Fossa Carolina: The First Attempt to Bridge the Central European Watershed—A Review, New Findings, and Geoarchaeological Challenges

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The Central European watershed passes through the southern Franconian Jura in Bavaria, Germany. This principal watershed divides the Rhine/Main catchment and the Danube catchment. In the early Middle Ages, when ships were an important means of transportation, Charlemagne decided to connect these catchments by the construction of a canal known as the *Fossa Carolina*. In this paper, we present for the first time ^{14}C data from the *Fossa Carolina* fill and document a high-resolution stratigraphic record of the Carolingian and post-Carolingian trench infilling. Our results provide clear evidence for peat layers in different levels of the trench infill, suggesting a chain of ponds. However, the majority of these peat layers yield mid-Medieval and younger ages. The period of major peat growth was during the Medieval climatic optimum. Therefore, our preliminary results do not prove the use of the trench during Carolingian times. However, first results from the reconstruction of the Carolingian trench bottom support the hypothesis that the *Fossa* was primarily planned as a navigable chain of ponds and not as a continuous canal. In the eastern part of the trench, a dam is located that was postulated in former studies to be part of a barrage for supplying the Carolingian canal with water. New ^{14}C data indicate much younger ages and do not support the Carolingian barrage concept. © 2011 Wiley Periodicals, Inc.

INTRODUCTION

In the south of Germany at the valley watershed dividing the Altmühl–Danube catchment from the Main/Rhine catchment (Figure 1), there is the largest geological engineering building project that is associated with the early Medieval inland navigation (Molkenthin, 2006): the Karlsgraben, also known as the *Fossa Carolina*. Apart from the Kanhave canal (Blair, 2007), located on Samsø Island (Denmark), the Karlsgraben is deemed to be the first attempt to construct a man-made waterway north of the Alps. Although ships were probably not the primary means of early Medieval interregional transport in Central European inlands (Elmshäuser, 2002), the evident importance of the *Fossa Carolina* is expressed by the decision of the Pope to send delegates with many gifts to the construction site (Molkenthin, 2006). The symbolic character of the construction for both the Carolingian empire and royal power should also be kept in mind (cf. Squatriti, 2002).

Despite the important infrastructural and geostrategic relevance of the construction (cf. Ettel, 2007), there are few geoarchaeological findings pertaining to the history of the *Fossa Carolina* from the onset of construction until present. Furthermore, it is not clear whether the canal was ever used as a working waterway. Existing knowledge regarding the canal history is mainly based on secondary sources derived from historical findings.

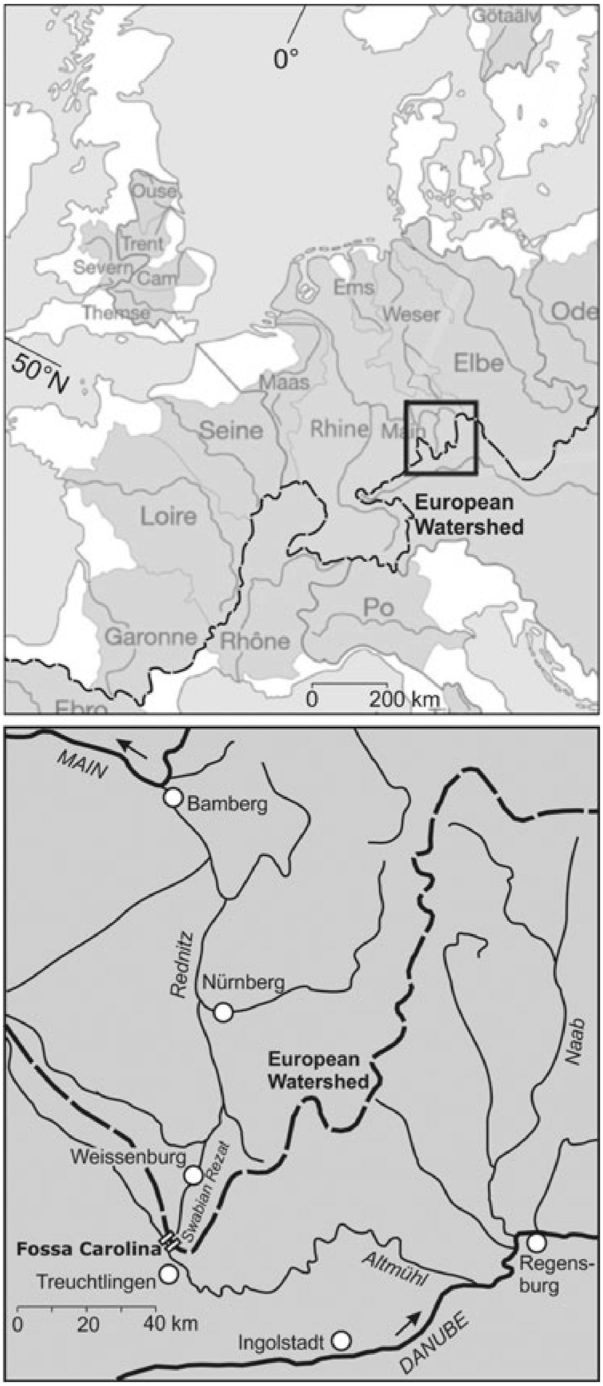

Figure 1 The *Fossa Carolina* (Karlsgraben) links the Altmühl–Danube and the Rezat—Main/Rhine catchments across the main European watershed divide (LfU, 2004, modified).

In this paper, we present a review of the scientific state of the art research into the *Fossa Carolina*. Up until now, *in situ* geoarchaeological findings from drilling and excavation campaigns remain scarce. In particular, chronological information derived from *in situ* remains is lacking. Therefore, the major aim of this paper is the presentation of *in situ* chronological data alongside new sedimentological findings from our current drilling and excavation program, which provide new insights into the technical conception of the *Fossa Carolina*. These findings clearly show that future geoarchaeological research is without question necessary to clarify the nature and usage of this early Medieval construction and to find firm evidence for its use during Carolingian times.

STATE OF THE ART

Geographical Setting

The *Fossa Carolina* is located in the Southwestern German Escarpment landscape. It is surrounded by Upper Jurassic (Malm) carbonate rocks (Schmidt-Kaler, 1993). The study area belongs to the Southern Franconian Alb, which is subdivided into slightly undulating foothills and valley fills, the high escarpment (450–500 masl), and the Jurassic plateau (König, 1996). The Swabian Rezat (Rhine catchment) and the Upper Altmühl River (Danube catchment) flow through the undulating Lias and Dogger foothills (Jätzold, 1962).

The *Fossa Carolina* does not lie directly on the Dogger α (Opalinus Clay) but rather on remains of Miocene lake deposits. This lake resulted from an asteroid impact that sealed the Miocene drainage system. Miocene clayey silts and clayey sands are covered by Quaternary alluvial fills consisting of coarse sands, silts, and silty clays down to a depth of 5 m (Schmidt-Kaler, 1993).

The valley fills of the northern part of the *Fossa Carolina* are different from the alluvial fills in the southern part. Because of the very weak gradient of the Swabian Rezat headwater, the groundwater influence has resulted in the development of the Rezat fen. This fen is located to the north of the road connecting Grönhart and Dettenheim and to the east of the rail track (Figure 2). The fen grades smoothly toward the north into alternating layers of peat and sandy silt with soft consistency and high water content (Koch & Leininger, 1993).

The location of the *Fossa Carolina* is closely associated with the position of the Altmühl and the Swabian Rezat rivers, which are situated on either side of the European Watershed (Figure 2). The Altmühl is a tributary of the Danube River, which in turn flows into the Black Sea. The modern mean water level of the Altmühl is 408.3 masl (Koch & Leininger, 1993) and was probably the same in Carolingian times, as indicated by the presence of Bronze and early Hallstatt Age barrows in the flood plain near Graben (Schwarz, 1962). Due to the gentle gradient of the Altmühl (0.3–0.5‰), its vertical erosion force is unlikely to be very strong (Apel, 1976). The navigability of the Altmühl near Solnhofen was documented in the vita

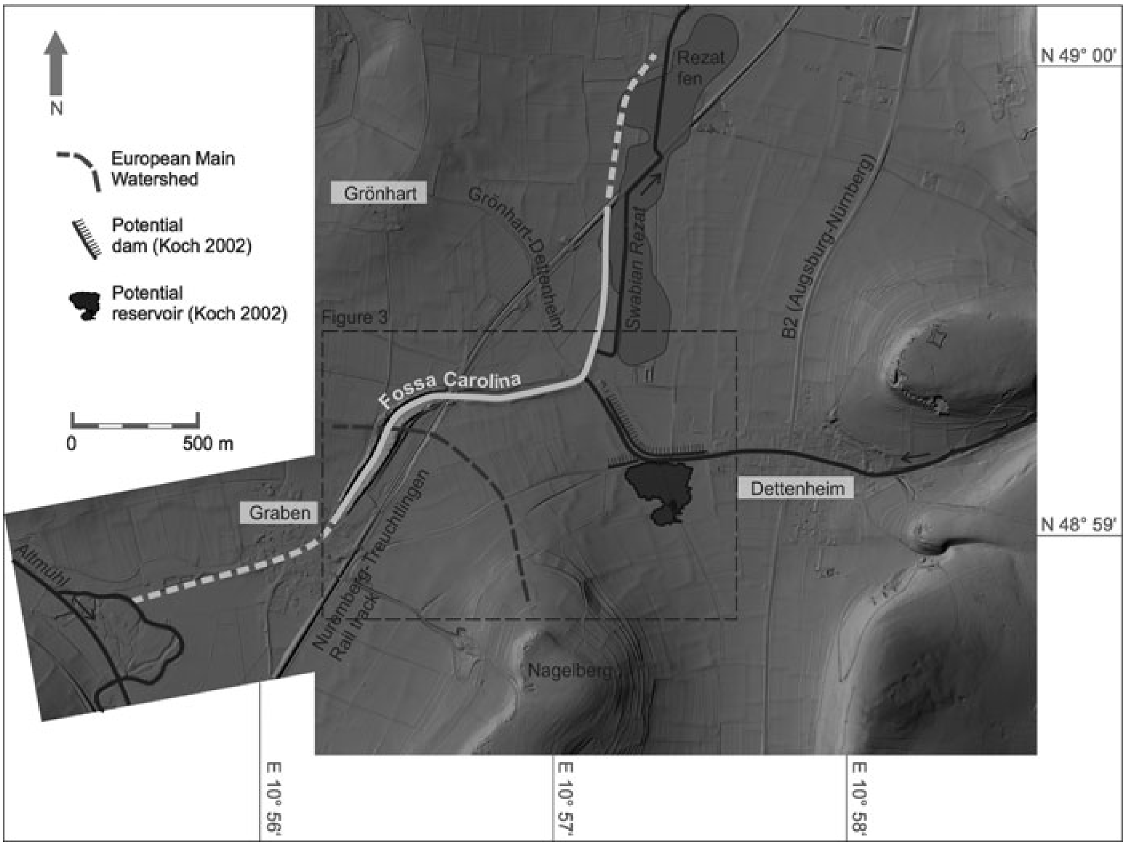

Figure 2 Course (light gray line) of the *Fossa Carolina* between the Altmühl and Swabian Rezat rivers in Middle Franconia. The gray dotted line shows the potential continuation of the known course. According to Koch (2002), the plotted dam on the Rezat was used during Carolingian times for supplying water into the *Fossa Carolina*. Airborne LIDAR data were provided by the Bavarian State Conservation Office. We used Global Mapper 12 for data management and mapping of the digital elevation model.

of St. Sola (†794) and should also be valid for the 13-km long section upstream until Graben (Koch & Leininger, 1993).

The Swabian Rezat flows northward from Dettenheim to the east of the *Fossa Carolina* (Figure 2) and into the Main, a tributary of the Rhine that flows into the North Sea. The Swabian Rezat was navigable during Medieval times from Weissenburg downstream (Koch & Leininger, 1993). The Swabian Rezat was probably rerouted in Carolingian times into an artificial channel. The Swabian Rezat bends three times and runs finally straight to the north on the west side of the Rezat fen (Figure 2; Koch, 2002).

The present pond of the *Fossa Carolina* is fed by a stream that rises in the east part of the *Fossa Carolina* and is filled up additionally with seepage water (Beck, 1911). The outlet of the pond flows through Graben into the Altmühl.

In Bavaria, a transitional climate between the western maritime and the eastern continental climates predominates. According to Köppen, Bavaria is integrated into the Cfb zone with fully humid warm temperate climate (Kottek et al., 2006). The mean annual temperature in Weissenburg is 8.6°C with a mean maximum in July (17.8°C) and a mean minimum in January (–0.5°C). Mean annual precipitation is 674 mm with maximum values in July (85 mm) and minimum values in February (37 mm) (Mühr, 2007).

Location and Course of the *Fossa Carolina*

The monk Ekkehard from Niederaltaich (Bavaria) related in 1140 in his work *Auctarium Ekkehardi Altahensis* the *Fossa Carolina* for the first time at the village of Graben near Weissenburg in Middle Franconia, Bavaria. On this basis, an exact localization was possible (Beck, 1911; Figure 2).

The *Fossa Carolina* crosses a flat ridge of the European Watershed with a local summit level of 420 masl (Schwarz, 1962). In this area, it forms a valley watershed between the Altmühl and Rezat catchments. The chosen location for the canal appears ideal: the Rhine/Main

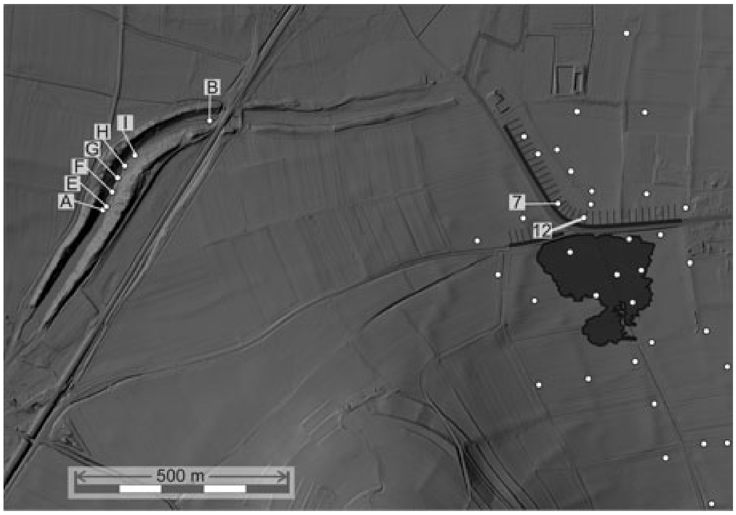

Figure 3 Detailed scene with locations and names of the current coring sites at the *Fossa Carolina* (A, B, E, F, G, H, I) and at the dam (with corings 7 and 12). According to Koch (2002), the dam was part of the *Fossa Carolina* water-regulation system. The white dots show 2–4 m drillings of the soil survey program in the area of the assumed Swabian Rezat dammed reservoir. We compute a volume of about 55,000 m^3 for a potential water reservoir by the use of airborne LIDAR data.

(Swabian Rezat) and Danube (Altmühl) river systems here display their lowest separating distance (ca. 1800 m, Hofmann, 1965) and a minimum difference in altitude between the peak of the watershed and the Altmühl level (only 12 m; Spindler, 1987).

At the north-eastern end of the village Graben next to the rail track between Nuremberg and Treuchtlingen, there are still remnants of the *Fossa Carolina* visible: it is the former course laterally framed by two parallel, SW–NE oriented 40-m wide dams (Figure 3). Currently, the first 300 m are filled with water (Figure 4) creating a pond with a water depth of 1–2 m. The maximum difference in altitude between the present day trench and the dam crest is 12 m (Koch & Leininger, 1993). The trench has a width of 25 m, which narrows to 14 m after the pond. After bridging the watershed, the *Fossa* turns into eastern direction right in front of the rail crossing (Figure 3). The remnants of the *Fossa* are still clearly visible over 400 m beyond the rail track as far as the Grönhart–Dettenheim connecting road. The continuation of the remnants beyond this intersection in northward direction straight through the Rezat fen up to the rail track can be detected in the Light Detection and Ranging (LIDAR) data (Figure 2). Topographic measurements in 1993 confirmed this northward continuation of the *Fossa* over a distance of ca. 1000 m. In this northern section, the remnants of the *Fossa Carolina* have a maximum height of only 70 cm (Koch, 2002). North of the rail track, there are no more remnants detectable.

During the last 400 years, several modifications to the construction are known to have taken place. The dam at the southern end of the pond was built in the second half of the 16th century. During the War of the Spanish Succession (1701–1714), the *Fossa Carolina* was used as a barrier against approaching enemies (Berg-Hobohm & Kopecky-Hermanns, 2011), and the banks were probably enlarged. Berg-Hobohm and Kopecky-Hermanns (2011) presume that this might be an explanation for the larger bank on the south side in the west–east-oriented section after the rail track. Since 1790, both banks were locally used to obtain construction materials (Schwarz, 1962). The Nuremberg–Treuchtlingen rail track, which cuts through the *Fossa Carolina*, was built in the years between 1861 and 1868 (Schwarz, 1962).

In the 19th century, the remarkably broad main street of Graben was an open channel as far as the village church, until in 1860 it was filled in (Beck, 1911), and the southern outflow of the *Fossa Carolina* directed to the Altmühl piped through the village via a culvert (Keller, 2006). In the center of the village next to the main street, investigation by sediment coring has shown a transition from a 4-m thick layer of replenishment material to fluvial sediments at 408.8 masl; this depth might represent the former level of the Carolingian trench bottom (Koch & Leininger, 1993). At 3-m depth, the same study reports a 50-cm thick peat layer. Koch deduces from this that the southwest section of the *Fossa Carolina* passed at the course of the present main street and possibly reached up to the Altmühl flood plain (Koch, 1993a).

The northern continuation of the *Fossa Carolina* after the crossing with the Grönhart–Dettenheim connection road is barely perceptible because of considerable leveling activity since the drainage of the Rezat fen in the early 19th century for agricultural use (Koch & Leininger, 1993).

Motivations for Constructing the *Fossa Carolina*

In the late 8th century, the Lower Altmühl Valley was already intensively settled (Eigler, 2000; Laske & Schmidt,

Figure 4 *Fossa Carolina* with current pond looking North-northeast (Photo: Eva Leitholdt).

1993). The area that was amenable to settlement, and agricultural land use was limited to the narrow and flood-free valley zone. Important trunk roads crossed through the area (Hofmann, 1965; Koch, 1993b; Eigler, 2000), including:

1. The *Altstrasse*, a road directed west–east from Aalen via Treuchtlingen to Regensburg. Two thousand years ago the road was used to connect the salt deposits at the rivers Kocher and Jagst with the Celtic town Manching near Ingolstadt. The Romans extended the road for further use. It is said that the Nibelungs took this road to get to the Danube.
2. The north–south connection between Main and Danube, the so-called *Albrandstrasse* ran from Nuremberg to Augsburg (cf. today's main road B2; Figure 2). Pilgrims, traders, and armed forces could follow the extension of this road until Rome.

These Roman roads were still used in the early Middle Ages (Eigler, 2000), even though the quality of the roads may have been poor. Charlemagne, as a ruler who traveled constantly during his reign, required good connections between the different areas of his extensive empire. Beck (1911) suggests that in the years between 761 and 814 Charlemagne covered a distance of nearly twice the circumference of the earth. Since clearing in the thickly wooded Frankish Empire had just started, the rivers remained important transportation routes (Laske & Schmidt, 1993). Therefore in Carolingian times, ships were important means of both freight and passenger transport (Hofmann, 1965, 1976; Ellmers, 1993). Unfortunately, water transport from the Main to Danube was inhibited by two problems. First, navigable conditions on the Swabian Rezat ended near Weissenburg (Röder, 1974/75, Ellmers, 1993), even for medieval small boats with a shallow draught of 40–50 cm (Koch, 1993b). Second, the topographical constraint of the European Main Watershed prohibited a continuous waterway connection. Overcoming these obstacles and finally continuing the shipping route via Altmühl to the river Danube was only possible by leaving the ship and using the overland transport (Molkenthin, 2006).

Beside the intention of Charlemagne to build a continuous waterway network for his extensive travels, there are two more possible reasons for connecting the river systems of Main and Danube. On the one hand, the navigable connection would improve the trading situation considerably, especially in the face of the famine in the year 793 in the west empire, which was probably caused by a crop fungus. Hence, the people in the western

Empire depended on crop deliveries from the Danube region (Hofmann, 1965; Laske & Schmidt, 1993).

The Carolingian royal courts at Hallstadt, Forchheim, Fürth, Schwabach, and Weissenburg are all located on an ancient trade route, the *Rezat–Rednitz–Regnitz Route*, connecting the river systems of Rhine/Main and Danube, thus almost the entire route is passable by ship. The royal courts are each separated by a distance of 25–30 km, which corresponds with the daily upstream tow performance. The courts are situated at estuaries of small tributaries, which provide good landing facilities for the flat trading vessels. Weissenburg was the final stop for traders coming from the north. Here, they had leave to sell their merchandise or reload it on carts to carry it across the watershed to the Altmühl in order to continue their way by ship (Laske & Schmidt, 1993).

On the other hand, a waterway connection would also be useful for military purposes. From the 770s, frequent rebellions of the Saxons troubled the northwestern Empire. In addition, the Avars campaign in Pannonia and the invasion of the Saracens across the Pyrenees needed military attention. Therefore, Charlemagne had to transfer warriors, war material, and the navy across the empire (Beck, 1911; Hofmann, 1976). However, the very expensive and time-consuming canal construction would have saved only a few days for the navy transportation, but would have been a significant improvement for traders (Ellmers, 1993).

Technical Conception of the *Fossa Carolina*

The scientific community discusses two possible modes in which the *Fossa Carolina* was designed to bridge the European Watershed. In the following part both conceptions are examined.

The continuous canal

To connect the rivers Altmühl and Swabian Rezat directly with a continuous canal, access at the same level would be needed. According to different hydrological findings, the present mean water level of the Altmühl is between 407.75 (Röder, 1974/75) and 408.3 masl (Koch & Leininger, 1993). The water level could be kept at 408 masl by damming. This water level is reached by the Swabian Rezat close to Weissenburg (Figure 1)—at this point, the canal incision should have been done. Weissenburg would be the northernmost end point of the *Fossa Carolina*, if one infers a 1.5-km straightened channel bed of the Swabian Rezat beyond the observable northern end of the *Fossa Carolina* (Spindler, 1998). River boats of the 8th century with a length of 10–12 m and a width of 1.5 m had a draft of 30–40 cm. Hence, a water level of 0.5 m would have sufficed (Spindler, 1998). As the Rezat did not contain enough water to feed the canal, water from the dammed Altmühl would have had to be used (Röder, 1974/75). Spindler (1998) inferred potential remains of a barrage below the presumed southern access to the *Fossa Carolina*. This dam might have been located southwest of Graben next to the Gstadter Street near the railway underpass. The remains cross the valley on the southern edge of the Nagelberg and measure up to 0.6-m high in places. Following Spindler (1998), the 4-m wide dam was leveled and transformed to a gravel path. In order to build a continuous canal, in the section of the watershed (420 masl) incision of up to 13 m would have been needed to attain a water depth of 1 m (Spindler, 1987). Taking the necessary slope into account, the *Fossa* would have been 5-km long up to the point where it met the Rezat at the same level (Röder, 1974/75). An excavated volume of ca. 170,000 m^3 would have been accrued (Koch & Leininger, 1993).

The chain of ponds

An alternative means of bridging the watershed is a sequential chain of ponds at several levels. Double-walled locks were not yet known in Carolingian times—the oldest known examples were constructed in the Stecknitz Canal at the end of the 14th century (Spindler, 1998). Hence, at the end of each pond the ships would have had to be taken out of the water to the next pond (Molkenthin, 2006). After unloading the cargo, the ships would have been pulled across the dams by manpower or with the help of horses, perhaps on a rolling bridge or some other form of mobile platform. The overland transport of ships was already used in antiquity (Hofmann, 1965; Spindler, 1998).

Koch and Leininger (1993) assumed that after about 5 ramps from the Altmühl to the summit water level in 415 masl, there followed a stepwise descent of the canal to the confluence with the Swabian Rezat. The water could be retained in the trench, as shown by the present day pond. The surplus of water flowed into the next lower pond (Röder, 1974/75).

In contrast to Koch and Leininger (1993), who primarily argued that the filling of the summit water level was ensured by inflowing groundwater, Spindler (1987) doubted a sufficient groundwater discharge. According to Spindler, a barrage across the Altmühl valley comparable to that described above for the continuous canal would have been needed. By this means, the water level could be maintained at the same level in the southern section of the *Fossa Carolina* up to the first dam (Spindler, 1998).

In light of subsequent investigations, Koch (2002) has inferred potential remnants of a barrage to the east of the *Fossa Carolina* directly south of the intersection of the Grönhart–Dettenheim and Dettenheim–Graben connection roads (Figure 2). Following Koch, the dam might have been used as a reservoir for regulation of the water supply and was fed by the upper course of the Swabian Rezat, which has its origin in a shallow karst spring. From a hydrological point of view, a reservoir would seem to be useful as the springs of the shallow karst reveal highly seasonal discharge amplitudes (Zielhofer, 2004).

The chain of ponds seems to be a realistic conception. In several cartographic works of the last few centuries, a number of small ponds at the site of the *Fossa Carolina* are mapped that probably subsequently were filled in or silted up (Kerscher, 1993). In addition, Hans Trögl, the former chief of the Water Authority of Nuremberg, cited Redenbacher (1844) in his lecture on the April 21st, 2010 to argue that before 1784, the *Fossa Carolina* comprised a terraced chain of ponds that had been drained in 1844 apart from the lowest one.

In 1992, the working group of Koch, Kerscher, and Küster carried out a drilling program within the *Fossa Carolina* (Koch, 1993b, Koch & Leininger, 1993). At the northern end of the present pond, they found a 1.3-m thick peat layer beneath younger sandy sediments. Here, the trench bottom at the top of an alluvial fill (yellowish clay) was found at approximately 410 masl, which is higher than the water level of the Altmühl with 408.3 masl. To the east of the rail track, Koch infers from the corings that the former trench bottom was 3–4 m deeper, corresponding to a level of 414 masl. In the north section, only thin layers of peat are preserved (Koch, 1993b). These peat layers show that stagnant water must have been present for a long period of time. The efforts of the working group demonstrate that the canal was filled with water on further sections in addition to that of the present day pond. However, the findings were published without reliable, absolute age controls. Beneath the peat layers, there are mostly fine-to-coarse sands that could be *in situ* alluvial sediments or redeposited excavation material from the banks. Koch et al. did not present the sedimentological data in more detail. Therefore, from our point of view, a clear reconstruction of the Carolingian trench bottom remains very difficult. According to the findings of Koch, the probable level of the former trench bottom increases from the Altmühl flood plain to the Rezat fen at 414 masl. Hence, Koch concludes a chain of ponds from the existence of stagnant water and the constantly increasing level of the former trench bottom (Koch & Leininger, 1993).

Combination

According to Spindler (1998), a combined version has to be considered, too. In this view, a continuous canal was constructed first. Due to the laborious maintenance (dredging, stabilization of the embankments, etc.) this canal could only be sustained for a short time. Hence, the continuous canal might have been modified by inserting a number of dams to create a chain of ponds.

Start of Construction of the *Fossa Carolina*

No one knows exactly to whom the idea of the *Fossa Carolina* can be credited (Molkenthin, 2006). Einhard, who was the construction manager of the *Fossa Carolina*, accomplished the most buildings for Charlemagne (Beck, 1911). According to the Franconian annals, he was directing the construction of the *Fossa Carolina* in the autumn of 793 when Charlemagne arrived at the site (e.g., Beck, 1911; Hofmann, 1965; Molkenthin, 2006). In the same year, the Pope sent delegates with many gifts to the site (Molkenthin, 2006). In all likelihood, the work was already in progress in autumn 793, or at least the preparations (arrival of the workers, construction of accommodations, etc.) were finished. Otherwise Charlemagne would have had to wait too long until the actual construction started (Röder, 1974/75). There are several secondary sources that date the start of the construction to the year 792, for example, the monk Ekkehard from Niederaltaich (Beck, 1911), the Mosellani annals (Hofmann, 1965), and the Almannici and Weingartenses annals (Spindler, 1998).

Premature Abandonment versus Completion of the Work

The *Fossa Carolina* is often considered an *opus imperfectum*. In the only source from that time, the Franconian annals, it is written that heavy and continuous rainfall caused slides of the previously excavated material back into the trench. In addition, during the works, Charlemagne received troubling news concerning the rebellion of the Saxons and the invasion of the Saracens. This information plus missing further mentions of the project from that time (besides the brief note in the Franconian annals) as well as the present day remains of the canal lead to the conclusion that the construction of the *Fossa Carolina* was abandoned in December 793 before its completion (e.g., Beck, 1911; Hofmann, 1976).

Besides the difficult natural conditions, Hofmann (1965, 1976) detected also serious logistical problems. He calculated that at least 6000 workers were required at the site, a huge crowd that had to be provided with food,

accommodation, drugs, etc., which was a vast challenge at that time. However, his calculation is based only on the year 793, and hence, the effective working time was limited to 10 weeks. If the construction of the *Fossa Carolina* had already started before autumn 793 or even in 792, these logistical problems could be ignored, because for a longer working time, fewer workers would be required (Eigler, 2000). In this context, another interesting issue arises: no probable encampments or traces of them could be found until today. Eigler (2000) mapped all of the settlements already existing at that time as detected by their place names. Around the construction site, he found ca. 50 villages within a radius of 14 km (corresponding to a 3-hour walk) and 30 villages within a radius of 10 km (corresponds to a 2-hour walk). These could have provided up to 2000 workers plus board and lodging for foreign workers. In addition, at the royal court of Weissenburg, it was also possible to accommodate workers (Eigler, 2000).

Since the construction of the *Fossa Carolina* was far advanced in December 793 (Spindler, 1987), no construction-related but rather political problems could have caused the possible premature abandonment (Koch & Leininger, 1993). According to Pechmann, who was the architect of the Ludwig–Main–Danube Canal in the 19th century (the successor to the *Fossa Carolina*), the form of the slopes leaves no doubt that the canal achieved its complete width and depth. If Einhard had planned to dig deeper or even down to the present surface of the Altmühl, the width would not have been sufficient (Beck, 1911).

By interpreting several annals beyond the Franconian ones, Spindler (1998) assumes a successful completion of the canal project after a construction period of at least 1 year. In his opinion, the *Fossa Carolina* was functioning flawlessly, but for not more than 20 years. None of the other annals indicates a failure of the project and some even describe its use by Charlemagne. These contradictions to the Franconian annals could possibly be explained by a subsequent manipulation of the story motivated by power–political considerations. Louis the Pious, the son of Charlemagne, was outshone by his father throughout his lifetime. He was not interested in the canal and hence completely ignored its maintenance and subsequently had to justify its failure. The results are the revised Franconian annals, asserting that Charlemagne had to watch his ambitious started work collapse (Spindler, 1998). In the biography of Charlemagne (*Vita Karoli Magni*), there is surprisingly not any mention of this enormous opus (e.g., Beck, 1911; Hofmann, 1965; Molkenthin, 2006).

Finally, at the section east of the rail track, Küster (1993) has found pollen of Water Lily, which only grows in perennial waters. However, the pollen is not dated absolutely.

NEW GEOARCHAEOLOGICAL FINDINGS

Summarizing the proven facts about the *Fossa Carolina*, there can be listed its location close to the city of Weissenburg, the central part of its course according to still visible remnants, and the fact that the former trench bottom is located some meters below the today´s surface. There are many unresolved questions about the *Fossa Carolina*. The primary aims of our recent studies are to evaluate the chain of ponds theory, examine the barrage theory of Koch (2002), and provide sedimentological data and ^{14}C data for *Fossa* fillings for the first time.

Methods

Fieldwork

The first *Fossa Carolina* drilling program by our research group started in 2007. The drillings enable us to gain sediment samples from depth of 9 m or more. By comparing the levels of sediment layers along the *Fossa*, we are able to reconstruct the former trench bottom as well as refilling sequences over time. Within the *Fossa* fillings, two cores (A and B; Figure 3) with depths of 7 and 4 m were drilled with an Atlas Cobra Pro hammer and a 60-mm diameter open corer. The drilling points have been leveled using a Leica surveyor's optical level. The sediments within the corer were documented and investigated by field parameters (color, organic remains). Remains of terrestrial plants (charcoal and wood) were isolated and saved in aluminum foil for ^{14}C dating. In October 2010, a second drilling program was undertaken. Five cores (E, F, G, H, I) with total depths of between 6 and 9 m were drilled within the trench filling (Figure 3).

In order to prove the barrage theory of Koch (2002), we started in 2009 a geoarchaeological prospection at the site of Koch's presumed reservoir (Figure 3). A total of 36 Edelmann hand rotating drillings with depths of 2–4 m at the site of the reservoir, the dam, as well as the northern Rezat fen provide information about the local topographic, pedological, and palaeolimnological conditions. The drillings were done using a percussive hammer drill and liners with a diameter of 140 mm. The undisturbed soil horizons within the PE-liner were recorded according to the Manual of Soil Mapping (Sponagel, 2005).

LIDAR data

High-resolved airborne Laser scanning data were used to generate a digital elevation model (DEM). The data were

supplied by the Bavarian land surveying office in Munich. Using the DEM, we searched for remnants of the presumed Rezat dam (Koch, 2002) as well as those of the Altmühl dam discussed by Spindler (1998). The LIDAR data provides information about potential feed lines into the Fossa Carolina and remnants of camps for the Carolingian workers, too.

Laboratory procedures

We used grain-size analyses to reconstruct sedimentation sequences that reflect the infilling history of the trench. In addition, by comparing the grain-size composition, it is possible to identify similar layers for stratigraphic correlation along the infilled trench. For grain-size analyses, bulk samples (10 g) were left overnight in 25-mL dispersing solution (sodium hexametaphosphate $[NaPO_3]_6$—39 g/L H_2O). After the addition of 200 mL H_2O, the samples were shaken for at least 2 hours. The grain-size measurements of the sand fraction were carried out by means of the wet-sieve technique (2.0–0.63 mm: coarse sand; 0.63–0.2 mm: medium sand; 0.2–0,063 mm: fine sand). Coarse silt (0.063–0.02 mm), medium silt (0.02–0.0063 mm), fine silt (0.0063–0.002 mm), and clay (<0.002 mm) were measured by pipette analyses (Schlichting, Blume, & Stahr, 1995).

We used loss of ignition (LOI) to determine soil organic matter content. On this basis, we reconstruct the peat layers, that is, the levels of former semi-terrestrial zones of the ponds. The sediment samples were heated for 4 hours at 550°C in a muffle furnace (Heiri, Lotter, & Lemcke, 2001). The determination of LOI has been performed on cores A and B.

We used ^{14}C dating to gain chronological information. Remains of terrestrial plants (charcoal and wood) from *Fossa Carolina* sediment layers in cores A and B (Figures 5, 6; Table I) were processed by the accelerator mass spectrometry (AMS) ^{14}C laboratory in Kiel (KIA). At the site of the presumed dam of the water reservoir, we have taken five charcoal samples plus one sample of humic acid for ^{14}C dating (cores 7 and 12; Figure 3; Table I). All ^{14}C samples were analyzed by the AMS ^{14}C laboratory in Kiel (KIA). Radiocarbon ages were calibrated in Calpal (www.calpal-online.de), the calibration program of the Cologne radiocarbon lab.

In core B, we have analyzed 12 pollen samples that were taken from layers between 413.0 and 414.9 masl. The samples were prepared according to Jacomet and Kreuz (1999) at the laboratory of the University of Hohenheim. The counting and identification of the pollen took place at the laboratory of archaeobotany of the State Conservation Office of Baden-Wuerttemberg.

In core A, anthracological analyses were carried out by Werner Schoch (Langnau) from the initial infilling of the trench between 409.3 and 411.0 masl (Table II).

RESULTS

Stratigraphical Findings from the Trench Infill

The first core (A) starts at 408.5 masl and reaches 7 m up to 415.5 masl (Figure 5). In the lower part of core A, there are reddish fluvial sands up to a depth of 409.4 masl. Comparing the sediment texture of these clastic layers, they can be assigned to a homogeneous sedimentological sequence between 408.5 and 409.4 masl that was probably deposited within one single event (sequence AI in Figures 5, 7). Sequence AI is texturally distinct from the upper brownish layer (A35) in 409.4 masl with an aggregated sediment structure and considerably increased contents of organic matter (8.3%). Above the brownish layer are mainly sandy layers up to a level of 410.9 m a.s.l (sequence AII in Figures 5, 7). We have dated charcoal and plant remnants originating from this sequence (Table I). The first charcoal sample from 409.4 masl (A35) was dated to an age of 725 ± 34 cal. A.D. The second charcoal sample from an altitude of 410.9 masl (A26) indicates an age of 727 ± 35 cal. A.D. Regarding the age control of the initial infilling of the trench, KIA36406 radiocarbon sample at the base of the initial sequence (A35) features a mix of small charcoal particles (*Quercus, Alnus, Fagus sylvatica*; cf. Table II). The charcoals might indicate remnants of redeposited hearths or fire sites, which belong to the Carolingian construction period. The KIA36404 radiocarbon sample at the top of the initial infilling sequence (A26) is nonburned *Quercus* wood (cf. Table II). The wood remnants in the initial infilling sequence must belong to the pre-Carolingian forest because they are significantly older than the historical onset (793 A.D.) of the *Fossa* construction. Therefore, both ages might correspond to the felling of full-grown trees during the era of Charlemagne. The presence of unburned wood in the basal trench filling might indicate the integration of local timber in the *Fossa* building.

From 410.9 up to a level of 412.6 masl, there are mainly semi-terrestrial sediments with high contents of organic matter (10.0–38.5%). A piece of wood from 411.75 masl (A20) indicates an age of 1070 ± 46 cal. A.D. (High Middle Ages).

An uppermost thick and homogeneous sediment sequence can be detected between 412.8 and 414.9 masl (sequence AVII in Figure 5). The last sequence is characterized by low organic content, sandy sediments with a dominance of terrestrial features.

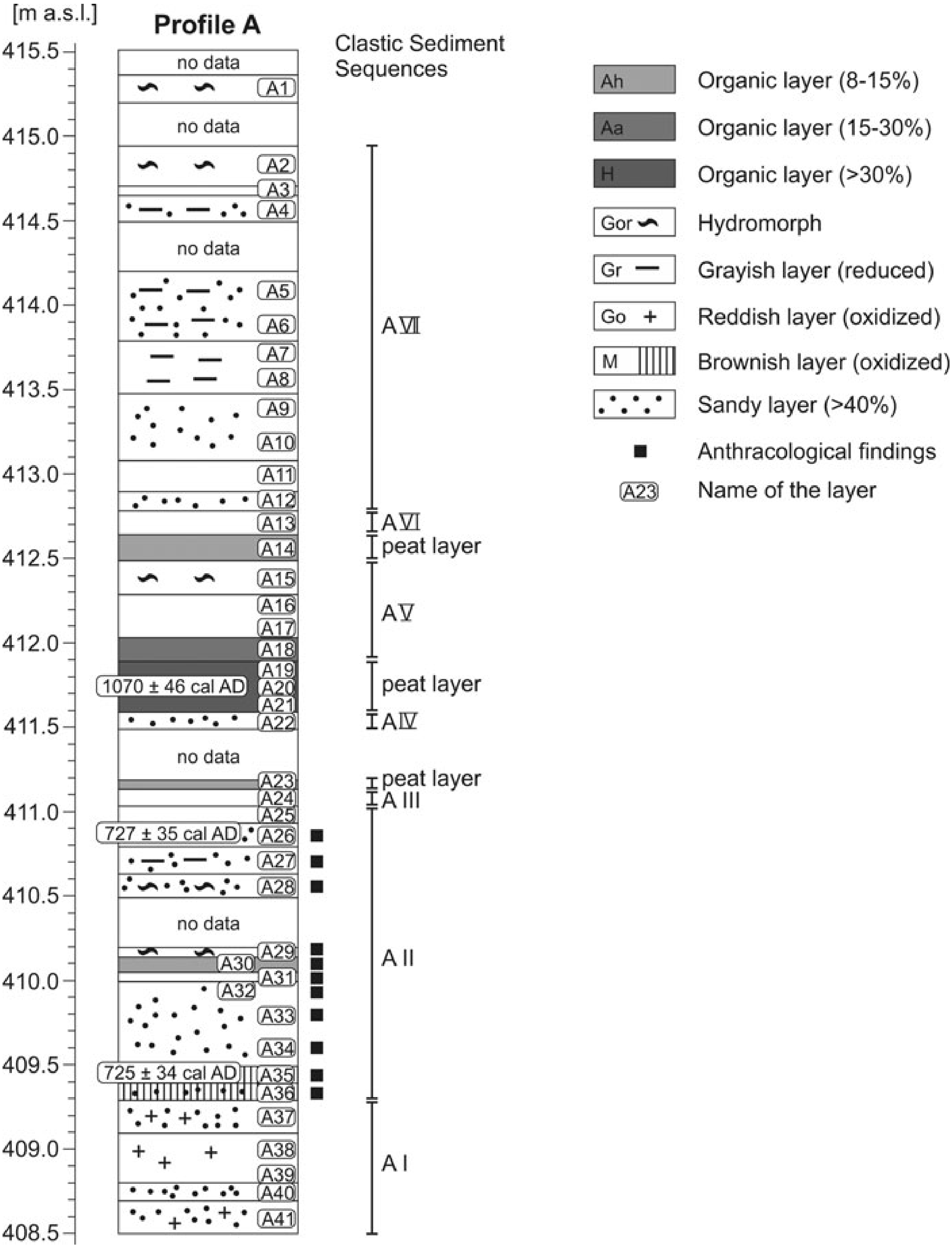

Figure 5 Profile A with ^{14}C dating and sedimentological data.

The profile of the second core B starts at 413.0 masl and extends 4 m up to 417.0 masl (Figure 6). The lower part of core B between 413.0 and 413.5 masl consists of clastic sediments with a maximum in the sand fraction. This section is quite homogeneous according to the sediment texture. On the basis of the cumulative grain-size curves, the sedimentological BI sequence is defined (Figures 6, 7). A wood remnant from 413.1 masl (B23) was dated to

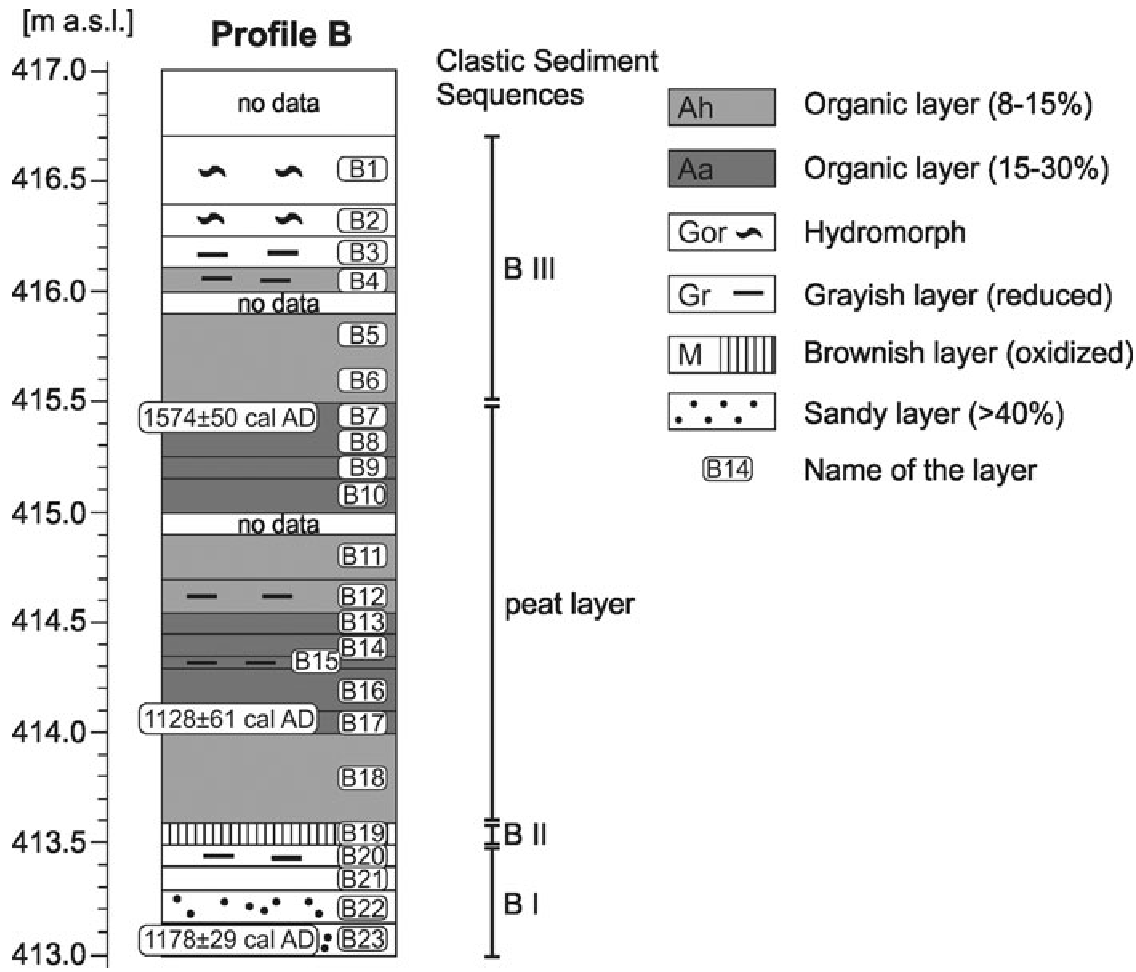

Figure 6 Profile B with ^{14}C dating and sedimentological data.

an age of 1178 ± 29 cal. A.D. (High Middle Ages). Therefore, it appears that the Carolingian trench bottom was not reached within this core.

Sequence BI is covered by a brownish layer with an aggregated soil structure and considerably increased organic matter content (11.7%). Above this layer is a thick sequence of organic-rich layers between 413.6 and 416.1 masl. These organic-rich layers feature contents of soil organic matter between 8.2% and 25.5%. A wood fragment from an altitude of 414.0 masl (B17) indicates an age of 1128 ± 61 cal. A.D. and a plant fragment from 415.4 masl (B7) reveals an age of 1574 ± 50 cal. A.D. Therefore, the organic-rich layers can be related to a period between High Middle Ages and early Modern Times.

From 416.1 masl upwards, there are again more clastic sediment layers (BIII). The sequence is characterized by more terrestrial features with decreasing organic contents.

Within cores E, F, G, H, and I (Figure 8), we have identified former trench bottoms and peat layers and compared their levels against adjacent cores (Figure 9). Core E starts at 407.0 masl and reaches 9 m up to 416.0 masl. The lowermost sequence up to 411.0 masl consists of fine clays. Core E is the only core showing these characteristic Miocene clay fillings. The peat layer is located at 412.4–413.0 masl. Core F starts at 410.6 masl and reaches 6 m up to 416.6 masl. Here, we have found a peat layer at 411.9–413.5 masl. Cores G and H start both at 409.6 masl and reach 7 m up to 416.6 masl. In core G, the peat layer is located between 412.8 and 414.4 masl. At core H, a peat layer is detected between 412.4 and 414.7 masl. Core I starts at 410.7 masl and reaches 6 m up to 416.7 masl. The peat layer is noted between 413.7 and 415.2 masl.

Pollen and anthracological findings

In contrast to the findings of Küster (1993), our results indicate poor preservation conditions for pollen. Only two of the 12 samples taken from core B contained sufficient pollen to obtain a pollen count: the first one in 414.7

Table I First *in situ* radiocarbon ages of the *Fossa Carolina* infill and the dam west of Dettenheim. The calibration (one sigma) of the conventional ages was performed using Cologne Radiocarbon Calibration, quickcal2007 ver.1.5; www.calpal-online.de.

Site/Layer	Location	Lab No.	Material	^{14}C [BP]	^{14}C [cal. A.D.]	δ^{13}C (‰)
A20	Canal filling (peat layer)	KIA36403	Wood	973 ± 28	1070 ± 46	−26.05 ± 0.24
A26	Canal filling	KIA36404	Charcoal	1267 ± 27	727 ± 35	−23.67 ± 0.09
A35	Canal bottom	KIA36406	Charcoal	1269 ± 27	725 ± 34	−24.50 ± 0.14
B7	Canal filling (peat layer)	KIA36407	Plant	307 ± 22	1574 ± 50	−27.33 ± 0.18
B17	Canal filling (peat layer)	KIA36408	Wood	882 ± 29	1128 ± 61	−29.50 ± 0.18
B23	Canal filling (peat layer)	KIA36409	Wood	859 ± 29	1178 ± 29	−30.89 ± 0.20
Core 7	Dam	KIA38898	Charcoal	332 ± 34	1555 ± 58	
0.70–0.80 m						−20.96 ± 0.25
Core 7	Dam	KIA38899	Charcoal	443 ± 31	1444 ± 13	
0.80–0.99 m						−25.25 ± 0.16
Core 7	Dam	KIA38900	Charcoal	813 ± 32	1220 ± 27	
1.50–1.70 m						−23.20 ± 0.27
Core 7	Buried A-horizon	KIA38901	Charcoal	1484 ± 42	577 ± 36	
1.77–1.90 m						−24.74 ± 0.43
Core 12	Dam	KIA38902	Charcoal	340 ± 31	1551 ± 58	
0.57–0.90 m						−22.59 ± 0.23
Core 12	Dam	KIA38902	Humic acid	320 ± 35	1561 ± 55	
0.57–0.90 m						−21.66 ± 0.24

masl (B11) and the second one in 413.3 masl (B22). Because of the poor preservation status, it can be assumed that the pollen spectrum is not completely conserved. Hence, there is very likely a residual concentration of more resistant pollen. Both samples are quite similar. The amount of tree pollen is very low at 37% (B11) and 29% (B22). Tree pollen is dominated by *Pinus* (pine) followed by *Quercus* (oak). In the spectrum of non-tree pollen, there were frequently observations of *Achillea* (yarrow), *Artemisia, Cyperaceae* (sedge), *Filipendula* (meadowsweet), and *Poaceae* (grass). Cereal types were dominated by *Hordeum* (barley). The pollen spectra (B11 and B22) indicate environmental conditions with important woodland clearings and a dominance of *Pinus*, *Quercus*, and cereals, which are typical for the Medieval period (cf. Knipping, 2000).

The anthracological findings from the initial trench infilling recovered in core A (Table II) reflect an ecological transition zone between a softwood flood plain forest (*Salix* sp., *Alnus* sp.) and a hardwood flood plain forest

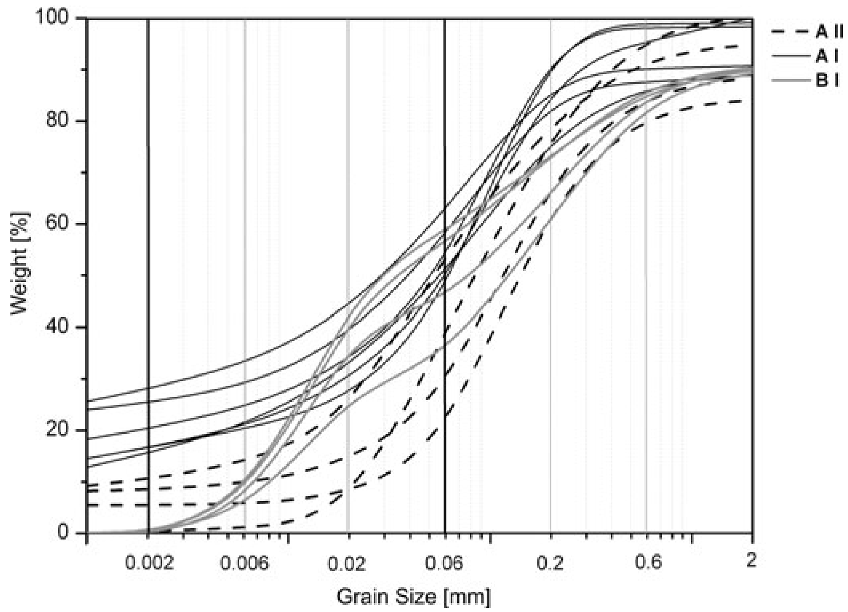

Figure 7 Classification of sedimentological sequences with the aid of cumulative grain-size curves. Comparing the sediment texture of the clastic layers, distinct clastic sediment sequences with homogeneous grain-size compositions can be defined. These homogeneous sequences are marked in Figures 5 and 6.

Table II Anthracological findings from the initial sedimentological sequence at the *Fossa Carolina* trench bottom. The plant remnants feature an ecological transition zone between a softwood flood plain forest (*Salix* sp., *Alnus* sp.) and a hardwood flood plain forest (*Quercus* sp.)

Altitude [masl]	Layer	^{14}C Sampling	Type of Wood	Number of Pieces	Material
411.0–410.8	A26	KIA36404	*Quercus* sp. (oak)	15	Wood, uncharred
411.0–410.8	A26		*Quercus* sp. (oak)	16	Wood, uncharred
410.8–410.7	A27		*Quercus* sp. (oak)	32	Wood, uncharred
410.7–410.5	A28		*Quercus* sp. (oak)	2	Wood, uncharred
410.3–410.2	A29		*Picea* sp. (spruce)	1	Twig, uncharred
			Bidens cernua (nodding beggar-ticks)	1	Seed fragments
410.2–410.1	A30		*Alnus* sp. (alder)	9	Wood
			Alnus sp. (alder)	10	Uncharred
			Fagus silvatica (beech)	1	Roots, uncharred
					Wood, uncharred
410.1–410.0	A31		*Salix* sp. (willow)	1	Twig, one tree ring
			Fagus silvatica (beech)	4	Uncharred
					Charcoal
410.0–409.9	A32		*Salix* sp. (willow)	1	Wood, uncharred
			Quercus sp. (oak)	1	Wood, uncharred
409.9–409.7	A33		*Bidens cernua* (nodding beggar-ticks)	1	Seed fragment
409.7–409.5	A34		*Salix* sp. (willow)	1	Twig fragment, uncharred
			Bark fragments, indeterminable	4	Uncharred
409.5–409.4	A35	KIA36406	*Quercus* sp. (oak)	2	Charcoal
			Betula sp. (birch)	1	Charcoal
			Maloideae (pome fruit)	1	Charcoal
			Alnus sp. (alder)	1	Charcoal
			Quercus sp., unclear	2	Thin root, uncharred
409.4–409.3	A36		*Quercus* sp. (oak)	1	Charcoal
			Alnus sp. (alder)	1	Charcoal
			Fagus silvatica (beech)	3	Charcoal

(*Quercus* sp.). Assuming that the anthracological findings correspond to the local vegetation just before the onset of the *Fossa* construction, the pre-Carolingian groundwater-table must be very close to the earth surface. Due to *Fossa* construction and the corresponding anthropogenic flood plain drainage, the groundwater table probably decreased at least 8 m in the central part of the *Fossa*.

Findings of the presumed water reservoir

In the area of the presumed water reservoir (Figure 3), there is no evidence of sedimentary features that point to stagnant water occupying a former reservoir. There is neither enrichment in organic matter nor enhanced clay deposition in the cores. There is also no evidence for soil hydromorphic features due to periodic backwater in former times. The dam drillings (Figure 3) clearly feature anthropogenic layers. Beneath a 30- to 50-cm thick plough horizon were found two to four different anthropogenic layers up to a depth of 120–180 cm. They are rich in small fragments of charcoal and bricks.

The five ^{14}C-dated charcoal samples plus one sample of humic acid were taken directly out of the dam from core 7 and core 12 (cf. Figure 3; Table I). The lowest sample of core 7 was taken out of a buried *in situ* A-horizon in 1.77–1.90 m depth. The charcoal features a pre-Carolingian age (577 ± 36 cal. A.D.). A charcoal sample from the lowermost anthropogenic layer between 1.50 and 1.70 m reveals an age of 1220 ± 27 cal. A.D. (High Middle Ages). A third sample from an anthropogenic layer between 0.80 and 0.99 m shows an age of 1444 ± 13 cal. A.D. (Late Middle Ages). The dating from an upper anthropogenic layer between 0.70 and 0.80 m indicates an age of 1555 ± 58 cal. A.D. (early Modern Times). In core 12, we have sampled charcoal and humic acid out of an upper anthropogenic layer between 0.57 and 0.90 m. The two dates display significant overlapping. The charcoal sample provides an age of 1551 ± 58 cal. A.D. and the humic acid yields an age of 1561 ± 55 cal. A.D. Hence, the layer was very likely deposited in early Modern Times as well as the upper anthropogenic layer in core 7 (Table I).

DISCUSSION AND GEOARCHAEOLOGICAL CHALLENGES

The first available radiocarbon data from the *Fossa Carolina* trench fillings confirm as expected that the canal

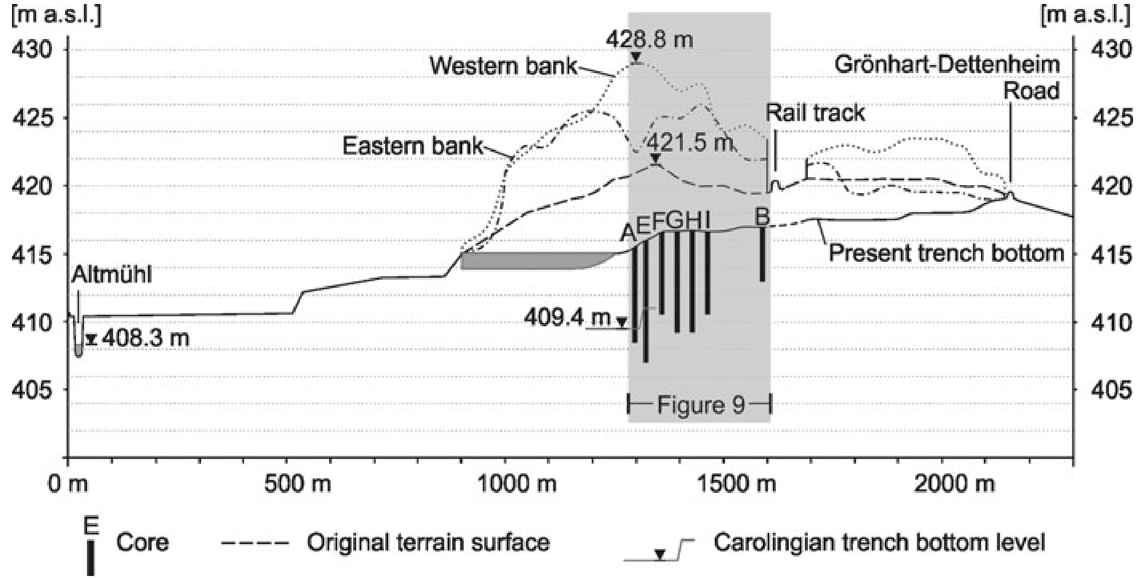

Figure 8 *Fossa Carolina* longitudinal profile with coring sites. In core A, the Carolingian trench bottom is reconstructed. The Carolingian level of the trench bottom (409.4 masl) is about 1 m higher than the mean current Altmühl level. The grayish rectangle features the limits of the detailed sketch in Figure 9.

construction has started in Carolingian times. However, this is in contrast to Pecher (1993), who interpreted the *Fossa Carolina* as a Roman project. Immediately north of the recent pond (core A), a brownish layer in 409.4 masl (A35) has been dated to 725 ± 34 cal. A.D. (Figure 5; Table I). The oxidized brownish layer with high silt content and enhanced soil organic matter content is very likely the Carolingian canal bottom. Below the brownish layer are *in situ* fluvial sands that were deposited during a single event according to its sedimentological homogeneity (Figure 7). Hence, the Carolingian trench bottom is clearly detectable as a brownish layer in core A. The level of the trench bottom (409.4 masl) is 1.1 m higher than the mean current Altmühl

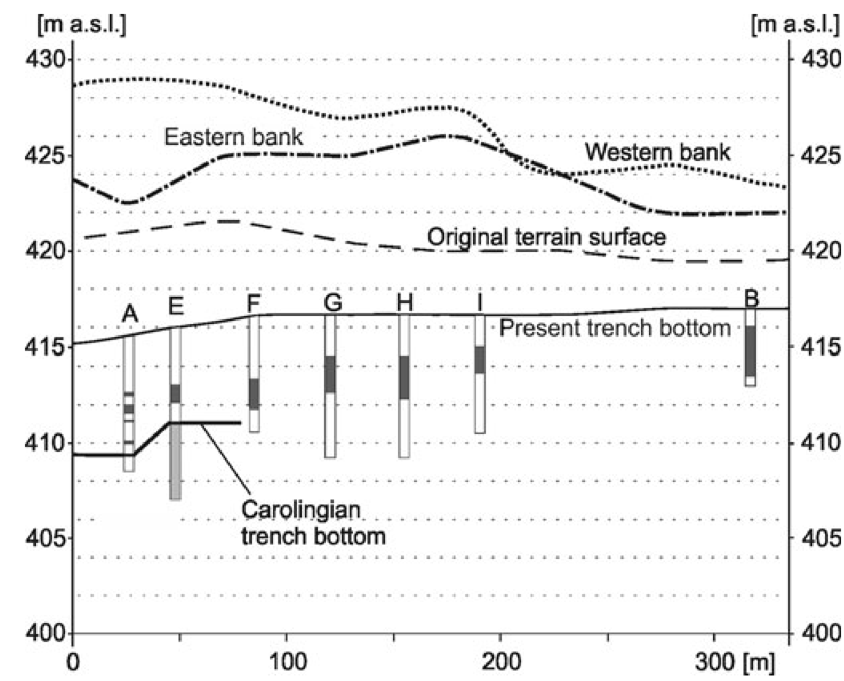

Figure 9 Detailed scene of the longitudinal profile. The sketch shows levels of the Medieval peat layers (dark gray), Miocene clay layers (light gray), and estimated levels of the Carolingian trench bottom.

level (408.3 masl). Since there is no evidence for a different water level of the Altmühl in Carolingian times (Koch & Leininger, 1993), there must have been a downward step within the canal longitudinal profile to connect the *Fossa Carolina* with the Altmühl (Figure 8). This could be the first evidence for the chain of ponds as technical concept (cf. Koch, 2002). A further indication for a chain of ponds can be found by comparing the levels of the dated trench bottom in core A and the Miocene clay layer in core E, originating from the filling of the Miocene Rezat–Altmühl Lake. In core E, the Carolingian trench bottom must be located above the thick clay layer that is reaching up to 410.7 masl (Figure 9). This step between core A and E would have at least a height of 1.3 m. For the first time, we have evidence for a clearly located step in the Carolingian trench bottom.

In core B, the Carolingian trench bottom is definitely not reached. The lowermost sediments in core B were deposited around 1178 ± 29 cal. A.D. There is also evidence for the Medieval infilling of the core B section by the pollen spectra, which reveal a very low amount of tree pollen (cf. Bork et al., 1998). According to our pollen findings and ^{14}C dating, the Carolingian trench bottom in the northeastern part of the central *Fossa* is below the level assumed by Koch and Leininger (1993).

The peat layers of core A and B have been developed in High Middle Ages. That implies the occurrence of a semiterrestrial phase especially in that period of time. Regarding the dating of the principal peat layers in detail, the ages coincide with the Medieval Warm Period (800–1300 A.D.; Mangini, Spötl, & Verdes, 2005). Therefore, a raised groundwater level during the Medieval Warm Period due to a climatic impact should definitely not be excluded for the growth of the principal peat layer in the *Fossa*.

Although the principal peat layers in the trench filling do not correspond with a Carolingian chain of ponds, the level of the peat layers reveals a stepped arrangement. There might be evidence for a multi-phase (late) Medieval to modern chain of ponds as already assumed by historical sources for the last centuries (Redenbacher, 1844; Beck, 1911). However, further drilling campaigns, dating, and sediment analyses of the trench filling are necessary for the clear reconstruction of the Carolingian and later trench bottoms.

Regarding the ^{14}C date from core A at 410.9 masl (727 ± 35 cal. A.D.) and from the trench bottom at 409.4 masl (725 ± 34 cal. A.D.), we have to assume a time interval for the initial infilling of the trench, which is not longer than the uncertainty of the ^{14}C dating technique. A short interval for the initial trench filling is also indicated by a homogeneous sediment sequence at the bottom of the trench (sequence AII, Figure 7). This feature suggests only a few or even a single sedimentation event. The abrupt back-filling of the trench had very likely already started in Carolingian times and might have been completed fairly quickly. The wood remnants in the initial trench filling support this thesis. The two early Medieval ^{14}C ages are similar but belong to different wood samples. Both ages might correspond to the felling of full-grown trees during the year of *Fossa* construction. Hence, our preliminary findings provide no clear evidence for a Carolingian use (cf. Spindler, 1998) of the *Fossa* so far.

According to our stratigraphical and chronological data from the eastern dam, there is no geoarchaeological support for Koch's (2002) barrage theory so far. The results suggest its construction not before the High Middle Ages (1220 ± 27 cal. A.D.; Table I). At least two subsequent augmentations of the dam in the 15th and 16th/17th century occurred. The time gap of ca. 600 years between the buried pre-Carolingian *in situ* A-horizon and the first verified dam fill cannot be explained so far. Although we are able to compute a volume of about 55,000 m^3 for a potential water reservoir by the use of airborne LIDAR data (Figure 3), the chronological data give no evidence for a Carolingian barrage in the west of Dettenheim. Perhaps, the ostensible remnants of a dam were just used as road stabilization for passing the Rezat flood plain. We used the LIDAR data also for prospecting the remnants of the Altmühl dam presumed by Spindler (1998). However, there are no authentic findings in the landscape that could confirm this theory.

There still remain many open questions about the history of the *Fossa Carolina*. It is not clear if the project was ever finished or the *Fossa* was ever in use. The falsification of the theory of the water reservoir reopens the question about the Carolingian water supply. For the reconstruction of the Carolingian trench bottom as well as for later bottom stages and knowledge about the (multi-phase) chain of ponds, new drilling campaigns and the development of further geoarchaeological frameworks are required.

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