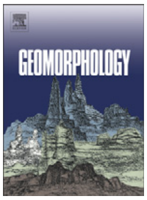
Geomorphology xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps

Thomas Wagner [a,*], Harald Fritz [a], Kurt Stüwe [a], Othmar Nestroy [b], Helena Rodnight [c], John Hellstrom [d], Ralf Benischke [e]

[a] *Institute of Earth Sciences, University of Graz, Heinrichstraße 26, A-8010 Graz, Austria*
[b] *Institute of Applied Geosciences, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria*
[c] *Institute of Geology and Paleontology, University of Innsbruck, Innrain 52, A-6020 Innsbruck, Austria*
[d] *School of Earth Sciences, University of Melbourne, Parkville, Victoria 3010, Australia*
[e] *Department of Water Resources Management, Institute for Water, Energy and Sustainability, Joanneum Research Forschungsgesellschaft mbH., Elisabethstraße 16, A-8010 Graz, Austria*

ARTICLE INFO

Article history:
Received 14 September 2010
Received in revised form 16 March 2011
Accepted 22 April 2011
Available online xxxx

Keywords:
Cave level
Planation surface
Stream terrace
Cosmogenic nuclide
Luminescence
Sediment burial

ABSTRACT

The transition zone of the Eastern Alps to the Pannonian Basin provides one of the best sources of information on landscape evolution of the Eastern Alpine mountain range. The region was non-glaciated during the entire Pleistocene. Thus, direct influence of glacial carving as a landscape forming process can be excluded and relics of landforms are preserved that date back to at least the Late Neogene. In this study, we provide a correlation between various planation surfaces across the orogen-basin transition. In particular, we use stream terraces, planation surfaces and cave levels that cover a vertical spread of some 700 m. Our correlation is used to show that both sides of the transition zone uplifted together starting at least about 5 Ma ago. For our correlation we use recently published terrestrial cosmogenic nuclide (TCN) burial ages from cave sediments, new optically stimulated luminescence (OSL) ages of a stream terrace and U–Th ages from speleothems. Minimum age constraints of cave levels from burial ages of cave sediments covering the last ~4 Ma are used to place age constraints on surface features by parallelizing cave levels with planation surfaces. The OSL results for the top section of the type locality of the Helfbrunn terrace suggest an Early Würm development (80.5 ± 3.7 to 68.7 ± 4.0 ka). The terrace origin as a penultimate gravel deposit (in classical Alpine terminology Riss) is therefore questioned. U-series speleothem ages from caves nearby indicate formation during Marine Isotope Stages (MIS) 5c and 5a which are both interstadial warm periods. As OSL ages from the terrace also show a time of deposition during MIS 5a ending at the MIS 5/4 transition, this supports the idea of temperate climatic conditions at the time of deposition. In general, tectonic activity is interpreted to be the main driving force for the formation and evolution of these landforms, whilst climate change is suggested to be of minor importance. Obvious hiatuses in Miocene to Pleistocene sediments are related to ongoing erosion and re-excavation of an uplifting and rejuvenating landscape.

1. Introduction

The landscape evolution of the Alps since the Late Neogene is a subject of topical interest (e.g. Frisch et al., 2001; Dunkl et al., 2005; Kuhlemann, 2007; Champagnac et al., 2009; Willet, 2010). The transition zone between the Alpine orogen and the Pannonian Basin around the city of Graz, Austria is a key site for this subject, as it provides considerable information regarding the evolution of landforms over this time period and has never been glaciated. Glacial carving can thus be excluded as a landforming process (Fig. 1a, Van Husen, 2000). The Mur River is the main drainage dissecting this region (Fig. 1a). It drains the Eastern Alps from the eastern edge of the Tauern Window into the Pannonian Basin, crossing the orogen-basin transition zone near the city of Graz. The landscapes of the Styrian Basin and the Highland of Graz, respectively south and north of this transition zone, comprise numerous planation surfaces and stream terraces which can be grouped into several distinct levels that cover a vertical spread of some 700 m. Due to the presence of karstifiable rocks in the Highland of Graz, phreatic cave levels are also developed (e.g. Maurin and Benischke, 1992).

In this paper we discuss the landscape evolution of this region by presenting a correlation of various levels and planation surfaces north and south of the orogen-basin transition zone. A relative chronology of these levels has previously been established (e.g. Winkler-Hermaden, 1955, 1957), but numerical ages of these landforms remain poorly constrained by scarce cross-correlations using dated volcanic rocks (Balogh et al., 1994) and some paleontological evidence (e.g. Mottl, 1946). The main objective of this work is to use recently available

---

[*] Corresponding author. Tel.: +43 316 380 5593; fax: +43 316 380 9865.
E-mail address: thomas.wagner@uni-graz.at (T. Wagner).

0169-555X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2011.04.024

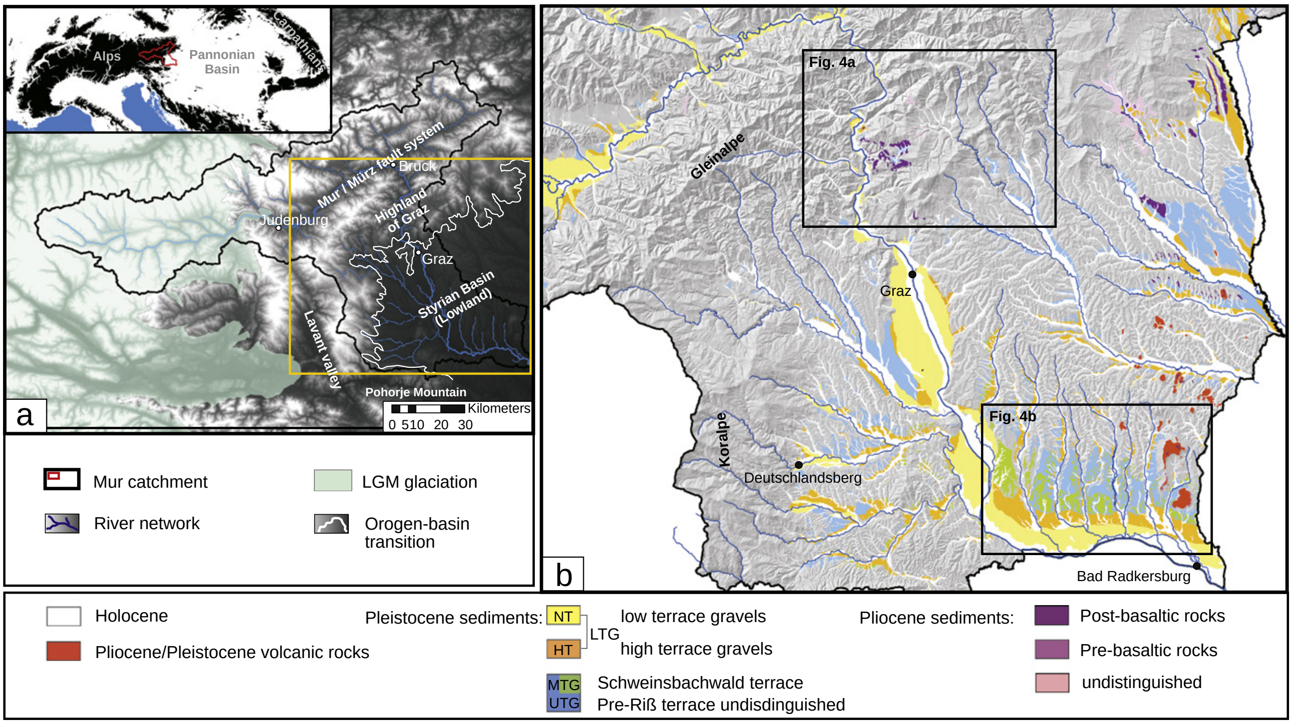


Fig. 1. The area of investigation. (a) The present catchment area of the Mur River, the river course and its tributaries, and the extent of the last glacial maximum (LGM) (Van Husen, 2000) on top of a DEM. Inset shows the Alpine–Carpathian–Pannonian realm (black above 600 m, white below) and the Mur catchment upstream of Bad Radkersburg in red color. Extent of (b) indicated by the orange box. (b) Pliocene, Pleistocene and Holocene sediment distribution (sediment covered planation surfaces and stream terraces) and Pliocene/Pleistocene volcanic rocks. Pleistocene sediments are subdivided into the low terrace gravels (NT, "Niederterrasse" or Würm terrace), the high terrace gravels (HT, "Hochterrasse", which can be further split into a Riss (penultimate) glacial terrace and the Helfbrunn interglacial terrace) and terraces that are pre-Riss (older than the previous ones). In the latter, the so-called Schweinsbachwald terrace is distinguished as the youngest subunit in the lowland, especially in the Grabenland, where this is morphologically feasible (and likely related to the lateral (southward) shift of the Mur River in the area). Further upstream such a differentiation was no longer possible as absolute age constraints are not available. The same holds true for the few Pliocene sediments in the region. Where possible, pre- and post-basaltic gravels are distinguished. LTG = lower terrace group, MTG = middle terrace group and UTG = upper terrace group. The detailed study areas shown in Fig. 4a (the Central Styrian Karst in the Highland) and Fig. 4b (the Grabenland region in the Lowland) are indicated by black rectangles.

geochronological data on the timing of these geomorphic markers (Wagner et al., 2010), to complement these with new OSL and U–Th ages and to propose a model for the topographic evolution across the orogen-basin transition including both the Styrian Basin and the Highland of Graz. Our correlation allows further understanding of the morphological evolution on the eastern margin of the Alps in general.

2. The study area—the Styrian Block and the River Mur

The Styrian Block is the subject of this study and is defined here as a region that consists of the Styrian Basin and the surrounding basement. The block is delineated by the Mur–Mürz fault zone in the north, the Lavanttal fault zone in the west, the Pohorje Mountain in the south and the Pannonian Basin (excluding the Styrian Basin) to the east (Fig. 1). It comprises three major tectonic units that have distinct landforms and different geological histories: (i) The Austroalpine crystalline basement south of the Mur–Mürz fault zone and east of the Lavanttal fault zone; (ii) The Paleozoic of Graz forming the Highland of Graz in the orogen basin transition zone near Graz and (iii) the Styrian Basin, being the westernmost lobe of the Pannonian Basin. These three parts of the Styrian Block all have their characteristic features. The *crystalline basement* comprises mountainous landscape of high grade metamorphic rocks with elevations more than 2000 m a.s.l. with rounded and flat summits and deeply incised valleys characteristic of a non-glaciated landscape. It forms a presumably slowly exhuming region as fission track ages in the range of 35–50 Ma are preserved (Neubauer et al., 1995; Hejl, 1997; Dunkl and Frisch, 2002). These data suggest a small amount of Neogene denudation. However, Hejl (1997) showed that increased exhumation within the last 5–10 Ma is likely. The Koralpe is an area of relics of Miocene relief; although breaks along the hillslopes of headward migrating tributaries of the Mur River with high stream power point toward geomorphic disequilibrium (Winkler-Hermaden, 1957; Robl et al., 2008a). The *Paleozoic of Graz* contains a highly karstified region of Paleozoic carbonates and schists called the Central Styrian Karst where peaks reach up to 1700 ma.s.l. No low temperature thermochronological data are available from within the Paleozoic of Graz. Finally, the *Styrian Basin* forms an undulating lowland (henceforth termed the Lowland of Graz) comprising Neogene sediments with elevations between 200 and 600 ma.s.l. Despite the topographic and morphological differences between the three different regions of the block, the Styrian Block appeared to have behaved as a single tectonic unit since the end of the Miocene (Wagner, 2010) and it will be the purpose of this study to demonstrate this.

The most important tectonic event related to the onset of the morphological evolution of the region is the formation of the Pannonian Basin east of the Alps (e.g. Dunkl et al., 2005). Major subsidence in the early to mid Miocene caused the onset of lateral extrusion (Ratschbacher et al., 1989) and initiated the formation of the Styrian Basin. This coincides with the development of the W–E directed drainage system typical for the Eastern Alps and related pull-apart basins along the major strike-slip zones, e.g. the Mur-Mürz fault system (Ebner and Sachsenhofer, 1995). In the Styrian Basin, a fully marine sedimentary pile developed between ~18 and 11 Ma, punctuated by volcanic activity around 15 Ma. According to Ebner and Sachsenhofer (1995), the basin has inverted since about 5–6 Ma causing the end of its aquatic evolution and the beginning of its uplift history. A second phase of volcanic activity

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

happened around the Plio-/Pleistocene boundary (Balogh et al., 1994; Gross et al., 2007). The onset of surface uplift in the hinterland is much less well constrained. The onset of general relief increase is inferred to have commenced around the Miocene/Pliocene boundary (Dunkl et al., 2005). Based on thermochronological data it is also known that at least 1000 m of sediment has been eroded since post-Middle Miocene times (Dunkl and Frisch, 2002) and vitrinite reflectance data and subsidence analysis in the Styrian Basin (Sachsenhofer et al., 1997) indicate that some 300–500 m of sediment has been removed in the last ~5 Ma. This time period coincides with the increase in eroded sediment volume of Kuhlemann (2007). An even more general spatially broad uplift within the last 5–6 Ma of the Alps has been recently discussed (Hergarten et al., 2010); this is also around the period when the inversion of the Pannonian Basin further east started (Horváth and Cloetingh, 1996; Bada et al., 2007). Ongoing lateral extrusion is indicated by GPS measurements (Bus et al., 2009) and strike-slip displacement along the major fault zones during recent glaciations of the region (Plan et al., 2010).

The course of the Mur River south of Bruck is of special interest within the Styrian Block as it is believed to be relatively young (post Middle Miocene). At the present time it forms a rather narrow valley upstream of Graz and then continues its course through the Styrian Basin. Whilst minor faults follow the same course as the river (Maurin, 1953), the Mur does not flow along any of the major faults in the region. Its formation has been related to headward migration and river capture of the Mur–Mürz drainage area (Dunkl et al., 2005; Wagner et al., 2010), however, the channel profile indicates morphological equilibrium and rather low values of stream power, in contrast to some of its tributaries (Robl et al., 2008a). Along its course, a series of planation surfaces, terraces and caves are developed up to many hundreds of meters above the current base level. The river also divides the landscape into a region with a peculiar but unexplained west–east asymmetry. In the mountainous region (known) caves and gravel deposits are predominantly preserved on the eastern side of the river. In the Styrian Basin this asymmetry is also apparent. Besides partial Pleistocene sediment cover, the youngest sediments in the western basin part are of Badenian age (Middle Miocene, ~13 Ma) whereas on the eastern part they are as young as Pannonian (Upper Miocene, ~7 Ma) with the occasional Pliocene pre- and postbasaltic gravels preserved around volcanic rocks (for the local Paratethys timescales used in this work see Piller et al., 2004). This hiatus in the west of more than 10 Ma becomes obvious in the geologic sketch map of Fig. 2 in Gross et al. (2007) and in the Austrian stratigraphic table of Piller et al. (2004). This asymmetry is still a matter of debate and no satisfying explanation is yet provided.

3. Morphological observations and their correlation

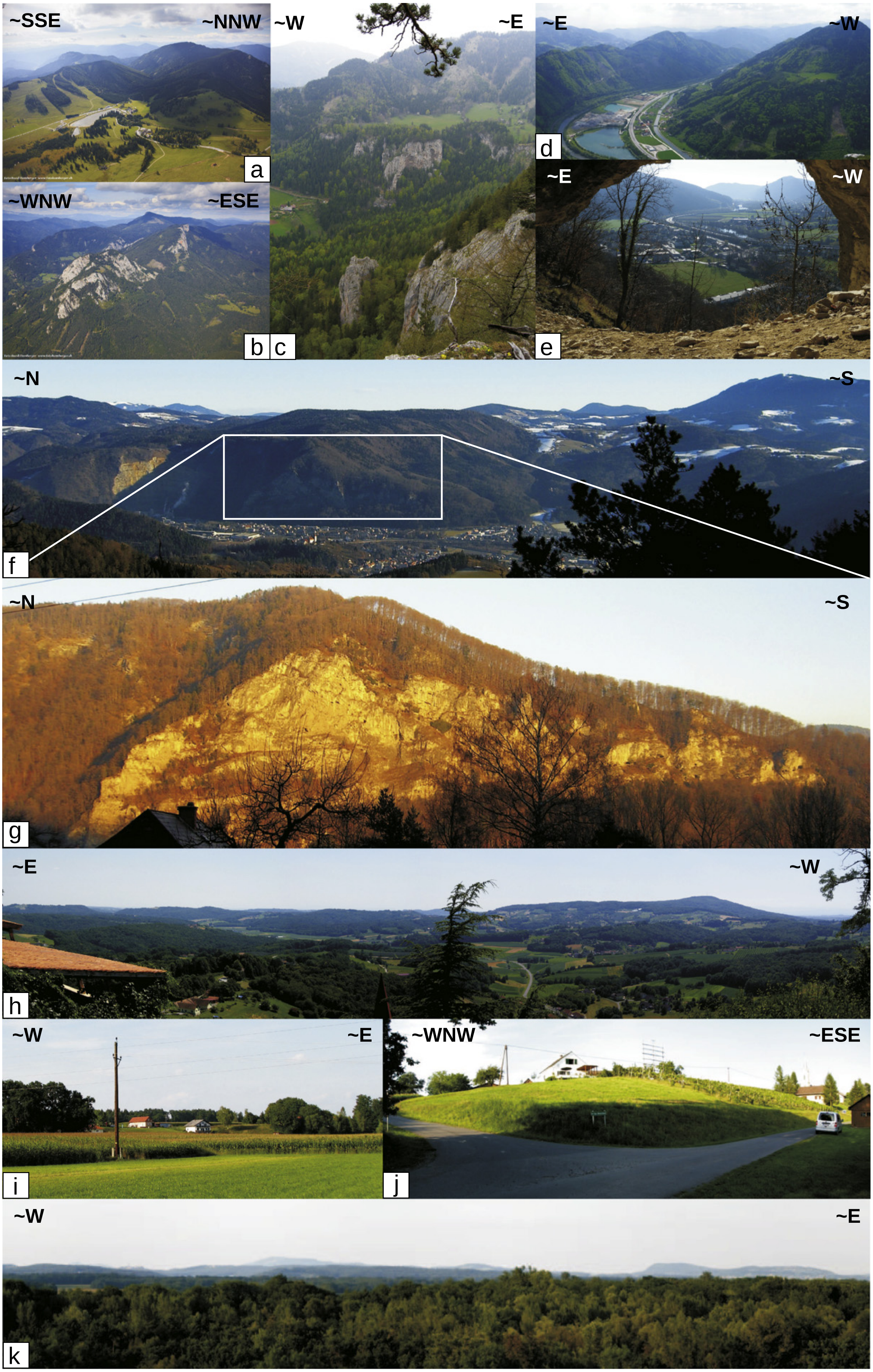
Along the course of the River Mur various geomorphic markers such as stream terraces, planation surfaces, denudation planes, and cave levels are preserved and will be used in the following to place constraints on the timing of landscape evolution (Table 1). The systematic investigation of these landforms by Winkler-Hermaden (1955, 1957) and later work based on his groundwork (e.g. Flügel, 1960; Untersweg, 1979; Gollner and Zier, 1985; Maurin and Benischke, 1992) provided a relative chronology of individual levels along studied profiles and the correlations to each other in the Styrian Block and beyond. Elevation differences of terraces and planation surfaces and different weathering intensities were the main distinctive features to distinguish the various levels from each other. Winkler-Hermaden (1957) identified the Kor and the Wolscheneck levels based on possible plain relics that can be found along crests of various elevations above 1300 ma.s.l. as the highest and oldest levels in the region. These levels will not be discussed here in more detail, as they find no counterparts in the Styrian Basin, they are badly developed (or preserved), their age constraints are rather ambiguous and signs of phreatic cave formation is absent (Untersweg, 1979).

3.1. Levels in the Styrian Block

Distinctive levels of the study area can be placed into two groups. The more elevated levels appear to be denudation plains, whereas levels at lower elevations are usually terraces. Below, we will touch on each of these levels starting from the highest: (i) The uppermost prominent level is the so-called Hubenhalt level (HUB) (Fig. 3). This level is presumably the oldest of all surfaces in the Styrian Block and occurs exclusively in the Highland at elevations around 1200 ma.s.l. It is of supposedly Middle Pannonian age (Winkler-Hermaden, 1957) and can be found as a pronounced planation surface east of the Hochlantsch summit: the Teichalm (Figs. 2a and 3a). The HUB is named after the Hubenhalt, a small planation preserved at a crest just southwest of Teichalm (Fig. 3a). (ii) The next lower (and younger) planation surface, possibly representing a dry valley, belongs to the Trahütten level (TH). The TH is pronounced at elevations of about 1000 ma.s.l. in the Highland and the crystalline basement and is supposedly of Latest Pannonian age (Winkler-Hermaden, 1957). This level is named after a planation surface on the eastern side of the Koralpe just west of Deutschlandsberg. This level is distinct due to its speleogenetic occurrences in the Central Styrian Karst, but not preserved in the Styrian Basin. In the Koralpe region, planations correlate well in elevation with planations in the Highland of Graz (Winkler-Hermaden, 1957) and further support the idea of a spatially broad evolution of planation surfaces along erosional base levels of that particular time over the whole Styrian Block regardless of lithology. This becomes even more evident for the subjacent level. (iii) The Hochstraden level (HS) is the highest level that can be observed both in the Highland and in the Lowland due to the preservation of denudation plains at about 550 ma.s.l. on top of a volcanic cone in the basin, the so-called Stradnerkogel (Fig. 3b). This level is of supposedly uppermost Pliocene age (Winkler-Hermaden, 1957). On top of this denudation plain so-called post-basaltic gravels are preserved in the vicinity of a locality named Hochstraden. An alias for this level is Kalkleiten–Möstl (Hilber, 1912). Kalkleiten is a locality to the north of Graz (Fig. 3a). It is an obvious planation surface termed the “balcony of Graz”. This system of planation surfaces was called “Gebirgsrandflur” by Untersweg (1979) and is highlighted as a level of continuous and widespread extent observed in various lithologies and across prominent faults. (iv) The double plain of Stadelberg/Zahrerberg (SB/ZB) is named after planations on the Stadelberg (~4 km east of St. Anna a. Aigen) and the Zaraberg (west of Klöch; previously named Zahrerberg) (Fig. 3b). This level is considered to be the last preglacial denudation plain developed around the Plio-/Pleistocene boundary and is found some 180 m to 300 m above the present base level of the Mur River. An exceptional view of the HS and the SB/ZB denudation plains is provided from the Kapfenstein castle on top of a volcanic cone (Fig. 2h).

The terrace levels that developed at lower elevations, from about 120 m above river level, down to the current base level of the Mur River, are obvious gravel terraces—that are often covered by thick loam deposits. In general these terraces are correlated to glaciations recorded in the headwaters of the Mur River (e.g. Piller et al., 2004). An upper terrace group (UTG) is distinguished from a middle terrace group (MTG) and a lower terrace group (LTG). The morphological distinction is easily identifiable in the Lowland where obvious terraces are developed, but is more difficult in the Highland as older terraces are obscured by younger sedimentation and erosion. (v) The UTG is suggested as representing an early Pleistocene outflow level and is placed somewhere in the Calabrian to Günz by Winkler-Hermaden (1955). (vi) The MTG includes terraces in the range of 40–100 m above the local base level. In the Lowland, in particular in the (Deutschen) Grabenland, the Schweinsbachwald terrace and a more elevated Rosenberg terrace are distinguished based on the different amount of denudation and dissection of the loamy cover section of these terraces. Further upstream along the Mur, the MTG and the UTG are not

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024



Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

Table 1
Condensed overview of levels preserved in the study area. Compiled with consideration of previous work by Winkler-Hermaden (1955, 1957), Untersweg (1979), Gollner and Zier (1985) and Maurin and Benischke (1992). Naming and proposed ages of these levels are listed according to various authors. Special features and peculiarities of the individual levels are highlighted. Approximate elevations of the levels for the study region are given in m above the present Mur River.

Level names	Aliases and/or subdivisions	Proposed age (W–H, 1955)	Features and peculiarities	Elevation above Mur River [m]
Kor level	–	Upper Sarmatian	Possible plain relics along crests	1200–1500
Wolscheneck level	–	Lower Pannonian	Possible plain relics along crests	900–1000
Hubenhalt level (HUB)	Glashüttner level	Middle Pannonian	First level indicating phreatic cave formation	700–800
Trahütten level (TH)	“1000 m—landscape”	Latest Pannonian	Pre-basaltic gravels	500–600
Hochstraden level (HS)	Kalkleiten-Möstl (Hilber, 1912); Gebirgsrandflur (Untersweg, 1979)	Uppermost Pliocene	Pronounced plain system; Pediment; postbasaltic gravels	325–450
Stadelberg/Zahrerberg level (SB/ZB)	–	Pliocene/Pleistocene	Last pre-glacial denudation plain(s)	180–300
“Obere Terassengruppe”, Upper Terrace Group (UTG)	–	Early Pleistocene, Calabrian to Günz	Early Pleistocene outflow level	80–120
“Mittlere Terassengruppe”, Middle Terrace Group (MTG)	Rosenberg terrace	Günz/Mindel to Mindel/Riss IG	Decarbonatisation, related to a warmer climate	60–100
	Schweinsbachwald or Kaiserwald terrace			40–60
“Untere Terassengruppe”, Lower Terrace Group (LTG)	“Hochterasse”, high terrace gravels (HT);	Riss to Würm glacial	Missing loamy cover sequence	35–40
	Helfbrunn terrace		Thick loamy cover sequence above “rotten” pebbles of crystalline rocks	25–40
	“Niederterrasse” (NT); low terrace gravels		Extended thick gravel deposit; 40 m deep trough below upper edge of Würm terrace	5–20
Alluvium	Mur floodplain	Holocene	Incised/nested in Würm terrace	0–10

distinguishable, because this is no longer possible in the narrower valleys. For simplicity, these terraces are referred to as having a pre-Riss age and termed older Pleistocene terraces of questionable age. However, it is noticeable that all these terraces are characterized by a top sequence of loam. (vii) The LTG is subdivided into the “Hochterrasse” (HT, high terrace gravels) and the “Niederterrasse” (NT, low terrace gravels). The HT is suggested to be of Riss glacial or Riss–Würm interglacial origin. Based on the fact that the HT relics in the Lowland have an obvious loam sequence developed on top of the gravels and the HT relics in the Highland lack this cover sequence, a further subdivision into a glacial and an interglacial terrace was suggested by Winkler-Hermaden (1955). The NT is an obviously pure gravel terrace of glacial origin related to the last glacial maximum (Van Husen, 1997) and is exclusively found along the Mur River and tributaries in the Koralpe region where local glaciers were established (Fig. 4c).

The various levels and planation surfaces listed above are concentrated in three key areas that will be discussed in some detail below. Two of them, the *Tanneben region* and the *Hochlantsch region*, are located within the Highland of Graz and belong to the Central Styrian Karst. In this area the abundance of caves and some remnants of planation surfaces have been studied in more detail. These are the regions of speleologic interest investigated by Wagner et al. (2010). The third region of interest is located in the Styrian Basin some kilometers downstream of Graz*: the Grabenland*, here, levels range from well preserved glacial and/or interglacial terraces to denudation planes at higher elevations on volcanic rocks.

3.2. The highland of Graz—in the Paleozoic of Graz

The Highland of Graz is part of the Paleozoic of Graz and consists of Paleozoic low grade metamorphic limestones, metavolcanics and schists. They comprise the Central Styrian Karst, an area of conspicuous landforms as old as the Miocene (Winkler-Hermaden, 1957) and which includes two regions of particular interest to our study: the Hochlantsch region and the Tanneben region (Fig. 3a). Various generations of planation surfaces, cave levels and dry valleys are apparent. Multi-stage entrenchment is obvious by these relics.

The Hochlantsch area at the northern edge of the Paleozoic of Graz includes the highest and possibly oldest levels recognized in the Highland of Graz. Various levels of karstification and caves formed as well as numerous planation surfaces (Fig. 2a–d). The largest cave system of the Hochlantsch region is the 4.4 km long Drachenhöhle system, some 500 m above the current river (entrance at 950 ma.s.l.). Cave systems show obvious stages of decay at elevations above ~1000 ma.s.l. as only remnants of previously interconnected systems are preserved. From the Teichalm peneplain at about 1200 m elevation (HUB level), a small lake drains through the Bärenschützklamm, a

Fig. 2. Field impressions of the study area: (a) Aerial photograph of the Teichalm planation (~1200 ma.s.l.), correlated to the Hubenhalt level. Downstream of the lake, the Mixnitzbach creek crosses the Bärenschützklamm gorge. (b) Aerial photograph from the Hochlantsch region. The Röthelstein (1263 ma.s.l.) in the foreground, with the Bucheben saddle (1081 ma.s.l.) and then the Rote Wand (1505 ma.s.l.) behind to the NE. The summit in the background is the Hochlantsch (1720 ma.s.l.). Aerial photographs (a) and (b) courtesy of Ruedi Homberger. (c) View from the Bucheben saddle towards north. Two planations are separated by a steep rockwall. The upper planation surface is correlated to the HS (here ~850 ma.s.l.) and the lower to the SB/ZB level (~700 ma.s.l.). (d) Planation surfaces along the Schiffal (~750 ma.s.l.) correlate to the SB/ZB level, seen from the Röthelstein close to the entrance of the Drachenhöhle (DH). Note the gravel pits and a swimming pond along the Mur River. (e) View from a cave of the Peggauerwand rockwall at 511 ma.s.l. down into the Mur valley towards south. Based on burial ages of cave sediments this cave level at about 100 m above the current base level of the Mur developed ~2.5 Ma ago. (f) View from the west towards the Tanneben massif. The plateau right above the rock wall and the quarry can be clearly seen. This planation belongs to the HS. The peak in the upper right of the picture is the Schöckl (1445 ma.s.l.) and the village visible in front of the Tanneben massif is Peggau (410 ma.s.l.). The town is located in the Mur valley, which forms the current base level. (g) Detailed photograph of the Peggauerwand rockwall. The obvious perched caves indicate former water tables and groundwater elevations, thereby illustrating relative valley lowering over the last million years. (h) View from Kapfenstein towards south. The plateau-like rise (~550 ma.s.l.) in the right of the picture is the Stradnerkogel. The planation surface is correlated to the HS. Further to the east planation surfaces of the Zaraberg and the Stadelberg are noticeable (~400 ma.s.l.). They belong to the subsequent SB/ZB level. (i) and (j) Terrace riser (anthropogenic changes are likely) of the Helfbrunn terrace, seen from the low terrace gravels. The investigated loam pit is situated some 100 m to the North. (k) View from Gosdorf “Murturm” towards the north. Terraces and planation surfaces are visible, although the forested floodplain makes it difficult to clearly see terrace risers. Note the grassland in the lower left of the picture, which belongs to the Helfbrunn terrace. In the background the volcanic cones of Stradnerkogel (left) and Klöch (right) with their pronounced denudation plains are noticeable.

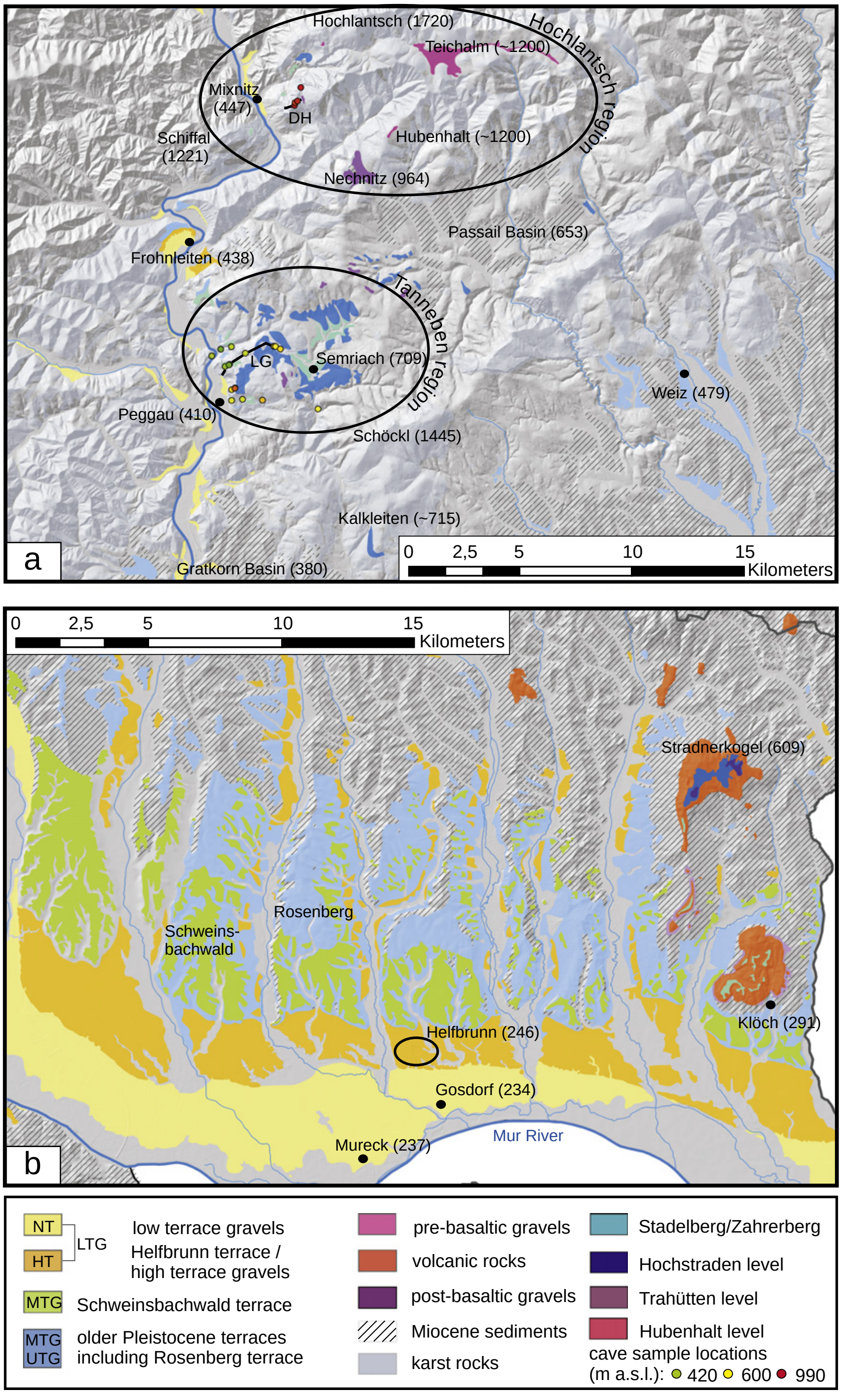


Fig. 3. More detailed level overview of the Highland (a) and the Lowland (b). (a) The Highland of Graz with the focus on the Hochlantsch region with the HUB (Teichalm), the TH (Bucheben); the HS (Burgstall top) and the SB/ZB (Burgstall base) and the Tanneben region with preserved levels related to the TH and lower levels. (b) The Grabenland as the main focus of the Lowland of Graz shows an obvious valley asymmetry and the various levels ranging from the denudation planes of the HS and the SB/ZB to the terrace levels of the UTG, MTG and LTG. Pre- and post-basaltic gravels related to volcanic rocks are also displayed. The loam pit where the samples for OSL dating were taken is indicated by a black circle. All numbers in parentheses are elevations in ma.s.l. For abbreviations refer to Table 1.

deeply dissected limestone gorge, in a westerly direction towards the Mur River (Fig. 2a). The channel profile of this creek (Mixnitzbach) shows an obvious knickpoint and stream power is the highest in the Mur catchment (Robl et al., 2008a) where the Mixnitzbach crosses a gorge (Bärenschützklamm). The dry valley of Nechnitz (964 ma.s.l.), where some of the highest Neogene fluvial deposits are preserved, is correlated to the TH and is suggested to indicate a former southward dewatering trend (e.g. Winkler-Hermaden, 1957). The occurrence of Upper Cretaceous Bärenschütz conglomerate at various elevations ranging from 600 to 1300 ma.s.l. is related to Neogene block tectonics along an obvious NE–SW trending fault zone crossing the Mixnitzbach (Gollner and Zier, 1985). However, a continuous plain relic on top of the younger (Neogene) Burgstall Breccia (Fig. 2c) is correlated with the HS and indicates no vertical displacement since the time of its evolution.

In the Tanneben region highest elevations are around 1100 m and the region thus preserves only levels at and below the TH. Relics of higher landforms are only preserved in isolated remnants of the

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

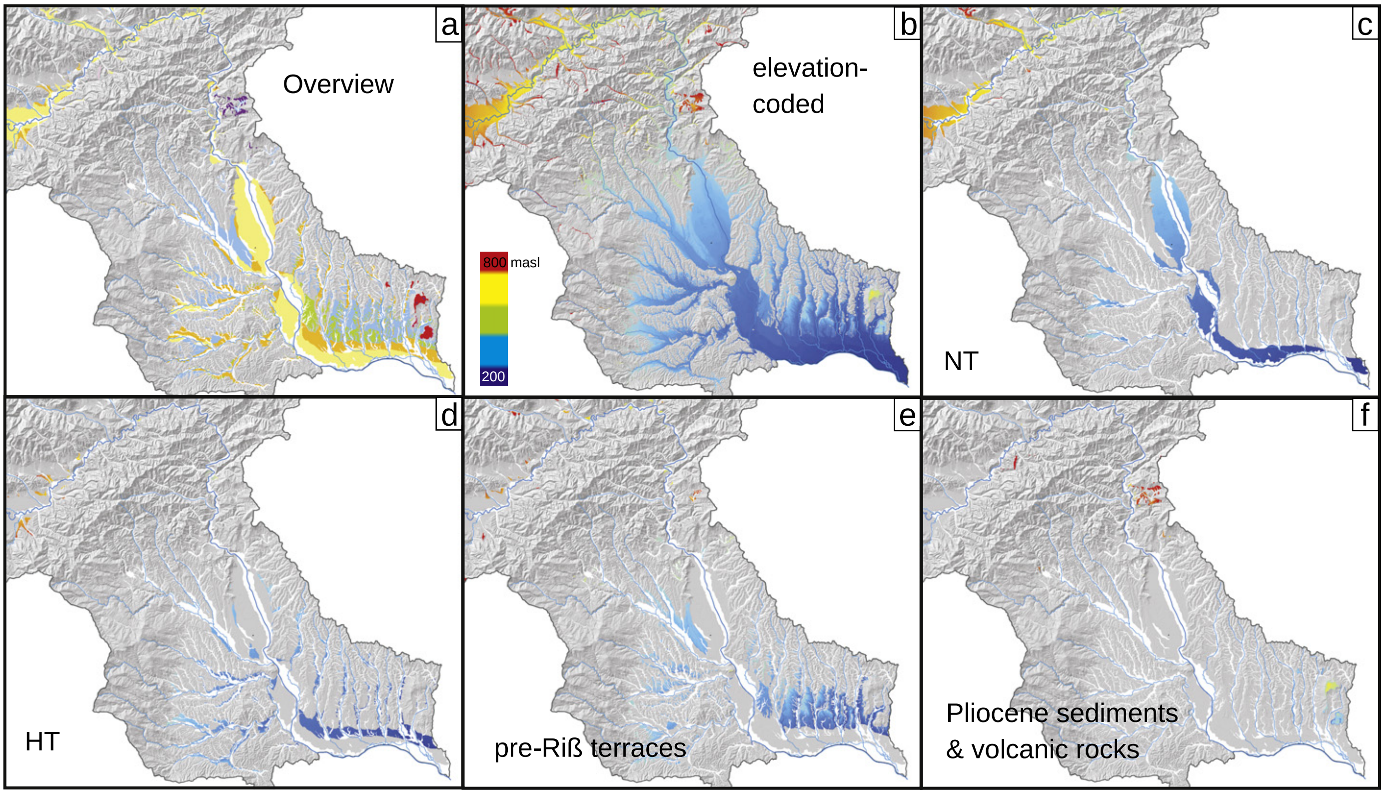


Fig. 4. Elevation-correlated sediment distribution for the various time slices from Pliocene to Pleistocene preserved in the Mur catchment. (a) Overview of Pliocene and Pleistocene sediments of the Mur catchment only; labeling according to Fig. 1. (b–f) Color-coding according to elevations from 200 ma.s.l. (blue) to above 800 m a.s.l. (red). (b) similar to (a) but color-coded according to elevation. (c) The low terrace gravels (NT) are exclusively found along the Mur River and along tributaries from the glaciated Koralpe summit; (d) the high terrace gravels (HT) are evenly distributed all over the tributaries. (e) The same is true for the higher terrace levels (not further sub-divided). (f) Almost no Pliocene sediments are preserved.

Schöckl limestones in the eastern part of the Semriach Basin. The Tanneben massif is also an area of great speleological significance, which is manifested by an abundance of some 300 caves relating to cave levels at and below the HS including one of the largest cave systems of the region: the ~6-kilometer long Lurgrotte system. An old burial age (see Section 4.1) of ~5 Ma from a cave which indicates remobilization from an older, higher and nowadays eroded cave level indicates the presence of older levels in former times (Wagner et al., 2010). However, the preserved lower levels are more prominent in this region than compared to the Hochlantsch area further north. The HS typified by the planation surface above the Peggauer Wand in the Tanneben massif (Fig. 2f) preserved widespread fluvial gravel spreads (e.g. Ertlhube) and are evidence of a low-gradient Paleo-Mur River prior to its incision into the present valley slightly further west. Later, the incision of the Mur River seems to be more vertical and not much lateral incision is observed in the Highland of Graz.

The Lurgrotte cave system has both autogenic and allogenic recharge from the Semriach Basin, a small intramontane Neogene depression and is known to be Austria's longest show cave with an active stream. Impressively, the hooklike course (a 90° bend) of the Lurbach creek upstream of Semriach shows the deviation from its former SW oriented drainage course (e.g. Maurin and Benischke, 1992). The Rötschgraben which drained the hinterland of the Tanneben massif prior to these changes in the hydrological setting (e.g. Untersweg, 1979) shows a prominent knickpoint, the so-called Kesselfall. The former dewatering of the Lurbach to the south into the Rötschbach is related to a swell at the southwestern side of the Semriach basin comprised of gravels of unconstrained age (Pannonian or younger). This swell is found at elevations corresponding to the HS, indicating the time of the Lurbach stream capture event and its subsequent subterraneous course (e.g. Maurin and Benischke, 1992). The paleo-Mur has also probably shifted westwards as a dry valley on the southern side of the Tanneben massif indicates (e.g. Maurin and Benischke, 1992). In this fluviokarst area the lowering of the erosion base, the Mur River, beheaded and diverted tributaries. Some of them disappear into ponors like the Lurbach into the Lurgrotte cave system (the main ponor), due to subterraneous corrosion and erosion. Due to the karst terrain, the equivalents to some planation surfaces along the Mur valley are preserved underground as karstic features. This allows the correlation of speleogenetic levels and surface forms. The Peggauer Wand (Fig. 2e–g) is a beautiful example where cave streams emerge as springs along the base of a valley wall. More elevated abandoned cave passages form speleogenetic levels and indicate paleo-base levels, representing former valley bottom elevations. The system shows three phreatic levels (e.g. Maurin and Benischke, 1992). The lowest permanently active level shows obvious signs of back-flooding that can be related to aggradation of sediments within the valley itself and consequently plugging and a temporary increase in the local base level (Wagner et al., 2010). Occurrences of gravels related to the last glacial advance and siphons ascending to the current outlet of the cave system indicate possible deeper karstification and consequently deeper valley incision prior to the last glacial maximum (LGM); but only in the order of a few meters to a maximum of 40 m. This value is based on drillings near the town of Peggau penetrating the gravel deposits down to the bedrock (Weber, 1969) and shows that the Mur River has not yet during the Holocene re-excavated sediments related to the LGM.

In general, speleogenetic levels encountered in the Central Styrian Karst are linked to surface levels. These were described by Wagner et al. (2010) and termed cave levels A to E. We will relate this nomenclature to the traditional level names described above. Cave level A can be correlated in elevation to the Trahütten level (TH); cave

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

level B to the Hochstraden Level (HS); C relates in elevation to the Stadelberg/Zahrerberg level (SB/ZB) and marks the lowest pre-glacial denudation plane; D represents the Upper Terrace group (UTG); and level E covers the Middle Terrace Group (MTG) and the Lower Terrace Group (LTG). The LTG in turn combines the high terrace gravels (HT) and the low terrace gravels (NT). The larger extent of level E identified by Wagner et al. (2010) is the consequence of various sublevels which are closely spaced and/or even overlapping, therefore causing (sub-) levels which are not distinguishable as individual speleogenetic levels. This is attributed to the episodic incision, aggradation and re-excavation of the Mur valley in that period of time. However, individual terraces are distinguished in the Styrian Basin, the Lowland of Graz, and allow a separation of these younger individual stages of landscape evolution.

3.3. The lowland of Graz—the Styrian Basin

In the Lowland of Graz, the so-called Grabenland region (Figs. 1b and 3b) is of particular interest. The Grabenland is a southward draining region of a series of parallel tributaries to the Mur River in the central Styrian Basin (Fig. 1b) and occurs between 200 m and 600 m above sea level. The highest elevations are typically those of the volcanoes. The Grabenland features a series of terrace levels and planation surfaces on the Plio/Pleistocene volcanoes that can be used to place time constraints on their formation. Importantly, the Grabenland is also the type locality of the high terrace gravels (HT). The so-called Helfbrunn terrace is the terrace right above the NT. As the latter is the terrace related to the last glacial maximum, the next higher one, the Helfbrunn terrace is generally, believed to relate to the penultimate glaciation (Riss) or to the Riss–Würm interglacial. The Helfbrunn terrace shows a much higher disintegration of the individual clasts compared to the low terrace gravels. This was the main argument for proposing an older age (Riss glacial) of this terrace (Fink, 1961). Mottl (1946) reported *Ursus spelaeus* in fluviatile cave sediments in a Kugelstein cave 40 m above the Helfbrunn terrace level, which occurred in the Mindel–Riss interglacial. As this cave belongs to another older level, a Würm–Riss interglacial has been suggested by Winkler-Hermaden (1955), who favored an interglacial origin of the terrace. The gravels of the Helfbrunn terrace are covered by an up to 8 m thick dust loam of rather questionable origin. This loamy section is not a classic loess deposit, however, as it is free of carbonate. There are at least two other obvious terraces at higher elevations: the Schweinsbachwald and the Rosenberg terrace (Fig. 3b) which are similar in composition to the Helfbrunn terrace with a thick loamy top section. The fact that the Helfbrunn terrace is accessible due to an outcrop in a former loam pit, enabled sampling along a profile from the top of the deposit down to the beginning of the gravel pack. The application of optically stimulated luminescence (OSL) dating allowed a minimum age constraint to be placed on the terrace deposit (Section 4.2.1).

Besides the terrace levels, there are also higher and thus probably older planation surfaces up to the volcanic cones of Klöch and Stradner Kogel (Fig. 3b). A very prominent denudation plane on top of the Zaraberg (or Zahrerberg) has developed. This level corresponds to the last denudation plane prior to the onset of climate deterioration around the Plio-/Pleistocene boundary (Winkler-Hermaden, 1955): the SB/ZB level. The number of the main stream terraces in the region (low terrace gravels, Helfbrunn terrace, Schweinsbachwald and Rosenberg terrace) matches with the four glaciations (Würm, Riss, Mindel and Günz). However, although tempting to infer, it does not mean that they necessarily correlate in time. To the contrary, Winkler-Hermaden (1955) argued that the more elevated loam covered terraces are of interglacial origin. Fig. 4 indicates various time slices of sediments of different times of deposition. It is evident that only the last glacial terrace is almost exclusively constrained along the Mur River and its tributaries from ice-free hinterlands do not contain gravels of the NT. We will address this observation in Section 4.2.

4. Age constraints on levels

An essential correlation between surface planation features and cave levels in the Tanneben region was performed by Maurin and Benischke (1992), who realized the potential of the preserved information in the caves in comparison to the more easily eroded surface features. As burial age data were not available at that time, they used the surface forms and their age estimates (based on the work of Winkler-Hermaden, 1955) to get an approximate age of the formation of various cave levels. Here we extend their work further up- and downstream, covering the whole Paleozoic of Graz and the Styrian Basin. In our approach, we use the new age constraints on the cave levels provided by Wagner et al. (2010), and correlate these across the orogen-basin transition with various planation surfaces. For the correlation we also use published K/Ar ages of volcanic rocks exposed in the Styrian Basin (Balogh et al., 1994) and new OSL age estimates from fine-grained deposits of a stream terrace in the Styrian Basin. Furthermore, U–Th ages of speleothem formation are used to draw conclusions on the climate conditions at their time of deposition. Combining all this numerical age information, the relative levels along the Mur River are placed into absolute time spans.

4.1. Ages of levels in the highland

Levels in the Highland are best dated through their proxy in the speleogenetic levels. The evolution of the various speleogenetic levels and their age can be constrained by ages of cave deposits (e.g. Stock et al., 2005). Dissolution caves are younger than the host rock and older than deposited sediments therein, if remobilization can be excluded. As the cave deposits provide minimum age constraints for the cave development, they also yield minimum age constraints of parallelized surface forms. Burial ages of allochthonous quartzose cave sediments were found to be best suited to constrain the age of cave passage formation (see Appendix B and e.g. Granger et al., 1997; Anthony and Granger, 2004, 2007; Refsnider, 2010). Table 2 extracts this information from the data presented by Wagner et al. (2010).

The HUB level including the Teichalm planation surface has no corresponding speleogenetic level of known age, so its age remains speculative. Cave level A, and consequently also the TH, is at least 4 Ma old, based on burial ages of allochthonous gravels from the

Table 2
Cave levels and their minimum age constraints based on sediment burial ages from Wagner et al. (2010).

Speleogenetic level	Samples	Minimum age (Ma)	Comments	Elev. above Mur (m)	Associated levels
A	DH4	~4	The "1000 m" level; Bucheben; Trahütten/Koralpe	500+	TH
B	DH1, DH2	~3.4	Tanneben plateau, Kalkleiten, Stradnerkogel	325–375	HS
C	Between LG2 and LG3	~3	Last pre-glacial denudation plains	210–250	SB/ZB
D	PWH3, FG1, KG1	~2.5	Corresponds to Plio/Pleistocene boundary	~100	UTG
E	Between SG3 and today	0–2.5	Multiple sublevels, complicated due to aggradations and re-excavations	0–75	MTG—Holocene

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

Table 3

U–Th age estimates of speleothems from the Lurgrotte (LG) and the Drachenhöhle (DG) caves in the Central Styrian Karst. Samples with a superscript # were previously published by Wagner et al. (2010). Activity ratios were determined at The University of Melbourne using a Nu Plasma MC–ICP–MS following the procedure of Hellstrom (2003). Ages are corrected for initial ^{230}Th using Eq. (1) of Hellstrom (2006) and an initial $[^{230}\mathrm{Th}/^{232}\mathrm{Th}]$ of 1.5 ± 1.5 (uncertainties fully propagated). 95% confidence intervals of the last digits of each value are given in brackets.

Sample	Lab no.	U ($\mathrm{ng\,g^{-1}}$)	$[^{230}\mathrm{Th}/^{238}\mathrm{U}]$	$[^{234}\mathrm{U}/^{238}\mathrm{U}]$	$[^{232}\mathrm{Th}/^{238}\mathrm{U}]$	$[^{230}\mathrm{Th}/^{232}\mathrm{Th}]$	Age (ka)	$[^{234}\mathrm{U}/^{238}\mathrm{U}]_i$
LG10-FST2	UMA02798 Jul-2009	51	1.384 (7)	2.632 (5)	0.00296 (3)	3.0	74.2 ± 0.6	3.013 (6)
LG10-FST1	UMA02797 Jul-2009	95	1.328 (8)	1.831 (5)	0.32516 (74)	2.2	92.6 ± 35.6	2.081 (107)
LG10-FSB#	UMA02796 Jul-2009	80	1.285 (7)	1.736 (4)	0.29751 (169)	2.1	99.9 ± 32.2	1.977 (88)
LG6-FSB#	UMA02795 Jul-2009	104	1.081 (5)	1.688 (5)	0.02254 (24)	1.9	99.6 ± 2.1	1.913 (7)
DH4-FST	UMA02794 Jul-2009	127	1.965 (8)	1.980 (4)	0.01681 (21)	2.9	228 ± 2.9	2.871 (14)
DH4-FSB#	UMA02793 Jul-2009	72	1.113 (10)	1.084 (4)	0.22907 (162)	1.4	559 (+inf/−110)	1.43 (+inf/–0.13)

Drachenhöhle (DH, Fig. 3a). The planation (or dry valley) of Nechnitz is slightly above this elevation, and thus may correlate in age, but has not been dated directly. Cave level B, analogous to the HS is more than ~3.4 Ma. We suggest placing its formation between 3.4 and 4 Ma; a rather short period of time for its wide extent in the study area (Untersweg, 1979). Level C and the SB/ZB level have to be placed ~3 Ma. The level D and the associated UTG is constrained by burial ages of ~2.5 Ma and marks the abandoning of cave passages just ~100 m above the current stream. From this time on, speleogenetic levels are more ambiguous. This has been related to episodic aggradation events in the Mur valley (Wagner et al., 2010) and is in agreement with the fact that the SB/ZB level is recognized as the last pre-glacial denudation plane (e.g. Winkler-Hermaden, 1955). The actual time constraint of ~2.5 Ma coincides with the onset of the Pleistocene climate deterioration. Level E contains various sub-levels which have to be placed within the Pleistocene. A more detailed subdivision is possible by analyzing the stream terraces further downstream in the Lowland; this will be discussed in Section 4.2. However, burial ages of level E that do not correspond to the actual abandonment of the passage level, and instead indicate an aggradation event ~450 ka most likely related to a damming event in the Mur valley. This concerns samples LG6 and LG8 from two different sub-levels of the Lurgrotte (LG, Figs. 3a and 7). This increase in sediment load was correlated with MIS 12 and the Mindel glaciations affecting the headwaters of the Mur catchment (Wagner et al., 2010). Although these samples did not yield information about the time of passage formation, they place lower limits of the passages extent at that period of time. This suggests that at this time, the local base level was already close to the current one. Ongoing re-excavation of gravels from the modern river bed demonstrates the current transport-limited state of the Mur River. This results in limited bedrock incision since the last glacial maximum in this particular case and also suggests a similar scenario may have occurred in previous interglacials. This is in accordance with the strong mean decrease in incision rates in the Pleistocene suggested by Wagner et al. (2010).

4.1.1. U–Th ages of speleothems

U–Th age estimates of bottom sections of speleothems which are stratigraphically related to some of the allochthonous cave sediments dated by TCN were used as minimum age control for the TCN ages (Wagner et al., 2010). These ages (Table 3) are an order of magnitude younger than related TCN burial ages, confirming the findings of Stock et al. (2005) that speleothem ages could considerably underestimate the age of void evolution. There are three more U–Th age estimates of the top sections of the speleothems presented here (Table 4). However, as their formation is mainly related to appropriate environmental conditions (Spötl and Mangini, 2006; Spötl et al., 2007) and the relation to the individual levels is secondary, we will discuss these data without the reference to the specific levels. In fact, the timing of formation of speleothems allows us to infer interglacial (or interstadial) times.

All U–Th ages of speleothems are in the range between 74 ka and 228 ka and were derived from flowstones and calcite false floors (flowstone that was deposited on sediments that have been eroded later). Ages from the Lurgrotte are at the younger end of this spectrum. Sample LG10-FST2 gave the youngest U–Th age of 74.2 ± 0.6 ka and could be correlated to Marine Isotope Stage (MIS) 5a. (Sample names are related to TCN burial age samples and are indicated by the similar sample name, and taken from the top (FST) or the bottom section (FSB) of the flowstone; Table 4). Another three of the Lurgrotte samples (LG6-FSB, LG10-FSB and LG10-FST1) yield ages between 90 and 100 ka, correlated to MIS 5c. Detrital thorium contamination of some of these samples resulted in rather large uncertainties (Table 4). These age ranges for speleothem formation from the Lurgrotte cave system suggests ice-free, soil-covered conditions consistent with interstadial conditions of MIS 5a and c. The single age of the Drachenhöhle sample DH4-FST of 228 ± 3 ka correlates to MIS 7 and further documents the match of speleothem formation and interglacial (or interstadial) times. The DH4-FSB yielded an age at the detection limit and will not be used for evaluation. A speleothem from the cave Moosschacht, located in the Tanneben massif close to Ertlhube at level B, indicates discontinuous speleothem growth at a time span of 105 to 80 ka (Spötl et al., 2007), similar to our samples from the Lurgrotte. Interestingly, Spötl and Mangini (2006) reported calcitic flowstone formation in fractures of the Pleistocene Hötting Breccia near Innsbruck at the same periods of time (between 100.5 ± 1.5 and 70.3 ± 1.8 ka), thereby demonstrating an ice-free central Inn valley. Although more detailed analysis of speleothem formation in the Central Styrian Karst would be desirable (see also Boch et al., 2010), these initial results are strong evidence for

Table 4

Luminescence ages of the Helfbrunn samples. The table includes details of grain size used in OSL analysis; average field water content of samples measured in the laboratory; potassium, uranium and thorium concentrations; the cosmic dose-rate; and the total effective dose-rate from the environment to quartz grains 4–11 μm in diameter taking into account the alpha efficiency factor; the number of aliquots measured (n); the burial dose; and the calculated age estimate.

Sample name	Grain size (μm)	Water content (%)	Potassium (%)	Uranium (ppm)	Thorium (ppm)	Cosmic dose rate (Gy/ka)	Total environmental dose-rate (Gy/ka)	n	Burial dose (Db) (Gy)	OSL age (ka)
HBT	4–11	22.7 ± 5	1.68 ± 0.08	4.10 ± 0.21	13.10 ± 0.66	0.18 ± 0.02	3.53 ± 0.13	24	242.3 ± 10.9	68.7 ± 4.0
HBS	4–11	22.7 ± 5	1.78 ± 0.09	4.10 ± 0.21	12.60 ± 0.63	0.09 ± 0.01	3.48 ± 0.13	24	280.1 ± 6.9	80.5 ± 3.7

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

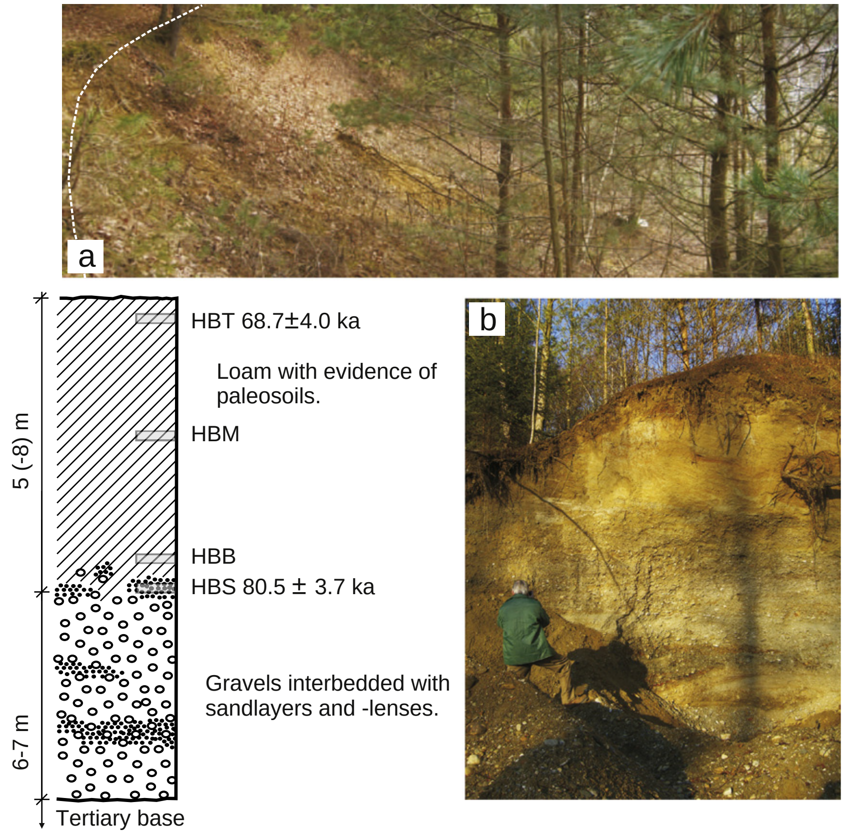


Fig. 5. The Helfbrunn terrace sampling location in a former loam pit, the type locality. A schematic profile (modified after Suette, 1986) indicating sampling points and the OSL age of the two dated samples HBT and HBS. HBM and HBB could not be dated, see Appendix A (a) View from the rim of the former loam pit (dashed white line) down the sampled profile. The base is close to where the gravels are encountered. (b) An outcrop near the sampled profile, where gravels are exposed. Person for scale.

ice-free, soil-covered conditions in the Styrian Block at periods of ~230, ~100 and ~70–80 ka.

4.2. Ages of levels in the lowland

The highest planation levels preserved in the Lowland are on Pliocene to Pleistocene volcanoes and correlate with the HS and the SB/ZB levels. The highest terrace level in the Lowland of Graz (UTG) correlates with the UTG in the Highlands and the dated cave level D (about 2.5 Ma). Thus, all other lower levels in the Lowlands are likely to be younger. In fact, all terrace levels are associated to various glaciation events in the Pleistocene (e.g. Van Husen, 2000). A relatively young phase of volcanic activity in the Styrian Basin is scattered over a time frame of 1.71 ± 0.72 to 3.76 ± 0.41 Ma based on K/Ar ages of these volcanic rocks (Balogh et al., 1994). These data place maximum age constraints on planation surfaces developing subsequently on these rocks and gravel accumulations that were deposited on top of these surfaces, the so-called post-basaltic gravels.

In the Mur catchment area, the volcanic cones of Klöch and Stradnerkogel are of particular importance: on both, planation surfaces are developed. At about 550 ma.s.l. a striking planation formed on the Stradnerkogel (Fig. 3b), the HS is named after this locality. On a lower level of the Stradnerkogel and on the Klöch basaltic rocks, the SB/ZB level can also be distinguished. Balogh et al. (1994) report a K/Ar-age of the basalt of Klöch of 2.56 ± 1.2 Ma. These data place a maximum age constraint on the SB/ZB level, and suggests that the formation of this last pre-glacial denudation plane might not be older than the upper limit of the basalt age (2.56 + 1.20 = 3.76 Ma). From the burial age data of level C, which is correlated to the SB/ZB level, we propose an age of at least 3 Ma. These data are in good agreement with one another. A bit more problematic is the K/Ar-age of the Stradnerkogel. A sample was analyzed by Balogh et al. (1994) from the quarry close to the above mentioned striking planation surface on the Stradnerkogel; this sample resulted in the youngest of all the reported K/Ar-ages (Balogh et al., 1994): 1.71 ± 0.72 Ma. This would imply that the HS is younger than 2.43 (1.71 + 0.72) Ma which is in contradiction with our data (level B ≥ ~3.4 Ma). This young K/Ar-age does not only disagree with the age constraints of level B (HS), but also with level C (SB/ZB) and to some degree even with level D (UTG). This raises some reasonable doubt about the single K/Ar-age or could suggest a vertical displacement of the Stradnerkogel region of some 100–200 m after the formation of the plain, which is not supported by any field evidence.

None of the levels below the UTG are well constrained in time by numerical age data. Only the lowest level (NT) is known to be of Würmian age (Van Husen, 1997). Interestingly, sediments related to the last glaciations (NT) are deposited exclusively in the Styrian Basin along the Mur River whilst being absent in tributaries where headwaters originate from non-glaciated regions (Fig. 4c, e.g. the ones in the Grabenland). This observation does not apply for higher and thus older terraces (Fig. 4d–e). The distinction from the NT is made by the fact that only the terraces found at higher elevations show extensive loamy cover sequences (excepting the terraces near Frohnleiten at elevated positions, likely related to Riss glaciation). The older "floor relics" show, according to Winkler-Hermaden (1955), a succession of gravels–gravel/sand–sand–sandy loam–loam. The terraces with a loamy upper section spread far into the plains downstream of Bad Radkersburg, in contrast to the glacial terraces which taper off closer to the orogen margin. This difference in characteristics resulted in the idea that the more elevated terraces

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

might be of interglacial or interstadial origin, not related to a glacial maximum (Winkler-Hermaden, 1955), however other authors, e.g. Fink (1961), favored a glacial origin.

4.2.1. OSL age constraints for the high terrace gravels

To contribute to the clarification of the absolute ages, we report here the first successful dating of the type locality of the Helfbrunn terrace, which belongs to the HT. The sample location is an abandoned loam pit near Gosdorf (Fig. 3b). The HT rises about 10 m above the last glacial gravel spreads (NT, Fig. 2i–j) of the Late Würmian glaciation. Because of the higher position, the terrace is believed to be of Riss–Würm interglacial (Winkler-Hermaden, 1955) or possibly Riss glacial origin (Fink, 1961). The terrace sequence can be divided into a loamy upper section and a gravel base. It is conspicuous that individual pebbles of the basal gravels are of a rather decomposed state (heavily weathered) compared to the intact gravels of the NT gravels and this was used to justify an older age of this terrace compared to the lower terrace (Winkler-Hermaden, 1955; Fink, 1961). Based on drillings done in 2008, it was proven that the gravel thickness is not more than about 6–7 m (below about 5–8 m of loam), with Tertiary sediments encountered thereafter (Fig. 5). This is an important confirmation that the Helfbrunn terrace is indeed an individual terrace that was deposited on its independent base level prior to further river incision and deposition of the next lower terrace, the NT. The top section of the terrace consists of up to 8 m thick loams which are interpreted in various ways and termed alluvial clay, dust loam or loess (Suette, 1986). Winkler-Hermaden (1955) suggested them to be mostly warm-temperate alluvial clays; whereas Fink (1961) was of the opinion that at the transition from gravels to loam, fluvial origin is likely but in the higher sections eolian processes were responsible for their formation. Fabiani and Eisenhut (1971) mentioned that pedologically these are cold temperate dust loams. The important point is that the shift from gravels to loams is without doubt of fluvial origin; this is manifested by an intercalation of gravels and loams. Winkler-Hermaden (1955) reported that gravels are found in the lower sections of the loam and vice versa, demonstrating a continuous sedimentation process. This fact was the motivation for dating the top loam section via OSL (Bøtter-Jensen et al., 2003) to obtain a time constraint for this terrace; however the actual absolute age of the base remains speculative. Four samples along a profile of the former loam pit were taken avoiding any exposure of the samples with sunlight (Fig. 5). Sample HBT was taken at the top of the terrace sequence and HBM in the middle of the loam section. HBB came from the bottom of the loam sequence along this profile and sample HBS from a sandy layer (or lens) directly below HBB and at the transition to the gravels. Along the sampling profile no change could be identified which would point to a change in climatic conditions in deposition. The loam sequence seems to be the consequence of a single stadial or interstadial period.

The OSL ages of the two successfully dated samples HBT and HBS are 68.7 ± 4.0 and 80.5 ± 3.7 ka, respectively. Detailed results are presented in Table 4 and information about sample preparation and measurement procedure is found in Appendix A. More details are shown in the supplement. These age estimates place the deposit in the Early Würm and not in the Riss–Würm interglacial or Riss glacial as previously suggested (Winkler-Hermaden, 1955; Fink, 1961). Although the sample HBB had to be rejected due to its high clay content, its position just above the HBS sample, a more sandy layer or lens at the transition to the gravel base, supports the idea that at least the transition of gravels and loams is of fluvial origin and this sample might represent a late stage of an alluvial sedimentation cycle. A continuous sedimentation process of the whole terrace sequence also suggests that the basal gravels belong to the Early Würm. These gravels could indicate outwash from ice advances correlated with MIS 5b or 5d and therefore allow speculation about the existence of these Early Würm stadials which are not yet reported from the Eastern Alps (Ivy-Ochs et al., 2008). The two samples span the whole dust-loam sequence, placing it into the interstadial correlated to MIS 5a and yield an average rate of deposition of about 0.5 mm/a. This dating attempt can be seen as the first successful study that allows the terrace formation to be constrained by a numerical age estimate.

5. Age correlations between highland and lowland

Various terraces and planation relics can be traced continuously from the Lowland into the Highland of Graz (Winkler-Hermaden, 1955). There is no sign of significant misalignment even at the (Alpine) orogen- (Pannonian) basin transition zone north of Graz (Fig. 6). A slight increase in the gradients of the individual levels along the Mur River from younger to older (higher up) levels is observed (Fig. 6 inset). This indicates the influence of an uplifting realm (e.g. Häuselmann et al., 2007a), however the signal is too small to account for high rates of uplift. Vertical offsets between the Highland and the Lowland are negligible in the time frame covered by these geomorphic markers, and thus allow the use of relative chronology which relates higher levels to be of generally older age (e.g. Winkler-Hermaden, 1955, 1957). Furthermore, it allows the application of available numerical age data of individual sites for the whole level further up- or downstream along the Mur River course. Fig. 7 assembles all these

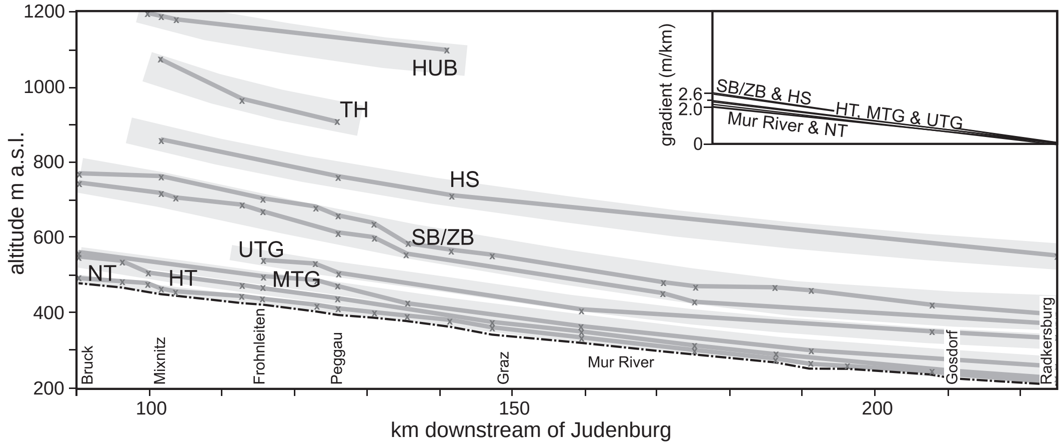


Fig. 6. Longitudinal channel profile of the Mur River and reconstruction of the longitudinal sections of the terrace and level spreads along the Mur River between Bruck and Bad Radkersburg. The profile is measured downstream starting at Judenburg, where the LGM terminal moraines are found. Minor deviations from general trends are likely related to various degrees of denudation and not the result of vertical displacements. The inset shows the various gradients indicating increasing gradients with increasing age and/or elevation from ~2 m/km of the current Mur River and the NT to ~2.6 m/km of the SB/ZB and the HS.

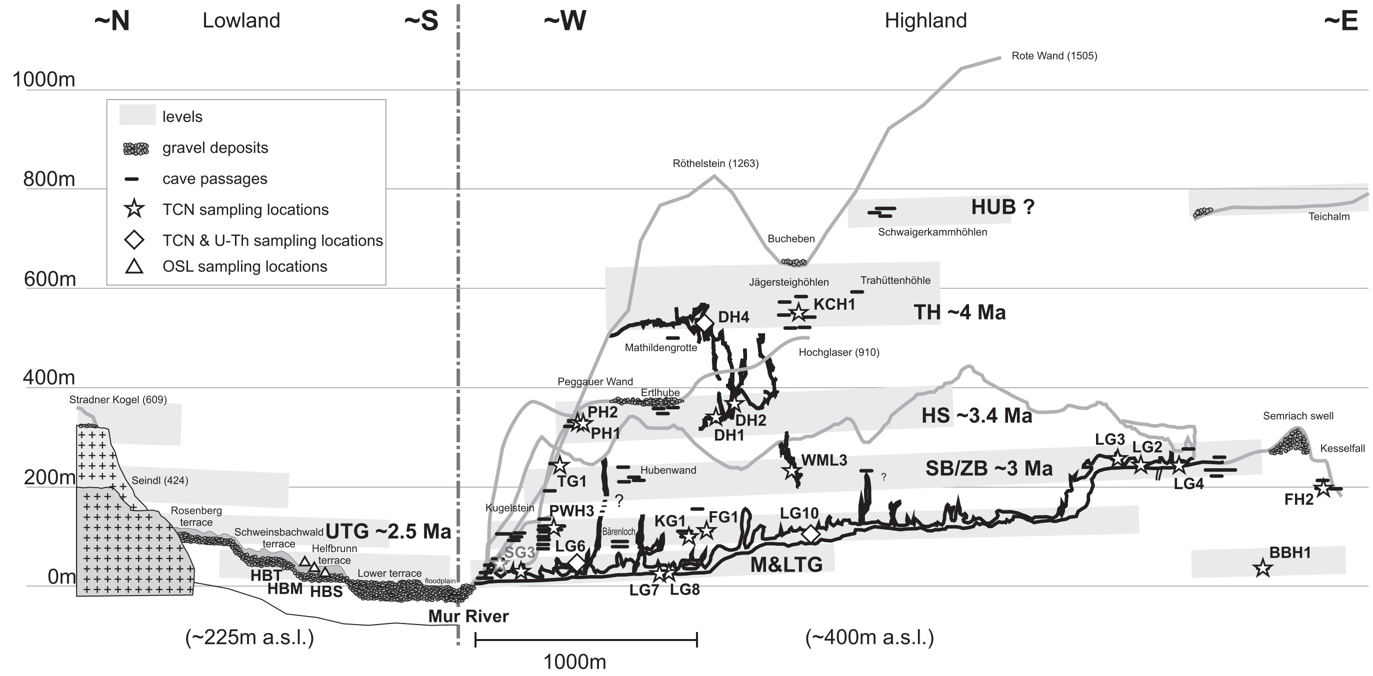


Fig. 7. Schematic projected profile of the Highland and Lowland of Graz. Elevations above the Mur River are modified and adapted from Wagner et al. (2010). The OSL sample locations are indicated by white triangles and dated TCN cave sediments by white stars. Sample locations where TCN and U–Th ages were measured are represented by white squares. Sample SG3, which is the only sample from the western river side has been depicted on the other river side for the sake of completeness.

observations and the current knowledge into a single schematic cross section.

The minimum age constraint of cave level A suggests the TH to be older than about 4 Ma, this does not contradict formation in Latest Pannonian (Winkler-Hermaden, 1955). The HS is thought to be older than about 3.4 Ma; thus the relatively young K/Ar age of the Stradnerkogel basalt (1.71 ± 0.72 Ma) is questioned. The SB/ZB level is based on the age constraint of level C of around 3 Ma, which is in agreement with K/Ar ages limiting it to be younger than ~3.8 Ma; it is supposed to be the last pre-glacial denudation plane. The UTG is suggested to be the first terrace related to climate deterioration at the beginning of the Pleistocene. The associated cave level D dated to about 2.5 Ma fits this interpretation as it places this level at the Plio-/Pleistocene boundary. This terrace level and the lower terraces are influenced by the episodic aggradation and re-excavation of sediment loads, some of which are preserved as stream terraces and have shaped the characteristic landscape along the Mur River in the Styrian Basin. These terraces are more developed and/or better preserved in the Styrian Basin than in the Mur valley, especially where it is rather narrow (e.g. north of Peggau). The Schweinsbachwald terrace belongs to the MTG and is placed classically in the Mindel glaciations (~450 ka, MIS 12). This age range is supported by the aggradation event observed in the Lurgrotte dated by the samples LG6 and LG8, although no direct correlation of this event with a terrace in the valley is possible. Winkler-Hermaden (1955) suggested a Great Interglacial origin of this terrace level, based on the up to 17 m thick loams found along the Kaiserwald terrace (e.g. Flügel, 1960) at the southwestern edge of the Graz Basin (equivalent to the Schweinsbachwald terrace). His conclusions were based on the fact that the loams are carbonate free, seen as an indication of a warmer climate where decarbonatisation would have occurred. Terraces that are attributed to the Riss glacial and are loam-free gravel accumulations (high terrace gravels) are rare in the study area. Around the town of Frohnleiten (Fig. 3a), gravels situated above the NT are related to the Riss. Some remnants were also documented by Winkler-Hermaden (1955) in the Graz Basin, e.g. in a loam pit of St. Peter which is no longer accessible. However in the predominant cases, the terraces above the NT are gravels covered by thick loams. The lowest of the loam covered terraces is the Helfbrunn terrace. The above reported OSL age constraints of this terrace suggest an Early Würm origin, making it somewhat younger than previously assumed and contradicting its glacial development.

The age of deposition of the Helfbrunn terrace coincides with the time of speleothem formation in the Tanneben massif (Section 4.1.1). This indicates that the loamy upper section of the Helfbrunn terrace cannot be a glacial deposit and instead supports the idea of Winkler-Hermaden (1955) that this deposit is of an interglacial (or interstadial) origin. However, the formation conditions of the gravel base of this terrace are more uncertain as no absolute age of this section is available. A continuous sedimentation process of gravel base and loam top would suggest that the gravels were deposited right before deposition of the loam base (≥ 80 ka). If the concept of glacial origin of these gravels from the headwaters of the Mur River catchment is favored (because of their decomposed state), a tentative correlation to ice advance during MIS 5 d is possible. Major glaciations during MIS 5 d and 4 are known from the Swiss Alps (e.g. Preusser et al., 2003), but the evidence in the Eastern Alps is still lacking and/or was obliterated during subsequent more extensive Late Würm (MIS 2) advances. At the moment, we can only speculate that these gravels could be the result of Early Würm glaciations. Although tentative, it would explain the diverse interpretation of the Helfbrunn terrace as being either of glacial or interglacial origin (e.g. Suette, 1986). An alternative scenario is to interpret this terrace as a fining upward fluvial deposit with alluvial clay and the occasional soil developed on top.

To conclude, OSL ages from the Helfbrunn terrace indicate a time of deposition of the HT during MIS 5a and an end of deposition around the MIS 5/4 transition. From U-Th ages of caves nearby, a time of formation during MIS 5c and 5a under relatively warm conditions is deduced. The combination of these results also suggests temperate conditions during deposition of the terrace. It is proposed that the terrace should be placed in the Early Würm, instead of its previously assumed Riss glacial or Riss–Würm interglacial age, and the gravel cover should not simply be termed a loess deposit.

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

6. The bigger picture: relief evolution of the Styrian Block

The elevation, age of the various levels and their correlation between Highland and Lowland, suggests that the Highland and the Lowland have a common evolution with respect to their vertical motions since the Late Miocene. Thus, we call them together the Styrian Block and propose here a unified relief evolution for this block. The onset of lateral extrusion east of the Tauern Window in the Ottnangian (Lower Miocene, ~18 Ma) (Ratschbacher et al., 1991) is the first stage of this evolution. It is related to the formation of conjugate strike-slip fault zones that delineate the Styrian Block: the Mur–Mürz fault zone to the north and the Lavanttal fault zone to the west. Intramontane pull-apart basins were filled and the onset of sedimentation in the Styrian Basin also occurred at this time (e.g. Ebner and Sachsenhofer, 1995). Lateral extrusion is only mechanically feasible if collision is aided by slab pull from the Carpathian subduction zone and the existence of conjugate strike-slip faults in the Eastern Alps (Selverstone, 2005; Robl et al., 2008b). Not necessarily much relief and topography development prior to this time is documented (Fig. 8 stage (a)).

Shallow marine sediments deposited in the Styrian Basin are related to marine ingressions in Badenian times (Fig. 8 stage (b); ~16–13 Ma). This allows the elevation of the basin to be placed at just below sea level. The Noric Depression (a term used to summarize all basins along the Mur–Mürz fault system) does not indicate a marine setting, but the evolution of the Fohnsdorf–Seckau Basin (east of Judenburg, Fig. 1a) with a brackish influx in relation to the Lavanttal Basin known for Lower Badenian marine sediments suggests only moderate altitudes at these times (Strauss et al., 2001). In Sarmatian and Early Pannonian times (Fig. 8 stage (c); ~12 Ma), increasingly brackish conditions were established within the Styrian Basin, related to the constriction of the Lake Pannon (Sacchi and Horváth, 2002; Harzhauser et al., 2004). However, there is still evidence of marine conditions in the Sarmatian related to sea level rises (Piller and Harzhauser, 2005). This is evidence that the region was still near sea level. In the intramontane basins, sediments of this time are no longer preserved (Ebner and Sachsenhofer, 1995).

In Pannonian times (Fig. 8 stage (d); ~9 Ma) the Styrian Block, especially the Styrian Basin, was affected by fluviatile-limnic to terrestrial deposition (e.g. Gross et al., 2007). Quartzose pebble deposits are common. Their origin (source) is questionable, although the crystalline frame of the Highland and Lowland of Graz is a likely source region (Skala, 1967; Maurin and Benischke, 1992). Again, no such sediments are preserved in the intramontane basins along the Mur–Mürz Fault. Ebner and Sachsenhofer (1995) suggested uplift based on subsidence analysis of the Styrian Basin during the Latest Pannonian (~5–6 Ma). Wagner et al. (2010) extended this finding to the Highland of Graz. Genser et al. (2007) observed the onset of uplift of the Austrian Molasse at about the same time. It can therefore be assumed that since then the region is uplifting.

Up to this point in time, sediments were deposited on top of each other in simple stratigraphic order. However, preserved sediments of Ottnangian to Sarmatian/Pannonian times are currently found at varying elevations (Fig. 8 stage (e)). Karpatian/Badenian sediments (~16 Ma) of the Passail Basin are found at ~650 ma.s.l. (Ebner and Gräf, 1982) and Sarmatian sediments found in the Gratkorn Basin (~20 km SW) are currently at ~425 ma.s.l. (Gross et al., 2007). This suggests fragmentation of the whole region after deposition although the actual timing of fragmentation is poorly constrained (e.g. Winkler-Hermaden, 1955). In Middle to Late Miocene times, a final rather strong subsidence was followed by the beginning of uplift in the Lowland (Ebner and Sachsenhofer, 1995) and the likely onset of uplift in the Highland (Wagner et al., 2010). Whether the deposition of Pannonian gravels from north happened prior to or after the fragmentation of the whole region is unclear. Ebner and Sachsenhofer (1995) reported fault-controlled subsidence during late Sarmatian times, which could have already caused the fragmentation prior to uplift. This is hard to differentiate because of the only partial preservation of Sarmatian and Pannonian sediments; this fact is expressed in Fig. 8 by combining stages (d) and (e).

After these stages, the fragmentation, gave way to a more continuously uplifting realm as denudation planes started to evolve (Fig. 8 stages (f) to (m)). Important at this point is that the denudation planes, planation surfaces and preserved gravel accumulations, as well as stream terraces found in the Highland and in the Lowland, are of decreasing elevation with decreasing age, which clearly indicates denudation and incision related to an uplifting Styrian Block. The actual formation of the present Mur River course has likely been initiated by the uplift of the region. Headward migration and final stream piracy of the Mur–Mürz catchment has to be placed in the Latest Miocene (Dunkl et al., 2005, Wagner et al., 2010).

The HUB level (Fig. 8 stage (g)) is only locally preserved in the Highland and absent in the Lowland. However, it is apparent in the Hochlantsch region (Teichalm, Fig. 3a) and shows clear signs of

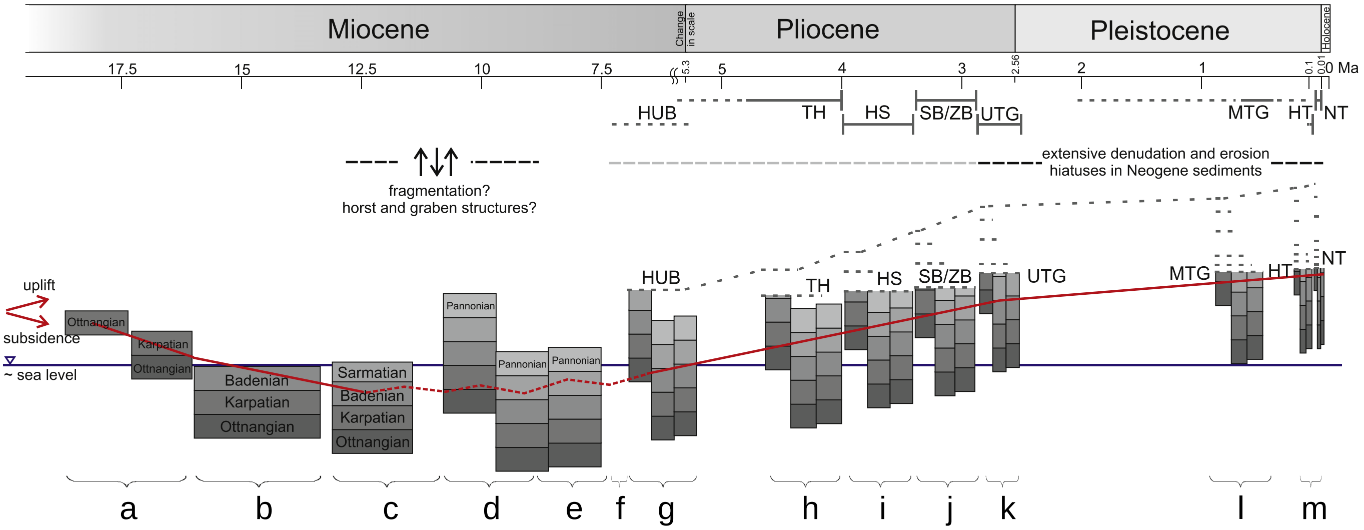


Fig. 8. Summary of relief evolution of the Styrian Block deduced from Neogene and Quaternary sediments, age constraints, and planation surfaces preserved in the landscape. Note the change in the time scale at the Mio-/Pliocene boundary. Explanation of relief evolution from (a) to (m) see Section 6.

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

karstification (e.g. Schwaigerkammhöhlen, Fig. 7), making this the highest level considered to be of significance for indicating a paleo-base level. The TH (Fig. 8 stage (h)) is preserved to a better extent, although no occurrences in the Styrian Basin are known. Nevertheless, this level is at least 4 Ma old, as deduced from cave sediments preserved at this level (Wagner et al., 2010). The HS (Fig. 8 stage (i)), dated to around 3.4 to 4 Ma and found today at about 325 to 450 m above the Mur River, is the first pronounced denudation plane clearly preserved in the whole region including the Lowland. A continuous level with a slightly increased gradient compared to the current Mur River gradient is observed. This could be the simple result of ongoing uplift in the region. The widespread extent of this level, including the Highland and the Lowland of the Styrian Block, provides an important constraint on the coherent behavior of the Styrian Block at subsequent times. The double plain system of the SB/ZB level (Fig. 8 stage (j)) is suggested to be the last denudation plane prior to the onset of climate deterioration (Winkler-Hermaden, 1955) and could be constrained to be around 3 Ma old. The levels extent is similar to that of the HS, due to its preservation on the young volcanic rocks in the Styrian Basin.

The upper terrace group (UTG) marks a shift in the landscape evolution as uplift and incision rates appear to have slowed down (Fig. 8 stage (k)). Based on sediment burial ages of this level, it can be placed right at the Plio-/Pleistocene boundary (~2.5 Ma). The onset of climate deterioration is suggested to be responsible for the strong increase in sediment discharge rates (e.g. Champagnac et al., 2009) reported by Kuhlemann et al. (2001, 2002). Wagner et al. (2010), however, only observed a decrease of incision rates of the Mur River resulting from ample sediment supply from the headwaters of the Mur River catchment without a clear sign indicating a relation to glaciations. The amount of sediments that would have had to be re-excavated or eroded from the intramontane basins and the Styrian Basin is likely to be considerable, if the former sediment cover of a few hundred meters reconstructed by Sachsenhofer et al. (1997) is taken into account. The MTG (Fig. 8 stage (l)) is not well constrained in time by our data and has to be placed somewhere between ~2.5 Ma (UTG, level D) and ~0.1 Ma (LTG), a rather long time range. However, the MTG as well as the UTG are not single terraces but an assemblage of various terraces which are hard to distinguish from each other, suggesting various stages (and times) of deposition. The LTG (Fig. 8 stage (m) is further sub-divided into the NT (low terrace gravels) and HT (high terrace gravels)). The NT is related to MIS 2 and the Late Würm glaciations. The HT has to be placed, according to our OSL ages of the Helfbrunn terrace, into the Early Würm related to MIS 5 (a–d?).

In general, during the Pliocene and in particular the Pleistocene (Fig. 8, stages (g)–(m)), considerable erosion and re-excavation of Miocene sediments from intramontane basins, the Styrian Basin and the surrounding basement, is inferred based on observed sedimentation hiatuses (Piller et al., 2004) and the preservation of planation surfaces of this time. The last ~2.5 Ma (stages (k)–(m)) indicate increasingly erosive times. This is supported by the observed decrease in incision rates of the Mur River at this time which has been attributed to increased sediment load from the headwaters of the Mur River (Wagner et al., 2010). However, if erosion had happened at an earlier point in time, tributaries in the non-glaciated parts of the Mur River catchment should have reached equilibrium in the meantime. According to Robl et al. (2008a), this is not the case and moreover, sediment budget data of the Eastern Alps (e.g. Kuhlemann, 2007) shows the same trend. All this evidence suggests that erosion and re-excavation is still adjusting to ongoing tectonic uplift of the whole region, and a geomorphic steady state is not yet reached (Hergarten et al., 2010).

7. The behavior of the styrian block—tectonic and climatic imprint

At the orogen margin of the Eastern Alps, degradational and aggradational settings are closely spaced and are known to have changed in time (e.g. Augenstein sedimentation: Frisch et al., 2001; post-Middle Miocene maximum sediment extent: Dunkl and Frisch, 2002).The vertical motion of the Styrian Block derived from above shows that the block uplifts since about 5–8 Ma. This poses the question as to the causes of this uplift. Whilst it is evident that within the last million years climatic changes occurred (global Cenozoic cooling trend), it is even more obvious that plate convergence (tectonic processes) have led to the formation of the European Alps and that these processes are still ongoing (e.g. Hergarten et al., 2010). The current cessation in convergence in the Western Alps, due to the present position of the Euler pole, could be a transitory setting. However, ongoing convergence is evident in the eastern parts of the Alps. The Adriatic plate is still pushing northward accompanied by counterclockwise rotation. It is also confirmed that the subduction roll back in the Carpathians ceased ~7–10 Ma ago (Cloetingh and Lankreijer, 2001) and that the Pannonian Basin has been inverting since ~5 Ma (Ruszkiczay-Rüdiger, 2007). Moreover, the possible influence of the Pannonian fragment that was proposed by Brückl et al. (2010) is worth mentioning. Underthrusting of this fragment by the European and the Adriatic plate could have caused the spatially broad uplift of the region (Wagner, 2010).

Pleistocene isostatic rebound in the foreland basins is well described in the Northern Alpine Foreland Basin (Genser et al., 2007). The Po Basin shows similar features, where the youngest marine sediments are presently above sea level if corrections for the loading of the overlying sediments are made (Scardia et al., 2006). The Styrian Basin provides similar evidence: marine sediments (~12 Ma old) are well above sea level (> 300 m a.s.l.) and subsidence analysis indicates onset of uplift around 5–6 Ma (Ebner and Sachsenhofer, 1995). A slight tilting of the Neogene basin fill within the Styrian Basin away from the orogen (here towards SE; Winkler-Hermaden, 1957) is similar to observations made in the foreland basin of France (Champagnac et al., 2007), however, isostatic rebound is not thought to be the primary mechanism here. The actual inversion of the Pannonian Basin is repeatedly used to account for stress changes in the region (e.g. Ebner and Sachsenhofer, 1995). Ongoing lateral extrusion (based on GPS data by Bus et al., 2009) and the lack of signs of fault reactivation or reverse faults (Wagner, 2010), however, suggest that uplift has to be explained by deep-seated mantle processes or a change of the degree of decoupling along plate boundaries (Willingshofer and Sokoutis, 2009).

The last ~4–5 Ma seem to be characterized by episodic, but spatially broad processes of uplift. Sediments were transported from the headwaters of the Mur River into the Styrian Basin and beyond. This is indicated by missing sedimentary sequences within the Noric Depression and parts of the Styrian Basin. This necessitates substantial erosion at a point later in time, however not necessarily as a direct result of climate changes: the mean erosion rate (modern area-weighted mean denudation rates) of 0.125 mm/a for the Eastern Alps in the Holocene from a compilation of Hinderer (2001) is of similar dimension as the ~0.1 mm/a incision rates inferred over the last ~4 Ma by Wagner et al. (2010). Palynological records do not show strong evidence for abrupt climatic changes that correlates with the sediment-yield data ~5.5 Ma ago (Willet, 2010 and references therein). Northern Hemisphere glaciations started ~2.5 Ma ago (Raymo, 1994), although major glacial erosion in the Alps is reported to have started ~1.8 Ma later (Muttoni et al., 2003; Häuselmann et al., 2007b).

A change in the whole erosional setting of our study area around 2.5 Ma is apparent from the change of predominantly preserved denudation plains prior to ~2.5 Ma to primarily stream terraces afterwards and a mean decrease in bedrock incision rates. This has already been attributed to an increase of sediment transported from the headwaters through the Mur valley since that time by Wagner et al. (2010). Furthermore, the OSL ages and morphological observations suggest that the four terrace levels prominent in the Styrian Basin do

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

not necessarily correlate with the four glacial maxima of Günz, Mindel, Riss and Würm. Direct evidence of Pleistocene glaciations is currently only proven for the last glacial (Würm) terrace (Van Husen, 1997 and references therein). The OSL ages of the Helfbrunn terrace (80.5 ± 3.7 to 68.7 ± 4 ka; MIS 5a to MIS 5/4 transition) and speleothem formation in nearby caves during MIS 5c and 5a indicate relatively warm conditions (ice-free, soil-covered) during the time of deposition. No direct indication for glacial origin can be found for the gravel base of the Helfbrunn terrace. Outwash material from glaciations in the headwaters of the Mur catchment is a potential source; whilst this sediment would have been produced during glacial times there is the potential for re-deposition in the subsequent interglacial following temporary storage. As such, the correlation of this terrace (and possible older ones as well) to glaciations in the Alpine region is hereby questioned. Sediments could be the simple product of erosion adjusting to ongoing uplift of the realm and remains a plausible alternative explanation. The hiatuses of sediments from the intramontane basins and the Styrian Basin are indications for re-excavation of these sediments, possibly related to the decrease in incision rates observed in the Mur valley (Wagner et al., 2010).

The aforementioned evidence for the apparently ongoing uplift poses the question as to what actually causes this uplift. Wagner (2010) correlated the uplift to the Pannonian fragment that is underthrust by the European and the Adriatic plates (Brückl et al., 2010). Delamination and/or convective removal of overthickened lithosphere are other possible explanations (Houseman et al., 1981; Genser et al., 2007). An alternative to these ideas is the approach of Hergarten et al. (2010), who supposed that the whole topography of the Alps developed around 5–6 Ma on top of a former relatively low mountain range. As the uplift signal is spatially broad, it is likely that some sort of deep-seated change in the geodynamic setting would have occurred at this time. The significance of Adria push (Bada et al., 2007) from the south as a key mechanism for the ongoing uplift is emphasized here. A single uplift pulse around 5–6 Ma is unlikely because this would have resulted in a subsequent decrease in the topography and a cessation in the sediment load would have been observed. Quite the opposite is the case in the Eastern Alps, where an increase around the Plio-/Pleistocene boundary is documented (Kuhlemann et al., 2001). As has already been mentioned by Wagner et al. (2010), a detailed trend of the uplift signal of the last 4–5 Ma is hard to deduce because stream piracy events and changing sediment loads are superimposed.

8. Conclusions

In this work we constrain the vertical motions of a tectonically important region at the eastern end of the Alps: the Styrian Block, for the last 4–5 Ma. This area is located outside the region covered by ice during glacial periods and includes parts of the Alpine basement east of the Lavanttal Fault and south of the Mur–Mürz Fault and parts of the westernmost Pannonian Basin, the Styrian Basin.

Cosmogenic nuclide burial ages of cave sediments show that a cave level ~500–600 m above the current base level formed about 4 Ma ago. This cave level is correlated with planation surfaces of the so-called Trahütten level (TH), which is preserved in the Highland of Graz. The prominent Hochstraden level (HS, ~325–450 m above present base level) could be constrained to have formed between 3.4 and 4 Ma by the same method. The level is pronounced in both, the Styrian Basin and the Highland of Graz. Importantly, it is preserved along different lithologies and across prominent previously active faults. The so-called Stadelberg/Zahrerberg level (SB/ZB, ~180–300 m above present base level) could be confirmed to be the last pre-glacial denudation plain with an age of ~3 Ma. In the Styrian Basin, the Upper Terrace Group (UTG) marks the onset of repeated aggradation in the Pleistocene by preserved stream terraces. The corresponding cave level indicates a time of formation around 2.5 Ma. The Middle Terrace Group (MTG) remains loosely constrained. The Lower Terrace Group (LTG) is divided into high terrace gravels (HT) and low terrace gravels (NT). The later has been shown to be of Late Würmian origin. The upper part of the HT in the Styrian Basin, the so-called Helfbrunn terrace could be constrained by luminescence dating to be only about 80–70 ka old, making a correlation to the MIS 5a possible. The end of deposition correlates with the MIS 5/4 transition. Speleothem formation in various levels of caves in the Highland of Graz based on U–Th ages correlate with MIS 5c and 5a, pointing towards relatively warm conditions. The formation of speleothems during MIS 5a, and the timing of deposition of the upper part of the Helfbrunn terrace also during MIS 5a, supports a relatively warm period during its formation and thus the Helfbrunn terrace does not necessarily correlate with a glacial advance in the Alpine region.

Incision rates of the Mur River show a decrease around the Plio-/Pleistocene boundary, suggested to be the consequence of increased sediment load from the hinterland. Observed hiatuses in the sediment record of the Noric Depression and the Styrian Basin in connection with observed geomorphic disequilibrium of the region imply erosion adjusting to ongoing tectonic activity over Pliocene times. Instead of the common theory for the repeated aggradation during this period of time up to the present as being a response to climate change in the Pleistocene, we propose a possible alternative explanation of simple erosion, redistribution and re-excavation of Neogene and Quaternary sediments as a consequence of uplift.

Correlation of various planation surfaces, cave levels and stream terraces indicate that the Styrian Block coherently uplifted some 600 m over the last 4–5 Ma. Our interpretation implies that the observed fragmentation of the block must have occurred prior to this time in the Miocene, thus allowing the preservation of these planar geomorphic markers at distinctive levels.

Supplementary materials related to this article can be found online at doi:10.1016/j.geomorph.2011.04.024.

Acknowledgements

Luminescence dating was carried out using the facilities at the University of Innsbruck, Austria. Sincere thanks to C. Spötl for hospitality. M. Gross is thanked for discussing paleontological aspects of the Miocene evolution. S. Niederl is thanked for permission to collect samples in the former loam pit of Helfbrunn. GIS-Steiermark is thanked for providing high resolution DEM data (© BEV, 2007). We thank J. De Waele, L. Plan and two anonymous reviewers for their useful comments. This research was funded by the “Kooperationsprojekt Erdwissenschaften NAWI Graz (§ 141)” and the ESF project I-152.

Appendix A. OSL sample preparation and measurement procedure

The OSL dating method combines a laboratory-derived estimation of radiation dose that sediment grains have received during the most recent period of burial with the local environmental dose-rate. Similar to the TCN burial age method, this method also determines when a sediment has been buried following deposition. By measuring the OSL signal from the natural dose (i.e. that received during burial) and OSL signals from a series of laboratory irradiations of known dose (used to calibrate the OSL signal from the natural dose), the amount of radiation that grains have received during burial can be determined, this is termed the equivalent dose (D_e). The radiation flux at a sampling location is termed the environmental dose-rate which has been estimated by laboratory measurements. Calculation of dose rates were done using conversion factors of Adamiec and Aitken (1998), the use of ADELE software (Kulig, 2005) and an alpha effectiveness value for quartz of 0.03 ± 0.01 (Mauz et al., 2006). The actual age of a sample (i.e. the time of burial since last exposure to sunlight) is simply the burial dose (in Gy) divided by the environmental dose-rate (in Gy/ka).

The sample HBB turned out to be dominantly clay-sized, precluding separation of a 4–11 μm fraction and thus had to be discarded. The other three samples HBT, HBM and HBS, were processed in the OSL laboratory at the University of Innsbruck under dim red-light conditions. Subsamples were removed for analysis of the radionuclide content (performed commercially by ICP-MS at "Activation Laboratories Ltd.") and water content measurements (an average value of the samples was used in environmental dose-rate calculations). Following standard techniques described in Wintle (1997), the remaining sample material was pretreated with 10% v.v. dilution of hydrochloric acid followed by 20 volumes hydrogen peroxide to remove carbonates and organic matter, respectively, prior to dry sieving. The 4–11 μm fraction was further treated with 32% hexaflourosilicic acid (1:40 solid:liquid ratio) for 7 days. Aliquots contained 1 mg of material that was pipetted onto aluminum disks of 9.7 mm diameter by settling through acetone. Whilst sufficient bleaching of the samples could not be verified because the samples had no coarse-grain component (which would allow analysis of the D_e distributions), previous work on fine-grained overbank deposits (e.g. Preusser, 1999) has demonstrated that luminescence signal in these deposits can be well-bleached.

Single aliquot OSL measurements were carried out using an automated Risø TL/OSL reader with optical stimulation from blue light emitting diodes (LEDs) with peak emission at 470 nm and IR diodes emitting at 830 Δ10 nm. The OSL signal was measured with an EMI 9635Q photomultiplier tube through a 7.5 mm thickness of Hoya U340 filter. Beta irradiation was performed using a calibrated 40 mCi $^{90}Sr/^{90}Y$ source. Luminescence analysis was undertaken using the single-aliquot regenerative-dose (SAR) (Murray and Roberts, 1998; Murray and Wintle, 2000) protocol; all samples showed a luminescence signal strongly dominated by a fast component (for an example from an aliquot of HBS see Fig. S1a) and a dose–response curve that could be fitted with a single saturating exponential (Fig. S1b). Preheat tests over the preheat temperature range 160–300 °C showed evidence of a plateau between 160 °C and 280 °C for all samples (results for HBS shown in Fig. S1c). A dose-recovery test was undertaken for each sample; for each sample 4 aliquots were bleached 100 s at 125 °C using blue LEDs to remove the natural signal, then given a laboratory dose close to the natural level termed the "given dose". This given dose was subsequently treated as a natural dose and measured using the SAR protocol with a preheat of 260 °C for 10 s, and a cutheat of 160 °C for 0 s. The results of the dose-recovery test can be seen in Table S1. For samples HBS and HBT the results were satisfactory, with a measured/given dose ratio consistent with unity, however for sample HBM the results of the two accepted aliquots were not within the accepted limits. For all three samples either 24 or 31 aliquots were prepared for analysis and D_e values derived using the same measurement parameters as in the dose-recovery test. For all aliquots the recycling ratios and IR-OSL depletion ratios (Duller, 2003) were within the accepted range (Table S2), and the recuperation following the natural was <2%. 24 D_e values were derived for HBS (Fig. S2) and HBT. The final burial dose for the samples was calculated from the dataset of D_e values using the Central Age Model (CAM, Galbraith et al., 1999). The results from HBM had to be discarded; a large scatter was evident in the D_e values (Fig. S2), which can possibly be attributed to the relatively large natural D_e. For this sample, the D_e values for the aliquots were typically $>2D_0$ value of the growth curve (Wintle and Murray, 2006; Table S2). When a sample has a $D_e>2D_0$ the intersection of the L_N/T_N value with the dose–response curves falls in the flatter near-saturation section (where the D_e value calculated is disproportionally sensitive to the L_N/T_N value) and thus no final age can be calculated.

Appendix B. TCN burial ages—methodology

TCN burial age dating is based on the fact that radiogenic cosmogenic isotopes accumulate in quartzose rocks/sediments near the Earth's surface and start to decay as soon as the sediment is buried and consequently shielded from further cosmic rays. By measuring the present ratio of a pair of isotopes (in this work, ^{26}Al and ^{10}Be) of the buried sediment, the burial age can be computed. This calculation is based on the fact that the ratio of the isotope pair near the surface is constant (in this instance, ~6.8:1.0) and will decrease as soon as the decay of the isotopes starts (due to the different decay constants of the individual isotopes). For technical details see Gosse and Phillips (2001) and Granger and Muzikar (2001).

References

Adamiec, G., Aitken, M.J., 1998. Dose-rate conversion factors: update. Ancient TL 16, 37–50.

Anthony, D.M., Granger, D.E., 2004. A Late Tertiary origin for multilevel caves along the western escarpment of the Cumberland Plateau, Tennessee and Kentucky, established by cosmogenic 26Al and 10Be. Journal of Cave and Karst Studies 66, 46–55.

Anthony, D.M., Granger, D.E., 2007. A new chronology for the age of Appalachian erosional surfaces determined by cosmogenic nuclides in cave sediments. Earth Surface Processes and Landforms 32, 874–887.

Bada, G., Horváth, F., Dövényi, P., Szafián, P., Windhoffer, G., Cloetingh, S., 2007. Present-day stress field and tectonic inversion in the Pannonian basin. Global and Planetary Change 58, 165–180.

Balogh, K., Ebner, F., Ravasz, C., 1994. K/Ar-Alter tertiärer Vulkanite der südöstlichen Steiermark und des südlichen Burgenlandes. In: Lobitzer, H., Csaszar, G., Dauer, A. (Eds.), Jubiläumsschrift 20 Jahre Geologische Zusammenarbeit Österreich-Ungarn 2. Geologische Bundesanstalt, Wien, pp. 55–72.

Boch, R., Spötl, C., Kramers, J., 2010. Wachstumsphasen von Stalagmiten im Katerloch (2833/59). Die Höhle 61, 48–56.

Bøtter-Jensen, L., McKeever, S.W.S., Wintle, A.G., 2003. Optically Stimulated Luminescence Dosimetry. Elsevier, Amsterdam. 355 pp.

Brückl, E., Behm, M., Decker, K., Grad, M., Guterch, A., Keller, G.R., Thybo, H., 2010. Crustal structure and active tectonics in the Eastern Alps. Tectonics 29, TC2011. doi:10.1029/2009TC002491 17 pp.

Bus, Z., Grenerczy, Gy, Tóth, L., Mónus, P., 2009. Active crustal deformation in two seismogenic zones of the Pannonian region—GPS versus seismological observations. Tectonophysics 474, 343–352.

Champagnac, J.-D., Molnar, P., Anderson, R.S., Sue, C., Delacou, B., 2007. Quaternary erosion-induced isostatic rebound in the western Alps. Geology 35, 195–198.

Champagnac, J.-D.-., Schlunegger, F., Norton, K., von Blanckenburg, F., Abbühl, L.M., Schwab, M., 2009. Erosion-driven uplift of the modern Central Alps. Tectonophysics 474, 236–249.

Cloetingh, S., Lankreijer, A., 2001. Lithospheric memory and stress field controls on polyphase deformation of the Pannonian basin–Carpathian system. Marine and Petroleum Geology 18, 3–11.

Duller, G.A.T., 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. Radiation Measurements 37, 161–165.

Dunkl, I., Frisch, W., 2002. Thermochronological constraints on the Late Cenozoic exhumation along the Alpine and West Carpathian margins of the Pannonian basin. EGU Stephan Mueller Special Publication Series 3, 135–147.

Dunkl, I., Kuhlemann, J., Reinecker, J., Frisch, W., 2005. Cenozoic relief evolution of the Eastern Alps—constraints from apatite fission track age-provenance of Neogene intramontane sediments. Austrian Journal of Earth Sciences 98, 92–105.

Ebner, F., Gräf, W., 1982. Bentonite und Glastuffe der Steiermark. Archiv für Lagerstättenforschung der Geologischen Bundesanstalt 2, 31–45.

Ebner, F., Sachsenhofer, R.F., 1995. Paleogeography, subsidence and thermal history of the Neogene Styrian Basin (Pannonian basin system, Austria). Tectonophysics 242, 133–150.

Fabiani, E., Eisenhut, M., 1971. Bodenbedeckung und Terrassen des Murtales zwischen Wildon und der Staatsgrenze. Berichtsbände der Wasserwirtschaftlichen Planung 20, 1–121.

Fink, J., 1961. Die Südostabdachung der Alpen. Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft 6, 123–183.

Flügel, H.W., 1960. Die jungquartäre Entwicklung des Grazer Feldes (Steiermark). Mitteilungen der Österreichischen Geographischen Gesellschaft 102, 52–64.

Frisch, W., Kuhlemann, J., Dunkl, I., Szekely, B., 2001. The Dachstein paleosurface and the Augenstein Formation in the Northern Calcareous Alps—a mosaic stone in the geomorphological evolution of the Eastern Alps. International Journal of Earth Sciences 90, 500–518.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: Part I, Experimental design and statistical models. Archaeometry 41, 339–364.

Genser, J., Cloetingh, S.A.P.L., Neubauer, F., 2007. Late orogenic rebound and oblique Alpine convergence: new constraints from subsidence analysis of the Austrian Molasse basin. Global and Planetary Change 58, 214–223.

Gollner, J., Zier, C., 1985. Zur Geologie des Hochlantsch (Grazer Paläozoikum, Steiermark). Jahrbuch der Geologischen Bundesanstalt 128, 43–73.

Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews 20, 1475–1560.

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024

Granger, D.E., Muzikar, P.F., 2001. Dating sediment burial with in situ-produced cosmogenic nuclides: theory, techniques, and limitations. Earth and Planetary Science Letters 188, 269–281.

Granger, D.E., Kirchner, J.W., Finkel, R.C., 1997. Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic 26Al and 10Be in cave-deposited alluvium. Geology 25, 107–110.

Gross, M., Fritz, I., Piller, W.E., Solimann, A., Harzhauser, M., Hubmann, B., Moser, B., Scholger, R., Suttner, T.J., Bojar, H.P., 2007. The Neogene of the Styrian Basin: guide to excursion. Joannea—Geologie und Paläontologie 9, 117–193.

Harzhauser, M., Daxner-Höck, G., Piller, W.E., 2004. An integrated stratigraphy of the Pannonain (late Miocene) in the Vienna Basin. Austrian Journal of Earth Sciences 95/96, 6–19.

Häuselmann, P., Fiebig, M., Kubik, P.W., Adrian, H., 2007a. A first attempt to date the original "Deckenschotter" of Penck and Brückner with cosmogenic nuclides. Quaternary International 164–165, 33–42.

Häuselmann, P., Granger, D.E., Jeannin, P.-Y., Lauritzen, S.-E., 2007b. Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland. Geology 35, 143–146.

Hejl, E., 1997. "Cold spots" during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics 272, 159–173.

Hellstrom, J., 2003. Rapid and accurate U/Th dating using parallel ion-counting multicollector ICP-MS. Journal of Analytical Atomic Spectrometry 18, 1346–1351.

Hellstrom, J., 2006. U–Th dating of speleothems with high initial ^{230}Th using stratigraphical constraint. Quaternary Geochronology 1, 289–295.

Hergarten, S., Wagner, T., Stüwe, K., 2010. Age and prematurity of the Alps derived from topography. Earth and Planetary Science Letters 297, 453–460.

Hilber, V., 1912. Die Taltreppe, eine geologisch-geographische Darstellung. Self-Published, Graz. 60 pp.

Hinderer, M., 2001. Late Quaternary denudation of the Alps, valley and lake fillings and modern river loads. Geodinamica Acta 14, 231–263.

Horváth, F., Cloetingh, S., 1996. Stress-induced late-stage subsidence anomalies in the Pannonian basin. Tectonophysics 266, 287–300.

Houseman, G.A., McKenzie, D.P., Molnar, P., 1981. Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. Journal of Geophysical Research 86, 6115–6132.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. Journal of Quaternary Science 23, 559–573.

Kuhlemann, J., 2007. Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Global and Planetary Change 58, 224–236.

Kuhlemann, J., Frisch, W., Dunkl, I., Szekely, B., 2001. Quantifying tectonic versus erosive denudation by the sediment budget: the Miocene core complexes of the Alps. Tectonophysics 330, 1–23.

Kuhlemann, J., Frisch, W., Szekely, B., Dunkl, I., Kazmer, M., 2002. Postcollisional sediment budget history of the Alps: tectonic versus climatic control. International Journal of Earth Sciences 91, 818–837.

Kulig, G., 2005. Erstellung einer Auswertesoftware zur Altersbestimmung mittels Lumineszenzverfahren unter spezieller Berücksichtigung des Einflusses radioaktiver Ungleichgewichte in der 238U-Zerfallsreihe, Unpublished BSc thesis, Technical University Bergakademie Freiberg.

Maurin, V., 1953. Über jüngste Bewegungen im Grazer Paläozoikum. Verhandlungen der Geologischen Bundesanstalt 1953, 216–220.

Maurin, V., Benischke, R., 1992. Morphogeny, paleohydrography and karst development. In: Behrens, H. (Ed.), Investigations with Natural and Artificial Tracers in the Karst Aquifer of the Lurbach System (Peggau-Tanneben-Semriach, Austria): Steirische Beiträge zur Hydrogeologie, 43, pp. 22–33.

Mauz, B., Packman, S., Lang, A., 2006. The alpha effectiveness in silt-sized quartz: new data obtained by single and multiple aliquot protocols. Ancient TL 24, 47–52.

Mottl, M., 1946. Die Kugelsteinhöhlen bei Peggau und ihre diluvialstratigraphische Bedeutung. Verhandlungen der Geologischen Bundesanstalt 1946, 61–69.

Murray, A.S., Roberts, R.G., 1998. Measurement of the equivalent dose in quartz using a regenerative-dose single-aliquot protocol. Radiation Measurements 29, 503–515.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved regenerative-dose single-aliquot protocol. Radiation Measurements 32, 57–73.

Muttoni, G., Carcano, C., Garzanti, E., Ghielmi, M., Piccin, A., Pini, R., Rogledi, S., Sciunnach, D., 2003. Onset of major Pleistocene glaciations in the Alps. Geology 31, 989–992.

Neubauer, F., Dallmeyer, R.D., Dunkl, I., Schirnik, D., 1995. Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics 242, 79–98.

Piller, W.E., Harzhauser, M., 2005. The myth of the brackish Sarmatian Sea. Terra Nova 17, 450–455.

Piller, W.E., Egger, H., Erhart, C., Gross, M., Harzhauser, M., Hubmann, B., van Husen, D., Krenmayr, H.-G., Krystyn, L., Lein, R., Lukeneder, A., Mandl, G., Rögl, F., Roetzel, R., Rupp, C., Schnabel, W., Schönlaub, H.P., Summesberger, H., Wagreich, M., 2004. Die Stratigraphische Tabelle von Österreich 2004 (sedimentäre Schichtfolgen). Österreichische stratigraphische Kommission und Kommission für die paläontologische und stratigraphische Erforschung Österreichs.

Plan, L., Grasemann, B., Spötl, Ch., Decker, K., Boch, R., Kramers, J., 2010. Neotectonic extrusion of the Eastern Alps: constraints from U/Th dating of tectonically damaged speleothems. Geology 38, 483–486.

Preusser, F., 1999. Luminescence dating of fluvial sediments and overbank deposits from Gossau, Switzerland: fine grain dating. Quaternary Geochronology (Quaternary Science Reviews) 18, 217–222.

Preusser, F., Geyh, M.A., Schlüchter, Ch., 2003. Timing of Late Pleistocene climate change in lowland Switzerland. Quaternary Science Reviews 22, 1435–1445.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M., Neugebauer, J., 1989. Extrusion in compressional orogenic belts: the eastern Alps. Geology 17, 404–407.

Ratschbacher, L., Frisch, W., Linzer, H.-G., Merle, O., 1991. Lateral extrusion in the Eastern Alps. Part 2: structural analysis. Tectonics 10, 257–271.

Raymo, M.E., 1994. The initiation of northern hemisphere glaciations. Annual Review of Earth and Planetary Sciences 22, 353–383.

Refsnider, K.A., 2010. Dramatic increase in late Cenozoic alpine erosion rates recorded by cave sediment in the southern Rocky Mountains. Earth and Planetary Science Letters 297, 505–511.

Robl, J., Hergarten, S., Stüwe, K., 2008a. Morphological analysis of the drainage system in the Eastern Alps. Tectonophysics 460, 263–277.

Robl, J., Stüwe, K., Hergarten, S., Evans, L., 2008b. Extension during continental convergence in the Eastern Alps: the influence of orogen-scale strike-slip faults. Geology 36, 963–966.

Ruszkiczay-Rüdiger, Zs., 2007. Tectonic and climatic forcing in Quaternary landscape evolution in the Central Pannonian Basin: a quantitative geomorphological, geochronological and structural analysis. PhD Thesis, Vrije Universiteit, Amsterdam, Netherlands.

Sacchi, M., Horváth, F., 2002. Towards a new time scale for the Upper Miocene continental series of the Pannonian basin (Central Paratethys). EGU, Stephan Mueller Special Publication Series 3, 79–94.

Sachsenhofer, R.F., Lankreijer, A., Cloetingh, S., Ebner, F., 1997. Subsidence analysis and quantitative basin modelling in the Styrian Basin (Pannonian Basin System, Austria). Tectonophysics 272, 175–196.

Scardia, G., Muttoni, G., Sciunnach, D., 2006. Subsurface magnetostratigraphy of Pleistocene sediments from the Po Plain (Italy): constraints on rates of sedimentation and rock uplift. Geological Society of America Bulletin 118, 1299–1312.

Selverstone, J., 2005. Are the Alps collapsing? Annual Review of Earth and Planetary Sciences 33, 113–132.

Skala, W., 1967. Kurzbericht über die Untersuchung von Fließrichtungen in den Basisschottern des Obersarmats im Steirischen Becken. Mitteilungen des Naturwissenschaftlichen Vereins für Steiermark 97, 28–31.

Spötl, C., Mangini, A., 2006. U/Th age constraints on the absence of ice in the central Inn Valley (eastern Alps, Austria) during Marine Isotope Stages 5c to 5a. Quaternary Research 66, 167–175.

Spötl, C., Offenbecher, K.-H., Boch, R., Meyer, M., Mangini, A., Kramers, J., Pavuza, R., 2007. Tropfstein-Forschung in österreichischen Höhlen—ein Überblick. Jahrbuch der Geologischen Bundesanstalt 147, 117–167.

Stock, G.M., Granger, D.E., Sasowsky, I.D., Anderson, R.S., Finkel, R.C., 2005. Comparison of U–Th, paleomagnetism, and cosmogenic burial methods for dating caves: implications for landscape evolution studies. Earth and Planetary Science Letters 236, 388–403.

Strauss, P., Wagreich, M., Decker, K., Sachsenhofer, R.F., 2001. Tectonics and sedimentation in the Fohnsdorf-Seckau Basin (Miocene, Austria): from a pull-apart basin to a half-graben. International Journal of Earth Sciences 90, 549–559.

Suette, G., 1986. Geologische Karte der Republik Österreich 1:50.000, Erläuterungen zu Blatt 208 Mureck. Geologische Bundesanstalt, Wien.

Untersweg, T., 1979. Morphologie des Schöcklgebietes. Ph.D. Thesis, Karl-Franzens University of Graz, Austria.

Van Husen, D., 1997. LGM and late-glacial fluctuations in the Eastern Alps. Quaternary International 38–39, 109–118.

Van Husen, D., 2000. Geological processes during the Quaternary. Mitteilungen der Österreichischen Geologischen Gesellschaft 92, 135–156.

Wagner, T., 2010. Young uplift in the non-glaciated parts of the Eastern Alps—geomorphological and geochronological constraints. Unpublished Ph.D. thesis, Karl-Franzens-University of Graz, Austria.

Wagner, T., Fabel, D., Fiebig, M., Häuselmann, P., Sahy, D., Xu, S., Stüwe, K., 2010. Young uplift in the non-glaciated parts of the Eastern Alps. Earth and Planetary Science Letters 295, 159–169.

Weber, F., 1969. Die refraktionsseismischen Messungen im Murtal zwischen Peggau und Eggenfeld (Mittelsteiermark) und ihre Bedeutung für die hydrogeologische Erforschung der quartären Schotterdecken. Steirische Beiträge zur Hydrogeologie 21, 5–25.

Willet, S.D., 2010. Late Neogene erosion of the Alps: a climate driver? Annual Review of Earth and Planetary Sciences 38, 411–437.

Willingshofer, E., Sokoutis, D., 2009. Decoupling along plate boundaries: key variable controlling the mode of deformation and the geometry of collisional mountain belts. Geology 37, 39–42.

Winkler-Hermaden, A., 1955. Ergebnisse und Probleme der Quartären Entwicklungsgeschichte am östlichen Alpensaum ausserhalb der Vereisungsgebiete. Österreichische Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse, Denkschrifte 110 180 pp.

Winkler-Hermaden, A., 1957. Geologisches Kräftespiel und Landformung. Springer Verlag, Wien. 822 pp.

Wintle, A.G., 1997. Luminescence dating: laboratory procedures and protocols. Radiation Measurements 27, 769–817.

Wintle, A.G., Murray, A.S., 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating procedures. Radiation Measurements 41, 369–391.

Please cite this article as: Wagner, T., et al., Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps, Geomorphology (2011), doi:10.1016/j.geomorph.2011.04.024