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Research article

Age and formation of the presumed Late Pliocene to Middle Pleistocene Mühlbach formation, High Rhine Valley, southwest Germany

Alexander Fülling[1], Hans Rudolf Graf[2], Felix Martin Hofmann[1], Daniela Mueller[1,a], and Frank Preusser[1]

[1]Institute of Earth and Environmental Sciences, University of Freiburg, Albertstr. 23b, 79104 Freiburg, Germany
[2]Dr. von Moos AG, Dorfstrasse 40, 8214 Gächlingen, Switzerland
[a]present address: Department of Geography and Planning, University of Liverpool, Chatham St, Liverpool L69 7ZT, United Kingdom

Correspondence: Frank Preusser (frank.preusser@geologie.uni-freiburg.de)

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Abstract: The drainage system of the Swiss Alps shifted from an eastward (Danubian) to a westward (Rhenian) direction during the Late Pliocene. Since then, the High Rhine Valley has acted as the major drainage path during both ice-free and glaciated periods in the past. The Mühlbach formation comprises the patchy remains of carbonate-free sediments that have been interpreted as an equivalent of Sundgau gravel. The Sundau gravel reflects remains of fluvial deposits related to the Late Pliocene drainage of the northern Swiss Alps through the Burgundian Gate towards the Bresse–Rhône Graben. However, the limited data available characterising the Mühlbach formation have led to opposing interpretations regarding its origin and age. Presented here are new data on the distribution and physical appearance of the formation, together with luminescence dating of deposits from the type locality. Sedimentological and petrographic analyses imply that the various deposits assigned to the Mühlbach formation do not represent a genetically coherent formation. In addition, consistent results of quartz and feldspar luminescence dating place deposition of sediments at the type locality at ca. 55 ka. This dates their deposition to the end of a pronounced cold period during the Late Pleistocene that has been shown to be characterised by slope processes at other sites. Altogether, the data presented imply that the Mühlbach formation is not uniform but rather comprised of mainly reworked weathered residues from different time periods.

Kurzfassung: Das Entwässerungssystem der Schweizer Alpen hat sich im späten Pliozän von einer östlichen (Donau) zu einer westlichen (Rhein) Richtung verlagert. Seither hat das Hochrheintal sowohl in eisfreien als auch in vergletscherten Perioden als Hauptabflussweg fungiert. Die Mühlbach Formation besteht aus lückenhaften Resten karbonatfreier Sedimente, die als Äquivalent zu den Sundgau Schottern interpretiert wurden. Letztere spiegeln Überreste fluvialer Ablagerungen wider, die mit der spätpliozänen Entwässerung der nördlichen Schweizer Alpen durch die Burgundische Pforte in Richtung des Bresse-Rhône-Grabens zusammenhängen. Die zur Charakterisierung der Mühlbach

Formation durchgeführten Untersuchungen haben jedoch zu widersprüchlichen Interpretationen hinsichtlich ihres Ursprungs und Alters geführt. Hier werden neue Erkentnisse zur Verbreitung und zum Erscheinungsbild der Einheit sowie Lumineszenzdatierungen an der Typlokalität vorgestellt. Sedimentologische und petrographische Analysen lassen darauf schließen, dass die verschiedenen Ablagerungen, die der Mühlbach Formation zugeordnet werden, keine genetisch kohärente Formation darstellen. Darüber hinaus belegen übereinstimmende Ergebnisse von Quarz- und Feldspat-Lumineszenzdatierungen, dass die Sedimente an der Typlokalität vor ca. 55 ka abgelagert wurden. Dies datiert ihre Ablagerung auf das Ende einer ausgeprägten Kaltzeit während des Spätpleistozäns, die nachweislich an anderen Standorten durch Hangprozesse gekennzeichnet war. Insgesamt deuten die vorgelegten Daten darauf hin, dass die Mühlbach Formation nicht einheitlich ist, sondern hauptsächlich aus umgelagerten Verwitterungsresten verschiedener Zeitabschnitten besteht.

1 Introduction

Choosing a site for Swiss nuclear waste disposal in the High Rhine area (Fig. 1) requires a detailed understanding of the long-term regional landscape evolution, as according to international agreement, disposal sites have to be safe for 1 000 000 years (e.g. Alexander et al., 2015). In repository long-term safety assessments, the development of landscape topography plays a key role, in particular in the expected rates of fluvial and glacial erosion as well as the question of neotectonics, i.e. whether or not a region is tectonically stable. The High Rhine area, known as *Hochrhein* in German, is situated at the intersection of the thin-skinned Jura fold–thrust belt to the south and the Black Forest to the north (e.g. Ziegler and Fraefel, 2009; Malz et al., 2019; Madritsch et al., 2024). Precision levelling data indicate that the eastern Jura Mountains are presently uplifted at a rate of ca. 0.3 mm yr^{-1} (Müller et al., 2002). However, it is not clear to what extent this is due to tectonic movements or how high the contribution of isostatic uplift is. Long-term and long-distance triggers, such as the role of the Upper Rhine Graben, are also poorly constrained. For the latter, precision levelling indicates a subsidence rate on the order of 0.5–0.6 mm yr^{-1} (Rózsa et al., 2005). Furthermore, tectonically and seismically active fault systems have been identified in that region (Behrmann et al., 2003).

Considering the long-term perspective, most of the drainage system of the Swiss Alps (the Aare system sensu lato) shifted from an eastward to a westward direction (Petit et al., 1996) during the Late Pliocene (Piacenzian – 3.60–2.58 Ma; Cohen et al., 2013). Previous work concluded that from this time onwards, a valley system has permanently existed in what is today known as the High Rhine Valley, i.e. the section of the Rhine River between Lake Constance and the Rhine knee at Basel (Fig. 1; Preusser, 2008; Ziegler and Fraefel, 2009). With this, the drainage system of most of the northern Swiss Alps disconnected from the Danube drainage system that ultimately ends in the Black Sea. The occurrence of fluvial deposits, known as Sundgau gravel (*cailloutis du Sundgau* in French; Fig. 2a), documents that the drainage system of the Swiss Alps went towards the west through the Burgundian Gate, i.e. the area between the Vosges and Jura mountain ranges, into the Bresse Graben, and eventually into the Mediterranean (Fig. 2a; Liniger and Hofmann, 1965; Petit et al., 1996; Preusser, 2008; Ziegler and Fraefel, 2009). The Alpine origin of these deposits is indicated by both gravel petrography, in particular the presence of radiolarite, and heavy-mineral spectra containing epidote, garnet, and amphibole (Petit et al., 1996). The age of the deposits is assigned to the Piacenzian based on rodents, molluscs, and pollen (formerly middle Reuverian; Petit et al., 1996).

At this time (Piacenzian), the valley that today hosts Walensee in the northern Alps southeast of Lake Zürich (Fig. 1) probably connected the upper part of the Rhine system to the Aare system (Graf, 1993). The northern part of the Alpine Rhine and the Lake Constance region likely continued draining towards the east (Danube system), but the drainage later turned westwards as a result of Early Pleistocene glaciation of the lowlands (Liniger and Hofmann, 1965; Petit et al., 1996; Preusser, 2008; Ziegler and Fraefel, 2009; Eberle et al., 2023).

In the High Rhine region, glaciofluvial and other processes related to past glaciations left a series of deposits in northern Switzerland and on the southern slopes of the Black Forest that occur at successively lower elevations with age (Graf, 2009a, b; Preusser et al., 2011), pointing to a stepwise lowering of the drainage network (Fig. 3). The controlling factors behind this evolution are not yet entirely understood. This concerns the role of the High Rhine Valley in particular, as it is situated between the area influenced by Alpine uplift in its upper reaches and subsidence in the Upper Rhine Graben further down the drainage pathway (Graf and Burkhalter, 2016). In the High Rhine Valley, the lowering of the drainage network follows the well-known pattern of the terraced morphostratigraphy, with the oldest Pleistocene deposits (*Höhere Deckenschotter*) situated in the topographically highest position (Fig. 3; Graf, 2009b; Preusser et al., 2011; Graf and Burkhalter, 2016). The *Tiefere Deckenschotter* intersects at a higher aggradation level and documents the next-youngest phase of valley formation.

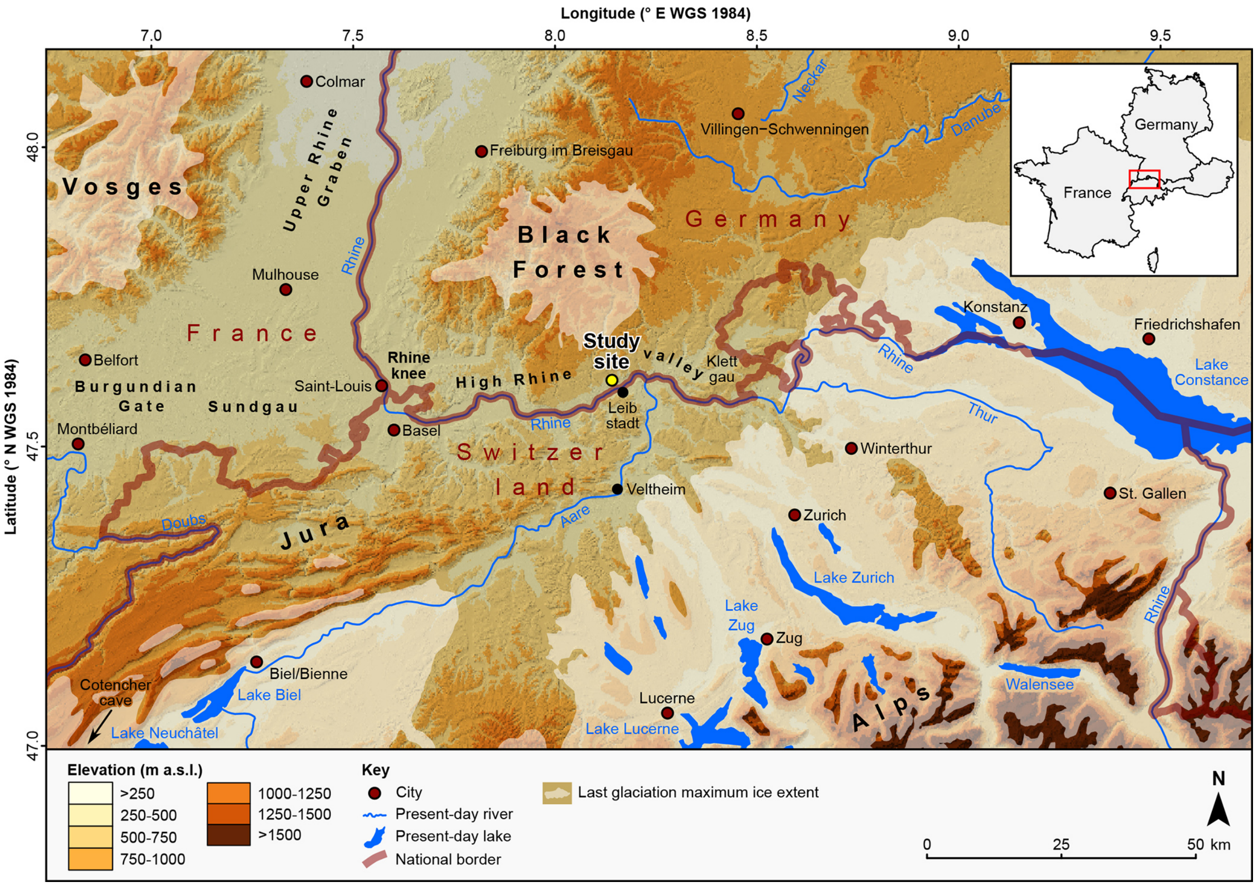

Figure 1. Topographical map of the region around the study site. Ice extent during the last glaciation maximum, following Ehlers et al. (2011). © DLR 2023 for the digital elevation model (TanDEM-X 30 m edited DEM; González et al., 2020) in the background. © European Environment Agency for rivers. For lakes, see BFS (2024). © EuroGeographics and FAO (UN) for national borders. © EuroGeographics © FAO (UN) © TurkStat for cities.

The term *Deckenschotter* is a fundamental part of the morpho-stratigraphic scheme developed by Penck and Brückner (1901–1909), where it represents two units of glaciofluvial outwash deposits and associated terrace surfaces attributed to the Günzian and Mindelian ages. These two glaciations in Bavaria are usually attributed to the final part of the Early Pleistocene and to the Middle Pleistocene (Doppler et al., 2011). While in the High Rhine area this term had already been introduced by Gutzwiller (1883, 1894) and Du Pasquier (1891) some years earlier than in Bavaria, it appears that this was due to continued exchange with Albrecht Penck (see Gutzwiller, 1894). According to Graf (1993), the two *Deckenschotter* units comprise four depositional units each (Fig. 3), two of which per unit are interpreted as glacial diamicts (till). The other four units represent coarse gravel deposits interpreted as being of glaciofluvial origin (Graf, 1993, 2009a). As a result, it is thought that northern Switzerland was affected up to eight times by lowland glaciations during the Early to early Middle Pleistocene (Preusser et al., 2011; Claude et al., 2017; Dieleman et al., 2022a). The Middle and Late Pleistocene *Hochterrasse* and *Niederterrasse* system at lower elevations also reflects several phases of deposition and incision (Fig. 3; Graf, 2009b; Preusser et al., 2011). Glaciers from the Alps reached the middle part of the High Rhine Valley at least twice during the Pleistocene. At around 500 ± 100 ka (Dieleman et al., 2022b), the most extensive Pleistocene Möhlin glaciation reached as far as 20 km east of the Rhine knee. Relicts of this glaciation are the deposits up to a few metres thick on the southern slopes of the Black Forest (Graf, 2009b; Preusser et al., 2011). The Beringen glaciation that has been correlated with marine oxygen isotope stage (MIS) 6 (191–130 ka according to Lisiecki and Raymo, 2005) reached its maximum just beyond the confluence of the Aare and Rhine rivers (Graf, 2009b; Preusser et al., 2011; Lowick et al., 2015). However, the exact location of the margin of the ice from both the Black Forest and the Alps remains largely unknown (Ramshorn and Wendebourg, 1986). The flat areas on the valley bottom in the High Rhine area are subdivided into several terrace levels (Kock et al., 2009), and Graf (2009b) assigned these levels to the Birrfeld glaciation (MIS 2; 29–14 ka according to Lisiecki and Raymo, 2005).

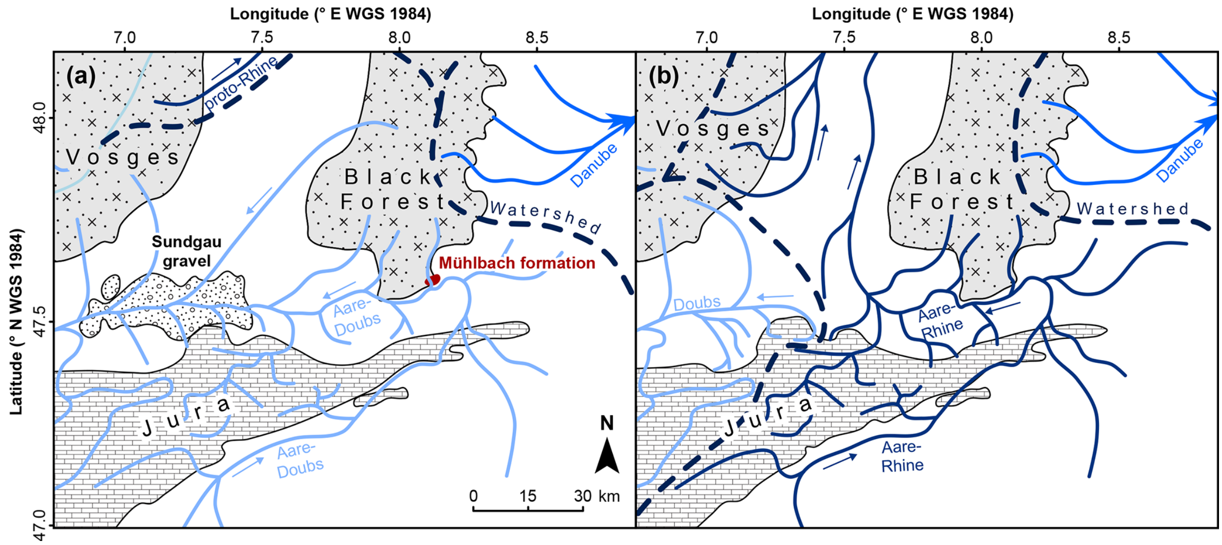

Figure 2. **(a)** River networks during the Aare–Doubs stage (4.2–2.9 Ma). Arrows denote drainage directions. Due to headward erosion of the proto-Doubs, the Aare River was deflected to the west, leading to the formation of the Sundgau gravel. The Mühlbach series apparently formed at the same time. **(b)** River networks during the Late Pliocene to Early Quaternary (Aare–Rhine and Doubs stages, 2.9–1.7 Ma). Arrows denote drainage directions. The Aare River was deflected into the Upper Rhine Graben. The lowering of the base level in the subsiding Upper Rhine Graben led to headward erosion of the tributaries of the Aare. Modified following Ziegler and Fraefel (2009).

The Mühlbach series (Ramshorn and Wendebourg, 1986; Verderber, 1992, 2003), named after a small stream in the High Rhine area, is a sediment formation that does not directly fit into the abovementioned scheme. Following the guidelines of the International Commission on Stratigraphy (available at https://stratigraphy.org/guide/index.html, last access: 2 September 2024), we hereafter refer to this geological unit as the Mühlbach formation. It only occurs in a small area (ca. 4 km^2) in the High Rhine Valley itself and on the southern slopes of the Black Forest. It has been exposed in various trenches as carbonate-free gravel, covered by solifluction layers. The gravel deposits reach a thickness of several metres and are often located directly on the bedrock surface. Based on its elevation, the carbonate-free gravel was originally assigned to *Höhere Deckenschotter* (Ramshorn and Wendebourg, 1986), but according to current knowledge (Graf, 2009b) this elevation should instead imply a correlation with *Tiefere Deckenschotter*.

Other authors (Verderber, 1992, 2003; Hofmann, 1996; Ziegler and Fraefel, 2009) interpreted the Mühlbach formation as being equivalent to the Sundgau gravel, based on overall morpho-stratigraphic considerations and its similar heavy-mineral spectrum (Hofmann, 1996). The observed normal magnetisation (Fromm, 1989) led Ziegler and Fraefel (2009) to suggest a correlation with the Pliocene Gauss Epoch (3.58–2.59 Ma; Piacenzian). In contrast, Verderber (2003) favoured a correlation with the early Quaternary Olduvai event (1.95–1.78 Ma; Roberts et al., 2013) based on Fromm (1989) and pollen analyses by Wolfgang Bludau (Pollenanalytische Untersuchungen am Hochrhein, Mühlbachserie und Laufenburg, Geol. Landesamt Baden-Württemberg, unpublished report, 1991). On the contrary, Graf (2009b) proposed a Middle Pleistocene age for the Mühlbach formation based on the observation that it incised into *Tiefere Deckenschotter* to a base level that was only reached during the Middle Pleistocene.

The Mühlbach formation appears to be a valuable archive of the deposition and erosion history along the High Rhine Valley, as it could represent the oldest evidence of drainage activity (e.g. Ziegler and Fraefel, 2009). However, the amount of data available to characterise and stratigraphically place this unit is limited and controversial. Given the controversy over its age and relevance in long-term regional landscape evolution, this study aims to revisit the Mühlbach formation. Based on previously obtained sedimentological (Graf, 2024) and new geochronological data, the age, formation, and stratigraphic relevance of the deposits will be re-evaluated.

2 The Mühlbach formation

Ramshorn and Wendebourg (1986) initially described the deposits of the Mühlbach formation, and Verderber (1992, 2003) subsequently investigated the deposits in detail. The latter included assigning a type locality, where outcrops were opened by hand and with an excavator, complemented by core drilling at Einschlag (Fig. 4). This includes an exposure with a height of 8 m along the Mühlbach, north of the village of Kiesenbach (Groschopf and Feldhoff, 2004a). The exposure revealed an alternate bedding of light clayey silt, fine-to-

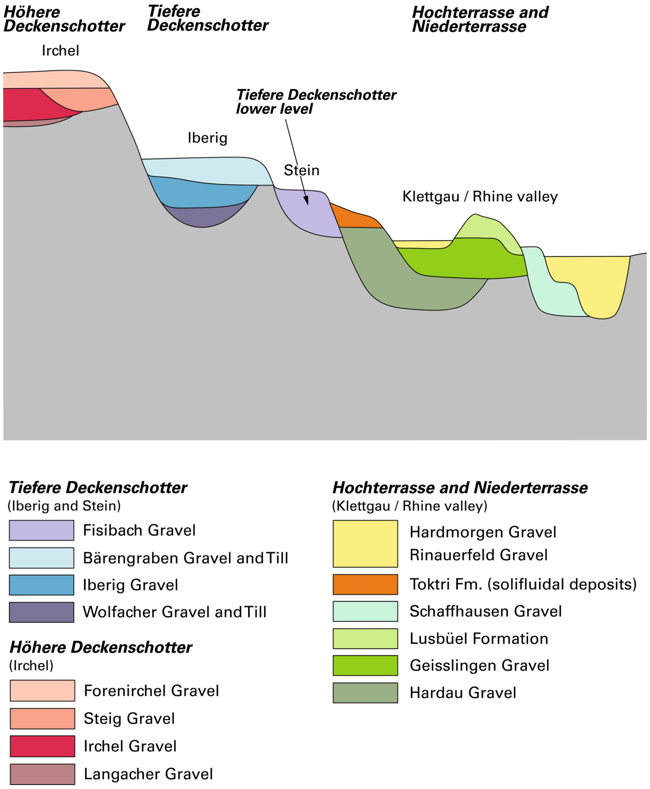

Figure 3. Schematic geomorphology of the High Rhine area (modified following Graf and Burkhalter, 2016). Please note that different formations can be identified within the individual morphological units.

medium sand, and clayey–silty gravel. The sediments turned out to be mostly free of limestone (Verderber, 1992, 2003). On geological maps, quite large areas with corresponding calcareous-free and heterogenic, loamy–gravelly deposits are assigned to the Mühlbach formation, with a weathering depth of > 3.5 m. Cemented gravel with limestone pebbles occurs underneath this unit (Groschopf and Feldhoff 2004a, b).

Verderber (1992) concluded that the various occurrences of non-calcareous sediments should be combined into one formation and estimated its (former) thickness to around 100 m. The lack of carbonates in these sediments was attributed to in situ weathering. As calcareous material occurs in till of the penultimate glaciation that was apparently deposited above the deposits of the Mühlbach formation, Verderber (1992) suggested that the series likely formed before the Middle Pleistocene. The sediment cores from the Einschlag drilling site turned out to be carbonate-free down to a depth of 14 m. Therefore, Verderber (1992, 2003) assumed that the deposits formed prior to *Tiefere Deckenschotter*.

Pollen analytical studies of the Mühlbach formation revealed a heterogeneous and partly contradictory picture (Wolfgang Bludau, Pollenanalytische Untersuchungen am Hochrhein, Mühlbachserie und Laufenburg, Geol. Landesamt Baden-Württemberg, unpublished report, 1991). Out of a total of at least 12 samples (not quantified precisely in the report), only 4 contained any pollen. Two of the samples with generally poor pollen preservation contained pollen of umbrella pine, hemlock fir, horse chestnut, and plants of the cypress family, usually typical of Early Quaternary or even Tertiary deposits (see Knipping, 2008; Hahne et al., 2009). However, the complete absence of beech did not support a correlation with the Early Quaternary. The two remaining samples suggested interglacial deposits of the "Riss Complex" (Middle Pleistocene) due to the occurrence of beech and wingnuts (*Pterocarya*). However, Wolfgang Bludau (Pollenanalytische Untersuchungen am Hochrhein, Mühlbachserie und Laufenburg, Geol. Landesamt Baden-Württemberg, unpublished report, 1991) emphasised that a pollen stratigraphic classification of the sediments based on individual samples is highly problematic.

Combining the observations from pollen analyses (Wolfgang Bludau, Pollenanalytische Untersuchungen am Hochrhein, Mühlbachserie und Laufenburg, Geol. Landesamt Baden-Württemberg, unpublished report, 1991) with the normal magnetisation of the sediment (Fromm, 1989) led Verderber (2003) to favour placing the deposition of the Mühlbach formation during the Olduvai event (1.95–1.78 Ma) in the inversely magnetised Matuyama Epoch. However, a correlation with the Gauss Epoch and hence the Pliocene was not excluded. Assignment of the Mühlbach formation to the Jaramillo event (1.07–0.99 Ma; Roberts et al., 2013) was considered unlikely, as this would require the depositing of ca. 100 m of sediment within scant tens of thousands of years (Verderber, 2003).

Graf (2009b) proposed an alternative interpretation of the Mühlbach formation by pointing out that large thicknesses of non-calcareous unconsolidated sediment are not necessarily the result of in situ soil formation. Graf (2009b) proposed that the deposits of the Mühlbach formation represent reworking of older, already weathered material and interpreted the fresh gravel observed in the lower sections at the Einschlag drilling site as *Tiefere Deckenschotter*. Hence, formation of the Mühlbach formation prior to *Tiefere Deckenschotter* appeared implausible, and a Middle Pleistocene maximum age was considered more likely (Graf, 2009b).

3 Methods

3.1 Geological mapping and logging

The geological mapping presented here is part of a larger campaign investigating the role of the High Rhine Valley and the Upper Rhine Graben in the long-term landscape evolution of northern Switzerland and neighbouring southern Germany (Graf, 2024). Overall, mapping was conducted based on information derived from existing geological maps (e.g. Pietsch and Jordan, 2014) as well as supplementary field surveys, an evaluation of several thousand exploratory borehole

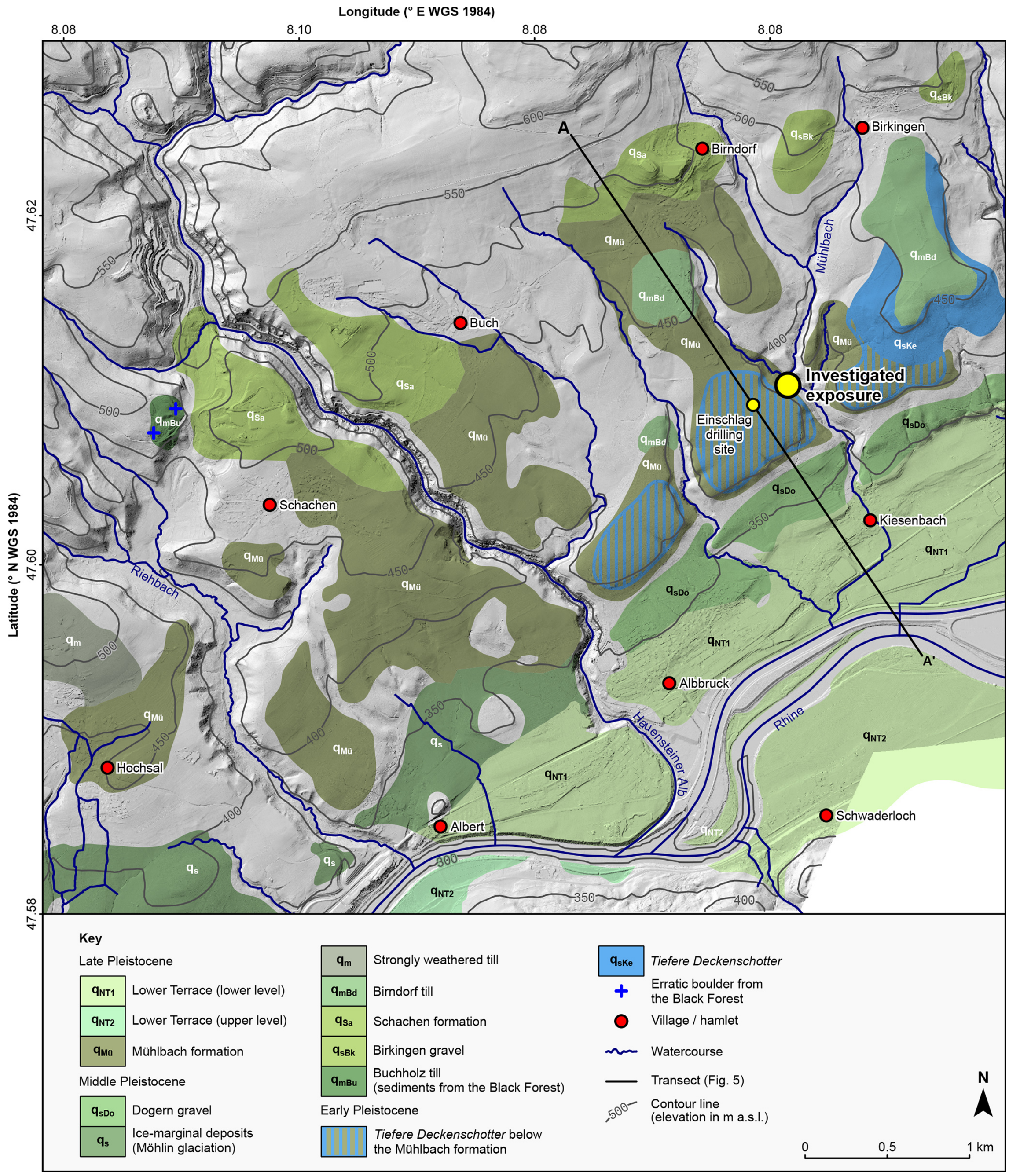

Figure 4. Revised geological map of the High Rhine Valley around the village of Albbruck (modified following Graf, 2024). For rivers, see LUBW (2022). Both the hill shading and the contour lines were derived from the DGM025 digital elevation model (x–y resolution – 0.25 m; available at https://opengeodata.lgl-bw.de/#/(sidenav:product/4), last access: 2 September 2024) from the Baden-Württemberg State Office for Geoinformation and Land Development (LGL; https://www.lgl-bw.de, last access: 2 September 2024).

logs, and sediment provenance analyses (pebble petrography as well as heavy-mineral analyses; Graf, 2024). Outcrop and drilling information, together with morpho-stratigraphic interpretations, was used to infer the elevation of the bedrock surface, i.e. the base of the unconsolidated Pleistocene sediments.

Lithostratigraphic logging was undertaken during fieldwork at the only natural exposure of the sediments in the Mühlbach, north of the village of Kiesenbach (Fig. 4; coordinates 47.61° N, 8.14° E; 379 m a.s.l.; WGS 1984), where about 6 m of material is exposed. The petrography of the basal gravel layer (sample HRH05) was subsequently assessed.

3.2 Luminescence dating

Samples for luminescence dating were taken from three fine-sand layers (MUE-01, MUE-02, and MUE-03) present in the exposure at the type locality at the Mühlbach formation near Kiesenbach (Table 1). In the laboratory, standard sample preparation steps (see Preusser et al., 2021) were applied to separate sand-sized quartz and potassium feldspar grains (MUE-01 – 150–250 µm; MUE-02 and MUE-03 – 200–250 µm). A Lexsyg Smart device (Richter et al., 2013) and the single-aliquot regenerative dose protocol (SAR) were used to determine the equivalent doses (D_e) for both quartz and feldspar (Murray and Wintle, 2000; Buylaert et al., 2009). For optically stimulated luminescence (OSL), a preheat of 200 °C for 10 s was applied prior to all measurements (Hoya U340 detection filter). For feldspar, the post-IR infrared stimulated luminescence (IRSL) protocol with a preheat of 250 °C for 60 s was used (Schott BG39 and 414/46 AHF BrightLine filters). After measurement of the conventional 50 °C IRSL signal, a second IRSL signal was stimulated at 225 °C. A so-called hot bleach at 270 °C for 50 s was applied after each test dose readout. The high temperature post-IR IRSL signal is considered to be more stable compared to the conventional 50 °C IRSL signal (Buylaert et al., 2009). This reduces the risk of underestimating the true age, which is typical of conventional feldspar IRSL dating due to anomalous fading (Wintle, 1973). At the same time, this signal is known to be less quickly reset by daylight (Buylaert et al., 2009). It should be noted that the effective temperature at the sample position in the Lexsyg Smart reader being used is about 20 °C higher compared to the more commonly used Risø reader (Mueller et al., 2020). This implies a potentially higher signal stability and lower light sensitivity of the post-IR IRSL used here compared to other studies (e.g. Lowick et al., 2015). Fading rates were determined for both IRSL and post-IR IRSL, and D_e values were corrected, following Kars et al. (2008). For all samples, the observed overdispersion and shape of D_e distributions justified using the central age model (CAM) of Galbraith et al. (1999).

The concentration of dose-rate-relevant elements was determined using high-resolution gamma spectrometry at VKTA Rossendorf e.V. For dose rate determination, we used the ADELEv2017 software (Degering and Degering, 2020; https://www.add-ideas.com, last access: 25 December 2023), assuming an a value of 0.07 ± 0.02 and an average water content of 18 ± 5 %. An internal K content of 12.5 ± 0.5 % was used (Huntley and Baril, 1997), while the cosmic dose rate was corrected for geographic position and overburden (Prescott and Hutton, 1994).

4 Results

4.1 Field observations

Geological mapping (Fig. 4) revealed that the Mühlbach formation occurs at localities where the corresponding geological map displays bedrock units (Groschopf and Feldhoff, 2004a, b). From the rock isohypses constructed based on exposures and from the Einschlag borehole, we deduced that in the southeastern area of the Mühlbach formation there is a flattening several hundred metres wide, pointing to a former fluvial channel (Graf, 2024). In contrast, the Mühlbach formation overlies bedrock in the other areas as a relatively thin cover (2–4 m; Figs. 4, 5). At just over 380 m a.s.l., its base is situated at an elevation that can easily be associated with the base of the *Tiefere Deckenschotter* in the area south of Leibstadt (south of the Rhine River). There, the basal plane has a very pronounced relief, in which it descends in steps from the southwest to the northeast from around 440 to around 370 m a.s.l. The highest deposits reach an elevation of up to around 470 m a.s.l. (Figs. 4, 5).

The sequence at the Mühlbach type locality (Fig. 4) mainly consists of clayey, silty, fine-sand light-brown sediment with intercalated layers or areas of silty fine-to-medium sand (with a light-grey colour aspect), as well as layers and lenses of clayey–silty gravel (Fig. 6). Sediment structures are hardly recognisable. The gravel in the lower part of the exposure exhibits a grain-supported structure, pointing to deposition in flowing water (Fig. 6).

The sequence begins at the bottom with a dominantly gravelly sequence, which has a conspicuously strongly red-coloured layer at the top. Clayey to silty sediments, which are partly very fine sand and contain individual gravel components as well as some gravelly layers, overlie this sequence. In general, the individual layers can only be traced over a short distance in the outcrop (Fig. 6).

The petrography of the basal gravel layer (sample HRH05) shows that no calcareous components are present. Local sediments (red sandstones, partly red carnelian) comprise 10 %; Alpine sandstones comprise 15 %; and quartzites, vein quartz, and chert comprise together about 45 %, while Black Forest crystalline (16 %) and Alpine crystalline rock fragments (14 %) are also present.

Screening three samples for their pollen content yielded very low pollen concentrations (zero, six, and five grains, respectively), which does not allow any interpretations regarding vegetation cover to be drawn (Maria Knipping, personal communication, 2024).

4.2 Luminescence dating

The first observation regards the relatively high amount of radioactive elemental material present in the sediment (Table 1) in comparison to previous studies. The samples from the Mühlbach formation have an average K content of about 1.5 %, an average Th content of ca. 13 ppm, and an average

Table 1. Summary table of luminescence dosimetry data showing the concentrations of dose-rate-relevant elements (K, Th, and U), the measured water content (W), and the calculated dose rates (D) for quartz and feldspar. It should be noted that an estimated uniform average water content of 18 ± 5 % was assumed to account for seasonal and climatic variations.

Sample	Depth (m)	K (%)	Th (ppm)	U (ppm)	W (%)	D quartz (Gy ka^{-1})	D feldspar (Gy ka^{-1})
MUE-01	2.2	1.59 ± 0.16	13.30 ± 0.84	4.06 ± 0.25	18.0	2.94 ± 0.19	3.83 ± 0.16
MUE-02	3.7	1.52 ± 0.10	12.74 ± 0.81	4.03 ± 0.24	19.4	2.82 ± 0.19	3.71 ± 0.13
MUE-03	4.4	1.55 ± 0.16	12.76 ± 0.79	3.75 ± 0.21	18.0	2.79 ± 0.24	3.67 ± 0.24

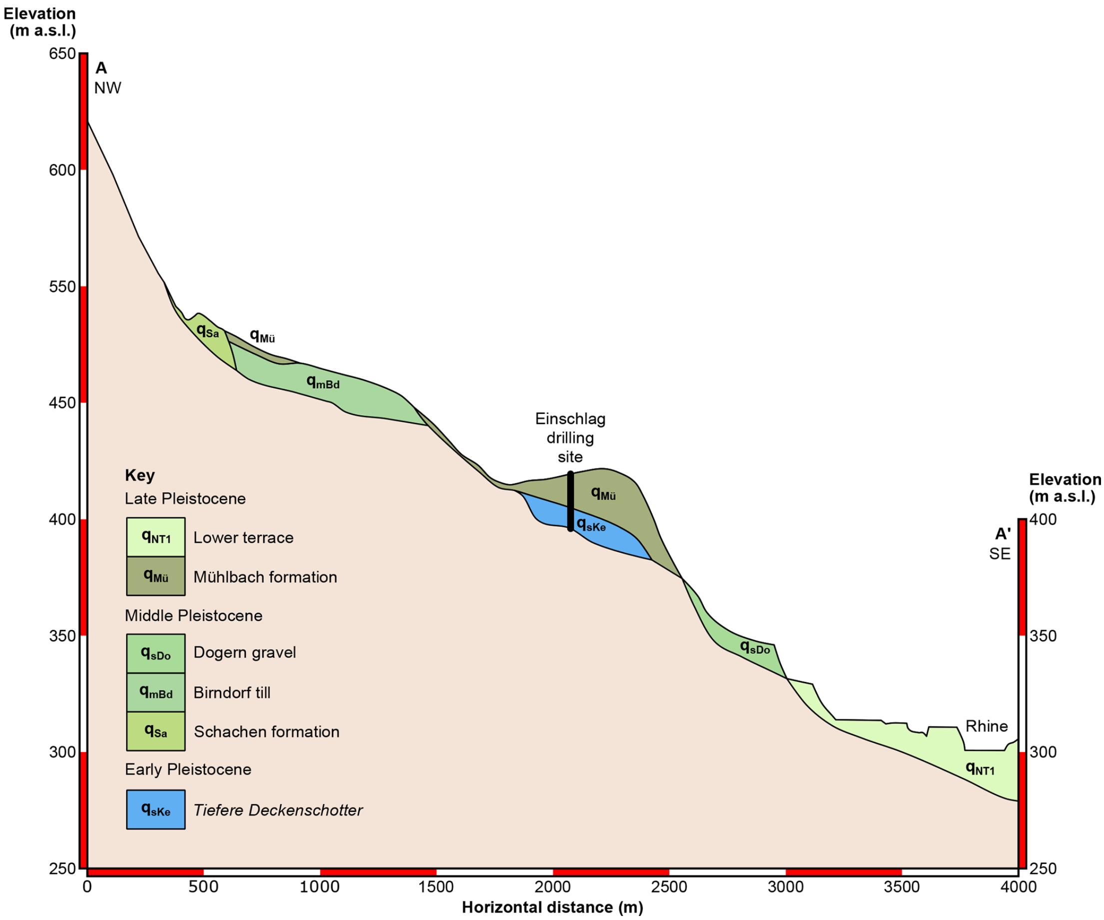

Figure 5. Transect through the type location of the Mühlbach formation.

U content of ca. 4 ppm. For comparison Lowick et al. (2015), who dated glacial samples from the nearby Klettgau region (Fig. 1), found average values of 1.1 % (K), 3.9 ppm (Th), and 1.46 ppm (U). Accordingly, the radioactive elemental content of the Mühlbach formation is about 140 % (K), 330 % (Th), and 270 % (U), significantly higher compared to glacial sediments that can be clearly assigned to an Alpine origin.

Another striking observation regards the intensity of the quartz OSL signal. While quartz from glacial deposits from the High Rhine region typically shows low, partly problematic OSL signals, requiring the rejection of large numbers (up to 50 %) of aliquots (e.g. Kock et al., 2009; Lowick et al., 2015; Trauerstein et al., 2017; Mueller et al., 2020; Mueller and Preusser, 2022), quartz from the Mühlbach formation shows a bright signal (Fig. 7a), and only 10 %–20 % of all aliquots had to be rejected (Table 2).

Fading measurements on the feldspar of MUE-01, following Kars et al. (2008), revealed g values of 2.4 ± 0.7 % per decade (IRSL at 50 °C) and 1.2 ± 0.7 % per decade (post-IR IRSL at 225 °C). Both fading rates were determined with the same post-IR IRSL protocol as was used for D_e determination. The observed overdispersion of the samples ranges between 8 ± 1 % (MUE-01, post-IR IRSL) and 24 ± 3 %

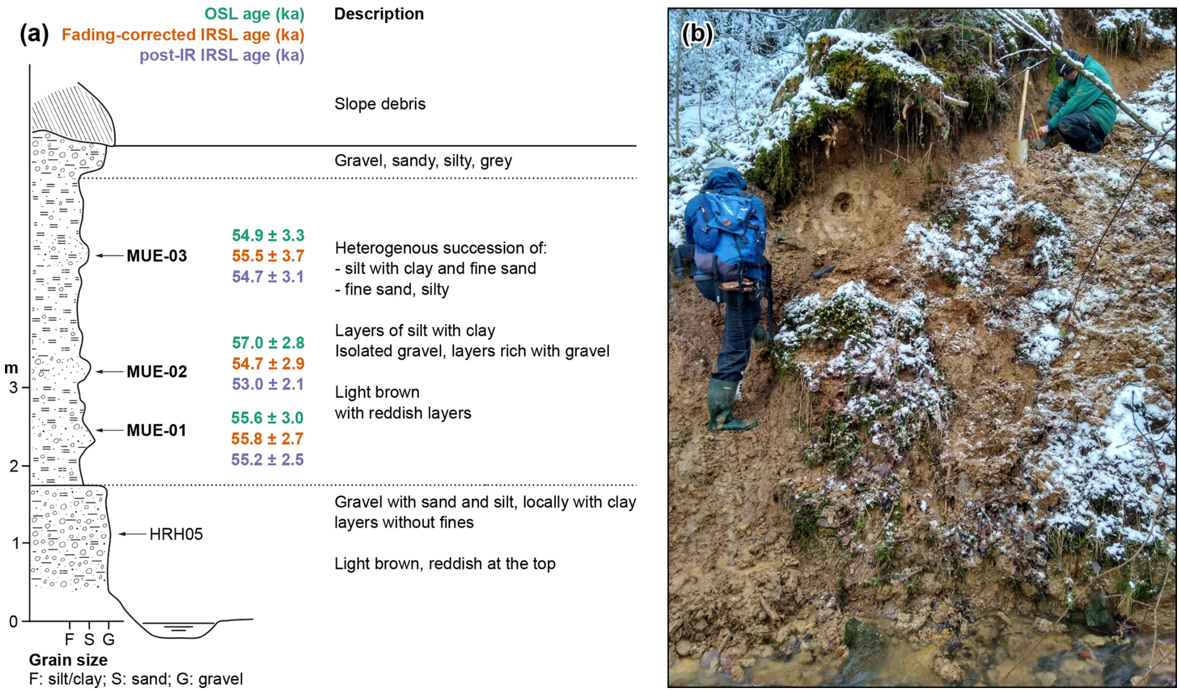

Figure 6. (a) Lithostratigraphic log of the investigated exposure at the Mühlbach formation, the location of the samples obtained for this study. OSL ages (in green), fading-corrected IRSL ages (in orange), and post-IR IRSL ages (not corrected for fading, in blue). **(b)** Photo of the exposure at the Mühlbach taken during fieldwork (photo courtesy of Lukas Gegg).

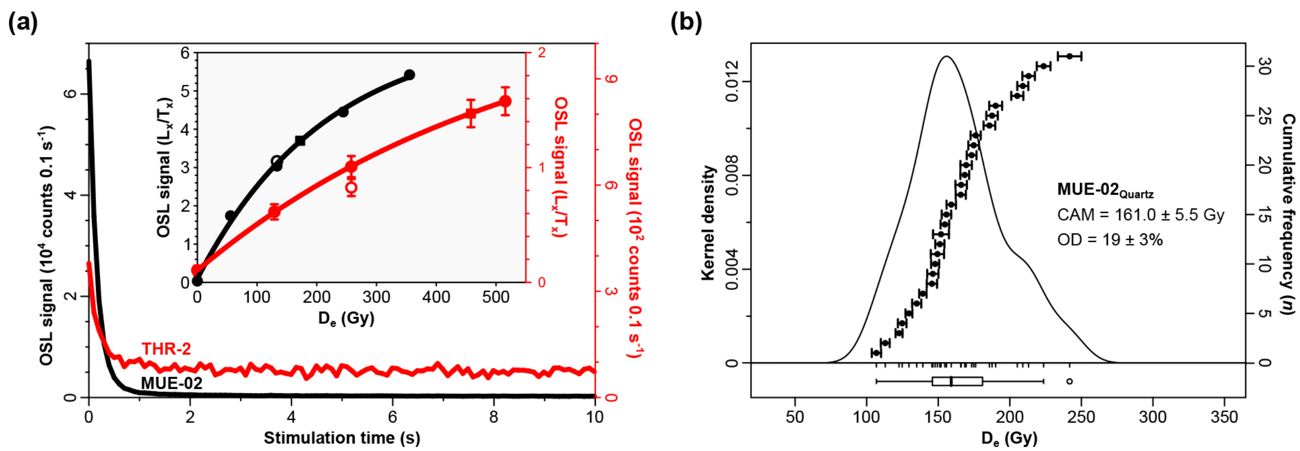

Figure 7. (a) Example quartz OSL decay curves from the Mühlbach formation (MUE-02 sample) and a sample taken from deposits of the *Hochterrasse* (sample THR-2; unpublished but similar to samples published by Kock et al., 2009) reveal a remarkably bright signal in quartz from the study site. Filled squares – natural luminescence signal; empty circles – repeated measurement of the first dose. **(b)** D_e distribution for the MUE-02 quartz sample.

(MUE-03, IRSL). As in previous studies (e.g. Lowick et al., 2015; Mueller et al., 2020), these values and the normal shape of the D_e distribution (Fig. 7b) are considered to reflect samples in which the luminescence signal was fully reset at the time of deposition. This observation justifies the application of CAM for calculating the mean D_e.

For quartz, we received three OSL ages with overlapping uncertainties (55.6 ± 3.0, 57.0 ± 2.8, 54.9 ± 3.3 ka), resulting in an average age (CAM) of 56.0 ± 1.7 ka. The feldspar IRSL ages without fading correction are on the order of 35 ka but increase to 55.8 ± 2.7, 54.7 ± 2.9, and 55.5 ± 3.7 ka after fading correction (CAM – 55.3 ± 1.7 ka). Without applying a fading correction, the post-IR IRSL ages are 55.2 ± 2.5, 53.0 ± 2.1, and 54.7 ± 3.1 ka (CAM – 54.1 ± 1.4 ka) but increase to almost 70 ka after applying a correction and are then significantly older than the other age estimates.

Table 2. Quartz (Q) OSL and feldspar (F) IRSL and post-IR IRSL summary data. n is the number of aliquots measured/accepted for analyses; OD is the overdispersion value observed for the different D_e distribution samples. D_e values for IRSL and post-IR IRSL have been corrected for fading following the approach of Kars et al. (2008). The bold values are regarded as reliable.

Sample	Mineral (method)	n	D_e (Gy)	OD (%)	$D_{e,\,Kars}$ (Gy)	OD_{Kars} (%)	Age (ka)	Age_{Kars} (ka)
MUE-01	Q (OSL)	37/30	163.5 ± 5.2	17 ± 2	–	–	**55.6 ± 3.0**	–
	F (IRSL)	30/30	132.9 ± 2.6	10 ± 1	212.1 ± 5.4	14 ± 2	35.0 ± 1.6	**55.8 ± 2.7**
	F (post-IR IRSL)	30/29	209.6 ± 3.3	8 ± 1	265.9 ± 4.8	9 ± 1	**55.2 ± 2.5**	70.0 ± 3.2
MUE-02	Q (OSL)	35/31	161.0 ± 5.5	19 ± 3	–	–	**57.0 ± 2.8**	–
	F (IRSL)	30/30	127.7 ± 4.2	18 ± 2	204.4 ± 8.0	21 ± 3	34.2 ± 1.6	**54.7 ± 2.9**
	F (post-IR IRSL)	30/30	198.0 ± 4.1	11 ± 2	251.5 ± 6.1	13 ± 2	**53.0 ± 2.1**	67.4 ± 2.8
MUE-03	Q (OSL)	35/28	153.0 ± 6.1	21 ± 3	–	–	**54.9 ± 3.3**	–
	F (IRSL)	30/28	132.6 ± 6.2	24 ± 3	205.0 ± 10.3	25 ± 4	35.9 ± 2.3	**55.5 ± 3.7**
	F (post-IR IRSL)	30/26	202.1 ± 7.5	18 ± 3	258.4 ± 11.6	23 ± 3	**54.7 ± 3.1**	70.0 ± 4.3

5 Discussion

5.1 Methodological aspects of luminescence dating

Although not an original objective of this study, performance of the different luminescence approaches reveals some important methodological implications as well as evidence regarding the provenance of the samples. In this context, it is interesting to note that the samples investigated here likely represent some of the best-performing quartz compared to other samples from the wider Alpine realm (e.g. Kock et al., 2009; Lowick et al., 2015; Trauerstein et al., 2017; Mueller et al., 2020). This applies to both the strong OSL emissions and the well-behaved performance during the SAR protocol. Such a distinct difference in the OSL properties can be seen as an indication of a different provenance of the samples; i.e. these are likely not of Alpine origin. However, while luminescence properties have been used as a tool to trace sediment provenance (e.g. Gray et al., 2019), this requires reference samples of different origins, information not available in the region at the moment. Nevertheless, while crystalline rocks usually show low quartz OSL signals (e.g. Preusser et al., 2006; Tokuyasu et al., 2010; Simkins et al., 2016), bright OSL signals have been observed (but not properly documented) in sediment directly derived from Triassic red sandstone (*Buntsandstein*) in the Upper Rhine Graben (Koehler et al., 2016). This sandstone was originally deposited in desert environments and may, hence, have experienced several bleaching and irradiation cycles in the past, a process that has been shown to increase OSL sensitivity (Pietsch et al., 2008; Sawakuchi et al., 2011). Thus, it appears likely that the bright OSL signals observed in the Mühlbach formation reflect substantial sediment input from the reworking of Triassic sandstone that is morphologically exposed above the outcrop investigated. In contrast, the high content of radioactive elements in the sediments is not typical of Triassic sandstone (Koehler et al., 2016, 2021) and may rather be attributed to crystalline rocks that form the base of the Quaternary sediments in the study area (Groschopf and Feldhoff, 2004a, b). Such high content of radioactive elements is quite typical of the crystalline rock that prevails in the southern Black Forest (Hofmann et al., 2024). In summary, the combination of quartz OSL properties and radioactive element concentrations observed in the Mühlbach formation is rather atypical for an Alpine origin and more likely reflects an important contribution of locally reworked bedrock from the study area to the sand fraction.

As the results of the quartz OSL dating appear very reliable, this offers the opportunity for cross-checking the performance of the feldspar measurements. These are usually considered more challenging in the region, in particular with regard to incomplete resetting of the signal prior to deposition (e.g. Lowick et al., 2015). For feldspar, it is shown that the fading correction applied to IRSL leads to ages that are in excellent agreement with the OSL ages. This implies that the correction procedure is appropriate and that the IRSL signal was fully reset at the time of deposition. In contrast, applying the fading correction to post-IR IRSL leads to highly overestimated ages compared to OSL. This could reflect either a residual dose present in the post-IR IRSL signal at the time of deposition or an overcorrection by the fading procedure. In fact, residual doses on the order of 10 Gy have been reported by others (e.g. Kars et al., 2014) and could explain the observed offset. On the other hand, it is striking that without fading correction, all three post-IR IRSL ages fit perfectly with both OSL and IRSL (fading corrected). Similar observations at other sites have led several authors to conclude that the observed g values are a laboratory artefact; carrying out a fading correction would thus be inappropriate (e.g. Thiel et al., 2011; Lowick et al., 2012; Gaar et al., 2013). We tend to follow this argumentation, as it appears rather unlikely that the uncorrected post-IR IRSL just by chance matches the OSL and IRSL estimates. Concordantly, Schulze et al. (2022) observed excellent agreement of OSL and post-

IR IRSL (200 °C) ages without fading correction for loess from the Kaiserstuhl, some 70 km northwest of the site investigated here. In loess, the effect of residual doses is much less relevant considering the wind-borne nature and more direct and likely prolonged light exposure of the sediment grains (Kars et al., 2014). Hence, it appears that the sediment grains of the Mühlbach formation have been exposed to daylight for rather prolonged periods of time before the final deposition. This speaks to rather low-energy environments such as overbank deposits (e.g. Abdulkarim et al., 2024) or colluvium (Oldknow et al., 2020), whereas in braided river deposits a significant offset has been observed between OSL and post-IR IRSL (e.g. Marik et al., 2024).

5.2 Formation and age of the Mühlbach formation

Previous studies assigned the Mühlbach formation to the Early Pleistocene due to the absence of limestone (Verderber, 1992), the presence of Tertiary pollen (Wolfgang Bludau, Pollenanalytische Untersuchungen am Hochrhein, Mühlbachserie und Laufenburg, Geol. Landesamt Baden-Württemberg, unpublished report, 1991), and the results of palaeomagnetic measurements (Fromm, 1989). However, according to mapping, the various deposits assigned to the Mühlbach formation are actually genetically incoherent formations. Some occurrences of cemented gravel, for example, more likely belong to *Höhere Deckenschotter*, while thin relicts at elevations below 450 m a.s.l. may belong to *Tiefere Deckenschotter* or could reflect material related to mid-Pleistocene Alpine glaciations. The fine-grained deposits investigated at the type location almost certainly represent local reworking by slope processes, as deduced from petrographic analyses, radioactive element content, and quartz OSL properties. In summary, we conclude that the Mühlbach formation is not a uniform formation but comprises weathering residues from different periods. Reworking of older sediments and soil also explains the absence of limestone and the presence of Tertiary to Early Pleistocene floral elements. It should be remembered that pollen analyses found very low amounts of pollen that have to be considered to be of low significance.

All dating results point towards an age of about 55 ka for the deposits of the Mühlbach formation in the exposure investigated. This places sedimentation at the type location to the boundary between marine isotope stages (MIS) 4 and 3 (57 ka according to Lisiecki and Raymo, 2005), which represents the end of a pronounced cold phase with steppe-to-tundra-like vegetation (Preusser, 2004).

Some studies have actually presented evidence suggesting a major glacial advance reaching the northern foreland of the Alps during MIS 4 (around ca. 65 ka; Preusser et al., 2007; Gaar et al., 2019; Gribenski et al., 2021), which implies low vegetation cover and high potential for reworking on slopes. Near Veltheim in the Jura Mountains, i.e. ca. 40 km to the southeast of the study site (Fig. 1), Gaar and Preusser (2012) dated karst fillings on a slope derived from locally weathered bedrock to ca. 63 ka. At Cotencher Cave northwest of Lake Neuchâtel (ca. 130 km to the southeast; Fig. 1), Deák et al. (2019) observed recurrent sediment transport from the slopes towards the cavity between ca. 67 and 36 ka. Hence, it appears that the reworking of sediments on slopes might be a regional phenomenon at least, rather than only a local phenomenon. Similar instability of slopes has been reported on the Swiss Plateau for the transition from MIS 2 to MIS 1, i.e. from the end of the last glaciation into the Early Holocene (Veit et al., 2017).

6 Conclusions

This study reveals that the Mühlbach formation almost certainly comprises a number of genetically unrelated units that were likely deposited during different times in the Pleistocene. At its type locality, the sediment appears to represent reworking on slopes that occurred around 55 ka, during a time with limited vegetation cover at the transition between full-glacial and stadial conditions. In summary, the use of the term Mühlbach formation appears inappropriate, in particular when referring to it as a unit of more than local relevance. It very likely should also not be interpreted as an equivalent of the Sundgau gravel and can thus not be placed into the context of the evolution of the Rhine–Aare fluvial network. However, this does not exclude the possibility that a Late Pliocene fluvial network draining the Swiss Alps crossed the High Rhine area, but there is no sedimentary evidence of this.

Data availability. All new data produced for this study are presented in Sect. 4.2. The source of the data used to produce figures is given in the figure captions.

Author contributions. HRG initiated the research and carried out all fieldwork besides the sampling of luminescence dating, which was done jointly by all authors. AF carried out the luminescence measurements with inputs by DM and FP. HRG wrote parts of the initial text that were revised by FMH and FP, who also prepared the draft of the paper. All authors contributed by additional writing, reviewing, and editing.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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References

Abdulkarim, M., Schmitt, L., Fülling, A., Rambeau, C., Ertlen, D., Mueller, D., Chapkanski, S., and Preusser, F.: Late Glacial to Holocene fluvial dynamics in the Upper Rhine alluvial plain, France, Quaternary Res., 121, 109–131, https://doi.org/10.1017/qua.2024.22, 2024.

Alexander, W. R., Reijonen, H. M., and McKinley, I. G.: Natural analogues: studies of geological processes relevant to radioactive waste disposal in deep geological repositories, Swiss J. Geosci., 108, 75–100, https://doi.org/10.1007/s00015-015-0187-y, 2015.

Behrmann, J. H., Hermann, O., Horstmann, M., Tanner, D. C., and Bertrand, G.: Anatomy and kinematics of oblique continental rifting revealed: a three-dimensional case study of the southeast Upper Rhine graben (Germany), AAPG Bull., 87, 1105–1121, https://doi.org/10.1306/02180300153, 2003.

Bundesamt für Statistik (BFS): Kartengeometrien ThemaKart – Set 2024, Bundesamt für Statistik [data set], https://dam-api.bfs.admin.ch/hub/api/dam/assets/30566934/master (last access: 1 April 2024), 2024.

Buylaert, J. P., Murray, A. S., Thomsen, K. J., and Jain, M.: Testing the potential of an elevated temperature IRSL signal from K-feldspar, Radiat. Meas., 44, 560–565, https://doi.org/10.1016/j.radmeas.2009.02.007, 2009.

Claude, A., Naki, A., Ivy-Ochs, S., Schlunegger, F., Kubik, P. W., Dehnert, A., Kuhlemann, J., Rahn, M., and Schlüchter, C.: Timing of early Quaternary gravel accumulation in the Swiss Alpine Foreland, Geomorph., 276, 71–85 https://doi.org/10.1016/j.geomorph.2016.10.016, 2017.

Cohen, K. M., Finney, S. C., Gibbard, P. L., and Fan, J.-X.: The ICS International Chronostratigraphic Chart, Episodes, 36, 199–204, https://doi.org/10.18814/epiiugs/2013/v36i3/002, 2013.

Deák, J., Preusser, F., Cattin, M.-I., Castel, J.-C., and Chauvière, F.-X.: New data from the Middle Palaeolithic Cotencher cave (Swiss Jura): site formation, environment, and chronology, E&G Quaternary Sci. J., 67, 41–72, https://doi.org/10.5194/egqsj-67-41-2019, 2019.

Degering, D. and Degering, A.: Change is the only constant – time-dependent dose rates in luminescence dating, Quat. Geochronol., 10, 101074, https://doi.org/10.1016/j.quageo.2020.101074, 2020.

Dieleman, C., Christl, M., Vockenhuber, C., Gautschi, P., and Akçar, N.: Early Pleistocene complex cut-and-fill sequences in the Alps, Swiss J. Geosci., 115, 11, https://doi.org/10.1186/s00015-022-00411-2, 2022a.

Dieleman, C., Christl, M., Vockenhuber, C., Gautschi, P., Graf, H. R., and Akçar, N.: Age of the Most Extensive Glaciation in the Alps, Geosciences, 12, 39, https://doi.org/10.3390/geosciences12010039, 2022b.

Doppler, G., Kroemer, E., Rögner, K., Wallner, J., Jerz, H., and Grottenthaler, W.: Quaternary Stratigraphy of Southern Bavaria, E&G Quaternary Sci. J., 60, 23, https://doi.org/10.3285/eg.60.2-3.08, 2011.

Du Pasquier, L.: Über die fluvioglacialen Ablagerungen der Nordschweiz (ausserhalb der inneren Moränenzone), PhD thesis, University of Zurich, Zurich, 128 pp., 1891.

Eberle, J., Eitel, B., Blümel, W. D., and Wittmann, P. (Eds.): Deutschlands Süden – vom Erdmittelalter zur Gegenwart, 4th edn., Springer, Berlin, 233 pp. ISBN 978-3-662-66232-8, 2023.

Ehlers, J., Gibbard, P. L., and Hughes, P. D. (Eds.): Quaternary Glaciations – Extent and Chronology: A Closer Look, Developments in Quaternary Sciences, 15, Elsevier, Amsterdam, Oxford, ISBN 9780444534477, 2011.

Fromm, K.: Paläomagnetische Untersuchungen zur Quartärstratigraphie im Südschwarzwald bei Schadenbirndorf, Report of Geowiss. Gemeinschaftsaufgaben, 16 pp., Hannover, 1989.

Gaar, D. and Preusser, F.: Luminescence dating of mammoth remains from northern Switzerland, Quat. Geochronol., 10, 257–263, https://doi.org/10.1016/j.quageo.2012.02.007, 2012.

Gaar, D., Lowick, S. E., and Preusser, F.: Performance of different luminescence approaches for the dating of known-age glaciofluvial deposits from northern Switzerland, Geochronometria, 41, 65–80, https://doi.org/10.2478/s13386-013-0139-0, 2013.

Gaar, D., Graf, H. R., and Preusser, F.: New chronological constraints on the timing of Late Pleistocene glacier advances in northern Switzerland, E&G Quaternary Sci. J., 68, 53–73, https://doi.org/10.5194/egqsj-68-53-2019, 2019.

Galbraith, R. F., Roberts, R. G., Laslett, G. M., Yoshida, H., and Olley, J. M.: Optical dating of single and multiple grains of quartz from Jinmium Rock Shelter, northern Australia: Part I, experimental design and statistical models, Archaeometry, 41, 339–364, https://doi.org/10.1111/j.1475-4754.1999.tb00987.x, 1999.

González, C., Bachmann, M., Bueso-Bello, J.-L., Rizzoli, P., and Zink, M.: A Fully automatic algorithm for editing the TanDEM-X Global DEM, Remote Sens., 12, 3961, https://doi.org/10.3390/rs12233961, 2020.

Graf, H. R.: Die Deckenschotter der zentralen Nordschweiz, Diss. ETH Zürich Nr. 10205, 1993.

Graf, H. R.: Stratigraphie und Morphogenese von frühpleistozänen Ablagerungen zwischen Bodensee und Klettgau, E&G Quaternary Sci. J., 58, 12–54, https://doi.org/10.3285/eg.58.1.02, 2009a.

Graf, H. R.: Mittel- und Spätpleistozän in der zentralen Nordschweiz, Beiträge geol. Karte Schweiz NF., 168, Bundesamt für Landestopografie Swisstopo, Bern, ISBN 978-3-302-40100-3, 2009b.

Graf, H. R.: Stratigraphie der pleistozänen Ablagerungen im Hochrheintal zwischen Waldshut und Basel, Ber. Landesgeol. 22, 2024

Graf, H. R. and Burkhalter, R.: Quaternary deposits: concept for a stratigraphic classification and nomenclature – an example from northern Switzerland, Swiss J. Geosci., 109, 137–147, https://doi.org/10.1007/s00015-016-0222-7, 2016.

Gray, H. J., Jain, M., Sawakuchi, A. O., Mahan, S. A., Tucker, G. E.: Luminescence as a sediment tracer and provenance tool, Rev. Geophys., 57, 987–1017, https://doi.org/10.1029/2019RG000646, 2019.

Gribenski, N., Valla, P., Preusser, F., Roattino, T., Crouzet, C., and Buoncristiani, J.-F.: Out-of-phase Late Pleistocene glacier advances in the western Alps reflect past changes in North Atlantic atmospheric circulation, Geology, 49, 1096–1101, https://doi.org/10.1130/G48688.1, 2021.

Groschopf, R. and Feldhoff, R. A.: Geologische Karte von Baden-Württemberg 1 : 25 000, Blatt 8314 Göhrwihl, LGRB Freiburg i.Br., 2004a.

Groschopf, R. and Feldhoff, R. A.: Geologische Karte von Baden-Württemberg 1 : 25 000, Blatt 8414 Laufenburg (Baden), LGRB Freiburg i.Br., 2004b.

Gutzwiller, A.: Molasse und jüngere Ablagerungen, Beiträge geol. Karte Schweiz, 19 pp., 1883.

Gutzwiller, A.: Diluvialbildungen der Umgebung von Basel, Verhandlungen der Naturforschenden Gesellschaft in Basel, 10, 512–690, 1894.

Hahne, J., Ellwanger, D., and Stritzke, R.: Evidence for a Waalian thermomer pollen record from the research borehole Heidelberg UniNord, Upper Rhine Graben, Baden-Württemberg, E&G Quaternary Sci. J., 57, 403–410, https://doi.org/10.3285/eg.57.3-4.7, 2009.

Hofmann, F.: Zur plio-pleistozänen Landschaftsgeschichte im Gebiet Hochrhein-Wutach-Randen-Donau: Geomorphologische Überlegungen und sedimentpetrographische Befunde, Eclogae Geol. Helv., 89, 1023–1041, https://doi.org/10.5169/seals-167933, 1996.

Hofmann, F. M., Rambeau, C., Gegg, L., Schulz, M., Steiner, M., Fülling, A., Léanni, L., Preusser, F., and ASTER Team: Regional beryllium-10 production rate for the mid-elevation mountainous regions in central Europe, deduced from a multi-method study of moraines and lake sediments in the Black Forest, Geochronology, 6, 147–174, https://doi.org/10.5194/gchron-6-147-2024, 2024.

Huntley, D. J. and Baril, M. R.: The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating, Ancient TL, 15, 11–13, http://ancienttl.org/ATL_15-1_1997/ATL_15-1_Huntley_p11-13.pdf (last access: 1 April 2024), 1997.

Kars, R. H., Wallinga, J., and Cohen, K. M.: A new approach towards anomalous fading correction for feldspar IRSL dating – tests on samples in field saturation, Radiat. Meas., 43, 786–790, https://doi.org/10.1016/j.radmeas.2008.01.021, 2008.

Kars, R. H., Reimann, T., Ankjærgaard, C., and Wallinga, J.: Bleaching of the post-IR IRSL signal: new insights for feldspar luminescence dating, Boreas, 43, 780–791, https://doi.org/10.1111/bor.12082, 2014.

Knipping, M.: Core drillings in the northern Upper Rhine Graben, Germany, Neth. J. Geosci., 87, 51–65, https://doi.org/10.1017/S0016774600024045, 2008.

Kock, S., Huggenberger, P., Preusser, F., Rentzel, P., and Wetzel, A.: Formation and evolution of the Lower Terrace of the Rhine River in the area of Basel, Swiss J. Geosci., 102, 307–321, https://doi.org/10.1007/s00015-009-1325-1, 2009.

Koehler, H., Wegmüller, F., Detrey, J., Diemer, S., Hauck, T., Pümpin, C., Rentzel, P., Sévêque, N., Stoetzel, E., Wuscher, P., Auguste, P., Bocherens, H., Lutz, M., Preusser, F.: Fouilles de plusieurs occupations du Paléolithique moyen à Mutzig-Rain (Alsace) – Premiers résultats, Bull. Soc. Préhist. Fr., 117, 429–474, 2016.

Koehler, H., Wegmüller, F., Audiard, B., Auguste, P., Bahain, J.-J., Bocherens, H., Dieme, S., Preusser, F., Pümpin, C., Sévêque, N., Stoetzel, E., Tombret, O., and Wuscher, P.: The Middle Paleolithic occupations of Mutzig-Rain (Alsace, France), in: The Rhine during the Middle Paleolithic: Boundary or corridor?, edited by: Koehler, H., Conard, N. J., Floss, H., and Lamotte, A., Kerns Verlag, Tübingen, ISBN 978-3935751353, 2021.

Landesanstalt für Umwelt Baden-Württemberg (LUBW): Fließgewässer (AWGN), Landesanstalt für Umwelt Baden-Württemberg [data set], https://rips-datenlink.lubw.de/UDO_download/Fliessgewaessernetz.zip (last access: 30 November 2023), 2022.

Liniger, H. and Hofmann, F.: Das Alter der Sundgauschotter westlich Basel, Eclogae Geol. Helv., 58, 215–229, https://doi.org/10.5169/seals-163265, 1965.

Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic ^{18}O records, Paleoceanography, 20, 1–17, https://doi.org/10.1029/2004PA001071, 2005.

Lowick, S. E., Trauerstein, M., and Preusser, F.: Testing the application of post IR-IRSL dating to fine grain waterlain sediments, Quat. Geochronol., 8, 33–40, https://doi.org/10.1016/j.quageo.2011.12.003, 2012.

Lowick, S. E., Buechi, M., Gaar, D., Graf, H. R., and Preusser, F.: Luminescence dating of Middle Pleistocene proglacial deposits from northern Switzerland: methodological aspects and stratigraphical conclusions, Boreas, 44, 459–482, https://doi.org/10.1111/bor.12114, 2015.

Madritsch, H., Looser, N., Schneeberger, R., Wohlwend, S., Guillong, M., and Malz, A.: Reconstructing the evolution of foreland fold-and-thrust belts using U-Pb calcite dating: An integrated case-study from the easternmost Jura Mountains (Switzerland), Tectonics, 43, e2023TC008181, https://doi.org/10.1029/2023TC008181, 2024.

Malz, A., Madritsch, H., Jordan, P., Meier, B., and Kley, J.: Along-strike variations in thin-skinned thrusting style controlled by pre-existing basement structure in the easternmost Jura Mountains (Northern Switzerland), Geol. Soc. Spec. Publ., 490, 199–220, https://doi.org/10.1144/SP490-2019-090, 2019.

Marik M., Serra E., Gegg L., Wölki D., and Preusser F.: Combined different luminescence dating approaches on fluvial gravel deposits from the southern Upper Rhine Graben, Quat. Geochronol., 82, 101536, https://doi.org/10.1016/j.quageo.2024.101536, 2024.

Mueller, D. and Preusser, F.: Investigating the applicability of a standardised growth curve approach on Middle Pleistocene sediments from northern Switzerland, Quat. Geochronol., 67, 101238, https://doi.org/10.1016/j.quageo.2021.101238, 2022.

Mueller, D., Preusser, F., Buechi, M. W., Gegg, L., and Deplazes, G.: Luminescence properties and dating of glacial to periglacial sediments from northern Switzerland, Geochronology, 2, 305–323, https://doi.org/10.5194/gchron-2-305-2020, 2020.

Müller, W. H., Naef, H., and Graf, H. R.: Geologische Entwicklung der Nordschweiz, Neotektonik und Langzeitszenarien Züricher Weinland, Nagra Technischer Bericht, Wettingen, NTB 99-08, 237 pp., 2002.

Murray, A. S. and Wintle, A. G.: Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol, Radiat. Meas., 32, 57–73, https://doi.org/10.1016/S1350-4487(99)00253-X, 2000.

Oldknow C. J., Carr A. S., Hooke J. M., and Shen Z.: The suitability of a low temperature post-IR IRSL signal for dating alluvial and colluvial "cut and fill" sequences in the Great Karoo, South Africa, Quat. Geochronol., 58, 101064, https://doi.org/10.1016/j.quageo.2020.101064, 2020.

Penck, A. and Brückner, E.: Die Alpen im Eiszeitalter, Tauchnitz, Leipzig, 716 pp., 1901–1909.

Petit, C., Campy, M., Chaline, J., and Bonvalot, J.: Major palaeohydrographic changes in Alpine foreland during the Pliocene-Pleistocene, Boreas, 25, 131–143, https://doi.org/10.1111/j.1502-3885.1996.tb00841.x, 1996.

Pietsch, J. and Jordan, P.: Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2014 (SGT E2) und ausgewählte Auswertungen, NAB 14-02, NAGRA 2014.

Pietsch, T. J., Olley, J. M., and Nanson, G. C.: Fluvial transport as a natural luminescence sensitiser of quartz, Quat. Geochronol., 3, 365–376, https://doi.org/10.1016/j.quageo.2007.12.005, 2008.

Prescott, J. R. and Hutton, J. T.: Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations, Radiat. Meas., 23, 497–500, https://doi.org/10.1016/1350-4487(94)90086-8, 1994.

Preusser, F.: Towards a chronology of the Late Pleistocene in the northern Alpine Foreland, Boreas 33, 195–210, https://doi.org/10.1111/j.1502-3885.2004.tb01141.x, 2004.

Preusser, F.: Characterisation and evolution of the River Rhine system, Netherlands J. Geosci. 87, 7–19, https://doi.org/10.1017/S0016774600024008, 2008.

Preusser, F., Ramseyer, K., and Schlüchter, C.: Characterisation of low luminescence intensity quartz from Westland, New Zealand, Radiat. Meas., 41, 871–877, https://doi.org/10.1016/j.radmeas.2006.04.019, 2006.

Preusser, F., Blei, A., Graf, H. R., and Schlüchter, C.: Luminescence dating of Würmian (Weichselian) proglacial sediments from Switzerland: methodological aspects and stratigraphical conclusions, Boreas, 36, 130–142, https://doi.org/10.1111/j.1502-3885.2007.tb01187.x, 2007.

Preusser, F., Graf, H. R., Keller, O., Krayss, E., and Schlüchter, C.: Quaternary glaciation history of northern Switzerland, E&G Quaternary Sci. J., 60, 21, https://doi.org/10.3285/eg.60.2-3.06, 2011.

Preusser, F., Büschelberger, M., Kemna, H. A., Miocic, J., Mueller, D., and May, J.-H.: Quaternary aggradation in the Upper Rhine Graben linked to the glaciation history of northern Switzerland, Int. J. Earth Sci., 110, 1827-01846, https://doi.org/10.1007/s00531-021-02043-7, 2021.

Ramshorn, C. and Wendebourg, J.: Geologische Untersuchungen unter besonderer Berücksichtigung des Quartärs im Gebiet um Birndorf und Unteralpfen (Südostschwarzwald), Diplom-Arbeit University of Freiburg i.Br., unpublished, 83 pp., 1986.

Richter, D., Richter, A., and Dornich, K.: Lexsyg – a new system for luminescence research, Geochronometria, 40, 220–228, https://doi.org/10.2478/s13386-013-0110-0, 2013.

Roberts, A. P., Tauxe, L., and Heslop, D.: Magnetic paleointensity stratigraphy and high-resolution Quaternary geochronology: successes and future challenges, Quaternary Sci. Rev., 61, 1–16, https://doi.org/10.1016/j.quascirev.2012.10.036, 2013.

Rózsa, S., Heck, B., Mayer, M., Seitz, K., Westerhaus, M., and Zippelt, K.: Determination of displacements in the upper Rhine graben Area from GPS and leveling data, Int. J. Earth Sci., 94, 538–549, https://doi.org/10.1007/s00531-005-0478-z, 2005.

Sawakuchi, A. O., Blair, M. W., DeWitt, R., Faleiros, F. M., Hyppolito, T., and Guedes, C. C. F.: Thermal history versus sedimentary history: OSL sensitivity of quartz grains extracted from rocks and sediments, Quat. Geochronol., 6, 261–272, https://doi.org/10.1016/j.quageo.2010.11.002, 2011.

Schulze, T., Schwahn, L., Fülling, A., Zeeden, C., Preusser, F., and Sprafke, T.: Investigating the loess–palaeosol sequence of Bahlingen-Schönenberg (Kaiserstuhl), southwestern Germany, using a multi-methodological approach, E&G Quaternary Sci. J., 71, 145–162, https://doi.org/10.5194/egqsj-71-145-2022, 2022.

Simkins, L. M., DeWitt, R., Simms, A. R., Briggs, S., and Shapiro, R. S.: Investigation of optically stimulated luminescence behavior of quartz from crystalline rock surfaces: A look forward, Quat. Geochronol., 36, 161–173, https://doi.org/10.1016/j.quageo.2016.09.002, 2016.

Thiel, C., Buylaert, J.-P., Murray, A., Terhorst, B., Hofer, I., Tsukamoto, S., and Frechen, M.: Luminescence dating of the Stratzing loess profile (Austria) – Testing the potential of an elevated temperature post-IR IRSL protocol, Quatern. Int., 234, 23–31, https://doi.org/10.1016/j.quaint.2010.05.018, 2011.

Tokuyasu, K., Tanaka, K., Tsukamoto, S., and Murray, A. S.: The characteristics of OSL signal from quartz grains extracted from modern sediments in Japan, Geochronometria, 37, 13–19, https://doi.org/10.2478/v10003-010-0020-6, 2010.

Trauerstein, M., Lowick, S. E., Preusser, F., and Veit, H.: Estimating the suitability of dim sedimentary quartz from Northern Switzerland for OSL burial dose estimation, Geochronometria, 44, 66–76, https://doi.org/10.1515/geochr-2015-0058, 2017.

Veit, H., Trauerstein, M., Preusser, F., Messmer, T., Gnägi, C., Zech, R., and Wüthrich, L.: Early Holocene cover beds on the Swiss Plateau: Genesis and palaeo-environment, Catena, 158, 102–112, https://doi.org/10.1016/j.catena.2017.06.012, 2017.

Verderber, R.: Quartärgeologische Untersuchungen im Hochrheingebiet zwischen Schaffhausen und Basel, Diss. Universität Freiburg i. Br., 169 pp., 1992.

Verderber, R.: Quartärgeologie im Hochrheingebiet zwischen Schaffhausen und Basel, Z. dt. Geol. Ges., 154, 369–406, https://doi.org/10.1127/zdgg/154/2003/369, 2003.

Wintle, A. G.: Anomalous fading of thermoluminescence in mineral samples, Nature, 245, 143–144, https://doi.org/10.1038/245143a0, 1973.

Ziegler, P. A. and Fraefel, M.: Response of drainage systems to Neogene evolution of the Jura fold-thrust belt and Upper Rhine Graben, Swiss J. Geosci., 102, 57–75, https://doi.org/10.1007/s00015-009-1306-4, 2009.