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Research article

Towards a quantitative lithostratigraphy of Pleistocene glaciofluvial deposits in the southern Upper Rhine Graben

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Abstract: The sediment fills of large terrestrial basins offer an opportunity to study and reconstruct regional-scale landscape history over time. An example of such a basin is the Upper Rhine Graben in central Europe, whose proximal, southern part has so far only sporadically been investigated sedimentologically. Three new drillings in close proximity have recovered the upper ∼40–60 m of the Quaternary sedimentary infill near the eastern graben margin north of Freiburg, Germany. Grain sizes, the rounding and shape of clasts, and the petrographic composition of the deposits have been determined and statistically analysed. The cored intervals consist of glaciofluvial gravels derived from and deposited by the Rhine system. While no consistent trends of the morphometric properties could be found, we succeeded in distinguishing two subunits within the topmost stratigraphic unit (Neuenburg Formation, Fm) based on compositional (i.e. gravel petrographic) data. An upper subunit (Hartheim Subformation, Sfm) enriched in lithologies representative of the Alpine orogen could be separated from a lower subunit (Nambsheim Sfm) that is enriched in lithologies of an outer-Alpine origin. We correlate these findings with a shift in the pattern of meltwater discharge from the Rhine glacier lobe that may have delivered more Alpine material into the study region during the last than during the penultimate glaciation and highlight the value of quantitative approaches and appropriate statistical evaluation for gravel petrographic studies.

Kurzfassung: Ablagerungen aus terrestrischen Becken bieten eine Gelegenheit für die Erforschung und Rekonstruktion der Landschaftsgeschichte auf regionalem Maßstab. Ein Beispiel für ein solches Becken ist der Oberrheingraben, dessen Sedimentfüllung im proximalen südlichen Abschnitt jedoch bisher nur sporadisch untersucht wurde. In drei neuen Bohrungen wurden die oberen ∼40–60 m der quartären Ablagerungen nahe des östlichen Grabenrands im Großraum Freiburg erschlossen, und ihre Korngrößen, Rundungsgrade und Kornformen sowie Geröllspektren erfasst und statistisch ausgewertet. Das Probenmaterial besteht aus Schmelzwasserschottern, die vom Rheinsystem geliefert und abgelagert wurden. Während in den morphometrischen Datensätzen keine konsistenten Muster erkennbar waren, gelang es, zwei Untereinheiten innerhalb der Neuenburg Fm., der obersten regionalstratigraphischen Einheit, zu identifizieren. Die obere Hartheim Sfm. enthält höhere Anteile an alpinen

Gesteinen, wohingegen in der unteren Nambsheim Sfm. mehr außeralpines Material vorkommt. Wir korrelieren diese Unterschiede mit einem veränderten Abflussmuster vom Rheingletscherlobus, dessen Schmelzwässer und Geröllfracht im Verlauf des Mittel- und Spätpleistozäns zunehmend in das moderne Rheintal geschüttet wurden. Wir zeigen außerdem, dass die klassische Schotterpetrographie verknüpft mit zeitgemäßen statistischen Methoden ein hilfreiches Werkzeug für die Stratigraphie sein kann.

1 Introduction

The reconstruction of the landscape evolution of an area of interest is best achieved by studying extensive stratigraphic profiles. In terrestrial environments, such investigations often suffer from the scarcity and typically discontinuous character of long sedimentary records. This is especially true for previously glaciated areas that are affected by recurring episodes of intensive erosion (Hughes et al., 2019), such as the northern Alpine foreland. This issue has mainly been addressed by the specific search for sediment sinks within these areas in recent years, for example subglacial overdeepenings (Gegg and Preusser, 2023, and references therein). However, such stratigraphic records occur rather isolated and may be dominated by specific local processes. Alternative targets could be regional-scale sediment sinks further downstream (Anselmetti et al., 2022). As an example, Salcher et al. (2017) could reconstruct fluvial aggradation over warm and cold periods from Marine Isotope Stage (MIS) 11 through MIS 5 from the infill of the Vienna Basin (Austria).

Another example of a regional-scale sediment sink is the Upper Rhine Graben (URG), a tectonic basin extending over > 350 km from Basel (Switzerland) to Frankfurt am Main (Germany). It developed in response to the onsetting Alpine orogeny during the Palaeogene as an incipient rift within the crystalline basement of the northern Alpine foreland and its (mostly Mesozoic) sedimentary cover (Edel et al., 2007; Schumacher, 2002). The URG has since episodically subsided and thus acted as a sediment trap (Berger et al., 2005; Schumacher, 2002), with continued tectonic activity until the present (Nivière et al., 2008; Ritter et al., 2009). The graben shoulders, which consist in the southern URG of the Vosges and the Black Forest, have been uplifted, with their sedimentary cover largely being stripped off and the debris partly being deposited within the URG (Fig. 1; e.g. Berger et al., 2005; Jautzy et al., 2024).

Throughout most of the Pliocene, the headwaters of the Rhine lay in the area of the Kaiserstuhl volcano. In the Late Pliocene–Early Pleistocene, however, first the Aare and later also the Alpine Rhine were deflected into the URG (Fig. 1; Hagedorn and Boenigk, 2008; Yanites et al., 2017; Ziegler and Fraefel, 2009), resulting in a modern catchment area of $\sim 35\,000$ km^2 (FGG Rhein, 2020). The Alpine sediment input into the graben presumably fluctuated considerably throughout the Pleistocene due to the repeated build-up of extensive and erosive valley glaciers during global cold periods (e.g. Ellwanger et al., 2011; Preusser et al., 2011). Upon melting of these ice masses, pulses of meltwater traversed the Rhine system, transporting vast amounts of debris into the URG – material that is direct evidence of glacial erosion in the Alpine headwaters (Ellwanger et al., 2011, 2012; Frechen et al., 2010; Preusser et al., 2021).

Towards the distal northern end, the Pleistocene infill of the URG is very diverse in character and has been rather extensively examined (e.g. Gabriel et al., 2013, and references therein; Gegg et al., 2024; Preusser et al., 2021; Przyrowski and Schäfer, 2015). In the southern part, glaciofluvial gravels deposited by braided rivers form a gigantic alluvial fan with a maximum thickness of > 200 m (Abdulkarim et al., 2024; Ellwanger et al., 2011, 2012; Huggenberger and Regli, 2006; Kock et al., 2009b; Marik et al., 2024). Despite their economic (Werner et al., 1996) and, potentially, regional (i.e. Alpine-scale) stratigraphic significance, studies focussing on these sediments have remained scarce. This might be due to an apparent lack of informative value of coarse-grained sediments that contain few environmental indicators, such as fossils or even organic material in general, which are notoriously difficult to date (e.g. Frechen et al., 2010; Marik et al., 2024).

In the following, we present results of a gravel-morphometric and gravel-petrographic analysis of material from three neighbouring boreholes near the eastern margin of the southern URG. In particular the use of petrographic data, a well-established stratigraphic tool in upstream areas (e.g. Graf, 2009), also proves useful in the proximal URG. We demonstrate the value and limitations of such quantitative approaches and of appropriate statistical evaluation. Our results are further discussed in and match with the context of the regional drainage development and glaciation history.

2 Pleistocene lithostratigraphy in the southern URG

Locally derived, dominantly sandy deposits referred to as the Iffezheim Formation (Fm) constitute the lowermost unconsolidated sediments deposited in the southern URG and are mainly attributed to the Pliocene (e.g. Scheidt et al., 2015; see Fig. 1). They are clearly distinguishable from the Alpine-dominated material above that represents the majority of the Pleistocene. The latter is not only different in composition (e.g. presence of carbonate in clasts and matrix or shift

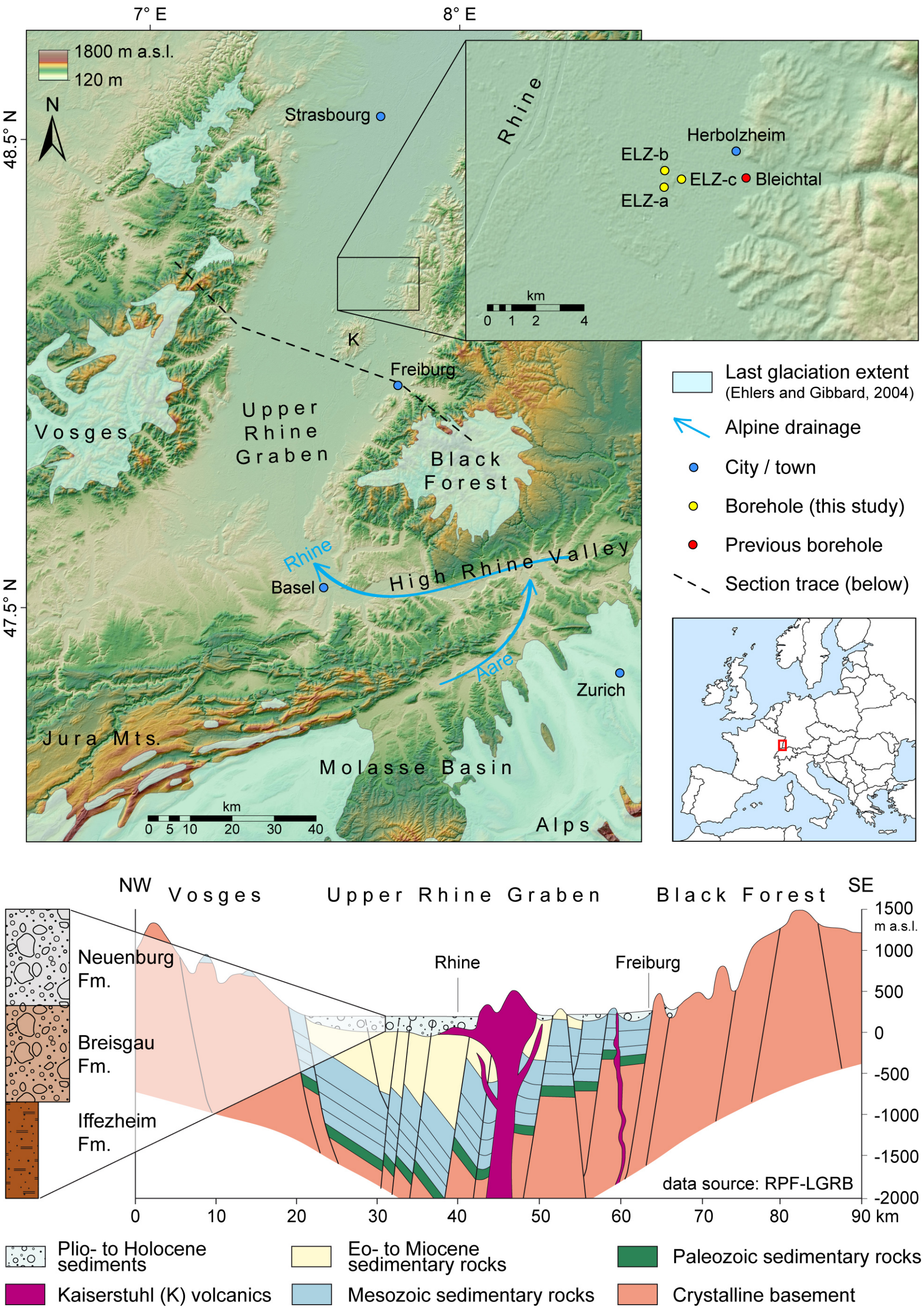

Figure 1. On the top is shown an overview map of the southern URG and its surroundings. The inset shows the locations of our boreholes (yellow dots) close to the outlet of the Bleichtal valley. On the bottom is shown a schematic cross-section illustrating the architecture of the graben and its infill (bottom; 10× vertically exaggerated; after Villinger, 2002, ©Regierungspräsidium Freiburg, Landesamt für Geologie, Rohstoffe und Bergbau) and specifically the Pliocene–Holocene succession of unconsolidated deposits (see text).

in the heavy-mineral spectrum from a stable spectrum towards dominance of garnet, epidote, and hornblende; Hagedorn, 2004; Hagedorn and Boenigk, 2008) but also significantly coarser. It is subdivided into a lower sandy or diamictic gravel unit (Breisgau Fm) that shows signs of alteration, such as weathered or disintegrating clasts, in an upward-decreasing intensity. The upper unit (Neuenburg Fm), in contrast, consists of "fresh" sandy gravels (Ellwanger et al., 2011, 2012; Wirsing and Luz, 2007). North of our study area, the Breisgau Fm and Neuenburg Fm are progressively more difficult to distinguish and are thus substituted by the Ortenau Fm (Wirsing and Luz, 2007).

The Breisgau Fm and Neuenburg Fm each consist of multiple individual, partly graded packages of sandy gravels. In the Neuenburg Fm, these can be attributed to two large-scale fining-upward cycles, the Nambsheim Subformation (Sfm) and the overlying Hartheim Sfm, which initiate with prominent and continuous block layers (Ellwanger et al., 2011, 2012). Radiometric dating suggests a (later) Late Pleistocene–Holocene age for the top of the Neuenburg Fm (Frechen et al., 2012, and references therein; Kock et al., 2009a, b; Marik et al., 2024), whereas to our knowledge no ages exist from deeper parts of the Neuenburg Fm or the Breisgau Fm. The geochronological positions have therefore mainly been inferred from conceptual ideas: the two block layers of the Neuenburg Fm have been correlated with upstream glacial erosion during the last and penultimate Alpine glaciations (Ellwanger et al., 2011, 2012; Frechen et al., 2010), which correspond to MIS 2–5d and MIS 6, respectively (e.g. Preusser et al., 2011). The Breisgau Fm in contrast is thought to represent the earlier phases of Alpine glaciofluvial input into the URG including the pre-penultimate glaciation (Ellwanger et al., 2011, 2012).

Although identified as a useful tool for stratigraphic subdivision in the Alpine foreland (e.g. Graf, 2009), detailed gravel petrographic studies for the Breisgau Fm and Neuenburg Fm are lacking. Werner et al. (1996) report average compositions, but more explicit data or statistical analyses have, to our knowledge, not been published.

3 Methods

Three groundwater exploration boreholes, ELZ-a, ELZ-b, and ELZ-c, were drilled in 2012/13 in the Elzwiesen district ∼ 1.5 km SW of the town of Herbolzheim, in close proximity to each other (Fig. 1) and with depths of 40–62 m (Table 1). A barrel auger (German *Schappe*) was used to collect the drill core material, which may result in internal mixing and partial loss of the sandy matrix but has the advantage of recovering gravel and large cobbles without notable damage to the individual clasts. The cored sediments were transferred into boxes, superficially cleaned, and described.

At a spacing of ∼ 4 m, the gravel and cobble fractions of full core meters were further analysed in order to identify potential variations in provenance and pre-depositional transport. The b axis of the largest cobble within each of these samples, if any were present, was measured by hand, and the material was dry-sieved using sieves with meshes of 63, 20, and 6.3 mm. The respective fractions were weighed, and grain size distribution curves were plotted, which are represented in the following by the 50th- and 90th-percentile grain sizes (D_{50} and D_{90}, respectively).

Then, the lithological composition of the entire coarse-gravel fraction (20–63 mm; 65–172 clasts) was determined, distinguishing various carbonates (light-grey and dark-grey to blackish as well as yellowish limestone and dolostones); other sediments (generic sandstones and conglomerates, Verrucano-type rocks, Taveyannaz sandstones, radiolarites, and cherts); plutonic (white, greenish, and reddish granites and aplites), metamorphic (quartzites, gneisses, amphibolites, and cataclasites), and volcanic rocks; and vein quartz clasts. Endmember analyses using the R packages EMMAgeo (Dietze and Dietze, 2019) and RECA (Seidel and Hlawitschka, 2015) were run on the resulting petrographic datasets. We ran both scripts with $n = 2$, 3, and 4 endmembers, as well as principal component analyses (variance–covariance matrix) and t tests using Past 3 (Hammer et al., 2001).

Additionally, for all limestone clasts, as these are generally the most abundant lithological group (Table S1 in the Supplement), the lengths of all three grain axes were measured, and the grain shape (blocky if $a \approx b \approx c$, platy if $a \approx b >> c$, or elongated if $a >> b \approx c$) and roundness (rounded, subrounded, subangular, or angular in comparison with a chart by Powers, 1953) were determined qualitatively. From these clast-morphological datasets, C40 (percentage of clasts with $c \leq 0,4 * a$), RA (percentage of angular clasts), and RWR (percentage of rounded clasts) indices were calculated (after Lukas et al., 2013).

4 Results

4.1 Sedimentary facies

All three boreholes recovered exclusively and terminated within unconsolidated sandy gravels. Sediments of ELZ-a and ELZ-c are of an overall grey colour and comprise diverse, fresh, and unweathered clasts (lithofacies A; Fig. 2a). The same applies to the interval from 0–53 m depth in ELZ-b. These fresh gravels consist of metre-scale packages that can be differentiated by slight variations in gravel grain sizes or sand content. Some packages show fining-upward trends (Fig. 3). In all profiles, block layers, i.e. horizons with abundant large cobbles, exist (around 20 and 37 m in ELZ-a; around 15, 29, 43, and 53 m in ELZ-b; and around 19, 22, and 34 m in ELZ-c; Fig. 2b). In the lower part of ELZ-c, at 53 m, a sharp colour change occurs. The gravels below (lithofacies B; Fig. 2c) are ochre-beige and polymictic with individual clasts appearing weathered (e.g. disintegrating granites). This section lacks distinguishable subunits and is comparatively rich in sand.

4.2 Gravel morphometrics

The median grain size D_{50} throughout all three boreholes is generally in the medium gravel range (mostly ∼ 15 mm), while D_{90} corresponds to coarse gravel to blocks (mostly ∼ 50 mm; Fig. 3; Table S1). In contrast, one of the block layers (ELZ-c, 19–20 m) yielded values of ∼ 50 and ∼ 100 mm, respectively. The gravels in the lower half of ELZ-a are notably coarser than in the upper half, and in ELZ-b, a coarser

Table 1. Groundwater exploration boreholes.

Borehole	Archive no.*	Coordinates	Elevation (m a.s.l.)	Final depth (m)
ELZ-a	7712/1928	48.2038° N, 7.7348° E	172.8	40.0
ELZ-b	7712/1930	48.2100° N, 7.7351° E	172.1	62.0
ELZ-c	7712/1933	48.2068° N, 7.7444° E	172.6	40.1

* Provided by the Landesamt für Geologie, Rohstoffe und Bergbau (LGRB).

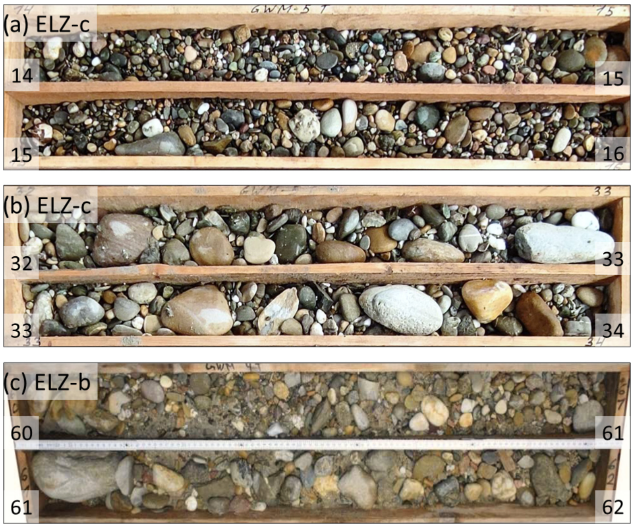

Figure 2. Examples of representative core intervals: **(a)** lithofacies A, Neuenburg Fm, ELZ-c 14–16 m; **(b)** lithofacies A, Neuenburg Fm, block layer, ELZ-c 32–34 m; and **(c)** lithofacies B, Breisgau Fm, ELZ-b 60–62 m.

interval occurs between ∼ 40 and ∼ 55 m depth. Consistent trends occurring similarly in all boreholes can however not be observed. Limestone clasts in selected core meters of the Elzwiesen boreholes are predominantly platy to blocky in shape, with a typical C40 value (percentage of clasts whose $c \leq 0,4 * a$) of 45–65 and outliers mostly connected to small sample sizes (< 20 clasts). The limestone clasts are generally rounded to subrounded, although, notably, some (sub)angular clasts of dark limestone occur. As for grain sizes, no consistent patterns can be observed. For example, samples from borehole ELZ-a show a jump towards lower values of RWR (percentage of rounded clasts) below ∼ 20 m depth, whereas RWR values increase slightly with depth in ELZ-c (Fig. 3).

4.3 Gravel petrography

The gravels encountered within the Elzwiesen drill cores are polymictic and colourful. The most abundant lithologies are light- and dark-grey limestones, radiolarites, quartzites, and vein quartz clasts (≥ 10 %; Table S1). Yellowish limestones, sandstones, cherts, white granites, and gneisses typically make up ≥ 5 %, whereas all other lithologies occur only in little numbers or sporadically. Generally, the cobble fraction consists predominantly of quartzite clasts. In the fresh, grey gravels of lithofacies A, a consistent compositional trend can be observed in all boreholes: in the top 15–20 m, dark limestones are especially abundant (∼ 14 % compared to ∼ 7 %), whereas in the lower part as well as in lithofacies B, quartzites and vein quartz clasts occur in slightly greater numbers (∼ 14 % each compared to ∼ 12 %; Table S1). One selected block layer (ELZ-c, 19–20 m) was especially rich in quartzites (Figs. 3, 4), which appeared to apply also to other block layers that were not sampled.

This trend is confirmed by endmember (EM) modelling. We present results here modelled using the RECA package (Seidel and Hlawitschka, 2015) with an EM value of $n = 2$, as this is the model run that yielded most consistent and best interpretable data (Fig. 3). Model results of the deterministic EMMAgeo approach (Dietze and Dietze, 2019), $n = 2$, are qualitatively similar, while larger numbers of endmembers in both cases convolute the results rather than provide clear additional information. (Theoretical) EM1 is rich in dark limestones; radiolarites; and, to a minor extent, (red) granites and gneisses, while (theoretical) EM2 is rich in light limestones, sandstones, and quartzites. The gravel samples from the upper lithofacies A (top 15–20 m) of all three boreholes consist of > 60 % (partly > 80 %) EM1 and are thus consistently different from the samples from lower lithofacies A and lithofacies B, which consist of EM1 and EM2 in largely equal shares (Fig. 3). According to two-sample equal-variance t tests, the probability that both upper lithofacies A vs. lower lithofacies A/lithofacies B have the same mean endmember scores is $p = 2.4 \times 10^{-7}$, while it is $p = 0.93$ for lower lithofacies A vs. lithofacies B. Similarly, principal component analysis distinguishes upper lithofacies A from lower lithofacies A and lithofacies B but does not separate the latter two from each other (Fig. 4).

5 Discussion

5.1 Stratigraphic classification

The recovered gravels represent the deposits of braided meltwater rivers that built up the Pleistocene mega-fan in the southern URG (e.g. Ellwanger et al., 2011, 2012; Werner et

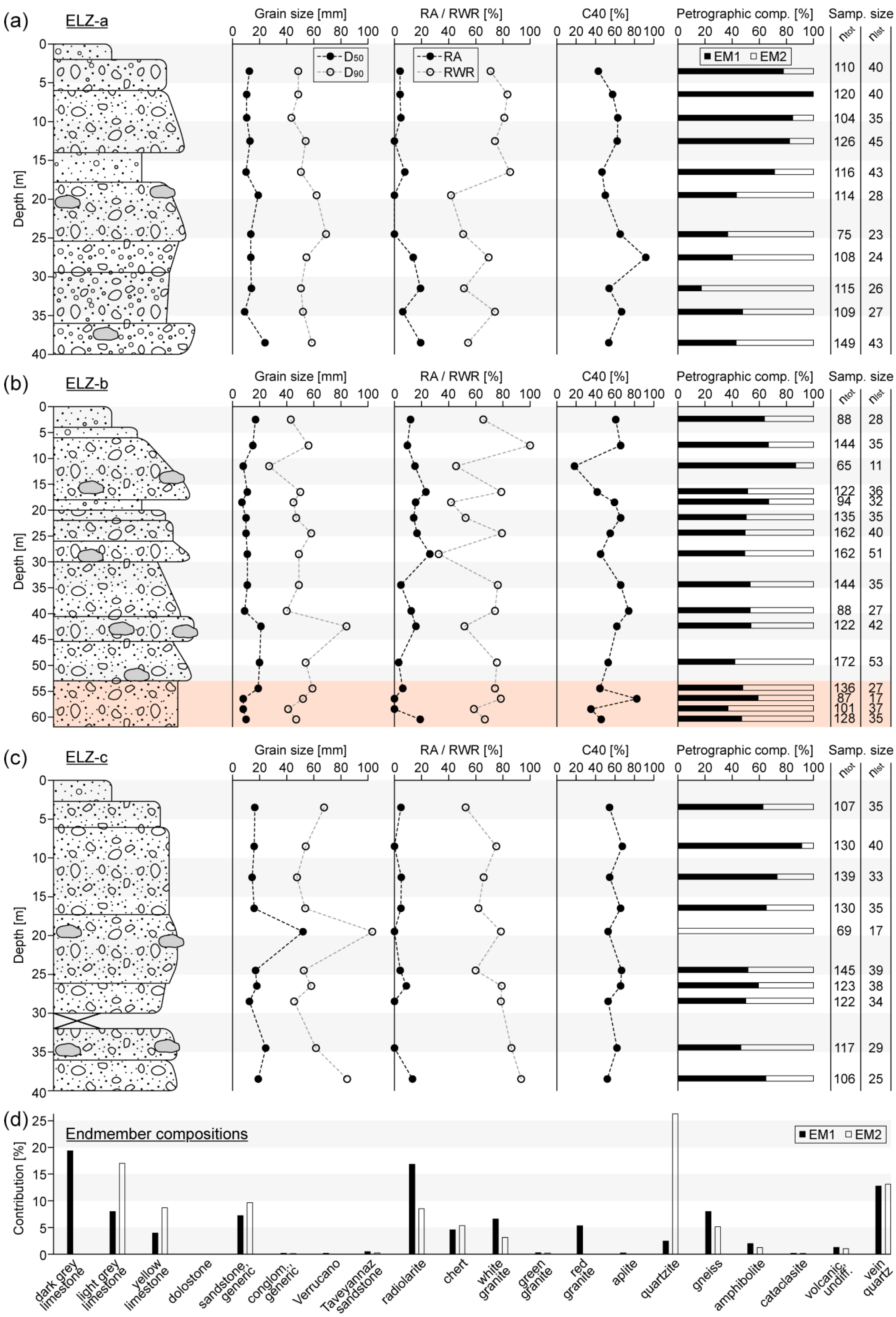

Figure 3. On the top are shown profile logs, morphometric indices, petrographic endmember data, and sample sizes (n_{tot}, total number of clasts; n_{lst}, number of limestone clasts) for boreholes ELZ-a, ELZ-b (orange-shaded interval: lithofacies B, Breisgau Fm), and ELZ-c. With the exception of ELZ-c at 19–20 m, the block layers were avoided when sampling. RA: percentage of angular clasts, RWR: percentage of rounded clasts (Lukas et al., 2013). On the bottom are shown compositions of modelled petrographic endmembers EM1 and EM2 (bottom; RECA model, two endmembers, convexity threshold of -6, weighing exponent of 1).

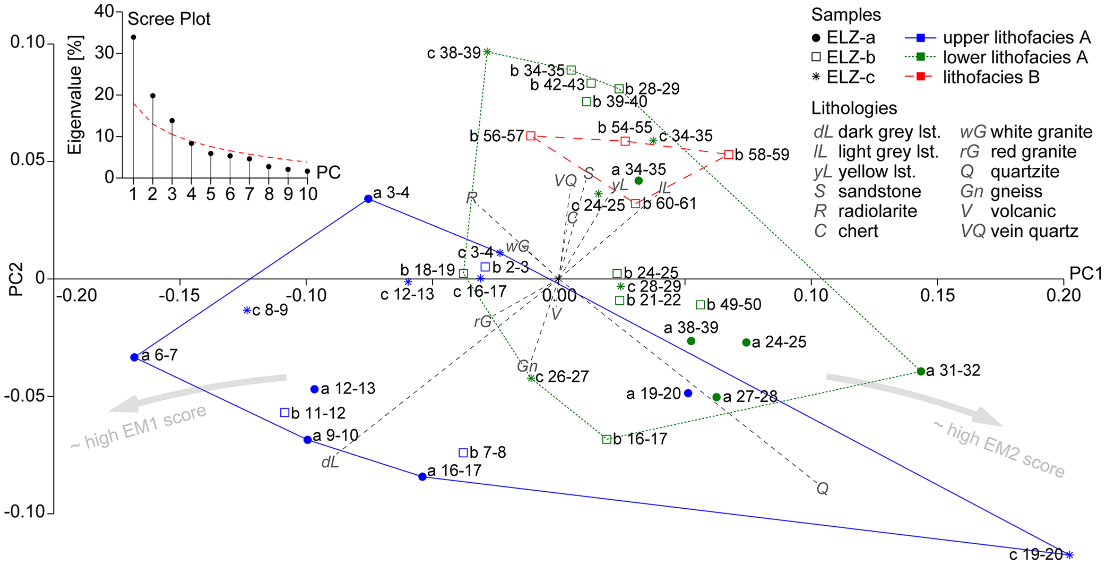

Figure 4. Principal component (PC) analysis of the petrographic samples distinguishes, with some overlap, the upper lithofacies A (Hartheim Sfm; high level of contribution of dark limestone (lst), gneiss, and red granite) of all three boreholes from lower lithofacies A and lithofacies B (Nambsheim Sfm and Breisgau Fm, respectively; high level contribution of light limestone, sandstone, vein quartz, and chert).

al., 1996). Lithofacies A is greyish in colour, and its clasts are fresh in appearance; thus it is interpreted as the Neuenburg Fm. The underlying lithofacies B of borehole ELZ-b has been subject to visibly more intensive weathering, resulting in an ochre-beige colour and individual disintegrating clasts. It is interpreted as the Breisgau Fm (Hagedorn, 2004).

The present data suggest that two subunits within the Neuenburg Fm can be distinguished not only by their basal block horizons (Ellwanger et al., 2011, 2012) but also by their gravel petrographic compositions. Endmember modelling and principal component analysis separate an upper Neuenburg Fm with comparatively high abundances of dark limestones, radiolarites, and crystalline rocks from a lower Neuenburg Fm with high abundances of light limestones, sandstones, and quartzites (Figs. 3, 4).

The boundary between the two subunits occurs at ∼ 20 m depth in ELZ-a and ELZ-c and at ∼ 15 m depth in ELZ-b. It coincides with the occurrence of larger blocks (see Fig. 3); therefore we correlate these subunits to the Hartheim and Nambsheim Sfm's after Ellwanger et al. (2011, 2012). Such a gravel petrographic distinction has previously not been successful (Werner et al., 1996) but should be confirmed at other sites with appropriate statistical approaches. A clear petrographic difference between the lower Neuenburg Fm and the Breisgau Fm is not apparent (Figs. 3, 4); however this might be due to only four samples being available from the latter.

5.2 Dynamics of the depositional system

The gravel morphometric datasets for individual profiles indicate the presence of putative trends, e.g. a shift towards more frequent rounded clasts at ∼ 20 m depth in ELZ-a (Fig. 3). The comparison with the neighbouring boreholes ELZ-b and ELZ-c however demonstrates that these putative trends are, in this case, not laterally consistent. We therefore refrain from drawing conclusions about general trends in e.g. effective transport distances and flow velocities. Considerable differences between the individual cores are probably due to factors such as the internal dynamics of the braided river network or differences in petrographical composition (and thus mechanical properties of clasts) of the specific samples.

Both the Neuenburg and Breisgau Fm's are, in the investigated drill cores, clearly dominated by far-travelled lithologies from the Alps and their foreland (see below; Frechen et al., 2010). Red Triassic sandstone (Buntsandstein) that crops out in the foothills of the Black Forest close to the drill site (cf. Fig. 5) have not been encountered in the petrography samples, although some gneisses could be of local origin (Stark et al., 2021). Similar findings are reported from the Bleichtal research drilling, which is located ∼ 3 km further east (Figs. 1, 5). Even there, at the outlet of a (presumably never glaciated) tributary valley, the Neuenburg Fm is characterised by a mostly pure Alpine gravel spectrum, while the Breisgau Fm has a mixed petrography (Stark et al., 2021). This petrographic pattern suggests that, in this area, the (Late) Pleistocene sediment input from the Rhine catchment vastly outweighed lateral sediment input from the graben margin going into the URG and that the deposition by the Rhine system even extended into the lower Bleichtal valley (Fig. 5). This is however not the case in the entire southern URG, as locally derived deposits (Zarten Sfm; Ellwanger et al., 2011, 2012) dominate around the outlets of

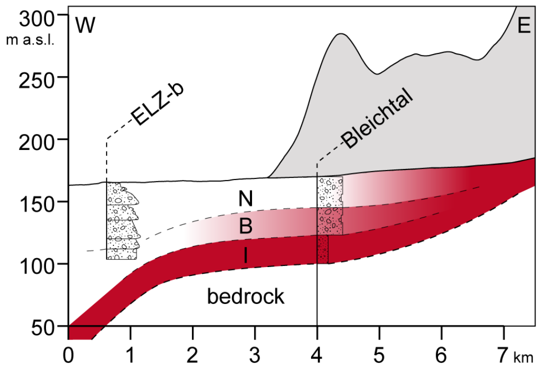

Figure 5. Simplified (swath) cross-section of the study area (cf. Fig. 1). The gravels of the Elzwiesen cores comprise a near-exclusive Alpine petrographic spectrum. For the Bleichtal research drilling (located within a tributary valley of the URG; Stark et al., 2021), the same applies to the Neuenburg Fm (N), while local input from lithologies of the Black Forest (qualitatively plotted in shades of red) can clearly be identified in the underlying Breisgau Fm (B). The Iffezheim Fm (I) consists exclusively of non-Alpine-derived sediment. Areas in grey represent the maximum topography of the adjacent hills (4 km swath width). Note that for larger-scale thickness maps of the respective units, the reader is referred to Wirsing and Luz (2007).

other tributary valleys. An example is the Dreisam valley in the Freiburg area (Hagedorn and Boenigk, 2008; Villinger, 1999; cf. Fig. 1), whose headwaters were, in contrast to the Bleichtal valley, extensively glaciated in the Late Pleistocene (Hofmann et al., 2020, 2022).

5.3 Sediment provenance

Statistical evaluation revealed a slight but consistent change in gravel petrography within the Neuenburg Fm. At a depth of 15–20 m, the abundance of light limestones, sandstones, and quartzites (EM2) decreases, while dark limestones, radiolarites, and crystalline rocks become more frequent (EM1; Figs. 3, 4). Light, beige-yellowish limestones stem from the Jura Mountains (Jordan et al., 2008; Meyer, 2013), whereas light-grey limestones are mainly derived from Middle Triassic outcrops in the High Rhine valley (Pietsch et al., 2016). Sandstones and quartzites are mainly derived from the Alps, either directly or by reworking of "Tertiary" deposits from alluvial fans into the Molasse Basin or from little subsided blocks at the URG margin (cf. Fig. 1; Berger et al., 2005; Graf, 2009). Dark limestones and radiolarites are attributed to the Helvetic and Penninic nappes and whitish or greenish crystalline rocks in the basement of the Alpine orogen (Hantke, 1987; Meyer, 2013; Pfiffner, 2010). Red granites and, in part, gneisses likely stem from the summit areas of the Black Forest (e.g. Schaltegger, 2000). The transition from the Nambsheim Sfm to the Hartheim Sfm at the Elzwiesen site is thus associated with a relative decrease in sediment input from the Alpine foreland, the Black Forest foothills, and the Jura Mountains (i.e. EM2 lithologies; Fig. 3) and an increase in influence from the Alps and the Black Forest themselves (i.e. EM1 lithologies). In previously published heavy-mineral compositions from several drillings in the southern URG (e.g. Hagedorn, 2004; Hagedorn and Boenigk, 2008), no consistent similar trend can be observed, although in some profiles (e.g. Bleichtal, Stark et al., 2021; Hartheim, Hagedorn and Boenigk, 2008; Riegel, Hagedorn, 2004), a suspicious increase in garnet and epidote occurs within the Neuenburg Fm.

Ellwanger et al. (2011, 2012) suggested that the Hartheim and Nambsheim Sfm's represent the last and penultimate Alpine glaciation, respectively, and especially their pleniglacial phases, before glacier bed overdeepenings in front of the retreating ice could intercept the sediment load of the meltwater streams. Although the Alpine Rhine River had been deflected towards the High Rhine valley and into the URG already in the Early Pleistocene (Yanites et al., 2017; Ziegler and Fraefel, 2009), meltwater still drained towards both the present-day High Rhine (i.e. west) and Danube (i.e. northeast) during pleniglacial conditions in the Middle and Late Pleistocene. However, Ellwanger et al. (2011) show further that the share of discharge towards the High Rhine grew progressively over time. This increase in meltwater discharge involved an increasing Alpine-derived sediment input into the southern URG, which would explain the petrographic shift observed within the Neuenburg Fm at the Elzwiesen site. A second factor may have been the regionally larger extent of the penultimate (Riss/Beringen according to the German/Swiss terminology, respectively) compared to the last glaciation (Würm/Birrfeld; Ellwanger et al., 2011; Preusser et al., 2011), resulting in a slightly larger outer-Alpine area affected by glacial erosion and delivering sediment, including local ice caps within the Jura Mountains (Graf et al., 2015).

Following Ellwanger et al. (2011, 2012), the Nambsheim Sfm and Breisgau Fm should differ from each other petrographically in a similar degree. Our data fail to differentiate these two units (Figs. 3, 4), which may be due to secondary modification of the Breisgau Fm through in situ weathering of susceptible lithologies (Ellwanger et al., 2011; Hagedorn and Boenigk, 2008) or simply as a result of only four samples available from the Breisgau Fm. It is further not clear why our samples show a stronger and statistically significant Black Forest signal in the shape of red-granite clasts in the upper Neuenburg Fm. The ice extent in the Black Forest was probably greater during the penultimate than during the last glaciation (Fiebig et al., 2011), and therefore that was likely also the case with the respective sediment yield. We assume that the relatively higher number of Black Forest granites in the Elzwiesen samples of the Hartheim Sfm is a local effect that is not representative of the entire southern URG – this should be tested by comparison with other sites.

Finally, it needs to be stressed that the correlation of the Neuenburg Fm to Würm–Riss/Birrfeld–Beringen could thus far not be confirmed, as numerical ages from the Neuenburg Fm correspond exclusively to the Late Pleistocene to Holocene (Frechen et al., 2012, and references therein; Kock et al., 2009a, b; Marik et al., 2024), and no ages from the Breisgau Fm have been reported yet. A better chronostratigraphic framework would be essential for further interpretations, especially in light of up to four block horizons occurring in the Elzwiesen drill cores (ELZ-b, Fig. 3).

6 Conclusions

In this study, we have targeted the glaciofluvial sediment fill (Neuenburg Fm and, to a lesser extent, Breisgau Fm) of the southern Upper Rhine Graben with a quantitative approach, assessing gravel morphometrics and petrographic compositions of samples from three boreholes in close vicinity to each other. Morphometric data (grain sizes, rounding, and shape indices) suggest putative trends for individual profiles, but the comparison with the neighbouring boreholes shows that these trends are not consistent. Caution is thus advised regarding the interpretation of general trends from a single stratigraphic record, especially if data point numbers are limited, and including as much additional data as possible is necessary.

In contrast, a consistent petrographic pattern could be shown with the help of endmember modelling and principal component analysis. With these techniques, the Neuenburg Fm could be subdivided into two subunits (Nambsheim and Hartheim Sfm's), a lower section enriched in rocks with an outer-Alpine source area and an upper section containing higher amounts of Alpine lithologies. This shift in the gravel spectrum is explained chiefly by an increasing share of meltwater derived from the Rhine glacier draining into the URG over consecutive Middle and Late Pleistocene glaciations. Our findings, while still to be tested at other sites, highlight the value of quantitative data if combined with appropriate statistical tools and thus hint at the potential informative content of gravel profiles. However, unanswered questions regarding the palaeogeographical and palaeoglaciological development stress the need for further petrographic as well as chronological data on the Pleistocene glaciofluvial deposits in the southern URG.

Data availability. Raw data of our gravel analysis are provided in Table S1 in the Supplement.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/egqsj-73-239-2024-supplement.

Author contributions. The project was developed by LG and UWS. Core description, data acquisition, and initial analysis was performed by FAG and NJ. LG carried on the analyses and interpretations and drafted the manuscript. The manuscript was finalised by LG and UWS and agreed upon by all authors.

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