JOURNAL OF QUATERNARY SCIENCE (2024) **39**(5) 691–709 ISSN 0267-8179. DOI: 10.1002/jqs.3623

JQS Journal of Quaternary Science QRA Quaternary Research Association

The onset of Pliocene–Early Pleistocene fluvial aggradation in the Southeastern Alpine Foreland (Velenje Basin, Slovenia) and its paleoenvironmental implications

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Received 14 September 2023; Revised 8 April 2024; Accepted 26 April 2024

ABSTRACT: In this study, we focused on the Pliocene–Early Pleistocene fluvial terraces in the Velenje Basin and reconstructed the morphostratigraphy, sedimentary depositional environment, provenance and age of the gravel deposits using geomorphological, sedimentological, petrographic and chronological analyses. Geomorphological mapping revealed the presence of two main river-terrace groups. The terraces in the older terrace group are severely degraded and preserved only as remnants capping high ground, while in contrast the younger group is better preserved. Detailed lithofacies analyses of four selected stratigraphic sections of the older terrace group show that the gravel was deposited in a meandering and wandering environment. The gravel consists of metamorphic, igneous, volcaniclastic, clastic and carbonate lithologies derived from the north, east and west from the Paka River catchments. To determine the timing of deposition, we performed isochron-burial dating using cosmogenic ^{26}Al and ^{10}Be. Our new age constraints date the deposition of the older terrace group to 2.7 ± 0.3 Ma. Establishing the aggradation and incision model of the Velenje Basin documents pronounced regional tectonic uplift during the Pliocene–Early Pleistocene, which led to incision and the subsequent formation of a terrace staircase.

KEYWORDS: isochron-burial dating; morphostratigraphy; provenance analysis; river terraces; Velenje Basin

Introduction

The Pliocene and Quaternary epochs were strongly influenced by frequent and abrupt changes in climate (Peizhen et al., 2001, Ezquerro et al., 2022). Sedimentary processes and the development of a drainage network were affected by the interaction of temperature, precipitation and tectonic activity (e.g. Bridgland and Westaway, 2014; Reiter et al., 2014). This interaction is evident in the sedimentary record of the highly dynamic Southeastern Alpine Foreland in Slovenia, which was strongly influenced by repeated glaciations in the Alps during the Pleistocene (Bavec and Verbič, 2011; Ferk et al., 2015; Ivy-Ochs et al., 2022). As a result, dramatic changes in fluvial aggradation and degradation occurred in this area, traces of which are archived in several intramontane basins (Mencin Gale et al., 2019a, 2019b). The onset of terrestrial sedimentation is marked by successions of clastic sediments representing the informal 'Plio-Quaternary' unit (*sensu* e.g. Mioč, 1978). Pliocene–Quaternary deposits are abundant in central, southern and eastern Slovenia (Buser, 2010) and are preserved as typical terrace staircase sequences. The evolution of fluvial terraces in this area generally conforms to the typical preservation pattern of uplifting areas with terrace staircases and lowering fluvial base levels (Bridgland, 2000, Bridgland and Maddy, 2002; Westaway, 2002; Bridgland and Westaway, 2008; Doppler et al., 2011, Van Husen and Reitner, 2011, Pazzaglia, 2013), resulting in the oldest Pliocene–Early Pleistocene terraces being located at the highest elevations (Mencin Gale, 2021). These deposits represent the highest and oldest Quaternary deposits in the Southeastern Alpine Foreland, comparable with the gravel deposits traditionally referred to as the Deckenschotter in the Northern Alpine Foreland (e.g. Graf, 1993; Ellwanger et al., 2011; Akçar et al., 2014; Claude et al., 2017; Dieleman et al., 2022).

The study of Pliocene–Quaternary stratigraphy in Slovenia is particularly challenging for several reasons. First, our knowledge of the Pliocene–Quaternary sequences is limited, especially in terms of morphostratigraphy, provenance and age. Some age constraints for the entire Pliocene–Quaternary fluvial sequence have been successfully applied in the area (Verbič, 2004; Mihevc et al., 2015; Cline et al., 2016; Poljak, 2017). However, such data are scarce and thus represent a large gap in the stratigraphy of the region, limiting our understanding of the Quaternary evolution of the entire Alps. Second, revealing the chronology of fluvial sediments and their landforms has been a key goal over recent decades (e.g. Rixhon et al., 2017). 'Plio-Quaternary' sediments presumably range from the oldest Quaternary to the Pliocene, which until a decade ago was a methodological limitation for dating because they are beyond the limits of various Quaternary dating techniques such as optically stimulated luminescence (e.g. Wintle, 2008; Rhodes, 2011). This challenge has now been overcome with a relatively new technique–isochron-burial dating with cosmogenic

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^{10}Be and ^{26}Al (e.g. Balco and Rovey, 2008; Erlanger et al., 2012; Granger, 2014).

We studied the Velenje Basin in eastern Slovenia, where Pliocene–Quaternary fluvial successions are well preserved. We established, for the first time, a detailed basin-scale morphostratigraphy, performed a lithological analysis of four selected sections, analyzed the sedimentary environment and provenance of sediments, and reconstructed the chronology using isochron-burial dating with cosmogenic ^{26}Al and ^{10}Be. This study represents the first quantitative chronology for the 'Plio-Quaternary' successions in the Velenje Basin and is one of the few such chronologies in a poorly studied area of the Southeastern Alpine Foreland. Furthermore, our results provide new insights into the Slovenian Quaternary stratigraphy in a pan-Alpine context and yield suggestions for a discussion of landscape evolution in relation to ongoing tectonic processes.

Study area

The Velenje Basin is located southeast of the Karavanke Mountains and southwest of the Pohorje Mountains and covers an area of ca. 29 km^2 with a length of ca. 15 km and width of 5 km (Fig. 1A). The basin is elongated in a west-northwest to east-southeast direction. The main river is the Paka River with Klančnica, Velunja and Ljubela tributaries (Fig. 1C). The catchment area of the Velenje Basin measures ca. 177 km^2, is hilly, has an average slope of 18.1° and receives about 1100 mm of precipitation per year in a continental climate (Perko and Orožen Adamič, 1998). The basin is structurally located at the boundary between the Southern and Eastern Alps between the dextral strike-slip Velenje, Šoštanj and Periadriatic faults, which are all part of the major Periadriatic Fault System (Fig. 1A, C), that runs through the European Alps (Fodor et al., 1998; Vrabec and Fodor, 2006). The basin was formed in the Pliocene by transtension between the Periadriatic Fault to the north and the Šoštanj Fault to the southwest (Vrabec, 1999a). The fault architecture of the basin resembles a half-graben geometry (Fig. 1D), with a trough-like depression 1000 m deep parallel to the Šoštanj Fault Zone (Vrabec, 1999b). The geology of the main catchment area is characterized by the Eisenkappel igneous zone to the northwest (Fig. 1C) (Bole et al., 2001; Dobnikar and Zupančič, 2009), the Miocene Slovenj Gradec Basin to the north (Ivančič et al., 2018a, 2018b), the Smrekovec volcanic complex to the west (Premru, 1983; Kralj, 1996, 2016a, b; Pamić and Balen, 2001;), the Permian and Triassic carbonate rocks to the east (Mioč and Žnidarčič, 1977), and the Smrekovec series rocks to the south (Mioč and Žnidarčič, 1977; Buser, 1978). The pre-Pliocene basement of the Velenje Basin consists of Triassic carbonates and Oligocene–Miocene clastic rocks (Brezigar et al., 1987b) (Fig. 1D).

The Pliocene–Pleistocene sedimentary succession is well constrained due to the large amounts of subsurface data collected during the active mining of coal in the basin (Figs 1 and 2). The succession consists of clastic sediments about 1000 m thick, which are divided into three main units (Brezigar et al., 1987a). The lowermost unit consists of a 450-m-thick Pliocene succession of clastic sediments composed of muddy gravel, sand, silt and clay. The middle unit is represented by lignite with a maximum thickness of 166 m (Markič and Sachsenhofer, 2010). The synclinal coal horizon laterally pinches out, and on its northwestern side it branches into several layers that intercalate with lacustrine deposits. The third and uppermost unit is 465 m thick in total and starts with a sharp contact at its base. It consists of Pliocene lacustrine sediments 255 m thick at the base, which gradually pass upsection into the 100-m-thick Pliocene lacustrine and marshy sediments. The age of this unit was constrained by mastodon remains originally attributed to the Pleistocene (Rakovec, 1968) and later revised to 3.6–2.6 Ma (Debeljak, 2017). This corresponds to the Early Villafranchian Biochronological Zone (the Villafranchian from 3.5 to 1.0 Ma *sensu* Rook and Martínez-Navarro, 2010), which contains Neogene European Mammal zones 16 and 17 (MN 16 and MN 17; Agusti et al., 2001). This age constraint was also confirmed by pollen analysis (Brezigar et al., 1987a; Šercelj, 1987).

The succession continues with 105 m of Pleistocene terrestrial and marsh sediments. At the surface, Holocene sediments are generally up to 5 m thick (Brezigar et al., 1987a), but locally in the Gaberke canyon they may be thicker than 15 m (Fig. 3A, B). The Upper Pliocene–Pleistocene marshy and terrestrial sedimentary unit corresponds to the 'Plio-Quaternary' as indicated in the basic geological map (Mioč and Žnidarčič, 1977) and reaches a total thickness of 205 m.

Materials and methods

Geomorphological analysis

Geomorphological analyses were performed in ArcGIS® Pro (ESRI, USA) using a digital elevation model (DEM) with a 1 × 1-m raster grid (Ministry of Environment and Spatial Planning, 2015). Geomorphological research included an analysis of topographic profiles and GIS-based shaded relief, elevation, slope inclination and slope-aspect mapping. The map layers were overlapped with topographic contours calculated at an equidistance of 1 m to further facilitate the geomorphological mapping. Geomorphological mapping was performed manually by visual inspection of the DEM and was later verified in the field.

Analysis of lithofacies and sedimentary provenance

Lithofacies analysis was performed on the following sections: (i) Velunja, (ii) Mladika, (iii) Topolščica and (iv) Škale (Fig. 4). The sections were logged using lithofacies codes (Evans and Benn, 2004). The Velunja and Mladika sections were logged and sampled by an abseiling technique. Further facies interpretation was based on various studies (Miall, 1977, 1978, 2006; James and Dalrymple, 2010). Clast lithological analysis (CLA) was applied and modified according to guidelines from several studies (Walden, 2004; Lindsey et al., 2007; Gale and Hoare, 2011). CLA was performed only for the Velunja profile due to the severe weathering of the clasts observed in the other sections. Sampling for gravel material was carried out as a bulk sampling of the exposed surface and to avoid biasing by sampling the most obvious clasts the 1.5–6-cm fraction was examined. Three samples were collected in the Velunja profile, containing 274 (sample VE-A), 48 (sample VE-B) and 185 (sample VE-C) clasts per sample. CLA of the rudaceous material (gravel) has traditionally been performed on the macroscopic level (e.g. Bridgland et al., 2012) with efficacy and statistical validity as the main advantage (Bridgland, 1986; Walden, 2004; Gale and Hoare, 2011). However, detailed microfacies analysis of the clasts significantly increases the quality of the provenance analysis and its spatial resolution (Mencin Gale et al., 2019a, 2019b). Accordingly, 32 thin sections were examined with a polarizing microscope.

Isochron-burial dating

Isochron-burial dating uses the half-life differences of ^{10}Be and ^{26}Al to determine sediment burial duration (e.g. Balco and Rovey, 2008; Bender et al., 2016; Dunai, 2010; Erlanger et al., 2012;

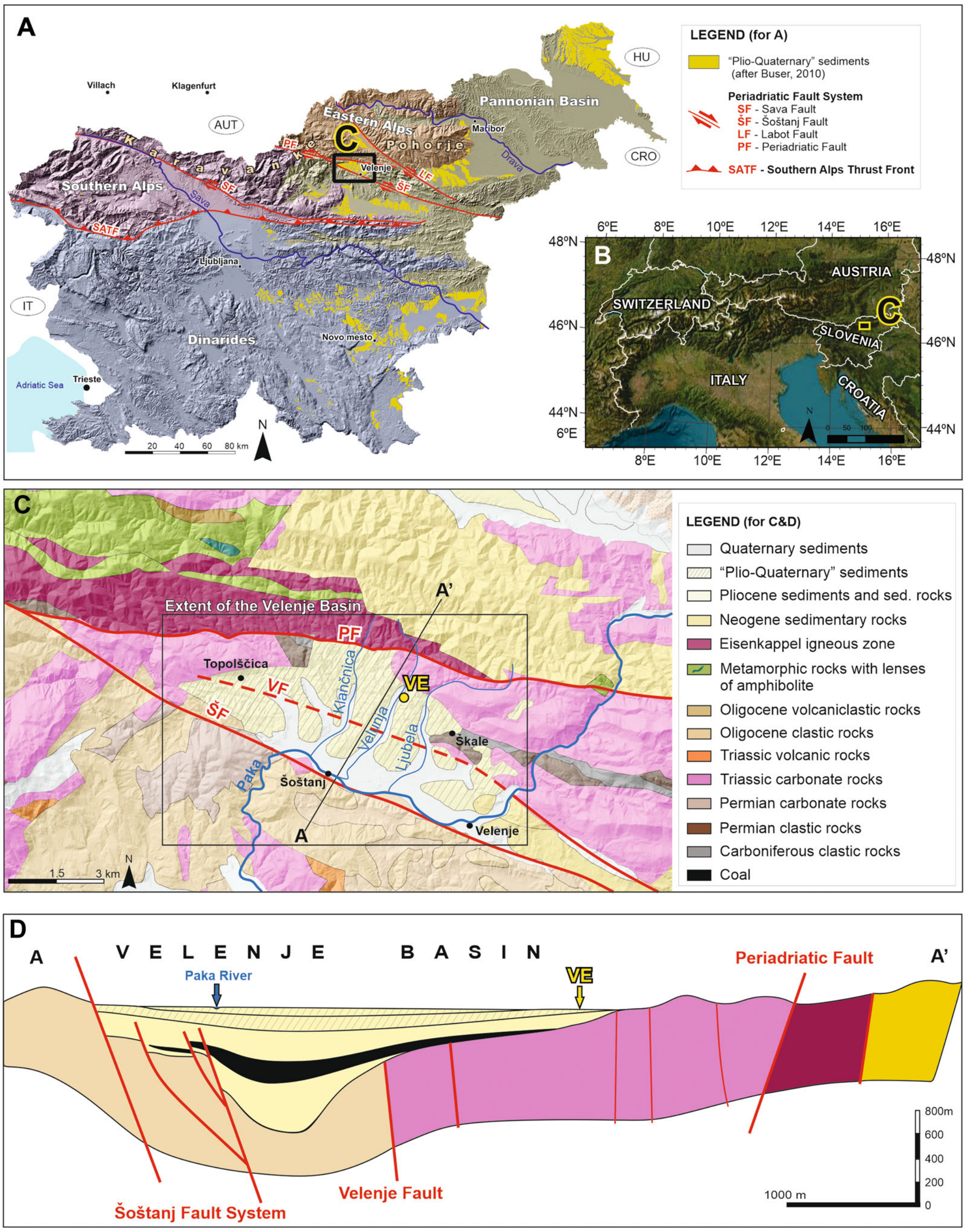

Figure 1. (A) Spatial distribution of 'Plio-Quaternary' units in eastern Slovenia at the transition between the Southern and Eastern Alps, the Dinarides, and the Pannonian Basin with marked extent of the Velenje Basin. The division of tectonic units is modified after Placer (2008). Basemap: shaded relief of the DEM 5 (digital elevation model with 5 × 5-m raster grid, Ministry of Environment and Spatial Planning, 2015). (B) Location of the Velenje Basin in the Southeastern Alpine Foreland, Slovenia (basemap: ArcGIS® Online basemap, ESRI, USA). (C) Geological map (after Buser, 2010) with marked extent of the Velenje Basin. Faults are adopted from Atanackov et al. (2021). (D) Cross-section across the central part of the Velenje Basin (modified after Brezigar et al., 1987a; Vrabec, 1999b) with indicated post-sedimentary deformations of the Pliocene to Quaternary sediments and perpendicular projection of the Velunja section location. There are a few structural discrepancies between the geological map and the cross-section. This is due to the different authors who compiled geological and structural data and the different focus of their research. [Color figure can be viewed at wileyonlinelibrary.com]

Granger, 2014; Nørgaard et al., 2023). After burial, nuclide concentrations drop due to decay, with ^{26}Al decaying faster than ^{10}Be. For isochron-burial dating, multiple samples from a single stratigraphic horizon or in a depth sequence (within 1 m or so of each other) but at depth within the deposit (for details see Balco and Rovey, 2008) are analyzed. In a ^{26}Al versus ^{10}Be plot, the measured concentrations from various samples form an isochron line, indicating that while the samples might have different initial (inherited) concentrations, they share a common post-burial nuclide production history. The slope of this line is directly related to the isochron burial time, reflecting the duration since the samples were buried and shielded from cosmic rays. This burial age can be iteratively modeled, taking into account the complex pre-burial exposure or erosion histories, until a satisfactory alignment is achieved across all measured data points (Balco and Rovey, 2008; Erlanger et al., 2012; Bender et al., 2016; Nørgaard et al., 2023). The Velunja profile is a natural outcrop and is suitable for isochron-burial dating due to the sufficient thickness and presence of quartz-bearing lithologies of which 10 samples were taken. They were sampled from the same stratigraphic horizon of the clast-supported gravel layer at 13.5 m depth in the lower part of the Pliocene–Early Pleistocene terrace.

Sample preparation for cosmogenic ^{10}Be and ^{26}Al analyses was performed at the Surface Exposure Laboratory of the Institute of Geological Sciences at the University of Bern,

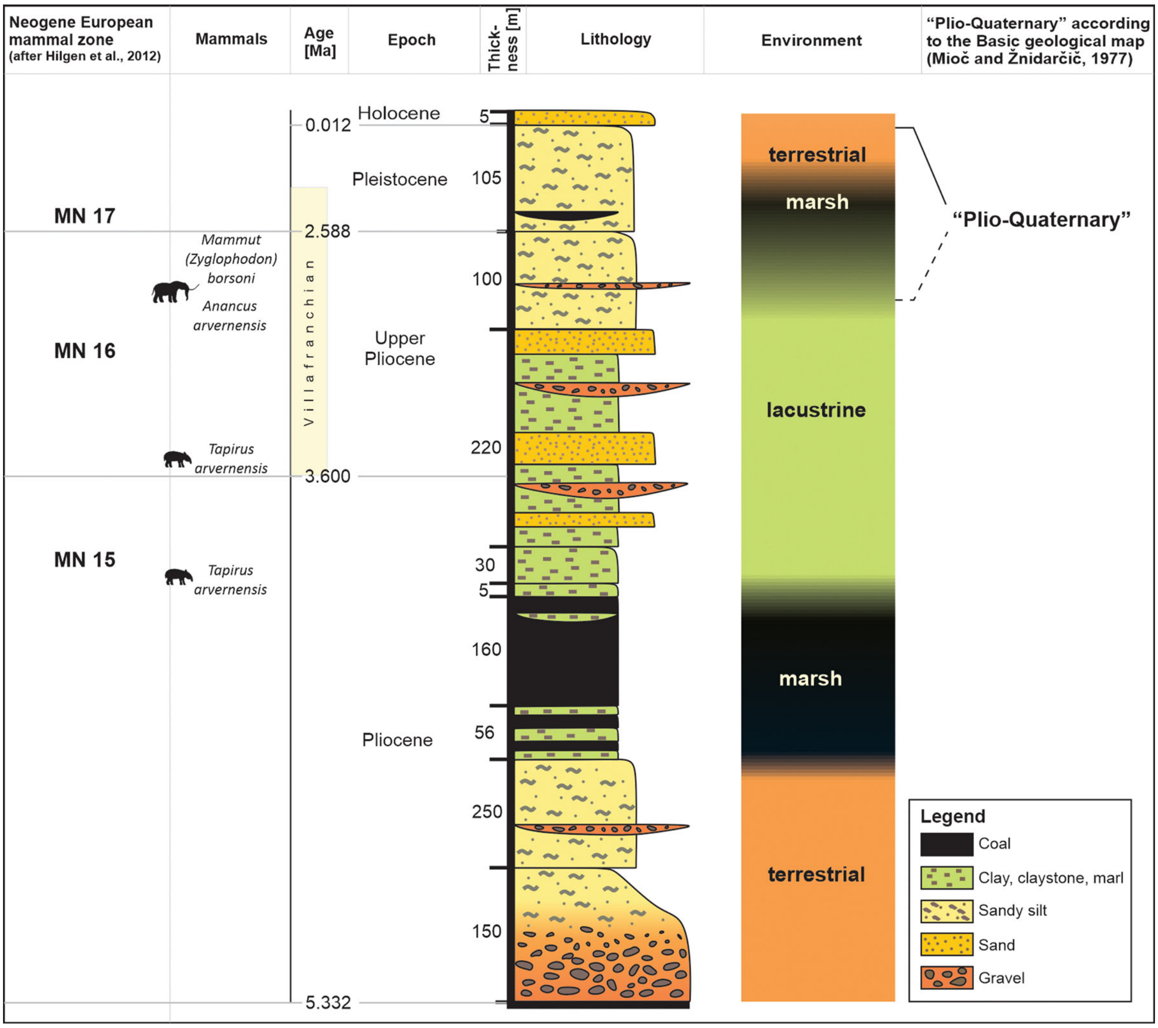

Figure 2. Sedimentary model of Pliocene–Quaternary strata in the Velenje Basin (modified after Brezigar et al., 1987a). 'Plio-Quaternary' unit (*sensu* Mioč and Žnidarčič, 1977) corresponds to the upper part of the succession. The thickness of the unit in the column is schematic. Relevant Neogene European mammal zones (MN 15, MN 16, MN 17) with marked mastodon remains in MN 16 are marked (adopted after Hilgen et al., 2012). [Color figure can be viewed at wileyonlinelibrary.com]

Switzerland. All 10 collected samples were processed for quartz isolation and only three of them yielded sufficient material for further processing: silicified carbonate (VE-10), vein quartz (VE-13) and granitoid (VE-14). Additionally, two amalgamated samples consisting of 0.5–5-cm quartz pebbles were collected (VE-15, VE-16). Samples weighted between 15 and 50 g. In the following step the samples were dissolved and then spiked with around 200 µg of Be carrier. The cosmogenic ^{10}Be and ^{26}Al were extracted following the sample preparation protocol described by Akçar et al. (2017). The ^{10}Be/^{9}Be and ^{26}Al/^{27}Al analyses were performed at the MILEA accelerator mass spectrometry facility at ETH Zurich (Maxeiner et al., 2019). The ^{10}Be/^{9}Be ratios were normalized to the ETH Zurich in-house standards S2007N and S2010N (Christl et al., 2013). They were corrected using a weighted average full-process blank ratio of $(2.76 \pm 0.18) \times 10^{-15}$, which represents the average from 20 full-process blank ratios measured from the same carrier bottle. Similarly, the ^{26}Al/^{27}Al ratios were normalized to the ETH Zurich in-house standards S2007N and S2010N (Christl et al., 2013) and corrected with a weighted average full process blank ratio of $(2.76 \pm 0.18) \times 10^{-15}$. Total Al concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP-OES) at the Institute of Geological Sciences of the University of Bern. The uncertainty for the ICP-OES measurements is ~3–5%. The isochron-burial age was calculated according to the cosmogenic nuclide burial dating method described in detail by Nørgaard et al. (2023) using the MATLAB® software package and scripts provided therein (v.1.02, available at github.com/cosmoJesper/PPINI since 3 June 2023).

Morphostratigraphic model

The final step was to define a morphostratigraphic model for the Velenje Basin, which is based on several variables that enable us to establish the age relationships between the mapped units.

The spatial relationships between individual landforms are identified by examining the relative elevations within the DEM and observing the erosional vs. depositional boundaries between the landforms. For example, the alluvial fan deposited over the terrace has a higher elevation, its slope decreases towards the underlying terrace and merges with it without any slope break, and its boundary with the underlying terrace generally forms lobes, indicating the depositional boundary.

The degree of landform preservation is assessed by inspecting a hillshade raster overlaid with 1-m contours. This includes an evaluation of the preservation of the terrace/fan-surface, identification of the possible former channel pattern, identifying erosional relief and identifying surfaces entrenched with a past/recent drainage network.

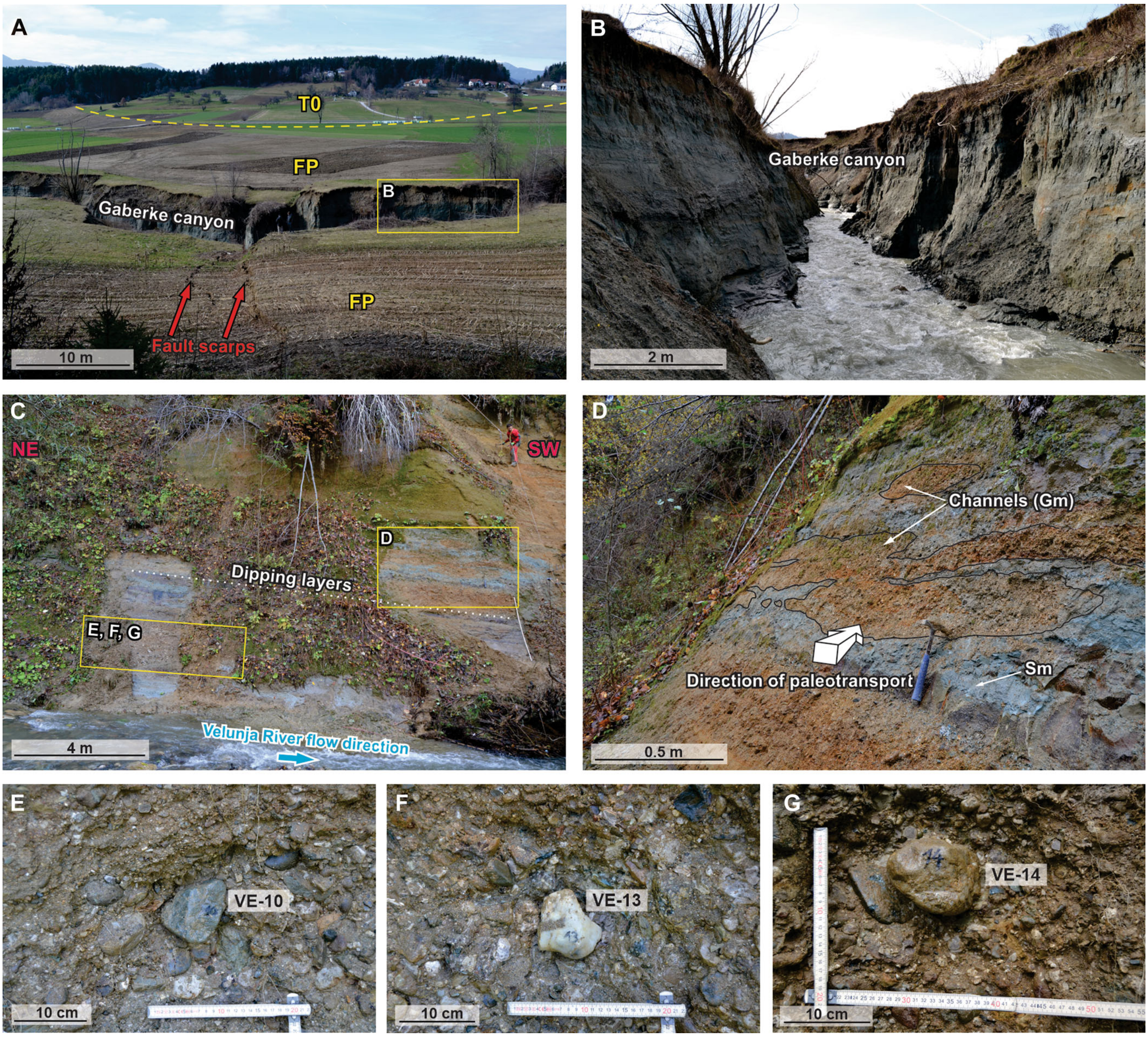

Figure 3. Field photographs of Quaternary outcrops and geomorphic features in the Velenje Basin. Viewpoints of the images are indicated in Fig. 4. (A) Deepening of the Gaberke canyon by the Velunja River and the fault scarps associated with subsidence due to mining. (B) Several meters of floodplain sediments exposed in the Gaberke canyon. (C) Velunja section (VE). The layers dip in the NE–SW direction, which corresponds to the direction of the present flow. (D) High lateral and vertical varieties with several channels in the Velunja section. (E–G) Isochron burial dating samples VE-10, VE-13 and VE-14, respectively. [Color figure can be viewed at wileyonlinelibrary.com]

The gradient of the landforms is assessed using a hillshade raster overlaid with 1-m contours and from topographic profiles.

Petrographic characteristics of the deposits were confirmed by field observations and laboratory work (CLA). Pliocene–Early Pleistocene deposits were inspected in detail in the laboratory; however, younger deposits were briefly inspected in the field at selected localities, where we checked for significant changes in petrographic composition.

Degree of weathering and pedogenesis. Despite the fact that no particular method was used to quantify the degree of weathering and pedogenesis, empirical evidence from the field showed that Pliocene–Early Pleistocene deposits are often highly weathered and subject to pedogenic alteration. This means that some of the clasts, depending on their lithology, completely disintegrated during sampling. Moreover, signs of soil development in particular layers was observed.

Age control (isochron-burial dating and biostratigraphic data). Age control of the fluvial sediments is constrained by the proboscidean fossils (Drobne, 1967; Rakovec, 1968) and isochron-burial dating.

Results

Geomorphological analysis

The morphostratigraphy of the Velenje Basin has been established by combining existing data (Basic Geological Map of Yugoslavia; Mioč and Žnidarčič, 1977), geomorphological analyses and field reconnaissance. The main results are illustrated with a geomorphological map (Fig. 4) and topographic profiles P1 and P2 (Fig. 5) indicating two terrace groups (T0, T1; Table 1) which were identified also in the field (Fig. 3). Sediments from terrace T1 were investigated in detail in the Velunja, Škale, Topolščica and Mladika sections, which are located on the terrace risers of T1 (Fig. 4).

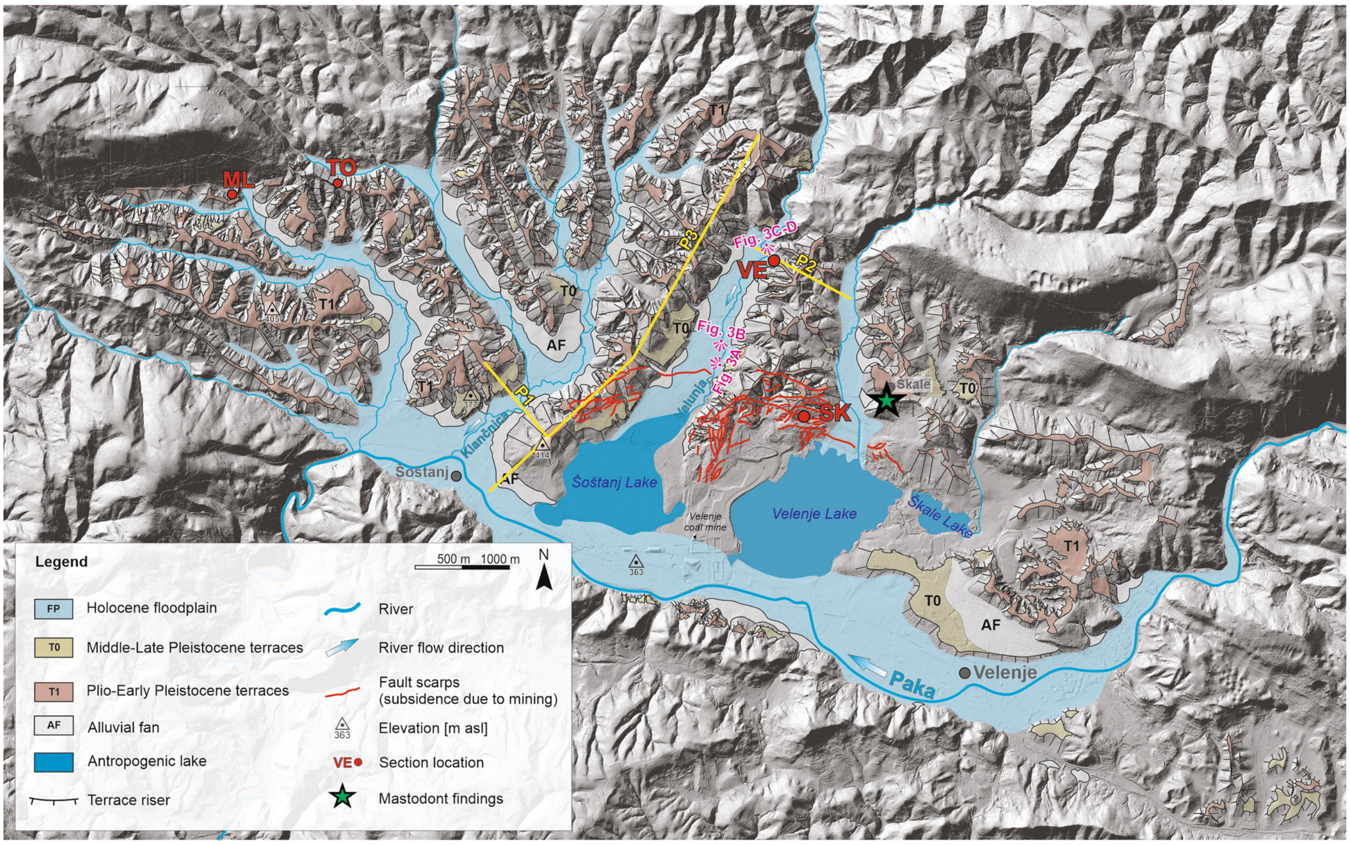

Figure 4. Geomorphological map of the Pliocene–Early Pleistocene, Middle–Late Pleistocene and Holocene terraces, fans and floodplains with locations of the studied sections marked (VE, SK, TO, ML). Shaded relief from lidar data (Ministry of Environment and Spatial Planning, 2015). [Color figure can be viewed at wileyonlinelibrary.com]

Lithofacies analysis

Profiles, thickness and interpretation of the Velunja (1), Mladina (2), Topolščica (3) and Škale (4) stratigraphic sections indicate the occurrence of six different facies (Table 2; Fig. 6). The contacts between lithofacies are gradational, and in parts erosional. The sandy facies is present in all of the sections in the Velenje Basin and prevails over fine-grained and gravelly facies.

(1) The *Velunja section* (Fig. 3C, D) is located 4.5 km NNW of the city of Velenje at 405 m above sea levels (asl). This natural outcrop of 14.3 m thickness is located in the immediate vicinity of the Velunja River. The deposits consist of gravel intercalated with sandy and occasional muddy layers. The paleotransport direction estimated from the orientation of the visible structures (channels) is NW–SW, which is approximately the same as today.
(2) The *Mladika section* is located 2.9 km NW of Velenje at 379 m asl. The section is a road cut and exposes 11.6 m of sediments. The prevailing type of sediment is sand and to a lesser degree mud and clay.
(3) The *Topolščica section* outcrops in a road cut ca. 7.8 km NW of Velenje at 441 m asl. The sediments of the 5-m-thick section comprise mostly sand and gravel.
(4) The *Škale section* is also a road cut located 8.4 km NWW of Velenje at 397 m asl. The section is 4 m thick and consists of gravel and sand.

Sedimentary provenance analysis

The results of CLA of the Pliocene–Early Pleistocene sediments of the Velenje Basin are based only on the Velunja profile, where three samples, VE-A, VE-B and VE-C, were taken at profile depths of 6, 10.8 and 13.2 m. The results are summarized in Fig. 7, where clast counts of general lithogroups of metamorphic, igneous and volcaniclastic, clastic, carbonate rocks and quartz-bearing clasts (quartz and chert) are depicted. Igneous and volcaniclastic rocks and quartz-bearing lithologies (quartz and chert) were found in all three samples in the Velunja section, metamorphic rocks in VE-A and VE-B, and carbonate rocks only in the lower VE-C sample. Microfacies analysis of the clasts is presented in detail in Fig. 8(A–I) and in Appendix S1.

The samples show a distinct change in the lithology and quantity of clasts (Fig. 7), indicating that changes were observed within a relatively short depositional record from a single river, discounting possible erosion of the outcropping units. We interpret these changes to be related to variations in the local drainage of the Paka River and its tributaries (Klančnica, Velunja, Ljubela Rivers). This example demonstrates that there is no need for a drastic change in the drainage area to significantly alter the petrographic fingerprinting of a particular river. A river can simply change its course for some time and start eroding rocks that were once covered.

Cosmogenic nuclide analysis and isochron-burial age calculation

The results of cosmogenic ^{10}Be and ^{26}Al measurements show $^{10}Be/^{9}Be$ ratios between $(0.95 \pm 0.11) \times 10^{-14}$ and $(8.88 \pm 0.35) \times 10^{-14}$ (Table 3). The full process blank correction accounts for 3–27% of the measured $^{10}Be/^{9}Be$ ratios. The blank-corrected ^{10}Be concentrations vary between $(5.93 \pm 0.99) \times 10^{3}$ and $(24.13 \pm 0.98) \times 10^{3}$ atoms g^{-1}. The total Al amount varies between 0.8 and 8.2 mg, and the total Al concentrations between 40 and 540 p.p.m. The measured $^{26}Al/^{27}Al$ ratios range from $(0.50 \pm 0.10) \times 10^{-14}$ to $(63.49 \pm 3.52) \times 10^{-14}$. The ^{26}Al concentrations range between

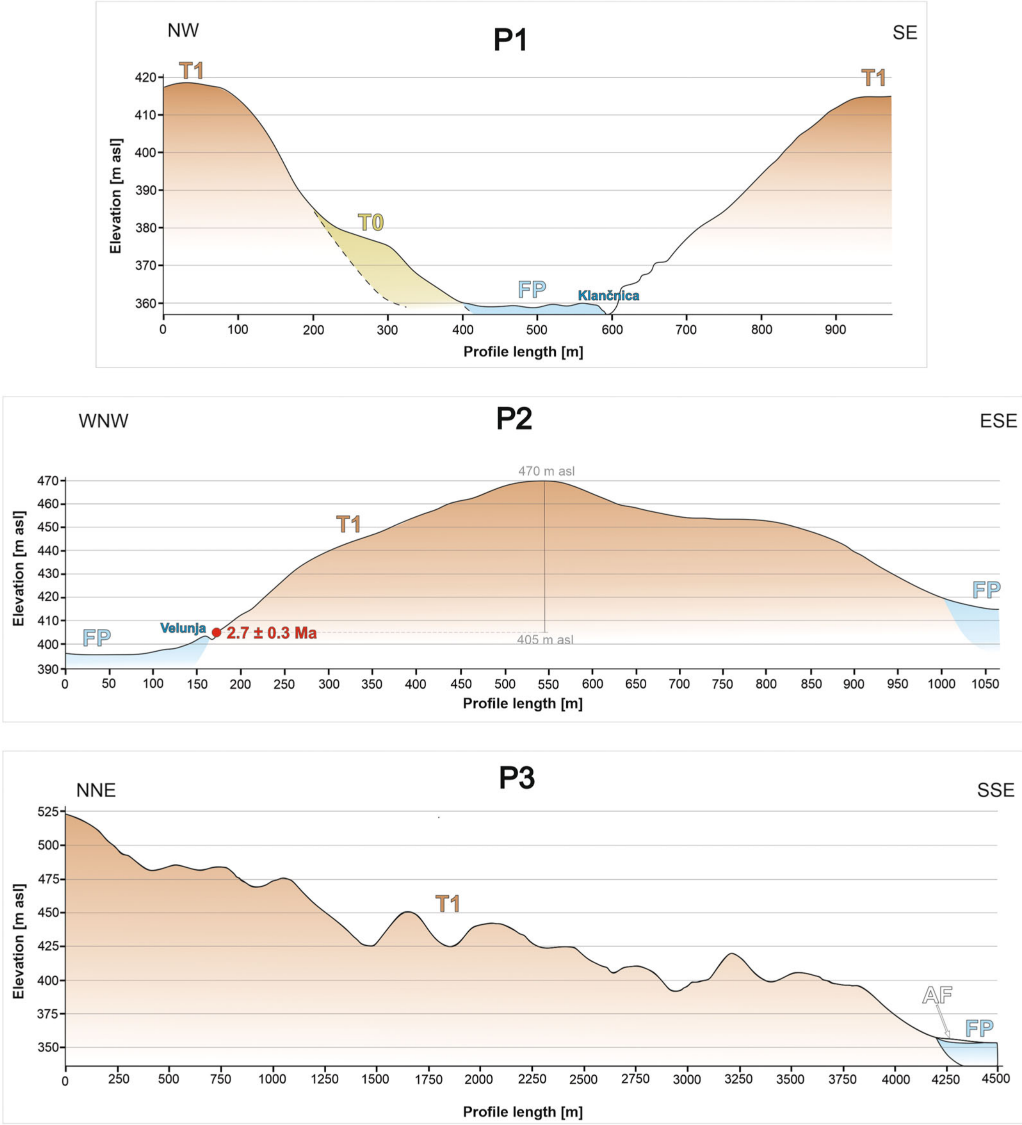

Figure 5. Topographic profiles P1, P2 and P3 with present-day elevations of the terraces and fans. Location of the profiles is depicted on Fig. 4. Location of the age dating of 2.7 ± 0.3 Ma in the Velunja section (VE) is indicated in Profile P2. [Color figure can be viewed at wileyonlinelibrary.com]

$(39.61 \pm 3.44) \times 10^3$ and $(63.49 \pm 3.52) \times 10^3$ atoms g^{-1}. The $^{26}Al/^{10}Be$ ratio ranges from 2.40 ± 0.31 to 10.04 ± 2.62. We calculated isochron-burial ages following the methodologies outlined in Erlanger et al. (2012) and Nørgaard et al. (2023), using an initial ratio of 6.97 (Borchers et al., 2016). Utilizing the code developed and provided by Darryl Granger, as described in Erlanger et al. (2012), we determined an isochron-burial age of 3.1 ± 0.2 Ma. Applying Bayesian linear regression (Bender et al., 2016) yielded an isochron slope of 1.67 ± 0.12, from which we calculated an isochron-burial age of 3.0 ± 0.2 Ma. Using the input parameters given in Table 4, we applied the P-PiNi code (version 1.02; Nørgaard et al., 2023), which is designed for modeling burial ages in landscapes with non-steady erosion. Our model produced an isochron-burial age of 2.7 ± 0.3 Ma, corresponding to an erosion rate of 3071 ± 363 g cm^{-2} Ma^{-1} (Fig. 9). The P-PiNi code also estimated post-burial concentrations of 9575 ^{10}Be and 39 052 ^{26}Al atoms g^{-1}. All ages calculated using the three approaches mentioned previously overlap within the 2-sigma confidence interval. To verify the modeled isochron-burial age obtained from the P-PiNi code, we conducted an independent analysis using an in-house MATLAB® code. This code computes post-burial cosmogenic ^{10}Be and ^{26}Al concentrations and the $^{26}Al/^{10}Be$ ratio, employing Eulerian and Lagrangian methods outlined in Knudsen et al. (2019) and integrating functions from Balco et al. (2008; available at hess.ess.washington.edu/math). Our analysis yielded post-burial concentrations consistent with those reported by the P-PiNi code, thereby validating the modeled isochron-burial age. Consequently, we chose this age for further discussion.

Discussion

Morphostratigraphic model

The schematic terrace staircase in the Velenje Basin is shown in Fig. 10. The ages are inferred from the revised traditional morphostratigraphy in the studied basin (Mioč, 1978) and supported by the finds of a mastodon (Drobne, 1967; Debeljak, 2017) and the isochron-burial age from this study. The classification into individual groups is based on comparison with morphostratigraphic models of other basins in the region (Mencin Gale et al., 2019a, 2019b).

The higher terrace group includes terrace T1, which is situated 20–80 m above the floodplain. The terrace surfaces are poorly preserved, mostly as flat-crested tops, so the exact number of terraces cannot be estimated. There are numerous

Table 1. Velenje Basin terrace morphostratigraphy with basic geomorphological characteristics. The ages from Mioč (1978) and Debeljak (2017) are given in different chronostratigraphic tables, but we have kept the original form for the sake of accuracy.

Terrace	Elevation (m asl)	Height above the floodplain (m)	Thickness (m)	Morphology of the unit	Composition of the sediments	Age		
						Mioč, 1978	Debeljak, 2017	This study
Flood-plain	351–415	—	≤15; based on the field estimation at Gaberke canyon	Mostly artificially reworked and urbanized with no visible former channel pattern	Fine-grained sediments (mud)	Quaternary	—	Holocene
T0	374–429	8–20	≤20; based on spatial extent and morphology	Well-preserved terrace surfaces are smaller and present only in a few places within the basin	Carbonate gravel and sands	Identified as single 'Plio-Quaternary' unit, not discriminated into terraces	—	Middle–Late Pleistocene
T1	395–533	20–80	205; subsurface data (Brezigar et al., 1987a)	Terrace preserved as erosional remnants with degraded morphology incised by the ephemeral and perennial streams. Morphology additionally degraded in parts with fault scarps formed due to mining. Probably consisting of more than one terrace (e.g. P2 and P3 on Figs 5 and 10), but impossible to distinguish due to high degradation.			2.6–3.5 Ma (Villafranchian)	Pliocene–Early Pleistocene. Dated to 2.7 ± 0.3 Ma in the lower part

Table 2. Lithofacies analysis of the sections

Lithofacies code	Description	Appearance in the profiles				Thickness (cm)	Interpretation
		Velunja	Mladika	Topolščica	Škale		
Fm	Massive silt and clay	x	x	x		10–100	Overbank, back-swamp or abandoned channel deposits
Sp	Fine- to coarse-grained cross-bedded sand	x	x			0–20 (layers are in parts pinching out)	Transverse or linguoid bars
Sm	Massive fine- to coarse-grained sand	x	x	x	x	10–400	Sediment of possible crevasse splay
Sm(d)	Fine- to coarse-grained sand with floating clasts	x	x	x			Sediment of possible crevasse splay or sand bars within the channel lag
Gm	Weathered clast-supported gravel that is sub-angular to rounded and poorly to medium sorted, ranging in clast size from 0.5 to 10 cm	x		x	x		Channel-lag deposits with a typical erosive base (supported with several visible channels in the VE section; Fig. 3C, D)
Gms	Matrix-supported, sub-angular to rounded, poorly sorted gravel of 0.5- to 20-cm clast size	x				80	Re-sedimented fluvial deposit, either by fluvial or slope processes

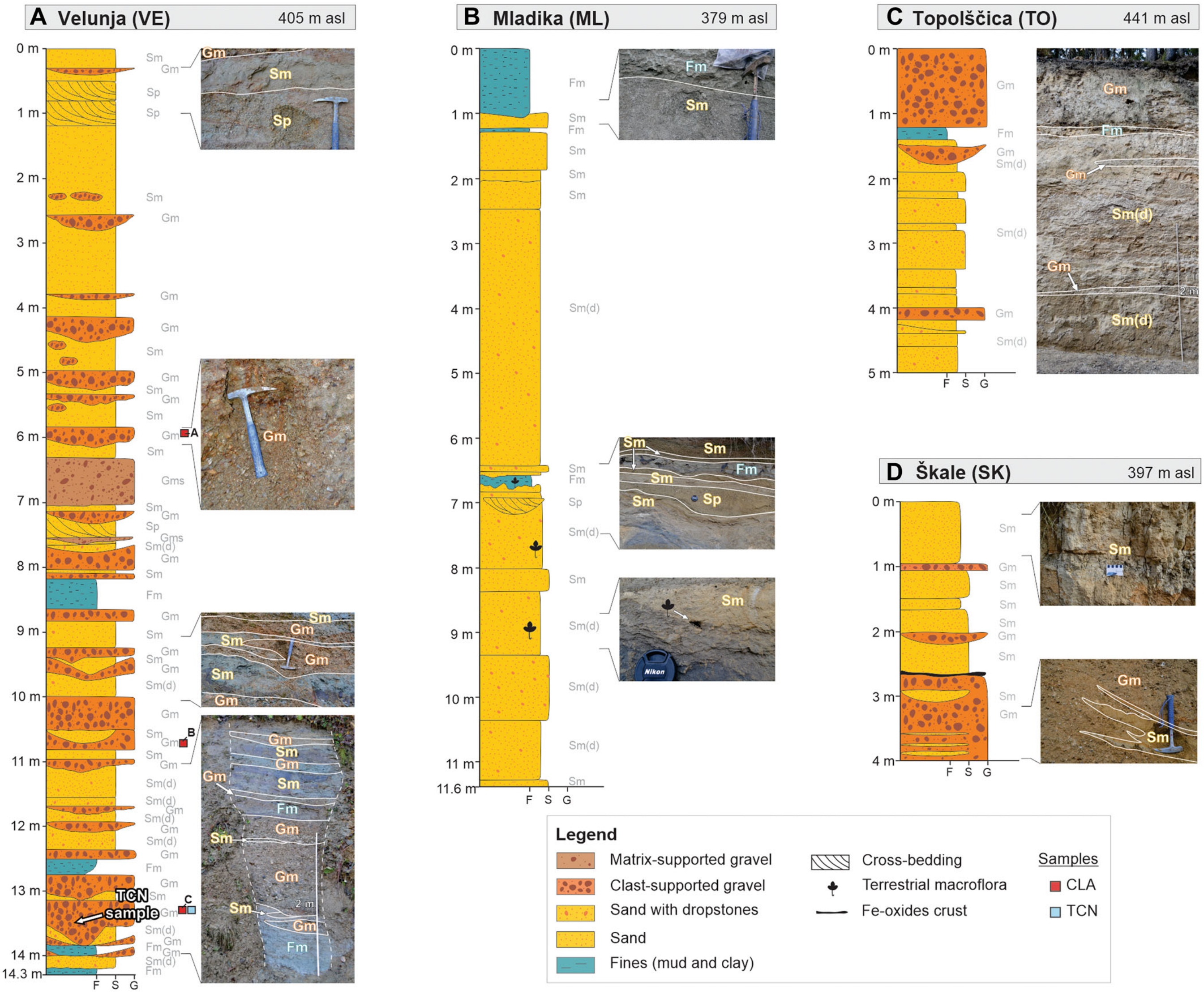

Figure 6. Lithofacies of the Pliocene and Pleistocene Velunja, Mladika, Topolščica and Škale sections in the Velenje Basin. For details of lithofacies codes, see Table 2. Abbreviations: CLA–clast lithological analysis, TCN–sampling location for isochron-burial dating. [Color figure can be viewed at wileyonlinelibrary.com]

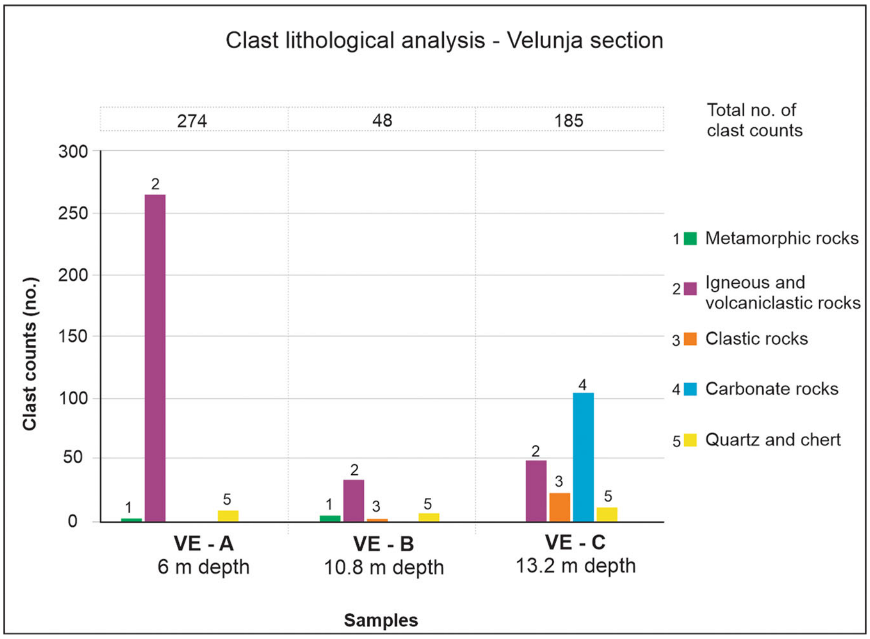

Figure 7. Clast lithological analysis of the Pliocene–Early Pleistocene sediments in the Velenje Basin. [Color figure can be viewed at wileyonlinelibrary.com]

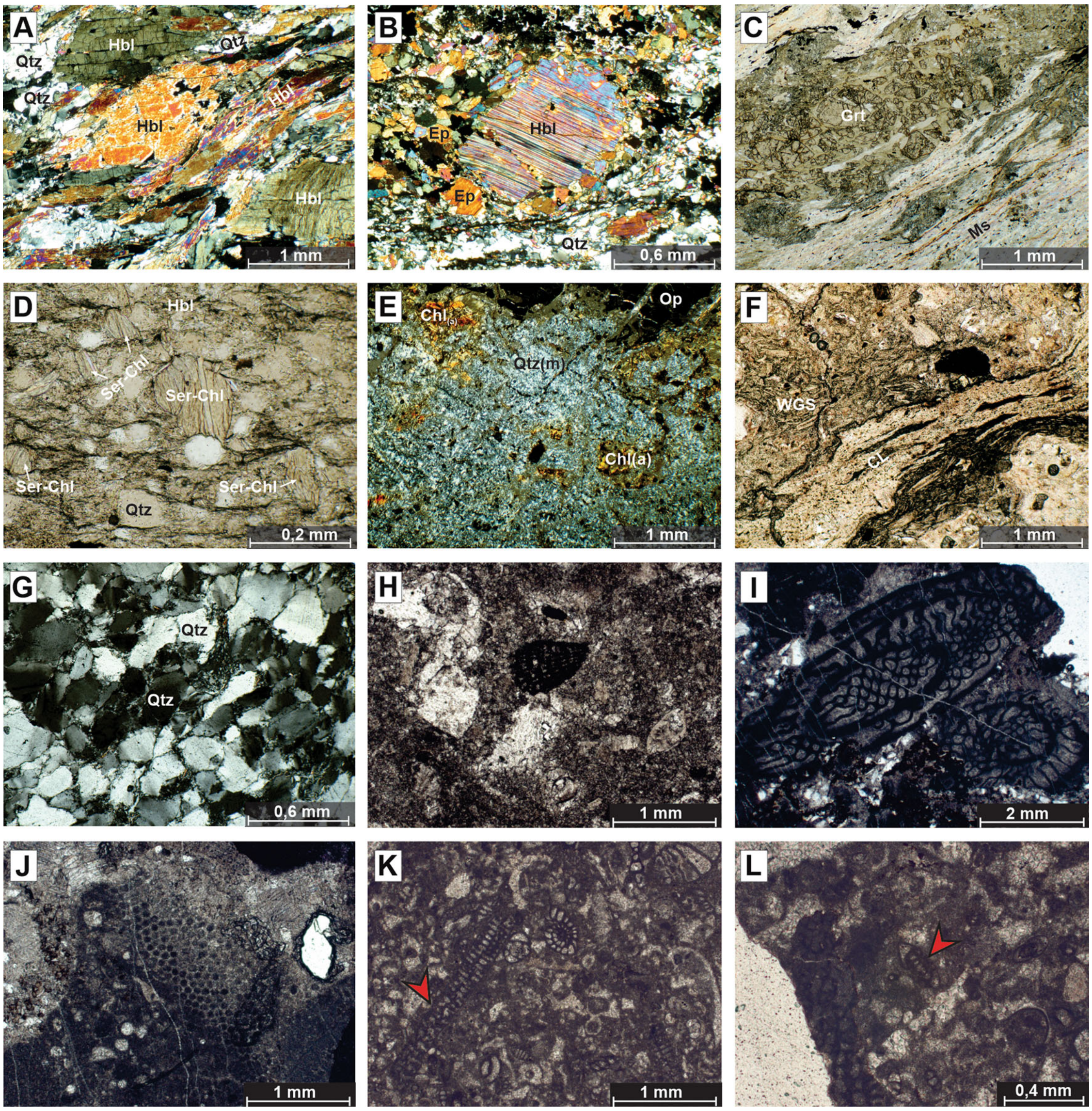

Figure 8. Microfacies of clasts in the Pliocene–Early Pleistocene sediments from the Velenje Basin in cross- (A, B, C, D, F, G) and plain-polarized light (E, H, I). (A) Phyllosilicate lamina in biotite chlorite muscovite schist composed of quartz, muscovite, chlorite and biotite with accessory titanite, tourmaline, apatite and opaque minerals (thin section VEB 4). (B) Plagioclase phenocryst in porphyritic sienogranite intergrowing within the matrix implying epitaxial growth (thin section VEC 3.1). (C) Sericitized plagioclase, stretch quartz, epidote and chlorite in a sample of altered tonalite (thin section VEA 2). (D) Diabase with altered (chloritized, epidotized, stilpnomelanitized) rutile (thin section VEB 5). (E) Fine-grained vitric tuff (Oligocene) consisting of fine-grained glass shards and sub-microscopic tuffaceous matrix (thin section VEA 8.3). (F) Quartz sandstone to mudstone of Val Gardena Fm. (thin section VEA 8.1). (G) Lithic quartz sandstone (presumably Carboniferous; thin section VEA 19). (H) *Earlandia* sp. in recrystalized matrix (red arrow) in the sample of intraclast bioclast wackestone (thin section VEA 15.5). (I) Dubious foraminifera interpreted as? *Aulotortus tumidus* (red arrow) in a sample of intraclast peloid packstone (thin section VEA 15.7). Abbreviations: Qtz–quartz, Op–opaque minerals, Ms–muscovite, Ep–epidote, Chl–chlorite, Pl–plagioclase, Rt–rutile, M–glassy groundmass, GS–glass shards. [Color figure can be viewed at wileyonlinelibrary.com]

Table 3. Sample dataset and cosmogenic ^{10}Be and ^{26}Al information at the Velunja section (46.398107°N, 15.082611°E, 405 m asl)

Sample no.	Sample weight (g)	Be mass (mg)	^{10}Be/^{9}Be ($\times 10^{-14}$)	Blank correction (%)	^{10}Be concentration (10^3 at. g^{-1})	Total Al (mg)	Total Al (p.p.m.)	^{26}Al/^{27}Al ($\times 10^{-14}$)	^{26}Al concentration (10^3 at. g^{-1})	^{26}Al/^{10}Be
VE-10	15.4422	0.1978	0.95 ± 0.11	27.3	5.93 ± 0.99	8.23	532.64	0.50 ± 0.10	59.52 ± 11.90	10.04 ± 2.62
VE-13	47.3362	0.1982	8.88 ± 0.35	2.9	24.13 ± 0.98	0.83	17.45	16.30 ± 0.9	63.49 ± 3.52	2.63 ± 0.18
VE-14	47.2890	0.1976	3.97 ± 0.22	6.5	10.37 ± 0.61	2.20	46.55	3.95 ± 0.20	41.02 ± 2.10	3.96 ± 0.31
VE-15	50.2631	0.1987	4.83 ± 0.32	5.4	12.07 ± 0.86	2.09	41.58	4.27 ± 0.37	39.61 ± 3.44	3.28 ± 0.37
VE-16	30.0068	0.1988	5.59 ± 0.57	4.7	23.58 ± 1.06	1.06	35.33	7.16 ± 0.53	56.49 ± 4.20	2.40 ± 0.31

Accelerator mass spectrometry (AMS) measurement errors are at 1σ level, including statistical (counting) error and error due to normalization of standards and blanks. The error-weighted average ^{10}Be/^{9}Be full-process blank ratio is $(2.60 \pm 0.31) \times 10^{-15}$. ^{26}Al/^{10}Be ratios are calculated with the CRONUS-Earth exposure age calculator and are referenced to 07KNSTD [http://hess.ess.washington.edu/math/ (v. 2.3); Balco et al., 2008 and update from v.2.2 to v.2.3 published by Balco in June 2016].

ephemeral and perennial streams and extensive erosion of the hillslopes. The terrace surfaces run in the same downstream direction as the modern rivers. Risers are much higher than in the lower terrace group. The gravels are extensively weathered, sometimes to the point where the clasts disintegrate during sampling. The relative age of this unit was previously constrained by the fossil finds of the gomphothere *Anancus arvernensis* and '*Mammut*' *borsoni*. The fossil finds were excavated near the village of Škale in 1964 (Fig. 4; Drobne, 1967) and were located about 2 km SE of the Velunja section at ~400 m asl (Rakovec, 1968). Both of these species lived into the Early Pleistocene (Athanassiou, 2016; Baleka et al., 2022; Koenigswald et al., 2022). The latest revision of stratigraphic and paleontological data suggested an age of 3.5–2.6 Ma, corresponding to the lower Villafranchian biochronological unit and mammal zone MN 16 (Debeljak, 2017). Isochron-burial dating of the sediment in the lower part of the terrace staircase in the Velunja section within this study yields an age of 2.7 ± 0.3 Ma. This calculated age is thus in perfect agreement with the mastodon findings. Since the sample was collected in the lower part of the unit, the age represents the onset of sedimentation of the Pliocene–Early Pleistocene unit. Terrace T1 is presented in the schematic profile (Fig. 10) as a single or multiple depositional events that was/were later incised with several erosional terraces (fill-cut terraces). An alternative explanation would be that the sequence was deposited in multiple phases of deposition and aggradation. With this data set, we do not have sufficient evidence to support either scenario since the surface expression could be the same for different types of terrace formation (Lewin and Gibbard, 2010) and the chronological and sedimentological data are insufficient. However, the fill–cut terrace system seems more plausible since the morphology shows an unpaired character of the terraces and undulating morphology (Fig. 5).

Table 4. Input parameters used in modeling of the isochron-burial age of the Velunja section

Parameter	Velenje Section
Coordinates (decimal °)	46.398107°N, 15.082611°E
Sink elevation (m asl)	405
Starting depth (g cm^{-2})	3000
^{26}Al/^{10}Be production ratio (spallation)	6.97 (after Borchers et al., 2016)
Source elevation (m asl)	405–4000
Source bedrock density (g cm^{-3})	2.5–2.7
Source interglacial erosion rate (m Ma^{-1})	10–2000
Source bedrock plucking depth (m)	0.01–10
Sink erosion rate (g cm^{-2} Ma^{-1})	1–10 000
Sink burial time (Ma)	1–5

The lower terrace group includes the T0 terrace, which lies 8–20 m above the active floodplain. It has well-preserved terrace surfaces and terrace risers; however, the terrace surfaces are smaller and occur only in a few places in the basin. The terrace surfaces slope downstream along modern rivers. The age of the terrace presumably pre-dates the Holocene. In the other basins in the area (Mencin Gale et al., 2019a, 2019b), fluvial patterns were preserved on the floodplain but not on the older terraces, so we assumed that a terrace above the floodplain is considerably older than the floodplain. However, the floodplain in the Velenje Basin has been completely artificially reworked and no former channel pattern is preserved. Nevertheless, a Middle–Late Pleistocene age is postulated as it is the first terrace above the floodplain, and the surface is relatively well preserved compared to the higher terraces, much like the Middle–Late Pleistocene terraces in other basins in the area (Mencin Gale et al., 2019a, 2019b).

The floodplain (FP) was attributed to the Holocene, and has a flat surface crossed by the modern Paka River and its tributaries (Klančnica, Velunja, Ljubela Rivers). The floodplain is flat and mostly artificially reworked, so that no former channel pattern is visible.

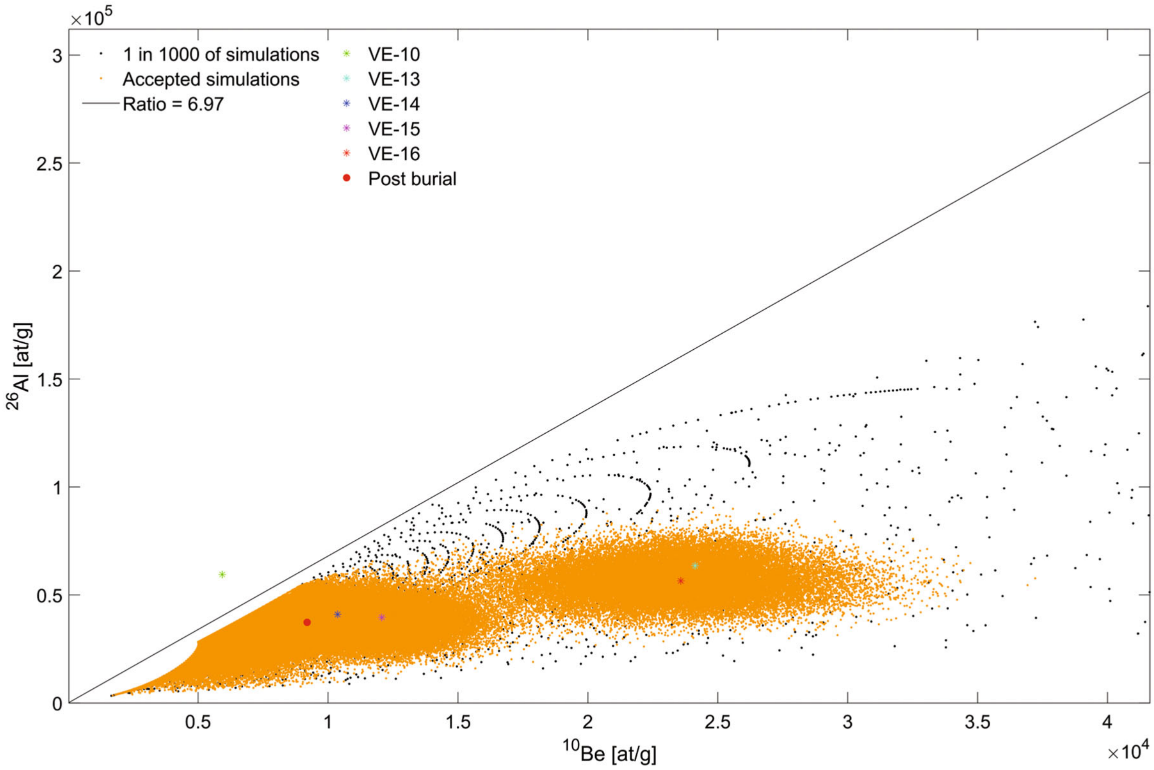

Figure 9. P-PINI-derived ^{26}Al vs. ^{10}Be plot and modeling results (see Nørgaard et al., 2023 for further details). [Color figure can be viewed at wileyonlinelibrary.com]

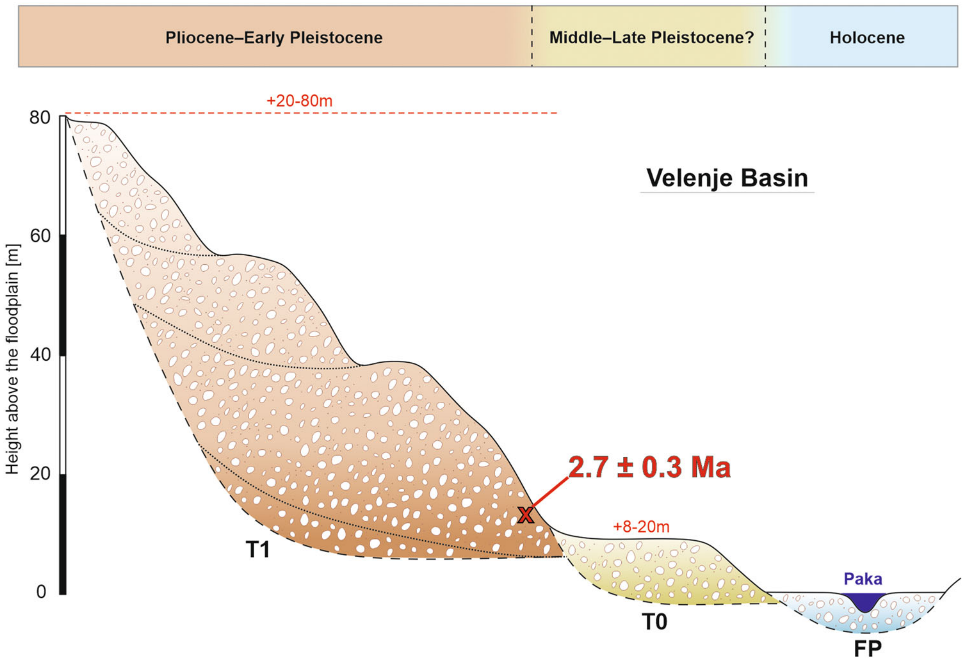

Figure 10. Schematic profile with ages of the terrace staircase in the Velenje Basin. Terraces are marked (T0 and T1), together with their relative heights above the Holocene floodplain (FP). Pliocene–Early Pleistocene terraces (T1) are preserved only as erosional remnants with highly degraded morphology; therefore, the number of depicted terraces cannot be quantified since the exact number of terraces cannot be inferred. T1 terraces are depicted as a single depositional event with subsequent aggradation (fill-cut), but dashed lines indicate the alternative possibility of multiple phases of deposition and aggradation. [Color figure can be viewed at wileyonlinelibrary.com]

Interpretation of depositional environment

A depositional environment was deduced from the Mladika and Velunja sections, which are sufficiently thick for reliable interpretation. The observed characteristics with prevailing massive sandy facies in the Mladika section can be interpreted as being deposited in a crevasse splay, typical of a meandering river environment. In the Velunja section, the high-energy gravel facies, large lateral and vertical variations, and the channel pattern (several smaller channels) point to a braided river environment. However, the moderate- and low-energy fluvial facies prevalent in this section suggest a lower flow velocity and lower stream power, indicating a meandering river environment. We therefore interpret that the sediments of the Velunja section were deposited in a wandering river environment (*sensu* Miall, 2006), which is an intermediate category between braided and meandering rivers, since evidence of both types is present in the section. The paleodrainage direction was estimated from the north–south 2-D transects and roughly corresponds to the present-day flow direction that is approximately NE–SW (Fig. 3D). The Topolščica and Škale sections are thinner but point to an environment similar to that interpreted for the Velunja section. An iron oxide crust ('limonite' crust) occurring in the Škale section is considered a post-depositional pedogenetic feature, probably related to oxidative precipitation of iron oxides in the water table.

Provenance of Pliocene–Early Pleistocene sediments

The provenance of the Pliocene–Early Pleistocene sediments correspond to the paleo-Paka River drainage and its tributaries and suggests drainage from north to south (Fig. 11). *Metamorphic rocks*, represented by schist, outcrop in the area north of the basin, whereas they do not occur in the catchment area of the present-day Paka River and its tributaries. This implies that the source rocks were either eroded, or outcrops were not mapped due to the lack of a detailed geological map. Another explanation is that the schist pebbles were reworked from Miocene conglomerates. This has already been stated in the recent literature (Ivančič et al., 2018a, 2018b) and supported by additional fieldwork of the Miocene conglomerates, where the presence of schist clasts was confirmed. *Igneous and volcaniclastic rocks* are represented by several lithotypes. Granite, sienogranite and tonalite are characteristic for the Eisenkappel (Železna Kapla) igneous zone that outcrops north and northwest of the Velenje Basin. Diabase presently outcrops north and northwest of the basin; however, its characteristics are more similar to the formations occurring further north in Austria. However, these areas are not in the drainage area of the basin, so we assume that this type of diabase has either been eroded or its outcrops are not mapped in sufficient detail on the available geological maps at a scale of 1:100 000 (Mioč and Žnidarčič, 1977; Mioč et al., 1983). Reworking from the Miocene conglomerate containing diabase is also not excluded, but we did not find any reports on diabase clasts in the literature (Ivančič et al., 2018a, 2018b), nor in the field when examining Miocene conglomerates in the Paka catchment. The keratophyre corresponds to Triassic volcanic formations outcropping around the entire basin. The tuff is attributed to the Oligocene Smrekovec Series occurring in the immediate vicinity east, south and west of the basin. *Clastic rocks* are represented by several types of sandstone attributed to different formations. Lithic quartz sandstone to mudstone is attributed to the Val Gardena Formation outcropping east of the basin and tentatively to the Carboniferous occurring north and east of the Velenje Basin. Quartz sandstone, presumably of Neogene age, occurs north and east of the basin. *Carbonate rocks* include mudstone and (intraclast) peloid packstone/wackstone attributed to the Werfen Formation that outcrops north, east and west of the basin, and to the Anisian–Rhaetian shallow-marine formations located north, east and west of the Velenje Basin.

In addition to the provenance results, the channel geometry observed in the Velunja section (Fig. 3C, D) and decreased terrace surface elevations towards the south (Profile P3, Fig. 5) also indicate drainage from the north. Since present-day streams also flow from the north, the drainage direction has remained unchanged since the Pliocene–Early Pleistocene. The same

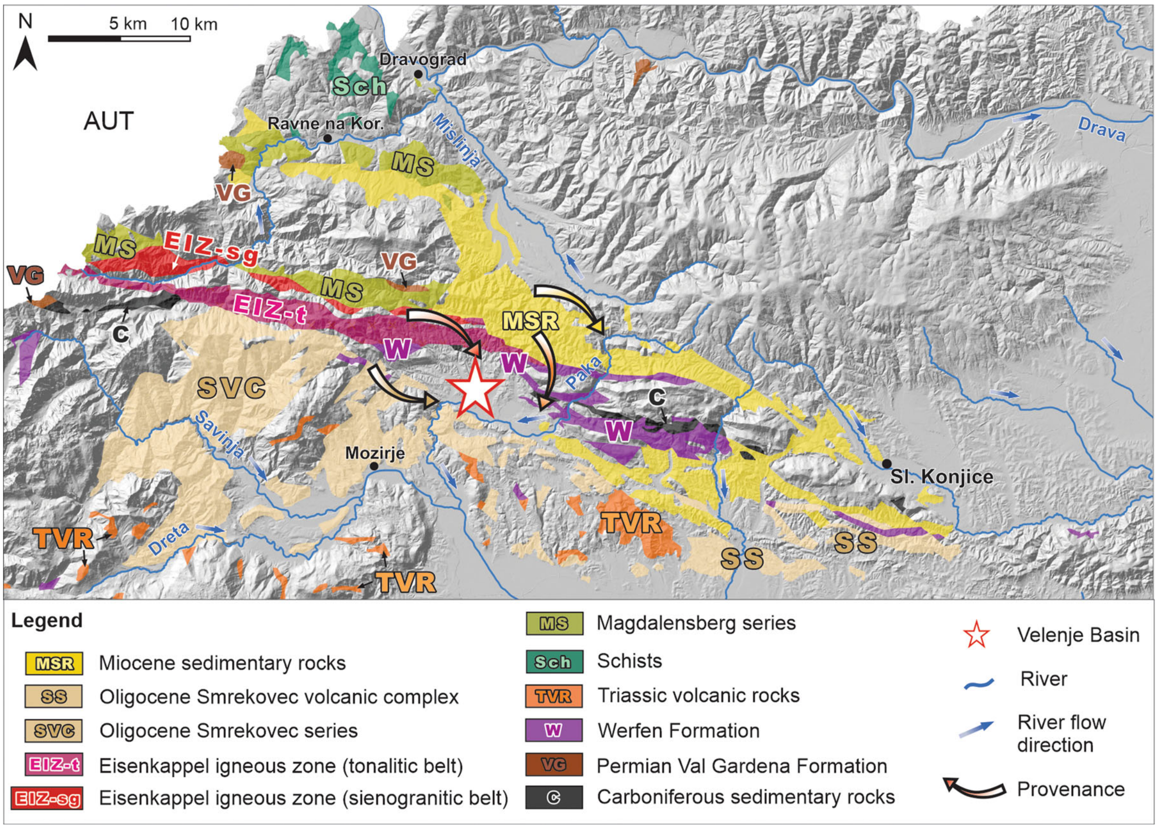

Figure 11. Provenance of Pliocene–Early Pleistocene gravel deposits in the Velenje Basin. Geological map is modified after Buser (2010). Basemap: shaded relief of the DEM 5 (digital elevation model with 5 × 5-m raster grid, Public Information of Slovenia, The Surveying and Mapping Authority of the Republic of Slovenia, DEM 5, 2006). [Color figure can be viewed at wileyonlinelibrary.com]

observation was obtained from the nearby intramontane basins, Slovenj Gradec, Nazarje, Celje and Drava-Ptuj (Mencin Gale et al., 2019a, 2019b).

The results of CLA may be subject to certain uncertainties, such as pre- and post-depositional changes (e.g. *in situ* dissolution). By pre-depositional changes we refer to the reworking of sediments through transportation and the different durability of the various lithologies. Quartz-bearing rocks are more resistant to erosion and destruction during transport than calcite-bearing rocks. Moreover, the hardness of the rocks also plays an important role (Attal and Lave, 2009). Secondly, by post-depositional changes we refer to the *in situ* dissolution of carbonate-bearing lithologies. We found no evidence of this in the field (e.g. empty weathered voids of suspected clasts). In addition, the textures in the Velunja section are clearly preserved (Fig. 3C, D). Therefore, if *in situ* dissolution took place, it must have occurred to a lesser extent.

Timing of the onset of Pliocene–Early Pleistocene sedimentation

Samples for age dating of the Velunja section did not reach the Pliocene lacustrine sediments that represent the basement of the Pliocene–Early Pleistocene gravely unit, so the thickness between sampled deposits and the basin is unknown. The geological column (Fig. 2) shows that the unit reaches a thickness of 205 m in the central part. Furthermore, the geological cross-section (Fig. 1D), which is very well constrained with numerous subsurface data due to the active coal mining in the Velenje Basin, shows that the unit becomes significantly thinner towards the north. The Velunja section is located close to the northern boundary of the basin (location is marked on Fig. 1D) with considerably less overburden (65 m at the sampling location) which implies that the sampling location is probably positioned in the lower part of the unit.

The isochron-burial age of 2.7 ± 0.3 Ma of the Pliocene–Early Pleistocene gravel in the Velunja section thus represents the age of the lower part of the succession and the approximate timing of the onset of Pliocene–Early Pleistocene sedimentation. The age is in perfect agreement with the biostratigraphic data of the mastodon findings. Although the mastodon finds were in a lacustrine unit, the similar elevations of the isochron-burial dating samples (405 m asl) and the mastodon finds (~400 m asl; Rakovec, 1968) indicate that the lacustrine and gravely units are time-equivalent. Debeljak (2017) postulated that *Anancus arvernensis* and '*Mammut*' *borsoni* lived in the Late Pliocene (Piacenzian), which lasted from 3.6 to 2.58 Ma. The Piacezian was characterized by a humid subtropical climate (Debeljak, 2017). The pollen record indicates the presence of thermophilic forests with evergreen deciduous vegetation (Šercelj, 1968), which provided a suitable environment and abundant food for the species found in the Velenje Basin.

Pliocene–Quaternary fluvial sequences as markers of tectonic processes in the area of Slovenia

Tectonic activity, along with climate and surface processes, is one of the most important factors controlling landscape evolution (e.g. Bishop, 2007; Burbank and Anderson, 2001). The South-eastern Alpine Foreland has long been subjected to tectonic processes, which are expressed in its complex geologic structure (Vrabec and Fodor, 2006; Weber et al., 2006; Placer, 2008). Due to the neotectonically active Adria-Europe collision zone (e.g. Vrabec and Fodor, 2006), in which the studied area is located, with its numerous active faults (Atanackov et al., 2021), we propose that tectonic activity played a key role in the development of the terrace staircase. An immediate response to collision-related regional uplift is archived in the terrace staircases of the Velenje Basin. Fluvial basins can provide valuable evidence of tectonic processes (Burbank and Anderson, 2001; Hugget, 2007; Wegmann and Pazzaglia, 2009; Wilson et al., 2009; Ponza et al., 2010). The use of river terraces as kinematic indicators and to infer tectonic processes is widespread in the Alpine Foreland (Wilson et al., 2009; Pazzaglia et al., 2021) and elsewhere (Castelltort et al., 2012; Viveen et al., 2020; Cao et al., 2021; Pazzaglia et al., 2021).

In addition to the regional tectonic uplift of the Alps and Dinarides, local tectonic activity has played a highly important role in the development of the basins and the landscape (Fig. 12; Atanackov et al., 2021). The area lies in the transpressive Periadriatic Fault System, so the tectonic uplift at regional scale can be attributed to the activity of this fault system. Within this transpressive system, the Velenje Basin is actually transtensive. The basin formed as the result of subsidence along the Periadriatic and Šoštanj Faults. The subsequent tectonic subsidence was a strong controlling factor that triggered fluvial deposition during basin formation, while regional tectonic uplift preserved sediments in terrace staircases. Some important remarks regarding the local tectonic processes in the Velenje Basin can be outlined on the basis of the spatial distribution and extent of the landforms in comparison with the adjacent basins (Fig. 13). On Fig. 13 we provide a comparison of the geomorphological maps of the Slovenj Gradec, Nazarje (Mencin Gale et al., 2019a), Celje, Drava-Ptuj (Mencin Gale et al., 2019b) and Velenje Basins (this study). The Velenje and Slovenj Gradec Basins stand out in terms of the extent of their Pliocene–Early Pleistocene surfaces and the absence of younger surfaces in comparison with the Nazarje, Celje and Drava-Ptuj intramontane basins in the vicinity. After sedimentation of the Pliocene–Early Pleistocene deposits starting around 2.7 Ma, the terraces were formed by pronounced incision resulting from regional tectonic uplift (Vrabec and Fodor, 2006). Continuous uplift would normally cause continuous incision and the formation of younger terraces (e.g. Bridgland, 2000, 2002; Westaway, 2002). However, in the Velenje and Slovenj Gradec Basins, only one lower terrace occurs along with the floodplain, suggesting that a change in the system occurred some time after the Early Pleistocene (Fig. 12). Thus, the explanation may lie in tectonic changes. It is possible that transtension, which caused the rate of subsidence along the Šoštanj (Velenje Basin) and Labot/Lavantall Fault (Slovenj Gradec Basin) to increase after the Early Pleistocene and, coupled with regional tectonic uplift in the Periadriatic Fault System, established an equilibrium in the course of erosion and aggradation, i.e. a steady state. An alternative explanation for the steady state could be local transtension coupled with a decrease in regional tectonic uplift after the Early Pleistocene. Currently, aggrading deposition is ongoing on the floodplains, suggesting a continuation of the steady state.

We are fully aware that this interpretation needs to be supported in any further work with a chronological framework on several sites within the basin and furthermore in adjacent basins to gain a regional perspective.

Chronology of the Early Pleistocene deposits in the Alpine region

Early Pleistocene deposits are very challenging to study due to the obscured geomorphological features, fewer dating methods available due to the old age, and fewer outcrops which are usually poorly preserved. Numerical age dating of sediments in the Velenje Basin is one of the few dated localities of the Early Pleistocene deposits available in the Alpine foreland. A recent review by Monegato et al. (2023) provided an important state-of-the-art data set of all relative and numerical age dating of the Early and Middle Pleistocene deposits. In this study we present the compilation of solely numerical age dating of Early Pleistocene deposits in the Alpine region (Fig. 14; Table 5). Numerical age dating of Early Pleistocene deposits is available only in Switzerland, Germany and Slovenia. Therefore, this study sets the Velenje Basin on the map as one of the very rare datapoints of numerical age dating of Early Pleistocene deposits in the Alpine foreland. Moreover, it represents one of the oldest ages around the Plio-Pleistocene boundary.

Conclusions

Through the use of geomorphological, sedimentological, provenance analysis and numerical age dating we have

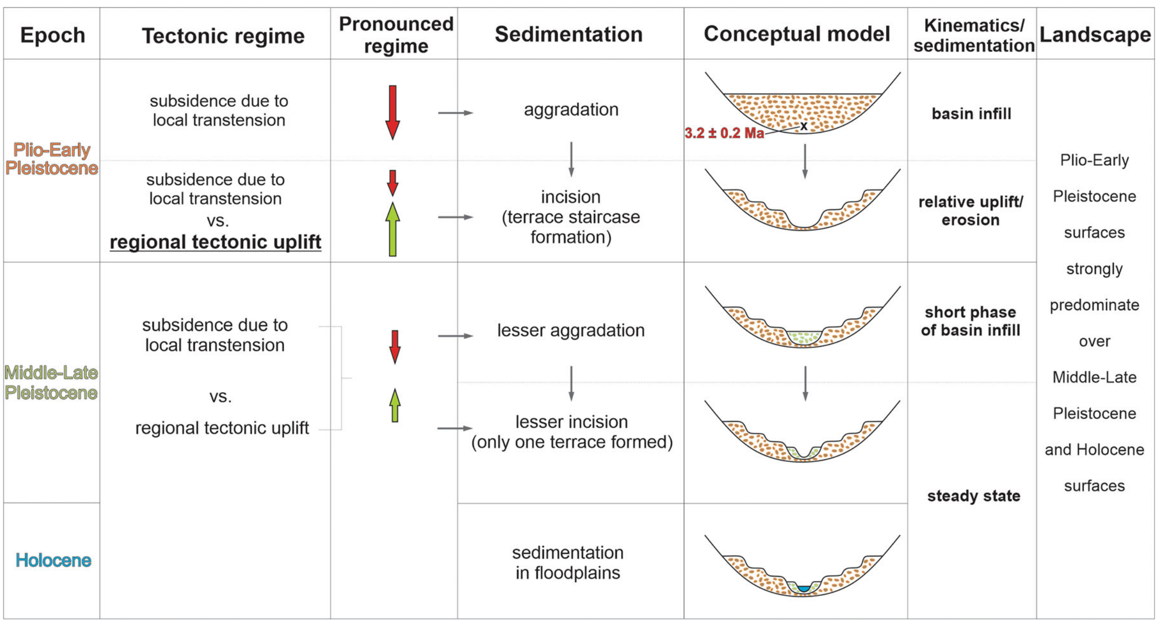

Figure 12. Aggradation and incision model in the Velenje and Slovenj Gradec Basins, suggesting aggradation followed by pronounced incision; thus, the formation of terrace staircases in the Pliocene–Early Pleistocene was followed by a relatively steady state from the Middle Pleistocene onwards, resulting in fewer formed terraces. [Color figure can be viewed at wileyonlinelibrary.com]

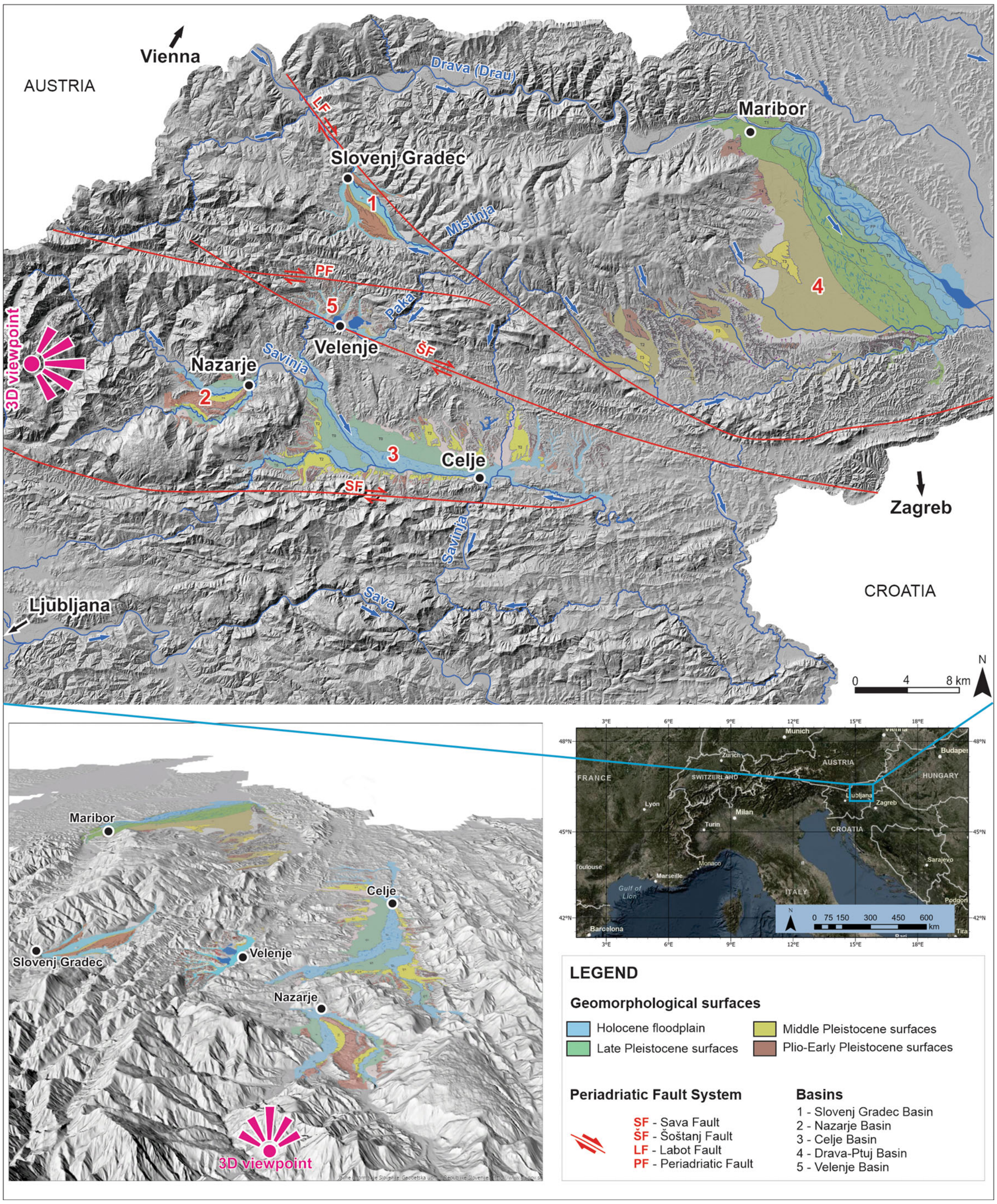

Figure 13. Comparison of the geomorphological maps of the (1) Slovenj Gradec, (2) Nazarje (Mencin Gale et al., 2019a), (3) Celje, (4) Drava-Ptuj (Mencin Gale et al., 2019b) and (5) Velenje Basins (this study) with indicated modern drainage network. The Velenje (5) and Slovenj Gradec Basins (1) stand out in that Pliocene–Early Pleistocene terraces strongly prevail over Middle and Late Pleistocene terraces. [Color figure can be viewed at wileyonlinelibrary.com]

investigated the landscape evolution of the Velenje Basin in the Pliocene–Quaternary. The terrace staircase includes several terraces that are severely degraded and a younger terrace that is better preserved. Our results show that the Pliocene–Early Pleistocene sediments were deposited in a meandering and wandering river environment. The petrographic composition of the gravel deposits suggests they are of local origin, and drainage from the east, north and south and can be attributed to the paleo-Paka River and its tributaries. This indicates that the drainage in the Pliocene–Early Pleistocene roughly corresponded to the present drainage scheme. The established chronology using isochron-burial dating with cosmogenic ^{26}Al and ^{10}Be represents the first numerical chronology of the Early Pleistocene sediments in the Velenje Basin and one of a few in the entire Alpine Foreland. The results suggest that fluvial aggradation in the Velenje Basin started no later than 2.7 Ma, which is in full agreement with the findings of *Anancus arvernensis* and '*Mammut*' *borsoni* that lived in the Late Pliocene (3.6–2.58 Ma).

By coupling geomorphological analysis and isochron-burial dating with cosmogenic ^{26}Al and ^{10}Be we were able to constrain the aggradation–incision model for the Velenje Basin, which provides grounds for discussion of tectonic processes. This area is strongly influenced by the junction of the Southern and Eastern Alps bounded by the Periadriatic Fault System. We propose that tectonic activity played a key role in Pliocene–Quaternary landscape evolution in the Southeastern Alpine Foreland.

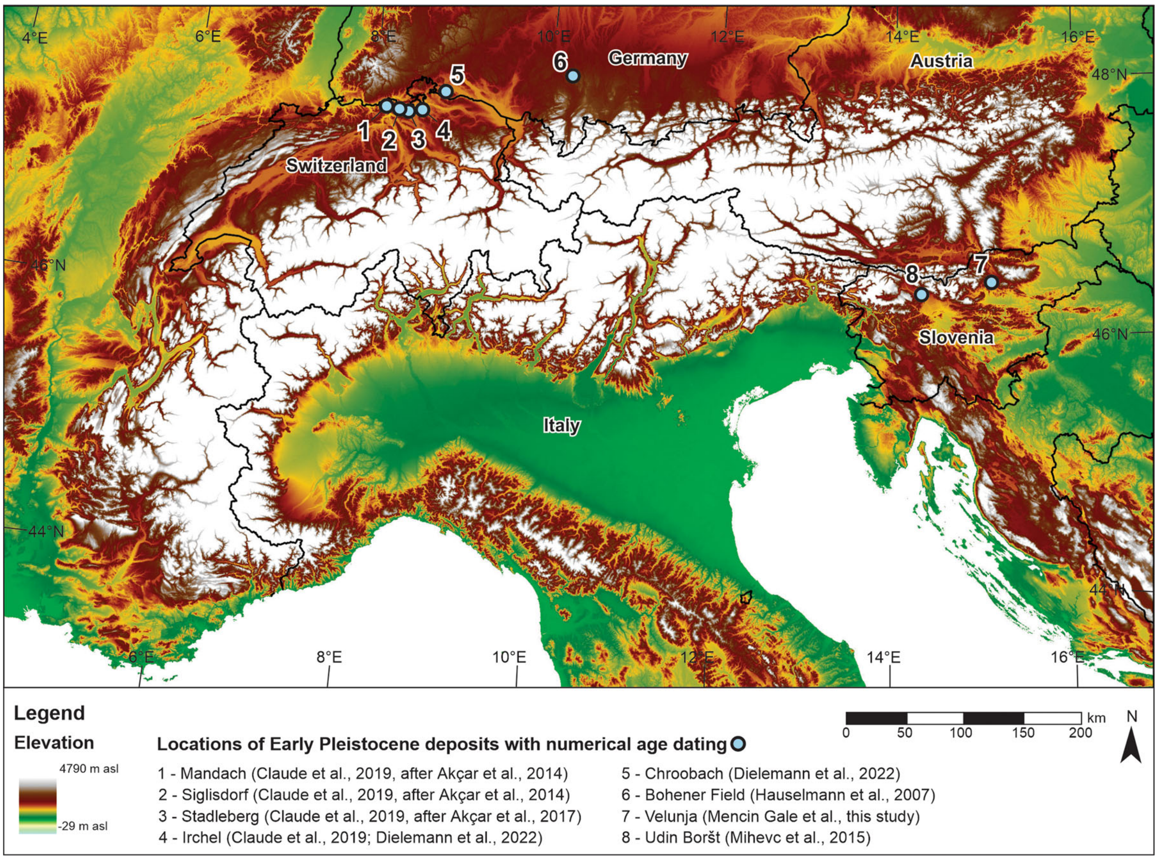

Figure 14. Locations of the numerical age dating of Early Pleistocene sediments in the Alpine foreland. [Color figure can be viewed at wileyonlinelibrary.com]

Table 5. Age dating of the Early Pleistocene deposits in the Alpine region

Locality	Age (Ma)	Age dating method	Country	Reference
Mandach	0.8 + 1.4 – 0.4	Depth profile	Switzerland	Claude et al., 2019 (recalculated after Akçar et al., 2014)
Siglistorf	1.5 ± 0.4	Isochron-burial dating		Claude et al., 2019 (recalculated after Akçar et al., 2017)
Stadlerberg	2.4 + 2.3 – 1.2	Depth profile		Claude et al., 2019 (recalculated after Akçar et al., 2014)
Irchel Steig	0.4 + 1.7 – 0.2	Depth profile		Claude et al., 2019
Irchel Steig	0.9 ± 0.4	Isochron-burial dating		Claude et al., 2019
Irchel Hutz	0.9 ± 0.4	Isochron-burial dating		Claude et al., 2019
Wilemer Irchel	2.8 + 1.8 –1.0	Depth profile		Claude et al., 2019
Irchel Hasli	1.3 ± 0.1	Isochron-burial dating		Dieleman et al., 2022
Irchel Hochwacht	2.6 ± 0.1	Isochron-burial dating		Dieleman et al., 2022
Irchel Shartenflue	1.3 ± 0.1	Isochron-burial dating		Dieleman et al., 2022
Chroobach	1.8 ± 0.1	Isochron burial dating		Dieleman et al., 2022
Bohener Field	2.35 + 1.08 –0.88	Burial dating	Germany	Häuselmann et al., 2007
Udin Borst	1.86 ± 0.19	Burial dating	Slovenia	Mihevc et al., 2015
Velunja	2.7 ± 0.3	Isochron-burial dating		This study

Acknowledgements. This work was supported by the Slovenian Research and Innovation Agency (ARIS) in the frame of the Young Researchers program under grant no. 38184, the postdoctoral project under grant no. Z1-50029, the research programss Regional Geology under grant no. P1-0011 and Dynamic Earth under grant no. P1-0419 carried out at the Geological Survey of Slovenia. E.M.G. was additionally supported by the Swiss Government Excellence Scholarship for Foreign Scholars and Artists. The authors would like to express gratitude to Mirka Trajanova, Polona Kralj, Luka Gale and Dragomir Skaberne for conducting petrographic analysis and Juliana Gajić and Mladen Štumergar for help in the preparation of the samples. We would like to thank Dr Stephanie Neuhuber and an anonymous reviewer for comments that significantly improved an earlier version of the manuscript.

Author contributions—Eva Mencin Gale: conceptualization (equal); investigation (lead); methodology (lead); resources (lead); validation (equal); visualization (lead); writing–original draft preparation (lead); writing–review & editing (lead). Petra Jamšek Rupnik: conceptualization (lead); investigation (equal); methodology (equal); resources (equal); validation (lead); supervision (lead); writing–original draft preparation (equal); writing–review & editing (equal). Naki Akçar: methodology (equal); resources (equal); supervision (equal); writing–original draft preparation (equal); writing–review & editing (equal). Marcus Christl: resources (equal), writing–original draft preparation (equal); writing–review & editing (equal). Christof Vockenhuber: resources (equal), writing–original draft preparation (equal); writing–review & editing (equal). Flavio S. Anselmetti: conceptualization (equal), supervision (equal); writing–original draft preparation (equal); writing–review & editing (equal). Andrej Šmuc: conceptualization (equal), supervision (equal); writing–original draft preparation (equal); writing–review & editing (equal).

Conflict of interest—The authors have no conflicts of interest to declare.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supporting information

Additional supporting information can be found in the online version of this article.

Microfacies analysis of the Velenje Basin.

Abbreviations. als, above sea level; DEM, digital elevation model; MN, Mammal Neogene; CLA, clast lithological analysis; ICP-OES, inductively coupled plasma optical emission spectrometry.

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