Quaternary river terraces and hillslope sediments as archives for paleoenvironmental reconstruction: new insights from the headwaters of the Main River, Germany

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with 9 figures and 3 tables

Abstract. This paper deals with the analysis of hillslope sediments and of fluvial terraces and how they are used as paleoenvironmental archives for obtaining new information on the landscape evolution in a small dry valley in the headwaters of the Main River in northern Bavaria, Germany. Both, traditional geomorphologic approaches, such as field observations and qualitative petrographic analyses of fluvial gravels, and modern numerical dating techniques, are applied. Qualitative petrographic analyses were used as a tool to identify the origin of fluvial terrace gravels and to draw conclusions on the genesis of the particular terrace aggradation. In order to establish a local chronological framework for the fluvial history during the Late Quaternary, luminescence dating techniques along with 14C-dating methods are used to reassess age estimations for the Würmian T2-terrace made by previous studies. Information on the paleoenvironmental conditions of the research area are drawn from the malacological analysis of a unique community of fossil terrestrial mollusks with a surprising variety of species, so far not reported for the region of northern Bavaria. The presented results indicate that fluvial systems have always to be considered as individuals, responding in a very specific way to changes in environmental conditions and reflecting the unique settings of the investigated catchment.

Keywords: river terrace, OSL dating, Quaternary, river deflection, Northern Bavaria, mollusk assemblage, petrographic analysis, fluvial gravels

1 Introduction

River terraces are widespread geomorphic features. Their formation is mainly controlled by changing tectonic and climate conditions and therefore they can be used as archives for paleotectonic and paleoenvironmental reconstruction. River terraces are often interpreted as the expression of changing climates and especially as a result of numerous transitions between cold and warm conditions within the Quaternary and their corresponding changes in vegetation, sediment supply and transport capacity (e.g., Antoine et al. 2007, Bridgland & Westaway 2008, Busschers et al. 2008, Vandenberghe 2008, 2015). However, the timing of incision and accumulation phases of fluvial systems and therefore the formation of river terraces in relation to climate is still not fully understood (e.g., Mol et al. 2000, Schulte et al. 2008, Vandenberghe 2015, Viveen et al. 2013).

Before the 1990s, many studies on river terraces were primarily based on morphological analyses, such as extent and relative heights of terrace levels, and on their sedimentological characteristics, i.e. petrographic composition and weathering degree of the terrace gravels. Furthermore, classical field-based methods, such as field topographic measurements, grain size
measurements and geomorphological mapping, together with quantitative approaches, like hydraulic geometry and formulae for bedload transport, were frequently applied in studies dealing with fluvial geomorphology (Piégay et al. 2015).

The informative value of fluvial archives and their significance for paleoenvironmental research, however, strongly depend on a precise dating of the terrace formation. In the past, the lack of age determinations using numerical dating methods had often to be regarded as a serious limitation for paleoenvironmental interpretations of fluvial archives in general and specifically of those investigated in the research area of the study in hand.

In southern Germany, the evolution of river drainage systems is on the whole greatly affected by the individual developments of two important river systems, those of Danube and Rhine rivers (e.g., Eberle et al. 2010). This is particularly true for the complex river drainage system of Northern Bavaria close to the European watershed. Due to the subsidence of the Upper Rhine Graben, the River Rhine was able to enlarge its catchment area by stepwise headwater erosion and river deflections, leaving behind an irregular drainage system characterized by various triangular and rectangular changes in the courses of the involved rivers (e.g., Eberle et al. 2010, Schirmer 2010, 2012). After the overall establishment of the Main River as the longest right bank tributary of the Rhine drainage system by the end of the Pliocene, there were still further river deflections occurring in the headwaters of the Main River during the Quaternary. The latest of these Upper to Middle Pleistocene river deflections took place in an oversized valley.
named Trebgast Valley in the north of the city of Bayreuth, Bavaria, Germany (Fig. 1). Within this valley, five Pleistocene terrace levels were distinguished and interpreted as the result of a very complex landscape evolution in which two local rivers, the Red Main River and the Steinach River, were involved (e.g., Kleber & Stingl 2000, Zöller et al. 2011).

In order to understand the processes responsible for the recent drainage system, a precise local chronostratigraphy based on numerical dating methods should be established. Only this can provide a reliable database and chronological framework for the reconstruction of paleoenvironmental conditions associated with the formation of the different terraces in the research area.

Over the last two decades, luminescence dating, especially the optically stimulated luminescence (OSL) method, has become a commonly applied standard method for yielding sedimentation ages of fluvial deposits (e.g., Fuchs et al. 2001, Lauer et al. 2010, 2014). Despite several serious methodological challenges (e.g., incomplete resetting of the luminescence signal during fluvial transport or problems in dosimetry due to the heterogeneous composition of the fluvial sediments), the advantages of luminescence dating techniques are obvious: they enable the dating of (fluvial) sediments far beyond the last glacial-interglacial cycle and, by using quartz and feldspar minerals as dosimeters, suffer from almost no limitation of dateable material (e.g., Rittenour 2008).

This paper gives an overview of the fluvial history and landscape evolution of the Trebgast Valley. We present new findings based on intensive fieldwork as well as on numerical dating approaches. As the timing of the final deflection of the Steinach River is of special interest for the reconstruction of the Late Pleistocene and Early Holocene landscape evolution, the study in hand was focused on attempts to date the aggradation of the youngest terrace level (T2 level) accumulated by the primary Steinach River, a tributary of the Main River. The presented OSL and radiocarbon dating results rise questions about the timing of the latest river deflection stated by previous studies (e.g., Kleber & Stingl 2000, Zöller et al. 2007, 2011) and, in general, highlight new questions regarding both, process and timing of gravel aggradation in fluvial systems in the northeastern part of Bavaria.

2 Study area

2.1 General information and river drainage system

The research area, a small, oversized dry valley in the headwaters of the Main River, is situated in the north-east of Bavaria, Germany (Fig. 1). Nowadays, the valley is drained by a small creek called Trebgast. The Trebgast Valley is a former interconnection between the Red Main/Steinach drainage system in the south and the White Main River in the north (e.g., Kleber & Stingl 2000, Zöller et al. 2007, 2011).

With the White Main River and the Red Main River, there are two headwater streams of the Main River dominating the drainage system of the study area. While the first originates in the Variscian basement area of the Fichtel Mountains, the latter has its origin in a Middle Jurassic sandstone area south of the city of Bayreuth. Both rivers join near the town of Kulmbach,
forming the Main River, which is, with a total length of about 527 km, the longest right bank tributary of the River Rhine.

A third river, important for the present-day drainage system as well as for the Quaternary development of the study area, is the river Warme Steinach (hereafter mentioned as Steinach River). It is a tributary to the Red Main River, with their confluence within the city of Bayreuth.

The evolution of the Trebgast Valley has been discussed among geoscientists since the beginning of the 20th century (e.g., Reck 1912, Henkel 1917). Mainly based on morphological and lithological evidence, this long lasting controversy focused on the question whether the Trebgast Valley was originally drained by the Red Main River (e.g., Reck 1912, Seefeldner 1914, Stadelmann 1924, Körber 1962) or whether it had to be interpreted as a former valley of the primary Steinach River (e.g., Henkel 1917, 1920, Emmert & Weinelt 1962). Other studies (e.g., Ertl 1987, Veit 1991) dealt with specific topics within the research area. But it was not until recently that new studies (e.g., Kleber & Stingl 2000, Zöller et al. 2007, 2011) were able to prove the participation of both rivers in the evolution of the Trebgast Valley and to derive the landscape evolution model described below (see section 2.3).

2.2 Geological and geomorphological setting

The research area is part of a transition zone between two major tectonic units (see Fig. 2). The lithology of the valley is characterized by Triassic sandstone, claystone, marl and limestone formations. To the east, the surroundings of the valley are dominated by the crystalline basement

Fig. 2. Geological map of Upper Franconia. The region is divided into two major geological units. The Northern Franconian Alb in the west is built up of Mesozoic sedimentary rocks. In the eastern part, plutonites and metamorphic rocks dominate the lithology, exposed in the crystalline basement area of the Bohemian Massif. The Trebgast Valley itself is located in a transition zone developed within sandstone formations of Lower Triassic origin (orange color scheme).
of the Bohemian Massif, primarily exposing plutonites and metamorphic rocks. In the west, the study area is bordered by the Northern Franconian Alb consisting of Jurassic sedimentary rocks. The geology of the transition zone is dominated by the so called “Franconian Lineament”, a NW to SE striking tectonic fault system, separating the Variscian Bohemian Massif from the adjacent South German Block and its Permo-Mesozoic sedimentary cover (e.g., Duyster 1995). The study area itself belongs to the intermittent Upper Franconian Bloc-Faulted Zone, which exposes Triassic to Jurassic sedimentary rocks displaced by numerous anatomizing faults running more or less parallel to the Franconian Lineament.

The Trebgast Valley itself can be subdivided into four sections and is displayed in detail in Fig. 3: (1) The uppermost reaches are characterized by a wide and flat valley bottom. This overall 4 km long section clearly shows a south-north orientation and is separated from the Red Main River valley by a steep slope of 10–15 m and a very flat watershed. No river or creek has been able to develop within this part of the valley so far. To the east, the valley slightly raises with 3 clearly distinguished steps from 355 m a.s.l. to 400 m a.s.l., indicating a staircase of at least 3 river terraces. To the west, the valley is bordered by slightly, but sometimes steeply ascending slopes developed in sandstone formations of Upper Triassic origin.

Fig. 3. Detailed map of the Trebgast Valley showing the five Pleistocene terrace levels identified for the research area by previous studies. The alignment of the terraces was adopted from Kleber & Stingl (2000).
(2) Downstream the village of Bindlach, the valley overall bends to the north-west and generally follows the direction of the Middle Triassic limestone cuesta. After a short distance of narrowing, the valley floor widens again, revealing an oversized valley. This part of the study area is drained by the Trebgast Creek, which enters the abandoned valley floor at the village of Bindlach. The width of the valley is in contrast to the dimension of the creek. Within this approximately 8 km long section several river terrace staircases can be found on both sides of the valley. Overall 5 different Pleistocene terrace levels have been distinguished so far (Figs. 3 and 4).

(3) Before bending to the north and entering the very narrow lowermost part of the valley, the valley floor broadens even more to a wide and flat basin, the so called “Lindau Basin” (Fig. 6). Within this morphological depression several terraces are visible. The levels of these terraces correspond to those in the main part of the Trebgast Valley. Situated in the transition zone between the Lindau Basin and the present-day Trebgast Valley, a small fen, slightly surmounted by a humble hill, can be found. Previous studies (e.g., Zöller et al. 2007) interpreted this fen as a key site for the reconstruction of the Late Pleistocene and Holocene landscape development of the Trebgast Valley and its surroundings.

(4) In the lowermost part of the research area the Trebgast Creek bends to a north-eastern direction, intersecting a ridge consisting of geomorphologically resistant Lower Triassic sandstone, before discharging into the White Main River near the village of Trebgast. Here, the valley can be described as a very narrow, even gorge-like valley, deeply incised into the sandstone formations and showing steeply ascending hill slopes. Within this section, no terrace staircases could be detected so far. Only the youngest river terrace of the T1 level was identified.

2.3 Fluvial history

Based on intensive petrographic and geomorphologic analyses, Kleber & Stingl (2000) composed a detailed map of the different terrace levels (Figs. 3 and 4) and derived a very complex
landscape evolution model. The evolution of the fluvial system within the study area is shown in Fig. 5.

Thereafter, the Steinach River and the Red Main River at first jointly flowed through the Trebgast Valley, depositing the river terraces of the two oldest levels (T5 and T4 levels). Presumably during an accumulation phase of the third last glacial period, a first river deflection took place, separating the Steinach River and the Red Main River.

Fig. 5. The different evolutionary stages of the Trebgast Valley. The maps are based on the complex multi-stage landscape evolution model proposed by KLEBER & STINGL (2000).
After that, there followed a long lasting period during which the Steinach River solely drained the Trebgast Valley, whilst the Red Main River already used its present-day course. Derived from sedimentologic and morphostratigraphic evidence (Veit 1991), Kleber & Stingl (2000) concluded that this evolutionary stage persisted for approximately 300,000 years, beginning at the end of the third last glacial period and ending with the final deflection of the Steinach River some time after the Last Glacial Maximum (LGM). This long lasting intermediate stage comprised the penultimate glacial period, which Kleber & Stingl (2000) assigned the forming of the T3-terrace to, and the Würmian glacial period, during which the T2-terrace gravels were deposited.

As a result of the Steinach River’s deflection, the Trebgast Valley fell dry, with the Trebgast Creek using the abandoned valley downstream of the village of Bindlach. During this last stage, the youngest fluvial terrace (T1 level) was able to develop, restricted to the lowermost part of the valley.

3 Methods and materials

In order to shed light on the fluvial history and the landscape evolution of the Trebgast Valley, intensive fieldwork was combined with laboratory analyses. The results from qualitative petrographic analyses of previous studies (e.g., Kleber et al. 1988; Zöller et al. 2011) were compiled and expanded by new petrographic studies of fluvial gravel deposits. To gain additional information on the paleoenvironmental conditions, the composition of the malacofauna, extracted from periglacial slope deposits, was analyzed. The study in hand makes a first step to establish a chronological framework for the different phases of fluvial evolution by determining indirect age information for the aggradation of the upper Würmian terrace (T2) based on dating hillslope sediments by applying luminescence dating techniques along with radiocarbon AMS dating.

3.1 Qualitative petrographic analyses

Qualitative petrographic analyses of terrace gravels are used as an important tool to characterize different terrace levels and draw conclusions on their catchment areas.

While the Steinach River originates east of the research area within the crystalline basement of the Fichtel Mountains, the Red Main River’s headwaters can be found further to the south, within an area covered by Mesozoic sedimentary rocks (see Fig. 2). Therefore, the composition of the terrace gravel deposited by these rivers should be significantly different and can thus be used to draw conclusions on the participation of these two rivers in the terrace accumulation.

Besides the ubiquitous quartz gravels, specific lithologies are indicative of the different headwater areas. Phyllite, metamorphic and granite gravels are characteristic for the Steinach River. Although the Middle Jurassic sandstones are commonly prone to weathering, some iron agglutinated and, thus, weathering resistant gravels can be found in certain layers of these sandstone formations (Dogger β formation). These so called limonite crusts can, thereby, be transported over long distances and used as gravels indicative of the catchment area of the Red Main River.
For the presented study, the results of extensive petrographic analyses, made during the 1980s and previously summarized by Kleber et al. (1988), were compiled with results gained during various fieldtrips regularly performed with students of the University of Bayreuth over the last two decades (e.g., Zöller et al. 2007) and analyses from new sites investigated for the study in hand, over all resulting in a very reliable database concerning the composition of the terrace gravel. The new sampling sites for the presented study were located in the middle and lowermost part of the valley (see Fig. 6). At least one petrographic analysis per investigated terrace was performed on material directly originating from the respective gravel beds.

On every site a number of at least 300 gravels was sampled and subdivided into 7 petrographic classes (phyllite, metamorphic, limonite sandstone, granite, quartz, quartzite, other sandstones; see Table 1 and Fig. 7). As proposed by Müller (1964), the analyses were restricted to gravels showing a diameter from 2 cm up to 20 cm, separated by dry sieving. Gravels with a diameter bigger than 20 cm were registered but not used for counting. For every petrographic class of gravels, abundance was counted and relative frequency was calculated.

### 3.2 Malacological analyses

With terrestrial mollusks being strongly sensitive to variations in temperature and moisture, fossil mollusk communities have proved to be extremely useful for paleoenvironmental and paleoclimatic research (see for example Rousseau 1987). In order to gain additional information on the paleoenvironmental conditions for the deposition of the loess-bearing slope detritus at a location in the middle part of the valley (49° 59’ 49” N, 11° 36’ 15” E, 362 m a.s.l., hereafter named the Crottendorf site), a malacological analysis was performed on a mollusk assemblage detected in the oldest lens of loess-like material. A sample of about 30 kg of sediment was taken, sieved and washed to extract the mollusk shells. Thereafter, the shells were counted, identified and classified following the classifications established by Ložek (1964) and Puisségur (1976). As analyses of mollusk samples are normally carried out based on a standardized sample volume of about 10 liters, the absolute frequencies yielded in the presented study have to be divided by three in order to be comparable with the results of other studies.

For the three dominant species, the juvenile/adult ratios (J/A) were either calculated according to Moine et al. (2008) for *Pupilla muscorum* or visually estimated for *Succinella oblonga* and *Trochulus hispidus* owing to a more difficult distinction of juveniles and broken adults (absence of a particular ornamentation of the lip marking the adult age) for the first and to the hazardous aperture recovery for the later. Variations of this ratio reflect changes in the reproduction rate and in the juvenile survival. With both strongly depending on the temperature during the reproduction season (Moine 2003), the J/A ratio allows qualitative conclusions on the seasonal development of temperatures in the study area.

### 3.3 Sediment dating

#### 3.3.1 Luminescence dating

OSL and IRSL dating techniques were used for the presented study. OSL dating was applied to the coarse grain quartz fraction (90–200 µm), using a single aliquot regenerative-dose (SAR)
protocol (e.g., Murray & Wintle 2000). In order to avoid an age overestimation due to incomplete resetting of the luminescence signal during the last process of transportation and deposition, small aliquots of about 100–300 grains were used, enabling to detect incompletely depleted samples (e.g., Fuchs & Wagner 2003). Furthermore, the age model of Fuchs & Lang (2001) was applied. The IRSL approach was carried out on fine grain material (4–11 µm), using both, the SAR protocol for a fine grain quartz sample and the multiple aliquot additive-dose (MAAD) protocol (e.g., Mauz et al. 2002) for a polymineral sample.

Following standard procedures for sample preparation (e.g., Fuchs et al. 2010), all luminescence measurements were carried out at the University of Bayreuth on an automated Risø-Reader TL/OSL-DA-15, equipped with a $^{90}$Y/$^{90}$Sr β-source for artificial irradiation and blue LEDs (470 ± 30 nm) for OSL stimulation as well as infrared light-LEDs (875 ± 80 nm) for IRSL stimulation. The luminescence signal was detected using a Thorn-EMI 9235 photomultiplier, combined with a 7.5 mm U-340 Hoya filter for the OSL measurements and a 3 mm Chroma Technology D410/30x interference filter for the IRSL measurements, respectively. All luminescence ages (OSL and IRSL) are given as kilo years (ka) with their 1σ-errors.

Fig. 6. Detailed map of the research area. The sampling sites for the qualitative petrographic analyses are highlighted by green triangles. The outcrop which both, the OSL and the $^{14}$C-samples, along with the material for the malacological analyses were taken from is marked by yellow hexagons.
3.3.2 14C-dating

The $^{14}$C analysis of mollusk material was handled by the LSCE, Gif-sur-Yvette, France, on unidentified whorl fragments of shells from *Pupilla* genus. Indeed, Pigati et al. (2004) showed that the North American taxa *Pupilla blandi* has a modern $^{14}$C activity similar to that of the vegetation. However, for a reliable evaluation of the calculated radiocarbon age in this study, it is essential to emphasize that Pigati et al. 2010 showed that species of *Pupilla* genus may sometimes include dead carbon leading to age overestimations reaching up to 1 ka. The yielded conventional age, given as years before present (a BP), was calibrated using the calibration software Calib 6.1 based on the calibration curve IntCal09 (Reimer et al. 2009). This calibrated age is given as calendar years before present (cal BP) considering a 2 sigma error. With the mollusk samples taken from slope deposits originating from the Upper Triassic limestone cuesta, furthermore a significant hard-water effect has to be reconsidered for these samples. This hard-water effect may cause an age overestimation of several hundred years (Wagner 1998). Therefore, the yielded radiocarbon age can merely be interpreted as a maximum sedimentation age.

3.3.3 Sampling strategy (see Figs. 6 and 9b)

All dated luminescence samples (OSL and IRSL) were taken at the Crottendorf site and originate from layers or lenses of loess-like material, embedded into heterogeneous periglacial slope sediments. Here, these slope sediments were exposed over a total length of several hundred meters, superimposing the T2 terrace gravels with a minimal thickness of about 6 meters. Most of the identified layers and lenses were found to be strongly affected by cryoturbation (see Fig. 9a). The radiocarbon sample was taken from the oldest discovered lens consisting of gleyed loess-like material that contained numerous mollusk shells suitable for $^{14}$C dating.

4 Results

4.1 Petrographical analyses

Qualitative petrographical analyses were performed on gravels from a total of 6 sites that have not been investigated in previous studies. The results of these analyses are shown in Table 1 and in the diagrams of Fig. 7.

Thereafter, all terrace levels are characterized by a dominant abundance of quartz and quartzite gravels. Combined, these two categories show relative frequencies between 56 % (PA_5a) in minimum and 69 % (PA_3 b) in maximum. Furthermore, all investigated terraces show high amounts of phyllites (up to 38.8 %) and considerable percentages of other metamorphic rocks (6.7 % in maximum). On the contrary, Middle Jurassic limonite crusts were just found in gravels originating from sites of the T5 level (12 % for location PA_5a and 22 % for location PA_5 b, respectively). Concerning the fact that all sandstones that could not clearly be identified to be of Middle Jurassic origin were assigned to the category “Other Sandstones”, the proportion of limonite crusts for these sites may, by all means, be even higher than displayed in the diagrams. Limonite crusts are either completely missing or show negligible proportions in the investigated gravels originating from the T2 and T3 sites.
Table 1. Results of the qualitative petrographic analyses for different fluvial terraces – sample codes, sampling locations, altitudes a.s.l. and gravel composition.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sampling location</th>
<th>Relative frequencies of the gravel composition grouped by petrographic classes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude [°N]</td>
<td>Longitude [°E]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T2-Terrace level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA_2a</td>
<td>50.051</td>
<td>11.532</td>
</tr>
<tr>
<td>PA_2b</td>
<td>50.054</td>
<td>11.534</td>
</tr>
<tr>
<td><strong>T3-Terrace level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA_3a</td>
<td>50.023</td>
<td>11.556</td>
</tr>
<tr>
<td>PA_3b</td>
<td>50.054</td>
<td>11.533</td>
</tr>
<tr>
<td><strong>T4-Terrace level</strong>(^a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA_4(^a)</td>
<td>50.020</td>
<td>11.577</td>
</tr>
<tr>
<td><strong>T5-Terrace level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA_5a</td>
<td>50.020</td>
<td>11.582</td>
</tr>
<tr>
<td>PA_5b</td>
<td>50.018</td>
<td>11.578</td>
</tr>
</tbody>
</table>

\(^a\) Although showing a densely distributed surficial accumulation of gravels, no gravel bed could be found at this site. The surficial gravels were interpreted as the result of a local displacement of material originating from a higher terrace level. Therefore, no petrographic analysis was performed for this location.

\(^b\) Phyllite and metamorphic gravels are indicative of the headwater area of the Steinach River.

\(^c\) Originating from a Middle Jurassic sandstone area in the south of the city of Bayreuth, iron agglutinated limonite sandstones are indicative of the catchment area of the Red Main River.
The results of the qualitative petrographic analyses partially confirm the findings of previous studies (Kleber et al. 1988, Kleber & Stingl 2000, Zöller et al. 2007). However, our findings also show discrepancies to the results of previous studies. We tried to take samples from a site that has so far been interpreted as a part of the T4 level (location PA_4, 50.020° N, 11.577° E, 358 m a.s.l.). At this site, gravels, which showed the typical spectrum of the T4 level, were found to be densely distributed on a flat, slightly inclined surface. After trenching, however, we were not able to find any gravel bed and, thus, could not determine the composition of the T4-gravel for this location.

Fig. 7. Results of the qualitative petrographic analyses for six sites representing three different terrace levels. With the gravels of the T2- and T3-terrace sites showing similar compositions, they can clearly be distinguished from the gravel compositions of the T5-terrace sites. Only the latter show a considerable proportion of limonite sandstones.

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4.2 The composition of the mollusk assemblage at the Crottendorf site

Based on our observations, the mollusk fauna from the Crottendorf site is the first terrestrial loess fauna detected in Upper Franconia. With a total of nine species it is richer than those from the Danube valley loess (BRUNNACKER & BRUNNACKER 1956) and characterized by a great variety rarely encountered outside of the Rhine Valley in Upper Weichselian loess deposits (MOINE 2008). A total abundance of 5534 individuals was counted for an investigated mass of about 30 kg of material. Even divided by three, this total abundance would by far outrange that of pure loess samples, in which abundance rarely reaches 200–300 individuals. The total abundance at the Crottendorf site equals that reported for mollusk samples originating from cryoturbated tundra gleys (MOINE et al. 2008, 2011). With the texture being quite sandy and no evidence for earthworm granules being found, the mollusk bearing sediments at the Crottendorf site could have been affected by flood deposit dynamics, resulting in a concentration of mollusk shells in the sample location. However, the complete lack of aquatic species and the good state of shell

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Absolute</th>
<th>Relative</th>
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<tbody>
<tr>
<td>Arianta arbusorum (2)</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>Columella columella (5)</td>
<td>4</td>
<td>0.07</td>
</tr>
<tr>
<td>Pupilla muscorum (5)</td>
<td>298</td>
<td>5.38</td>
</tr>
<tr>
<td>Vallonia pulchella (5)</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>Vertigo pygmea (5)</td>
<td>3</td>
<td>0.05</td>
</tr>
<tr>
<td>Trochulus hispidus (7)</td>
<td>853</td>
<td>15.41</td>
</tr>
<tr>
<td>Slugs (7)</td>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>Succinella oblonga (7)</td>
<td>3808</td>
<td>65.16</td>
</tr>
<tr>
<td>Pupilla alipoca (9)</td>
<td>769</td>
<td>13.90</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5534</td>
<td>100</td>
</tr>
</tbody>
</table>

Fig. 8. Compilation of the malacological results for the mollusk assemblage extracted from a lens of gleyed loess-like material embedded into hillslope sediments at the Crottendorf site (adopted from ZÖLLER et al. 2012).
preservation point to a short and smooth transportation process rather than to a displacement over long distances (Zöller et al. 2012).

Fig. 8 shows the absolute and relative frequencies of the counted mollusk shells, population indices and the affiliation of individuals and species to different ecological groups. Thereafter, the mollusk assemblage is dominated by *Succinella oblonga* (65%) followed by *Trochulus hispidus* (15%) and *Pupilla alpicola* (14%). These species require humid conditions and are, therefore, indicative of moist to wet environments mainly covered by short vegetation (Kerney et al. 1983, Falkner et al. 2001). Slugs, which are generally abundant in loess deposits, are almost completely missing at the Crottendorf site, which may as well be attributed to quite moist conditions. Besides, the low frequency of *Pupilla muscorum* (5%), and the few individuals of *Columella columella, Vallonia pulchella* and *Vertigo pygmaea* suggest a more diversified vegetation cover and a slightly drier soil surface in the close surroundings of the sampled gully (Zöller et al. 2012). Moreover, presently living at high elevation *Columella columella* and *Pupilla alpicola* are indicative of low temperatures.

The affiliation of individuals to their particular ecological group shows a distinct preference for hygrophilous and palustral species. On the contrary, the species’ distribution clearly indicates the sporadic presence of some species typical of dry and open environments.

For *Pupilla alpicola* a juvenile/adult ratio of 5.36 was calculated. For *Succinella oblonga* and *Trochulus hispidus* respective values of about 6 and more than 6 were estimated. These ratios point to convenient reproduction conditions, already been described in Nussloch (Rhine valley, Germany) and attributed to local increases in temperature during interstadial phases of the Upper Weichselian (Moine et al. 2008).

### 4.3 Dating results

#### 4.3.1 Morhostratigraphical findings

Several drill cores, extracted from the slope detritus at the Crottendorf site, clearly showed that the periglacial cover sediments overlie the gravels of the T2 level with a minimal thickness of about 6 meters. Therefore, the slope cover sediments were deposited after the aggradation of the T2-gravels and are, thus, younger than the latter. As there was no evidence for a significant, post-sedimentary erosion of the hillslope detritus by fluvial activity, we assume that the accumulation of the cover sediments took place after the final deflection of the primary Steinach River.

As mentioned above, most of the layers and lenses of loess-like material embedded into the slope detritus were strongly affected by cryoturbation (see Fig. 9a). Hence, these lenses as well as the slope detritus on the whole should have been deposited not later than during the Younger Dryas (12,900–11,600 cal BP).

#### 4.3.2 Numerical dating results

In order to ensure the above mentioned hypothesis derived from morphostratigraphical fieldwork, OSL, IRSL and $^{14}$C dating were applied on loess-like material sampled from the above described lenses. The analytic data for dose rate determination are listed in Table 2. The calculated
Fig. 9. a: Photo of a small lens of loess-like material embedded into the slope detritus at the Crottendorf site. Like others, this lens was affected by cryoturbation; b: the sampling situation for OSL-samples BT 580 to BT 584. This location was part of a several hundred meters long outcrop in periglacial slope sediments showing several distinct lenses and layers of homogeneous loess-like material. OSL-ages for coarse grain quartz samples are presented.

Table 2. Radionuclide concentrations, cosmic dose rates and total dose rates calculated for the coarse grain quartz fraction.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{238}$U [ppm]$^a$</th>
<th>$^{232}$Th [ppm]$^a$</th>
<th>$^{40}$K [%]$^b$</th>
<th>$D_{\text{cosmic}}$ [Gy/ka]$^c$</th>
<th>Total dose rate $D$ [Gy/ka]$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT 580</td>
<td>4.63 ± 0.33</td>
<td>15.78 ± 1.09</td>
<td>2.55 ± 0.10</td>
<td>0.21 ± 0.01</td>
<td>4.26 ± 0.24</td>
</tr>
<tr>
<td>BT 581</td>
<td>4.51 ± 0.31</td>
<td>15.25 ± 1.04</td>
<td>2.43 ± 0.10</td>
<td>0.20 ± 0.01</td>
<td>4.11 ± 0.23</td>
</tr>
<tr>
<td>BT 582</td>
<td>4.07 ± 0.28</td>
<td>15.94 ± 0.93</td>
<td>2.37 ± 0.10</td>
<td>0.19 ± 0.01</td>
<td>3.98 ± 0.22</td>
</tr>
<tr>
<td>BT 583</td>
<td>4.69 ± 0.37</td>
<td>12.24 ± 1.21</td>
<td>2.49 ± 0.10</td>
<td>0.19 ± 0.01</td>
<td>3.99 ± 0.23</td>
</tr>
<tr>
<td>BT 584</td>
<td>4.51 ± 0.37</td>
<td>12.83 ± 1.24</td>
<td>2.31 ± 0.10</td>
<td>0.19 ± 0.01</td>
<td>3.83 ± 0.23</td>
</tr>
<tr>
<td>BT 585</td>
<td>3.37 ± 0.55</td>
<td>17.00 ± 1.86</td>
<td>2.35 ± 0.10</td>
<td>0.21 ± 0.01</td>
<td>3.90 ± 0.26</td>
</tr>
<tr>
<td>BT 737</td>
<td>4.26 ± 0.21</td>
<td>11.64 ± 0.71</td>
<td>2.53 ± 0.10</td>
<td>0.09 ± 0.01</td>
<td>3.78 ± 0.21</td>
</tr>
</tbody>
</table>

$^a$ Determined by thick source $\alpha$-counting.
$^b$ Determined by ICP-MS.
$^c$ Cosmic dose rates were calculated according to Prescott & Hutton (1994).
$^d$ For dose rate calculation, a common water content of 15% was used for all samples. This value was derived using the average value of the possible water content range, based on the porosity of the samples and considering an error, which included the possible water content range (e.g., Fuchs et al. 2010, 2012, Prinz 2011, Scheffer et al. 2010).
Table 3. Sample codes, sampling locations, altitudes a.s.l., sampling depths, number of aliquots, equivalent doses, OSL and $^{14}$C ages.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Code</th>
<th>Sampling location</th>
<th>Altitude a.s.l. [m]</th>
<th>Sampling depth [cm]</th>
<th>$n^a$</th>
<th>$n^b$</th>
<th>$k^c$</th>
<th>$D_e$ determination and age calculation</th>
<th>$D_e$ [Gy]</th>
<th>OSL age [ka]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude [°N]</td>
<td>Longtitude [°E]</td>
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<td>Coarse grain quartz – SAR protocol</td>
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<tr>
<td>BT 580</td>
<td></td>
<td>49.998</td>
<td>11.603</td>
<td>356</td>
<td>50</td>
<td>48</td>
<td>25</td>
<td>19</td>
<td>82.44 ± 2.04</td>
<td>19.4 ± 1.2</td>
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<td>11.603</td>
<td>356</td>
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<td>83.21 ± 1.97</td>
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<td>11.603</td>
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<td>34</td>
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<td>87.73 ± 2.57</td>
<td>22.0 ± 1.4</td>
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<td>49.998</td>
<td>11.603</td>
<td>356</td>
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<td>32</td>
<td>20</td>
<td>96.52 ± 2.49</td>
<td>24.2 ± 1.5</td>
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<td></td>
<td>49.998</td>
<td>11.603</td>
<td>356</td>
<td>150</td>
<td>47</td>
<td>38</td>
<td>17</td>
<td>106.59 ± 2.60</td>
<td>27.8 ± 1.8</td>
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<tr>
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<td></td>
<td>49.998</td>
<td>11.603</td>
<td>356</td>
<td>50</td>
<td>39</td>
<td>24</td>
<td>10</td>
<td>81.39 ± 2.67</td>
<td>20.9 ± 1.5</td>
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<tr>
<td>BT 737</td>
<td></td>
<td>49.997</td>
<td>11.604</td>
<td>355</td>
<td>450</td>
<td>94</td>
<td>44</td>
<td>31</td>
<td>114.41 ± 2.12</td>
<td>30.7 ± 1.8</td>
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<td></td>
<td>49.997</td>
<td>11.604</td>
<td>355</td>
<td>450</td>
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<td>–</td>
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<td>143.57 ± 7.40</td>
<td>29.0 ± 1.7</td>
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<td>Fine grain quartz – SAR protocol</td>
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<td></td>
<td>49.960</td>
<td>11.601</td>
<td>355</td>
<td>200</td>
<td>24</td>
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<td>13</td>
<td>139.65 ± 1.97</td>
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<td>$^{14}$C-dating</td>
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<td></td>
<td></td>
<td></td>
<td>26,810 ± 240 a BP</td>
<td>30,974 – 31,500 cal BP</td>
</tr>
</tbody>
</table>

$^a$ Number of measured aliquots.

$^b$ Number of aliquots passing the rejection criteria.

$^c$ Number of aliquots used for $D_e$ determination and age calculation after applying the age model of FUCHS & LANG (2001).

$^d$ For dose rate calculation an $a$-value of 0.07 ± 0.01 was adopted from KREUTZER (2012).

$^e$ For dose rate calculation an $a$-value of 0.04 ± 0.01 was adopted from KREUTZER (2012).
luminescence and \(^{14}\)C ages are compiled in Table 3 and the OSL ages for the coarse grain quartz fraction of samples BT 580 to BT 584 are illustrated in Fig. 9b.

AMS \(^{14}\)C-dating yielded a conventional age of 26,810 ± 240a BP, i.e. a 2\(\sigma\) calibrated age of 30,974–31,500 cal BP.

Within errors, all calculated OSL ages are in stratigraphic order, reaching from 19.4 ± 1.2 ka for the youngest investigated layer to 30.3 ± 1.8 ka for the oldest lens of loess-like material. Due to a lack of organic remnants, we were not able to gain \(^{14}\)C ages as independent age control, except for the mollusk bearing oldest lens. For this lens also an IRSL age was calculated. OSL and IRSL ages are identical within errors and both are in agreement with the calibrated \(^{14}\)C age, when considering the fact that this calibrated \(^{14}\)C age may most probably suffer from a distinct hard water effect and, therefore, overestimate the true sedimentation age by some hundred up to a few thousand years.

5 Discussion

5.1 Petrographical analyses

With all investigated terrace levels showing high amounts of phyllites and other metamorphic rocks, clear evidence could be found that the Steinach River was involved in the formation of all terrace levels. In the presented study, limonite crusts are restricted to the T5 level sites (PA_5a and PA_5 b). The scarce occurrence of limonite crusts in the spectrum of location PA_3a can be explained by dislocation processes from higher terrace levels. Therefore, the Red Main River has only been engaged in the accumulation of the oldest so far detected terrace level.

Concerning the investigated T4-level site (PA_4) where no gravel bed could be found, the detected surficial gravels have most probably to be interpreted as the result of a local displacement from a higher terrace level. With no gravel bed being detected at site PA_4, we cannot confirm the existence of a T4 level terrace at this location. Furthermore, no other suitable location was found in the lowermost and middle section of the valley to be clearly identified as part of the T4 level. Thus, from our findings we are so far not able to confirm the existence of a T4 level in the middle and lower part of the research area at all. Up to now, we are not sure how these findings have to be interpreted. Maybe the discrimination of T4- and T5-terrace levels proclaimed by previous studies was not correct for the Trebgast Valley. If this was true all locations previously mapped either as part of the T4-terrace or of the T5-terrace would represent the very same terrace level. This interpretation, however, is strongly contradicted by findings gained in the Red Main valley. Here, both terrace levels (T4 and T5) were identified and could clearly be discriminated. Thus, this problem needs further investigation.

5.2 T2-terrace accumulation and timing of the final deflection of the Steinach River

Our findings at the Crottendorf site concerning the age of the aggradation of the youngest Steinach River terrace (T2 terrace) apparently conflict with results yielded by previous studies (Kleber & Stingl 2000, Zöller et al. 2007).

Zöller et al. (2007) assumed the Lindau Moor to be a key site for the reconstruction of the Trebgast Valley’s development since the deflection of the primary Steinach River. They tried to draw geomorphologic conclusions out of palynological studies, conducted by Ertl (1987).
She was able to extract a 158 cm thick pollen profile, in which 14 different pollen segments were identified and correlated to the well established pollen zones Ib/c to Xa after Firbas (FIRBAS 1949, 1952). Thus, the pollen profile of the Lindau Moor spans the period between the Bölling interstadial (ca. 15,600 to 13,900 cal BP) and the Subatlanticum (later than ca. 2,800 cal BP).

Based on this pollen profile, ZÖLLER et al. (2007) argued that the clay and peat layers, building up the fen, could only accumulate under predominant slack water conditions. Relying on the assumption that the Lindau Basin had been eroded by a meander of the primary Steinach River, as suggested by the terrace levels observed in the basin, such slack water conditions should not have prevailed in that area until the primary Steinach River had abandoned the Trebgast Valley. With respect to the oldest dated clay layers, ZÖLLER et al. (2007) concluded that this final deflection should at least have occurred before the onset of the Bölling interstadial.

Furthermore relying on the traditional explanation of fluvial terraces to be landscape features typically accumulated during cold phases of glacial periods (e.g. KLEBER & STINGL 2000), a time frame for the final deflection of the primary Steinach River was deduced, spanning from the LGM to the Bölling interstadial (ZÖLLER et al. 2007).

Both, the luminescence and radiocarbon dating results in the presented study as well as the morphostratigraphical findings at the Crottendorf site, are in conflict with this previous age estimation. With the slope sediments being post-defective, overlying the gravels of the T2 level and being older than the Younger Dryas, the time frame for the deposition of the cover sediments would just range from the LGM to the Younger Dryas, if the age estimation of ZÖLLER et al. (2007) was correct. With this time frame merely comprising a period of not more than 2 to 8 thousand years in maximum, the thickness of the post-defective slope detritus can hardly be explained to have accumulated in such a short time, unless by a landslide. For a landslide, however, no evidence has been found so far (ZÖLLER et al. 2012).

Furthermore, the OSL dating results, supported by the AMS 14C dating, clearly show sedimentation ages of approximately $19.4 \pm 1.2$ ka for the youngest up to $30.7 \pm 1.1$ ka for the oldest lens of loess-like material, respectively. As the oldest gleyed loess lens within the periglacial cover sediments is underlain by 6 meter of slope sediments on top of the underlying gravels, the gravels of the T2 level were deposited quite a long time before the onset of the loess derivate’s deposition.

Therefore, the obtained OSL and 14C data indicate a significantly older age for the aggradation of the T2 gravel and point to intense fluvial geomorphodynamics during the Lower and Middle Pleniglacial rather than during the Upper Pleniglacial.

The discrepancy between the results of previous studies and those presented in this paper needs to be further discussed. In order to cope with the problem, the two above mentioned assumptions of a), the Lindau Moor being a key site for the reconstruction of the landscape evolution in the study area, and b), river terrace formation being a process typically for cold stages of glacial periods should be revisited.

The main argument for the opinion that the Lindau Basin was eroded by the Steinach River has to be seen in the fact that terrace levels within the basin correlate to terrace levels in the main part of the valley (KLEBER & STINGL 2000) and, thus, were interpreted to have been accumulated by the primary Steinach River.
However, first preliminary visual investigations of the surficial basin gravels during field trips clearly showed the composition of the basin gravels to be completely different from that of gravel sites in the main part of the valley. With the basin gravels overall showing a dominant abundance of quartz gravels, they completely lack metamorphic and phyllite gravels and, thus, don’t show any gravels indicative for the catchment area of the Steinach River. A great portion of ventifacts have been discovered among the basin gravels, typical for and quite frequent in some layers of the Lower Triassic sandstone formations (the so called “Kulmbach conglomerate”), outcropping on the lower slopes of the basin (Zöller et al. 2012).

Even though not yet being able to disprove the above described assumption, we now strongly doubt that the primary Steinach River has ever flown through the Lindau Basin. On the contrary, the basin may most likely have been eroded by a small tributary river, originating within the basin itself and depositing gravels comprising of locally reworked material from the very easily to erode Lower Triassic sandstone formations. In that case, the development of the Lindau Moor would completely be decoupled from the final deflection of the Steinach River and, thus, would no longer contradict a significantly higher age for this deflection.

Still, our findings do not match the traditional concepts of river terrace formation, attributing the forming of gravel beds to be typical of cold stages within glacial periods, and especially they do not agree with regional studies (e.g., Kleber & Stingl 2000, Zöller et al. 2007) which characterized the T2-terrace as geomorphic feature accumulated during the last glacial maximum. However, previous studies (e.g., Vandenberghhe 2002, 2003, 2008, 2015) have already shown that no simple correlation between climate change and fluvial processes can be assumed. Therefore, we interpret the results of the study in hand to be yet another evidence for the complexity of fluvial system response to paleoenvironmental changes and for its strong dependency on local conditions, such as size and shape of the catchment area or the specific regional settings of geology, morphology and vegetation.

6 Conclusion
Hillslope deposits and fluvial gravel aggradations were used as archives for yielding new information on the fluvial evolution of a small dry valley in the headwaters of the Main River in northern Bavaria, Germany. Besides qualitative petrographic analyses and investigations of a fossil terrestrial mollusk assemblage, luminescence dating techniques and AMS $^{14}$C dating were applied to date the sediments.

Qualitative petrographic analyses were used as a tool to identify the origin of fluvial terrace gravels and to draw conclusions on the genesis of the particular terrace aggradation. Based on these analyses, the findings of previous studies could partially be confirmed and additional evidence for a very complex landscape evolution, characterized by a minimum twofold river deflection, could be found. However, our results also prove the necessity of further petrographic analyses and a great need for a more detailed map of the terrace levels, based on a high resolution digital terrain model (DTM) of the study area.

The results from the malacological analysis showed a unique community of fossil terrestrial mollusks with a surprising variety of species, so far not reported for the region of northern Ba-
varia. The analyzed mollusk fauna provides valuable paleoecological information and indicate a very complex landscape setting characterized by generally cold and dry conditions in the near surroundings as well as by distinct more humid conditions for the actual sampling site.

The calculated luminescence and $^{14}$C ages are clearly in conflict with age estimates for the accumulation of the Würmian T2-terrace proposed by previous studies. The presented results for the dated hillslope detritus point to an older age of the underlying fluvial gravels (T2 terrace) and, thus, suggest a much earlier deflection of the primary Steinach River. They, thereby, indicate very intense fluvial geomorphodynamics during the Lower and Middle Pleniglacial rather than during the Upper Pleniglacial. However, this study has, so far, just been able to present indirect evidence for this conclusion. Hence, further investigations are needed. Direct dating of sand lenses embedded into the gravel beds of the T2 level are carried out at the moment and will directly yield sedimentation ages for the gravel aggradation. Not till then, we will be able to give a final answer to the question of the timing of the T2 terrace formation. But even now, the results of the study in hand indicate that traditional concepts of fluvial terrace aggradation should carefully be reconsidered. They generally raise questions concerning climatic conditions during the Lower and Middle Pleniglacial and their specific impacts on the timing and the processes of fluvial terrace formation. They also point to the fact that fluvial systems have always to be analyzed as individuals, responding in a very specific way to externally and/or internally driven changes in environmental conditions and reflecting the unique local and regional settings of the particular catchments.

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References


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