be traced out into the Styrian Basin (at least into the northern part of Graz), where it is underlain by marginal marine, lower Sarmatian sediments (Rollsdorf Formation; *Elphidium regium* to *Elphidium hauerinum* zone; Clar 1938; Flügel 1958, 1959; Gross et al. 2007a; Flügel et al. 2011). Index fossils are missing in the overlying Peterstal Mb.,



**Fig. 2** Gratkorn respectively St. Stefan clay pit (airborne laser scan and aerial photo combined; data GIS Steiermark; geodetic station points 1/2/3 (asl ~403 m); Austrian grid BMN M34 and WGS84 coordinates: 1

675422.39/222500.29 = 15°20'56.88"E, 47°08'14.48"N; 2 675428.58/222519.01 = 15°20'57.16"E, 47°08'15.09"N; 3 675433.50/222553.91 = 15°20'57.37"E, 47°08'16.22"N)

except the abundant findings of the fossil legume *Podocarpium podocarpum* in the clay deposit of Gratkorn, pointing to an age older than the Late Miocene (Meller and Gross 2006; compare Hably 1992; Erdei et al. 2007). However, in the area of Graz, the superimposed, predominantly mixed-siliciclastic Lustbühel Mb. contains rare marginal marine faunas as well as thin oolitic layers, indicative of a late Sarmatian age (*Porosonion* zone; Gross et al. 2007a; compare Kollmann 1965; Flügel 1997).

Age correlation independent of vertebrate biochronology

The position of the Gratkorn Fm. between biostratigraphically dated underlying Lower Sarmatian strata (Rollsdorf Fm.) and upper Sarmatian hanging wall sediments (Gleisdorf Fm.) relates its deposition to the so-called "Carinthian Phase" at the end of the early Sarmatian (Winkler 1927; Winkler-Hermaden 1957; Gross et al. 2007a, 2011a; Fig. 5). During that phase, a wide-ranging sea level fall is recorded in the Vienna Basin as



**Fig. 3** Gratkorn clay pit. **a** View towards the north (May 2005) during palaeobotanical sampling; soon after the first vertebrate remains were discovered in July 2005. Just ahead of the gravel path (*gp*), the fossil-bearing paleosol (*dotted line*) is already partly exposed. East (right) of the path, the subsequent deinothere excavation area (around geodetic section point 1, *black arrow*) is still covered by the clay deposit; **b** close-up of the northern working area (**a**; *white arrow* section through the clay deposit; *black arrow* remains of a large tree trunk; *dotted line* boundary between a debris (covering the paleosol in the north) and the hanging wall clay deposit); **c** view towards the north (August 2005) demonstrating a recurrent problem of the excavation site: the

entire base of the pit is flooded due to rainfall; **d** view towards the north (April 2006). In March 2006, further remains of a deinothere (Aiglstorfer et al. 2014a) were discovered, which encouraged the first systematic excavations. Major parts of the paleosol are still covered by the only roughly mined clay deposit; **e** deinothere excavation area in April 2006. Below the pelites (with grooves of the excavator shovel), ribs and long bones are visible (partly already plastered); **f** view towards southwest in July 2007. Despite ideal dry conditions, this photograph makes the second major problem at the Gratkorn site obvious: after mining of the clay deposit, the pit is successively backfilled. Thus, huge parts of the paleosol are currently inaccessible (see Fig. 1)



**Fig. 4** Field photographs. **a** Excavation team in August 2008. For the first time, a group of German students (LMU Munich, leaders: M.B. and Jérôme Prieto) joined the team of the Joanneum (M.G., N. Winkler and freelancers); **b** excavation technique (August 2010). After removal of the pelitic cap rock, the paleosol is systematically dug by hand with knives as

deep as possible (depending on the stage of weathering, usually about 10 cm); **c** demonstration of plastering of finds (August 2013); **d** excavation situation in August 2013. M.A. is checking the finds of two students (photographs courtesy of Manuel Kapeller, Manuela Aiglstorfer and Helmut Reindl)

well as in the adjacent Pannonian Basin and Austrian Molasse Zone (Kosi et al. 2003; Harzhauser and Piller 2004; Strauss et al. 2006; Schreilechner and Sachsenhofer 2007; Kováč et al. 2008). This enables a correlation of the Gratkorn Fm. with the “Carinthian Gravel” as well as with the sequence stratigraphical concept of the Styrian Basin (Gross et al. 2007a; Fig. 5). Repeatedly, enhanced up-lift of the Eastern Alps is suggested to trigger erosion of underlying rocks and the basinward progradation of alluvial/deltaic systems (e.g. Winkler-Hermaden 1951, 1957; Harzhauser and Piller 2004). However, a strong astronomical forcing of the entire 3rd order Sarmatian sequence (approximately corresponding to the TB 2.6 cycle of Haq et al. 1988) as well as its 4th order parasequences has also been suggested (e.g. Harzhauser and Piller 2004; Kováč et al. 2008; Lirer et al. 2009). Based on astronomical tuning, Lirer et al. (2009) proposed an age of about 12.2 Ma for the early/late Sarmatian boundary.

In distal areas of the Styrian Basin, the subsequent initial late Sarmatian flooding caused sedimentation of monotonous pelites with scarce marine faunas (Kollmann 1965). At the northern basin periphery, limnic pelites were deposited (Peterstal Mb./Gleisdorf Fm.). For these fine clastics, normal magnetic polarity is recorded at the Gratkorn clay pit (Moser 1997), implying a correlation to Chron C5An.1n (12.174–12.049 Ma after Hilgen et al. 2012).

Thus, by integrated stratigraphy—but independently of vertebrate findings—the vertebrate-bearing paleosol of the Gratkorn pit formed around the early/late Sarmatian boundary, about 12.2–12.0 Ma (early late Sarmatian; Gross et al. 2007a, 2011a; Harzhauser et al. 2008).

### Section and facies interpretation of Gratkorn

At the Gratkorn pit, calcareous pelites are exploited for cement production (Fig. 6). The vertebrate-bearing paleosol represents

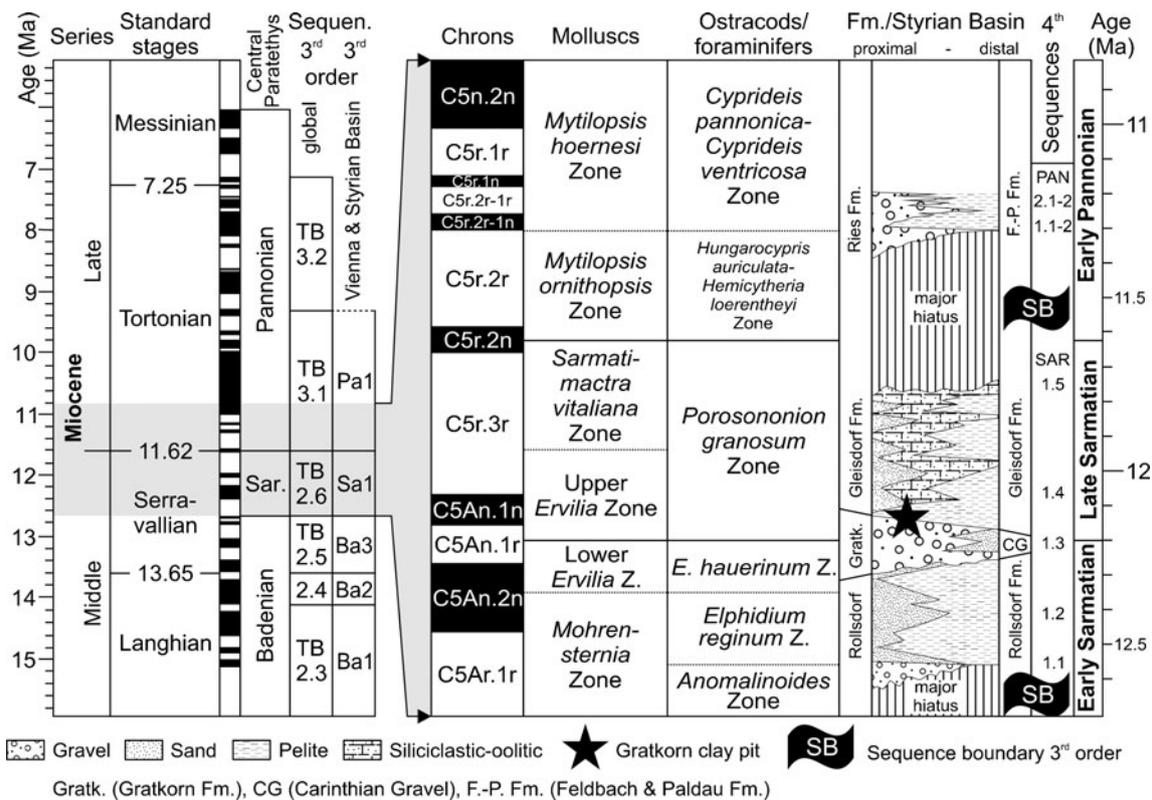


Fig. 5 Stratigraphical position of the Gratkorn site (modified after Gross et al. 2011a, b)

the mining floor. The sediment succession below the working level could be studied in two small prospecting holes only (one in the southern, one in the northern part of the pit; Figs. 2, 7). Gross et al. (2011a) has already described and discussed the southern section below the mining floor as well as the lithology of the hanging wall clay deposit. We refer to that work for details and offer here a condensed interpretation. In addition to Gross et al. (2011a), the section in the north (below the working horizon) is presented (for a section description, see Fig. 7). Both sections clearly demonstrate the lateral variability of the strata below a more or less uniformly developed clay deposit.

Facies interpretation of section I (southern part of the pit; see Gross et al. 2011a)

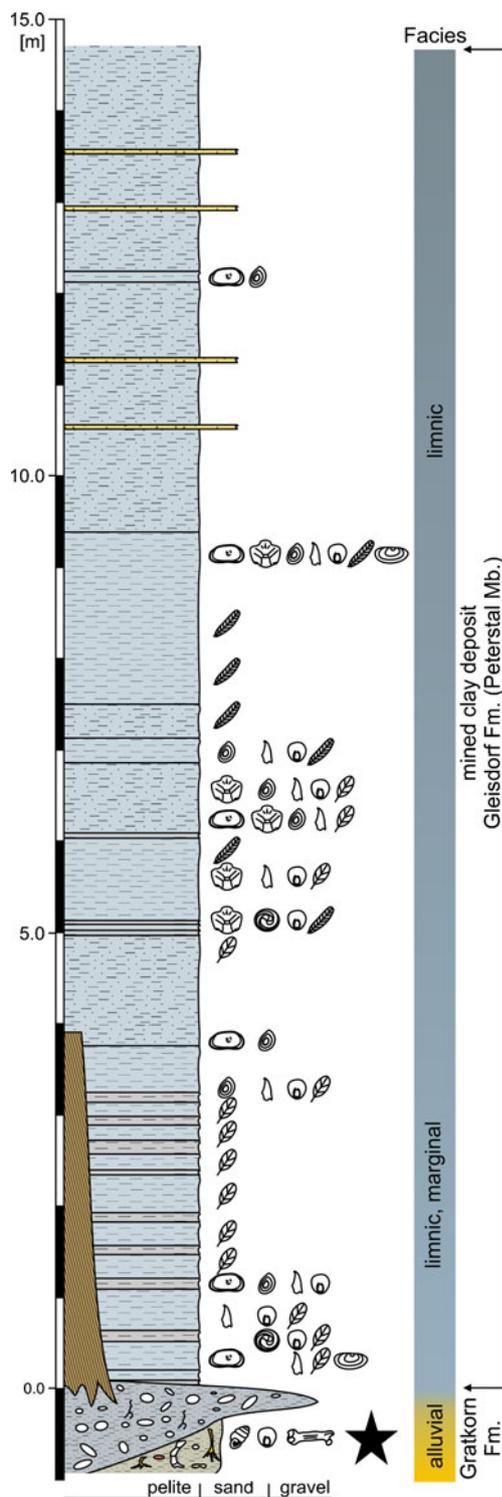
The basal gravels (I/1) are interpreted as gravel bar deposits of a braided river system, topped by sandy and silty fine sand layers (I/2, 3) of flash floods (crevasse splays) in an overbank environment (Figs. 7, 8a). Subsequent soft sediment deformation (dewatering) and indistinct pedogenic processes overprinted these layers to a certain degree. Similarly, layers I/4–5 are assumed to represent post-sedimentary altered deposits of a succeeding flooding event (crevasse splay).

Above, a sand layer (I/6) forms the base of a calcic horizon (I/7). The calcrete horizon contains ferruginous nodules (some might be rhizoconcretions) as well as cemented meniscate burrows (up to dm long, some cm wide). Carbonate nodules

are discrete or amalgamated to each other. Upon a diffuse, irregular boundary, a pelitic layer (I/8) follows, which includes many ferruginous nodules and some meniscate burrows. Layers I/6–8 are interpreted as deposits of another flooding event (crevasse splay) within an overbank environment. The moderately developed (stage III) calcrete (I/7) indicates an extended period ( $10^3$ – $10^4$  years) of pedogenesis as well as an overall arid/semi-arid climate with seasonally variable precipitation (Retallack 2001; for further palaeoclimate estimations, see Gross et al. 2011a; Böhme and Vasilyan 2014, this issue).

The sandy layer (I/9; Fig. 8a–c) indistinctly fines upwards and merges into silty fine sand (I/10) with abundant ferruginous nodules as well as burrows of variable shape and size. Large meniscate burrows (Fig. 8c) of both layers equal possible freshwater crayfish burrows from the Bavarian Upper Freshwater Molasse (Schmid 2002). As freshwater crab remains (*Potamon*) are rather abundant in the mined clay deposit (Klaus and Gross 2010), potamid crabs should be taken into account as producers of those burrows. We interpret both strata as crevasse splay deposits, which subsequently experienced weak pedogenesis and intensive bioturbation.

Layer 10 grades upwards into a ~0.4-m-thick, angular blocky structured, silty fine sand to fine sandy silt horizon (I/11a; Fig. 8d). Ferruginous nodules, numerous oxidised root traces, some septaria-like glaebules, clustered pits of hackberry (*Celtis*), a few terrestrial snails as well as extremely rare phosphatic coprolites occur. Layer I/11a passes gradually into



**Fig. 6** Section of the Gratkorn clay deposit (for legend, see Fig. 7)

a slightly laminated, intensively mottled fine sandy silt (I/11b; Fig. 8e), which encloses a lot of oxidised root traces, *Celtis* endocarps, snails and locally accumulated owl pellets as well as sand-filled burrows of variable dimensions (Havlik et al. 2014, this issue). The vertebrate fauna of Gratkorn (except rare fish remains from the hanging wall pelites) originate from

layers I/11a and b. Vertebrate remains are largely rubiginously stained, adhere to ferruginous rhizoconcretions and coatings as well as fibrous, drab-haloed root traces (for figures see Gross et al. 2011a). Traces of roots and ferric coatings are more prominent on the upper sides of bones. However, several remains (in particular from layer 11b) are almost whitish, while others are nearly black-coloured.

These strata are interpreted as pedogenically altered overbank deposits, influenced only occasionally from the braiding river system during flash floods. The rather uniform appearance of this floodplain paleosol (no distinct soil horizons), semi-articulated vertebrate remains (without signs of fluvial relocation), preserved pellets of nocturnal raptors and rare coprolite findings argue for a fairly short period of soil formation (probably in the order of only a few decades; Schmid 2002; Gross et al. 2011a; Aiglstorfer et al. 2014a, this issue; Havlik et al. 2014, this issue; Prieto et al. 2014a, this issue).

The co-occurrence of calcic (some are septaria) and ferric nodules, of aragonitic *Celtis* endocarps and snail shells as well as vertebrate bones and teeth indicate transient water-logging during soil development and thus to alternating wet and dry periods (Retallack 1997, 2001). This matches to a semi-arid to sub-humid climate with less than 500 mm mean annual precipitation during soil formation (Gross et al. 2011a; Böhme and Vasilyan 2014, this issue). Relict bedding, intense mottling and drab colouring hints of a more pronounced hydromorphic setting for the upper part of the vertebrate-bearing layer (I/11b) and a shorter inference of pedogenic processes in comparison to the lower part (I/11a). Especially, the preserved owl pellets signify a very rapid (<1 year?) burial of layer I/11b (Prieto et al. 2010b; 2014a, this issue; Gross et al. 2011a).

Ferric staining and incrustation of vertebrate remains as well as ferruginous rhizoconcretions refer to varying redox conditions within the soil (Brewer 1976; Retallack 1997). Usually, such features are typical for hydromorphic, weakly–moderately developed soils in warm, seasonal climates (Bao et al. 1998). Additionally, selective bleaching of bones due to thin, drab-haloed root traces points to seasonal variations in water-logging of the rhizosphere (Retallack 2001). Anyway, the variable colouring of vertebrate remains (especially in layer I/11b) hints of changing moisture of the paleosol. Possibly, even within one season, water-logging varied significantly laterally due to the local topography of the overbank area. Similarly, gastropod, and small and large mammal assemblages as well as isotope analyses indicate a well-structured, riparian landscape (Harzhauser et al. 2008; Aiglstorfer et al. 2014c, d, this issue; Prieto et al. 2014a, this issue). Nevertheless, modes of accumulation, surface exposure times and post-burial diagenesis certainly affected the taphocoenose to some degree (for further taphonomic considerations, see Prieto et al. 2010b; 2014a, this issue; Gross et al. 2011a; Havlik et al. 2014, this issue).

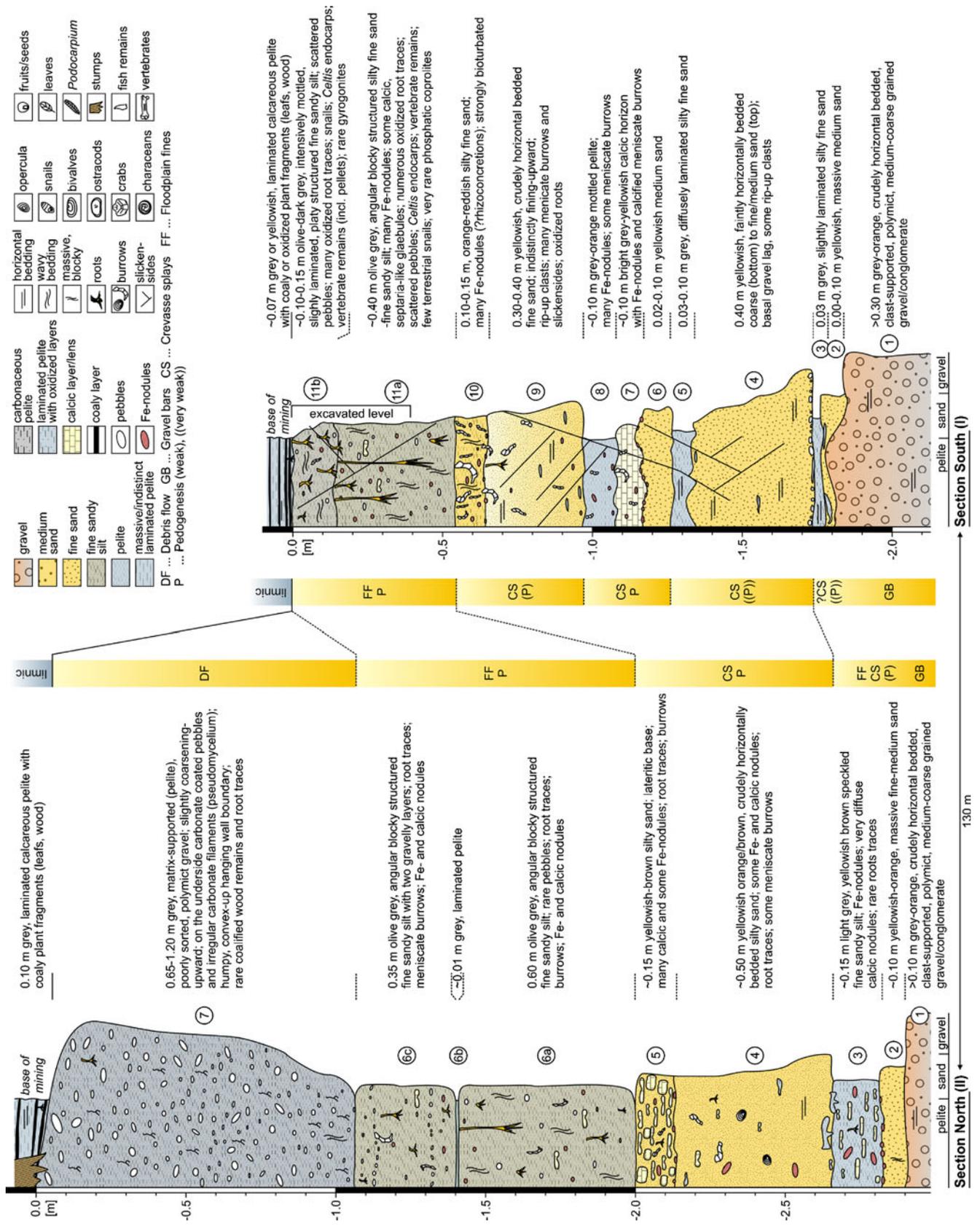


Fig. 7 Sections below the mining floor of the Gratkorn clay pit



**Fig. 8** Lithofacies of the Gratkorn section: **a** lower part of section in the southern exploratory trench (layers I/1–9; slickensides retraced with dotted line); **b** intensively bioturbated sand (especially layer I/10; white arrow burrow redrawn in **c**); black arrow ferruginous nodules, possibly rhizoconcretions; **c** example of a large (dm deep), meniscate burrow; **d** angular blocky structured, silty to fine sandy lower part (I/11a) of the Gratkorn paleosol enclosing a suid jaw (UMJGP 204652); **e** platy structured, silty upper part of the Gratkorn paleosol enclosing a disarticulated cricetid skeleton (i.e. skull, mandible, scapula; UMJGP 204003, 204020–21 white arrows; compare Prieto et al. 2014a, this issue: fig. 4a, b),

numerous, oxidised rhizoconcretions as well as whitish-coloured gastropod and *Celtis* remains; **f** polymict, matrix-supported gravel (debrite; II/7), exposed in the northern part of the Gratkorn pit; **g** detail of layer II/7 with carbonatic coated pebbles (white arrows) and irregular calcareous filaments (black arrow); **h** transition from the uppermost part of the paleosol (I/11b) to plant rich, laminated pelites (in this case, both are in an oxidised, olive–yellowish-orange coloured stage); **i** laminated, non-oxidised, grey pelite with cm-thick lignitic interlayers (lower part of clay deposit)

**Table 1** Vertebrate fossil species (except carnivore mammals) from the late Middle Miocene of Gratkorn and the reference to their scientific descriptions

Class	Order	Family	Taxon	Description			
Teleostei	Cypriniformes	Cyprinidae	Leuciscinae indet.	Böhme and Vasilyan 2014			
	Perciformes	Gobiidae	Gobiidae indet.	Böhme and Vasilyan 2014			
Amphibia	Urodela	Salamandridae	<i>Triturus</i> aff. <i>vulgaris</i>	Böhme and Vasilyan 2014			
			<i>Chelotriton</i> aff. <i>paradoxus</i>	Böhme and Vasilyan 2014			
			<i>Salamandra sansaniensis</i>	Böhme and Vasilyan 2014			
	Anura	Discoglossidae	<i>Latonia</i> sp.	Böhme and Vasilyan 2014			
			Bufonidae	<i>Bufo</i> cf. <i>viridis</i>	Böhme and Vasilyan 2014		
			Pelobatidae	<i>Pelobates sanchizi</i>	Böhme and Vasilyan 2014		
			Ranidae	<i>Pelophylax</i> sp.	Böhme and Vasilyan 2014		
	Reptilia	Testudines	Emydidae	<i>Clemmydopsis turnauensis</i>	Böhme and Vasilyan 2014		
				Chelydridae	<i>Chelydropsis purchisonae</i>	Böhme and Vasilyan 2014	
				Testudinidae	<i>Testudo</i> cf. <i>steinheimensis</i>	Böhme and Vasilyan 2014	
<i>Testudo</i> cf. <i>kalksburgensis</i>					Böhme and Vasilyan 2014		
Iguania		Gekkonidae	Gekkonidae indet.	Böhme and Vasilyan 2014			
Scincomorpha		Lacertidae	<i>Lacerta</i> s.l. sp. 1	Böhme and Vasilyan 2014			
			<i>Lacerta</i> s.l. sp. 2	Böhme and Vasilyan 2014			
			<i>Lacerta</i> s.l. sp. 3	Böhme and Vasilyan 2014			
			<i>Miolacerta tenuis</i>	Böhme and Vasilyan 2014			
			<i>Eclartitia</i> sp.	Böhme and Vasilyan 2014			
			Scincidae	Scincidae gen. et sp. indet.	Böhme and Vasilyan 2014		
			Anguimorpha	Anguinae	<i>Ophisaurus spinari</i>	Böhme and Vasilyan 2014	
Serpentes		Colubridae	Colubrinae sp. 1	Böhme and Vasilyan 2014			
			Colubrinae sp. 2	Böhme and Vasilyan 2014			
			Natricinae sp. indet.	Böhme and Vasilyan 2014			
	Elapidae		<i>Naja</i> sp.	Böhme and Vasilyan 2014			
	Galliformes		Phasianidae	<i>Miogallus altus</i>	Göhlich and Gross 2014		
				cf. <i>Palaeocryptonyx edwardsi</i>	Göhlich and Gross 2014		
Mammalia	Coliiformes	Coliidae	cf. <i>Palaeocryptonyx</i> sp.	Göhlich and Gross 2014			
			<i>Necromis</i> cf. <i>palustris</i>	Göhlich and Gross 2014			
			<i>Schizogalerix voesendorfensis</i>	Prieto et al. 2010b, 2014a			
	Eulipotyphla			Galericinae gen. et sp. indet.	Prieto et al. 2010b, 2014a		
				Talpidae	<i>Desmanodon fluegeli</i>	Prieto et al. 2010b, 2014a	
				Soricidae	<i>Dinosorex</i> sp.	Prieto et al. 2010b, 2014a	
				Chiroptera	Vespertilionidae	cf. <i>Myotis</i> sp.	Prieto et al. 2010b, 2014a
						Rodentia	Cricetidae
					<i>Democricetodon</i> n.sp.	Prieto et al. 2010a, 2014a	
					<i>Megacricetodon minutus</i>	Prieto et al. 2010a, 2014a	
					<i>Eumyarion</i> sp.	Prieto et al. 2010a, 2014a	
			Gliridae	<i>Muscardinus</i> aff. <i>sansaniensis</i>	Daxner-Höck 2010; Prieto et al. 2014a		
				<i>Miodromys</i> sp.	Daxner-Höck 2010; Prieto et al. 2014a		
			Eomyidae	<i>Keramidomys</i> sp.	Daxner-Höck 2010; Prieto et al. 2014a		
			Sciuridae	<i>Albanensia albanensis</i>	Daxner-Höck 2010; Prieto et al. 2014a		
				<i>Forsythia gaudryi</i>	Daxner-Höck 2010; Prieto et al. 2014a		
				<i>Blackia</i> sp.	Daxner-Höck 2010; Prieto et al. 2014a		
				<i>Spermophilinus bredai</i>	Daxner-Höck 2010; Prieto et al. 2014a		
	Castoridae	<i>Euroxenomys minutus minutus</i>	Prieto et al. 2014a, b				
	Lagomorpha	Ochotonidae	<i>Prolagus oeningensis</i>	Angelone et al. 2014; Prieto et al. 2012, 2014a			

**Table 1** (continued)

Class	Order	Family	Taxon	Description
			<i>cf. Eurolagus fontannesii</i>	Angelone et al. 2014; Prieto et al. 2012, 2014a
			Ochotonidae gen. et sp. indet.	Angelone et al. 2014; Prieto et al. 2014a
	Perissodactyla	Chalicotheriidae	<i>Chalicotherium goldfussi</i>	Aiglstorfer et al. 2014c
		Rhinocerotidae	<i>Aceratherium</i> sp.	Aiglstorfer et al. 2014c
			<i>Brachypotherium brachypus</i>	Aiglstorfer et al. 2014c
			<i>Lartetotherium sansaniense</i>	Aiglstorfer et al. 2014c
	Artiodactyla	Equidae	<i>Anchitherium</i> sp.	Aiglstorfer et al. 2014c
		Suidae	<i>Listriodon splendens</i>	Van der Made et al. 2014
			<i>Parachleuastochoerus steinheimensis</i>	Van der Made et al. 2014
		Tragulidae	<i>Dorcatherium nauii</i>	Aiglstorfer et al. 2014b
		Moschidae	<i>Micromeryx flourensianus</i>	Aiglstorfer et al. 2014b
			<i>?Hispanomeryx</i> sp.	Aiglstorfer et al. 2014b
		Cervidae	<i>Euprox furcatus</i>	Aiglstorfer et al. 2014b
		Palaeomerycidae	Palaeomerycidae gen. et sp. indet.	Aiglstorfer et al. 2014b
	Bovidae	<i>Tethytragus</i> aff. <i>koehlerae</i>	Aiglstorfer et al. 2014b	
	Proboscidea	Deinotheriidae	<i>Deinotherium levius</i> vel <i>giganteum</i>	Aiglstorfer et al. 2014a

Most of the fossil samples are deposited at the palaeontological collection of the Universalmuseum Joanneum, Graz. Reference specimens are housed in the palaeontological collections of the University Tübingen and the Bavarian State Collection of Palaeontology and Geology, Munich (see cited publications for details)

Ubiquitous root traces testify that the soils surface was planted in some way (compare Aiglstorfer et al. 2014b, d, this issue; Prieto et al. 2014a, this issue). However, only the primarily mineralised and thus favourably preservable *Celtis* endocarps provide concrete palaeobotanical evidence that medium-sized hackberry trees would have been growing on the fossiliferous substrate (layer I1a–b) at its time of formation (Havlik et al. 2014, this issue). Vital infaunal life on the floodplain soil is indicated by the abundant occurrence of subterranean snails (Harzhauser et al. 2008) and tentative insect ichnofossils (Havlik et al. 2014, this issue).

#### Facies interpretation of section II (northern part of the pit)

Corresponding to section I, gravels (II/1) were observed at the base of the trench and are overlain by massive sands (II/2) and—with a gradual boundary—by a silty unit with ferruginous and very diffuse calcic nodules (II/3). This rock package is interpreted as gravel bar deposits, topped by flash flood sediments (crevasse splay?) outside the active channel or as a bar top assemblage. In contrast to section I, a weakly developed calcic horizon (II/3) points to slightly more pronounced pedogenic alteration.

Rip-up clasts form a very indistinct boundary to the overlying, crudely horizontally bedded silty sands with traces of roots and various burrows (II/4). Larger burrows resemble backfillings of section I. Calcic nodules become much more frequent in the upper part (II/5), implying a correlation to the calcic horizon (I/7) of the former section. Whereas in section I

additional flooding events are recognised, here only one sedimentary unit (weakly–moderately pedogenically altered crevasse splay) could be differentiated, which again points to a highly structured alluvial plain with abundant and short-distance facies changes.

Above follows a blocky structured fine sandy silt with root traces and burrows (II/6a). Due to an interbedded thin pelitic layer (II/6b), it can be differentiated into two horizons. In the upper one (II/6c) two gravelly layers were observed. These strata are an equivalent of the excavated paleosol in the southern part of the clay pit (I/11). They are interpreted as pedogenetically overprinted overbank fines. However, the intercalated pelitic layer as well as two pebbly horizons in the upper part, suggest a multi-stage development of the paleosol. Possibly due to limited exposure conditions, no vertebrate remains were found here.

In section II, an up to 1.2-m-thick matrix-supported, slightly inverse graded gravel (II/7; Fig. 8f) with a humpy, convex-up relief is developed above layer II/6. It contains tiny, irregular calcareous filaments (pseudomycelia) and pebbles coated with carbonate on their underside (Fig. 8g). As far as observable, layer II/7 tapers off towards the south (Fig. 2). This bed is ascribed to a debris flow, which later on experienced weak pedogenesis. Irregular calcareous filaments and pebbles, carbonate-coated on their undersides, indicate initial calcrete formation within a generally at least ephemeral dry climate (Retallack 1997). Analogous to section I, immediately above the debris flow deposit, calcareous pelites with abundant plant fragments rest upon and document the rapid changeover to limnic facies.

## Section and facies of the mined pelites in the hanging wall

The vertebrate-bearing layer (I/11) and the debrite (II/7) in the northern part of the pit are covered by laminated, calcareous pelites with a large amount of carbonaceous or diagenetically oxidised leaf litter (largely monocotyledons, *Salix*, *Potamogeton*; Fig. 8h, i). Except for rare root traces in the lowermost centimetres of the clay deposit, pedogenic features are absent. Sporadically, slightly silicified, autochthonous lignitic tree trunks (*Taxodioxydon*; Havlik et al. 2014, this issue), possibly several metres in height and about 1 m in diameter, and which root upon the surface of the debris flow deposit (II/7; Fig. 3b), were excavated during mining.

In particular, the lower 4 m of the >15-m-thick clay deposit yield frequently cm-thick lignitic intercalations. Up-section, the pelites include only subordinately plant-rich and fine sandy layers (Fig. 8i). Diversity of the fossil leaf flora is quite low but dozens of carpologic taxa, besides several freshwater ostracod species, are documented from the clay deposit (Meller and Gross 2006; Gross 2008). Some layers enclose claws and exuvia of freshwater crabs (Klaus and Gross 2010), freshwater gastropods (e.g. *Bithynia* opercula), characean gyrogonites and fish fragments (bones and cyprinid pharyngeal teeth; Böhme and Vasilyan 2014, this issue). Sphaeriid bivalves were occasionally found in the lowermost parts of the section, while unionids are rarely present in the upper part. Sporadically, insect (beetle, bug) and isopod (woodlice) remains as well as avian eggshells were discovered in the lowermost part (Gross et al. 2011a; Havlik et al. 2014, this issue).

Based on the ostracod record, as well as on potamid crab and fish findings, a shallow, partly richly vegetated freshwater lake environment within a warm, perhaps subtropical climate is assumed as depositional setting for the clay deposit (Gross 2008; Klaus and Gross 2010; Böhme and Vasilyan 2014, this issue).

## The vertebrate fauna of Gratkorn and their biochronological significance

Fossil vertebrates from Gratkorn are exceptional by their preservation (Gross et al. 2011a; Havlik et al. 2014, this issue; Prieto et al. 2014a, this issue) as well as their diversity. To date, 65 vertebrate species (except carnivore mammals) have been described (Table 1), belonging to fishes (2 taxa), amphibians (8 species), reptiles (17 species), birds (4 species), and mammals (34 species), thus comprising all the major vertebrate groups. To our knowledge, this is so far the highest recorded vertebrate diversity for stratified deposits in the late Middle Miocene of Europe.

This high diversity, which is also documented by 17 terrestrial gastropod species (Harzhauser et al. 2008), may be explained by

ecosystem diversity, long-term and systematic excavations and the rapid sediment accumulation, minimising taphonomic biases. Furthermore, integrated stratigraphical investigations firmly correlate the Gratkorn Fm. chronostratigraphically with the beginning of the late Sarmatian s.str.

Thus, exceptional preservation, high biodiversity, extremely low time-averaging, and a substantiated chronostratigraphy are outstanding features, which render Gratkorn to a key locality for the Central Paratethys and beyond. Especially, mammalian biochronology has suffered from problems related to low diversity, missing documentation of excavations, high time-averaging, and unresolved geological and chronostratigraphical backgrounds, so far preventing mammalian biostratigraphic schemes on a continental scale for the Miocene.

Biochronological investigations, previously published and in different articles of this issue, concordantly place Gratkorn in the Mediterranean Neogene unit MN7+8 at the end of the Middle Miocene (Daxner-Höck 2010; Prieto et al. 2010a, b; 2012; 2014a, this issue; Gross et al. 2011a; Aiglstorfer et al. 2014b, c, this issue). However, a more detailed stratigraphical correlation is complicated by still insufficiently resolved evolutionary lineages, stratigraphically mixed comparative faunas, and, maybe most importantly, by a lack or uncertainty of chronostratigraphical ages for many of the Central European mammalian faunas (e.g. Aiglstorfer et al. 2014a, b, this issue; Prieto et al. 2014a, this issue). To overcome these problems, future work is needed, in which Gratkorn is a benchmark, towards a mammalian biostratigraphic subdivision of the Central Paratethyan area.

## Conclusions

The vertebrate fauna of Gratkorn is dated to the late Middle Miocene (early late Sarmatian), independently from vertebrate biochronology. It originates from pedogenically altered overbank deposits, formed on top of a fluvial sequence. Short-distance lithofacies changes indicate a highly structured alluvial plain, well mirrored by the palaeontological record. Pedogenic features signify alternations of wet and dry periods/seasons and hint of an overall semi-arid climate, well supported by palaeoherpetological as well as geochemical results (Böhme and Vasilyan 2014, this issue; Aiglstorfer et al. 2014d, this issue). Duration of paleosol formation is estimated to be in the order of decades or centuries at most (Gross et al. 2011a; Aiglstorfer et al. 2014a, this issue; Havlik et al. 2014, this issue; Prieto et al. 2014a, this issue). Thus, despite complex biotic and abiotic taphonomical processes, time-averaging of the Gratkorn fauna is low and enables an exceptional insight into the otherwise hardly documented terrestrial ecosystems of that time (Gross et al. 2011a; Havlik et al. 2014, this issue; Prieto et al. 2014a, this issue).

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