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The Fischbach Alps: A Geomorphological Record of late Neogene Uplift at the Eastern Margin of the European Alps

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Abstract

Low-relief surfaces at high elevations are peculiar features of the Eastern Alps that are best explained as relicts of morphological base levels that escaped erosive decay during uplift. To expand our knowledge of such surfaces in the Eastern Alps, the Fischbach Alps at the eastern end of the range are investigated. There, a large number of these elevated low-relief surfaces have been known for some time, but modern mapping is absent and their genesis is not well understood. A combined approach of field mapping, morphometric analysis of a digital elevation model and downstream projection of geomorphic equilibrium sections in river profiles was employed to: (i) create a geomorphological map of the region and (ii) to extract quantitative data from river profiles to infer the amount of uplift and incision. Six discrete levels of low-relief surfaces and relict landscapes are recognized at elevations between ~500 m and ~1600 m. Some of the lower levels are interpreted to relate to the well-known *Trahütten, Landscha* and *Stadelberg* levels, known from other parts of Styria, respectively. Mapped low-relief surface levels follow the northward directed topographic gradient in the mountainous region of the Fischbach Alps. The formation of elevated low-relief surfaces is consistent with a Piedmonttreppen model, where successive phases of tectonic uplift and tectonic quiescence led to a succession of incised landscapes and low-relief surfaces. However, the entire region south of the Mürztal was also then tilted towards the Styrian Basin by about ~1–2°. Swath profile analysis for the Raab and Weizbach Klamm suggests a minimum of ~400–450 m incision since the formation of the so called *Hubenhalt* level. This implies that the geomorphic response to tectonic uplift after the formation of the higher *Wolscheneck* and *Koralm* relict landscapes led to an estimated incision of up to 1000 m (868±101 m), relative to the base level of today's Styrian Basin at ~380 m. By comparing published age data to the presented mapping results, the onset for much of the uplift at the eastern end of the Alps is suggested to lie between ~4–7 Ma, before the formation of the *Hubenhalt* and *Trahütten* levels. Because the mapped levels correlate well with those in many other regions at similar elevations, a growing body of work now suggests that the underlying uplift event has a large wavelength.

1. Introduction

The topographic evolution of mountain belts like the Eastern Alps is the consequence of the interplay of rock uplift and erosion (Molnar and England, 1990; Sternai et al., 2019; Gradwohl et al., 2023). For the Eastern Alps, competing ideas have been put forward to explain the topographic evolution, arguing for either climate drivers of increased erosion (Willett, 2010), isostatic rebound due to deglaciation (Mey et al., 2016), isostatic adjustment induced by erosional unloading (Kuhlemann et al., 2002) and sub-lithospheric processes resulting in tectonic uplift (Wagner et al., 2011; Baran et al., 2014; Legrain et al., 2014). In most landscapes without relevant glacial history, fluvial processes play the dominant role in shaping the topography (Robl et al., 2017), but low-relief landscapes are often preserved at high surface elevations. In the absence of glacial erosion, these low-relief landscapes are generally interpreted as relicts of base levels that have not been eroded (Gradwohl et al., 2023). They thus provide a direct record of surface uplift. The Fischbach and Wechsel mountainous region of the Eastern

Alps (Fig. 1) remained mostly ice-free during the last glacial periods (except small cirque glaciers near the highest summits, e.g. van Husen (1997)) and record what is probably the largest contiguous region of elevated low-relief landscapes in the Eastern Alps (Gradwohl et al., 2024). The region thus lends itself to investigate these landforms as the pre-Pleistocene record of tectonic uplift. In this contribution we map elevated low-relief surfaces and knicks in river profiles in the Fischbach and Wechsel mountainous region (Winkler-Hermaden, 1957; Schuster et al., 2015) to widen the region of the Eastern Alps for which there is detailed mapping of low-relief surfaces and improve our understanding of the late Neogene to Pleistocene landscape evolution.

2. Low-relief landscapes in the Eastern Alps

Throughout the Eastern Alps different low-relief landscapes at higher elevations have been recognised and used to infer aspects of the surface uplift (Gradwohl et al., 2024). Most prominently, these surfaces have been known from the Dachstein and Hochschwab plateaus, where they have been termed the Augenstein landscape (Frisch et al., 2001) and been interpreted as an Oligocene surface that was present at base level ~30–40 Ma ago (Frisch et al., 1998). It was then later fluvially dissected during uplift. Some other, albeit much lower, low-relief surfaces are known from the eastern end of the Alpine range (Winkler-Hermaden, 1957). Recent studies from various mountainous region surrounding the Styrian Basin have investigated these lower surfaces in detail (Wagner et al., 2011; Legrain et al., 2015; Stüwe and Hohmann, 2021; Dertnig et al., 2017; Bartosch and Stüwe, 2019; Fig. 1) and showed that they can be correlated and that they are a reflection of a Piedmonttreppe (Stüwe and Hohmann, 2021 and references therein), where different low relief surface reflect stages of a successive uplift. These studies used these surfaces to infer a substantial surface uplift event causing 500–1000 m of uplift in the last 5 Ma. The implication of this interpretation is that there has been a hiatus in the surface uplift between its onset in the Oligocene and the renewed Pliocene uplift. While this interpretation is consistent with evidence from sedimentation in the surrounding basins (Kuhlemann et al., 2002; Kuhlemann, 2007) and from the tectonics of Miocene lateral extrusion (Robl et al., 2008a; Bartosch and Stüwe, 2017), the young Pliocene uplift is not very well constrained. In the Fischbach Alps, the low-relief surfaces that are probably related to this event are very prominent and form the focus of this paper.

2.1 The Fischbach Alps and the low-relief landscapes surrounding them

The Fischbach Alps are a unique piece of the landscape evolution puzzle of the unglaciated parts of the Eastern Alps, as they feature an extensive and nearly continuous set of elevated low-relief landscapes, characterized by smooth topography dissected by deeply incised valleys (van Husen, 1997; Schuster et al., 2015). The study area is here broadly defined as the area covering approximately 3000 km² between the most easterly parts of the Paleozoic of Graz, the Mürz valley to the north, the Wechsel mountains and Bucklige Welt to the east and the Styrian Basin to the south (Figs. 1, 2). In this area elevations range from ~300 m in the Styrian Basin to ~1800 m in the Stuhleck and Wechsel mountains. A small part of the study area, but a reasonable part of the Feistritz river catchment, is made up of rocks from the Paleozoic of Graz. Tectonically, the majority of the Fischbach Alps is part of the Koralpe-Wölz nappe system and the Semmering-Wechsel nappe system (Schuster et al., 2015; Flügel and Neubauer, 1984), where low, medium and high grade metamorphic schists and gneisses are present, but parts of it belong to the Silvretta-Seckau nappe complex. Interestingly, orthogneiss regions generally form topographic highs indicating some lithological control on landscape formation. Two major tectonic windows appear in the region where low phyllonites and Permo-Mesozoic rocks (Semmering quartzite) appear from underneath these nappes: The Fischbach window and the region around Waldbach (Fig. 3). In particular in the Fischbach window these low grade rocks are morphologically evidenced by steeply incised narrow valleys. To the south, both the crystalline rocks of the Fischbach Alps and the Paleozoic of Graz disappear beneath the Neogene rocks of the Styrian basin (Gross et al., 2007). In the Pöllauer Saifen catchment river terraces that interact with the Styrian basin have been mapped extensively by Nebert (1952). Several major faults cut the region. Amongst those, the Anger-Piregg Fault along the east margin of the Anger basement is also morphologically of interest as it marks the transition from more jagged topographic relief to the west and more gentle slopes to the east (Schuster et al., 2015) (Fig. 2). The other important structure in the region is that bounding the Waldbach basin to the west (Fig. 3). However, this fault does not appear to be reflected morphologically. Low-temperature geochronological ages dating final exhumation are sparse for the region, but van Gelder et al. (2020) report for the study region zircon fission track ages around 50 Ma and few isolated apatite ages around 30 Ma, both being older than the paleosurfaces and related sediments discussed below. However, for the Rechnitz window east of the region investigated here, Dunkl and Demény (1997) report of 7.3–9.7 Ma old apatite fission track ages. We will suggest below that these are older than the landscape evolution discussed here and their difference to the low temperature geochronological ages of the Mürz region or to those of the Koralpe does therefore not impinge on our story.

Morphologically, the highest part of this region has been referred to as Teufelstein-Landschaft, named after the prominent Teufelstein mountain (1489 m) by Schwinner (1935), who noticed that the higher mountain peaks along the Feistritz and Lafnitz catchments are all of very similar elevation and might have been connected in the

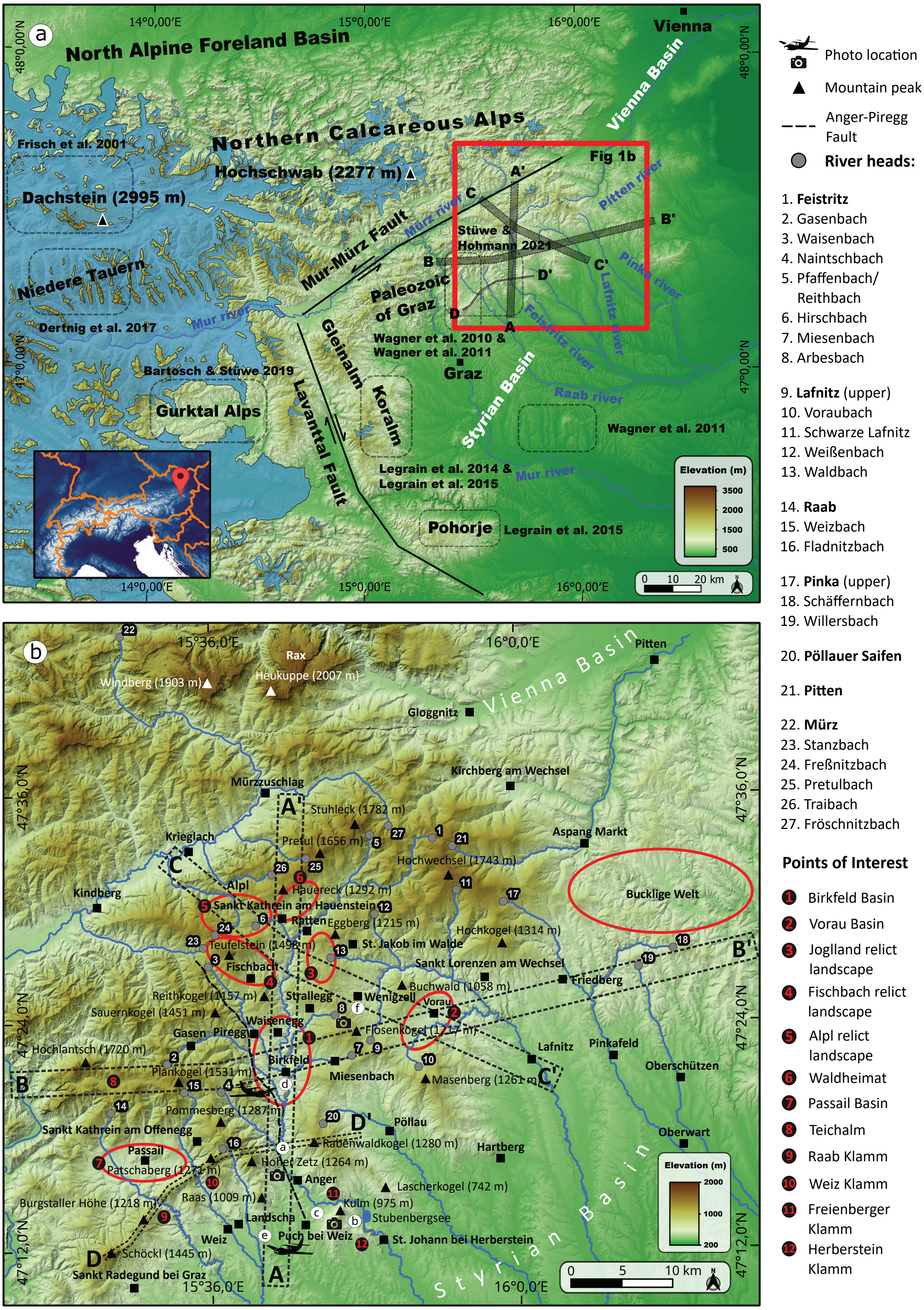

Figure 1: (a) Topographic map of the Eastern Alps with the study area (red square) and superimposed extent of Last Glacial Maximum (LGM) (van Husen, 1997). Note that the LGM extent may have been exceeded by several kilometres during earlier glacial stages. Dashed-line boxes show the distribution of similar studies in the Eastern Alps. Grey-shaded stripes indicate swath profile locations shown in Figure 10. The transition from Alpine orogen to the sedimentary basins is marked by the colour change from green to beige. For the Styrian Basin this transition is at ~350–500 m. (b) The study area in the Eastern Alps with the analysed rivers and tributaries (white numbers) and morphological areas of interest (red numbers). Dashed-line boxes indicate swath profile locations in Figure 10.

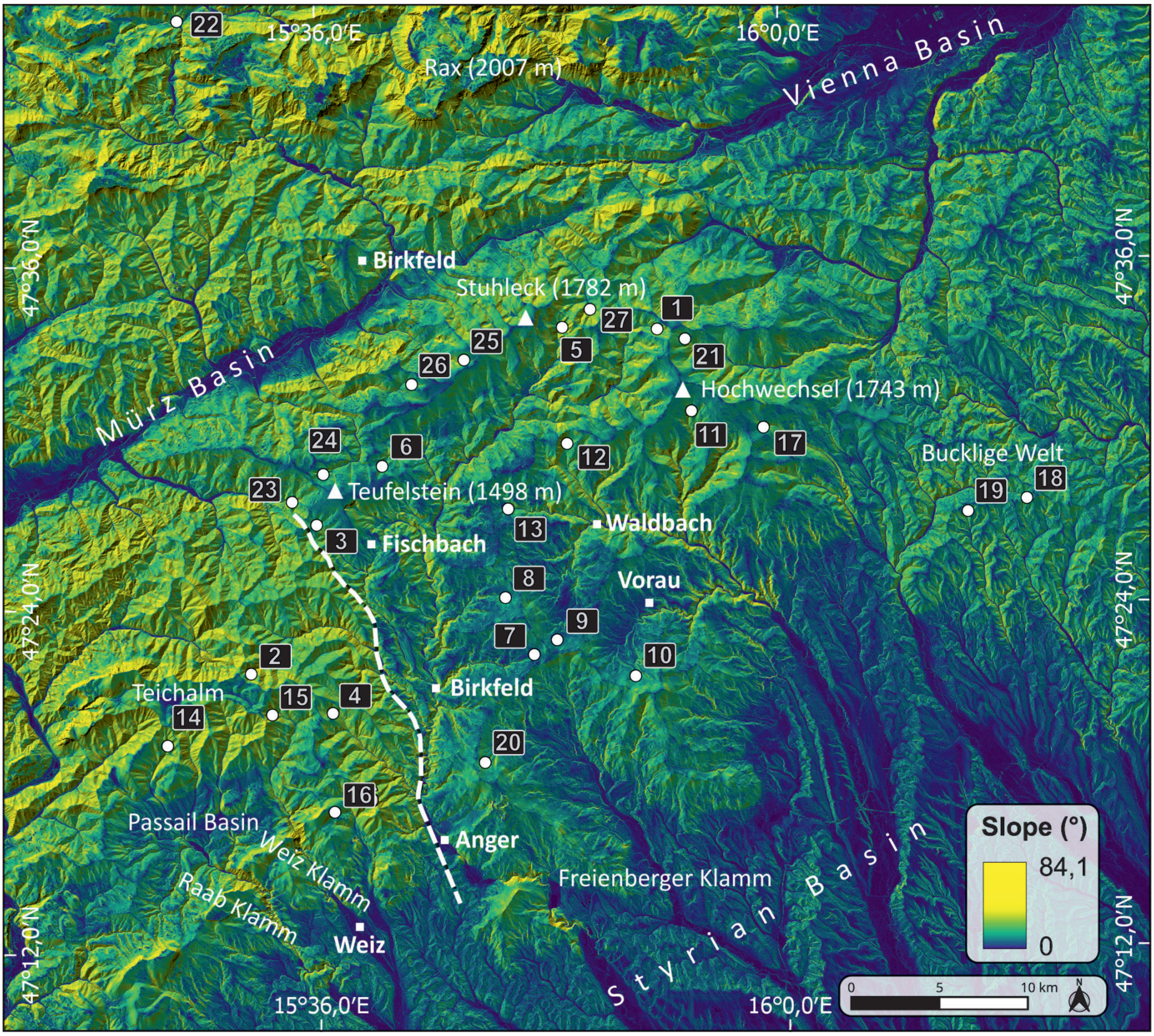

Figure 2: Slope map of the study area superimposed on hill-shaded DEM. The transition from blue to blue-green colours mark the threshold for pre-existing landscapes (except from the flat alluvium of the Styrian Basin). The low-relief surfaces of the Teufelstein-Landschaft (Schwinner, 1935) are easily recognizable to the east of the Anger-Piregg Fault (white dashed line).

past. Schuster et al. (2015) provides a good summary of the landscape evolution of the study area as well as new findings during the geological survey for the map sheet GK135 Birkfeld (Matura and Schuster, 2014). Evidence for young uplift of the region comes partly from the occurrence of terrestric Neogene sediments at elevations substantially above those of the Styrian basin (Fig. 3). The most noticeable occurrences are found in the Birkfeld area (Birkfeld Basin), the Lafnitz catchment (Lafnitz Basin), Vorau area (Vorau Basin), Waldheimat area (Waldheimat Basin) and the Bucklige Welt (Fig. 3). According to Schuster et al. (2015), Matura and Schuster (2014) the sediments (Blockschichten des Feistritz- und Lafnitztales and Grobschotter von Trog) covering the Birkfeld Basin (~720 m) are most likely of Karpatian – Pannonian age. On the map sheet GEOFAST136 (Hartberg) Neogene sediments covering the circumference of the Wechsel foothills near Hartberg and in the Vorau Basin, can for the most part be attributed to the Sinnersdorf-Formation, which is also of Karpatian age. The occurrence of Neogene sediments appears to be related to low-relief regions and therefore provides minimum constraints of their age (Fig. 4). We thus briefly summarise the relevant levels as they are known from regions surrounding the Fischbach Alps (see also Wagner et al., 2011).

The ***Stadelberg level*** represents the youngest and lowest pre-glacial low-relief surface. It can be traced along many parts of the Alpine orogen – Pannonian basin transition zone (Stüwe and Hohmann, 2021). This level derives its name (Stadelberg/Zaraberg level) from the low-relief hills of the Stadelberg near St. Anna am Aigen and the Zaraberg near Klöch. A minimum age of ~3 Ma was at-

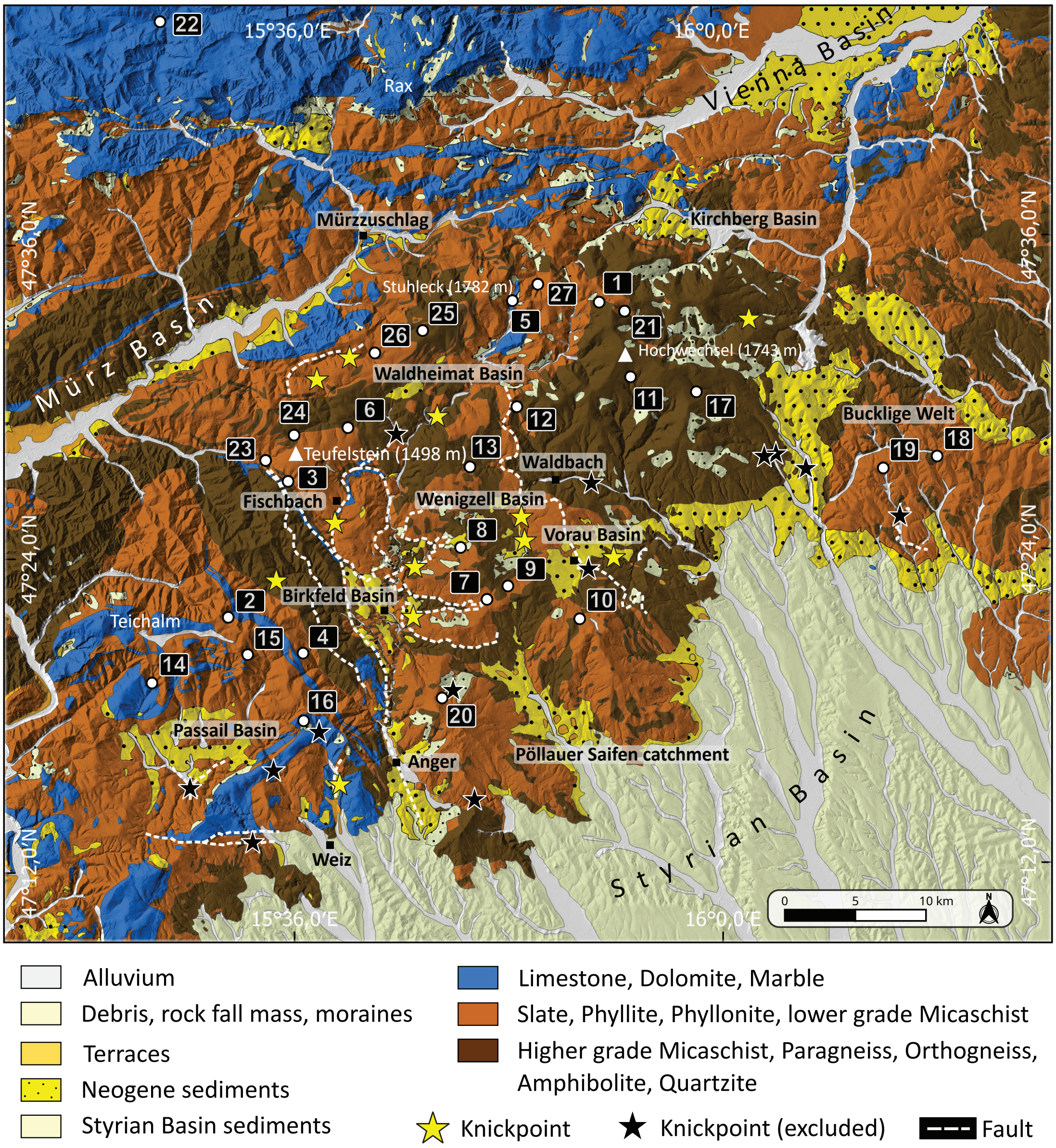

Figure 3: Geological map of the investigated region with special emphasis on the distribution of intramontane, Neogene sediments and fluvial terrace sediments in the Fischbach Alps. Geology is superimposed on a hill shaded DEM.

tributed to this level by Wagner et al. (2011) by correlation of sediment burial ages from caves north of Graz. Previous studies (Wagner et al., 2011; Stüwe and Hohmann, 2021) have shown that these surfaces are located at elevations between ~54–700 m.

The ***Landscha level*** is located above the Stadelberg level and is also referred to as the Hochstraden or Kalkleiten level. Early studies by Untersweg (1982) and Winkler-Hermaden (1957) recognised these low-relief surfaces at the transition from orogen to basin in the Grazer Bergland. Cave sediments from caves along the Mur valley have constrained the formation of these surfaces between ~3.4 Ma and ~4 Ma (Wagner et al., 2010; 2011). Although the correlation to the low-relief surface at Hochstraden is generally plausible, it hinges on the correlation within errors of K-Ar ages from Balogh et al. (1994) which is why a more suitable name is desirable. For this reason and its prominence within the study area this level is named after one of the very prominent low-relief surfaces near the Weizbach outflow at the town of Landscha ~160 m above the current base level (Fig. 4). Landforms of this level are most prominent and best preserved at the transition from the mountainous landscape to the basin at Landscha near Weiz, south-east of the Raab Klamm (gorge) and Vorau but are also recognised about 15 km upstream of the Feistritz river at Birkfeld and Miesenbach. Within the Lafnitz catchment this level is easily recognisable in the whole Vorau Basin. The Bucklige Welt north-east of Pinkafeld features the most continuous landscape of the Landscha level. Apart from the Birkfeld Basin, Neogene sediments related to this level can also be found downstream of the Feistritz

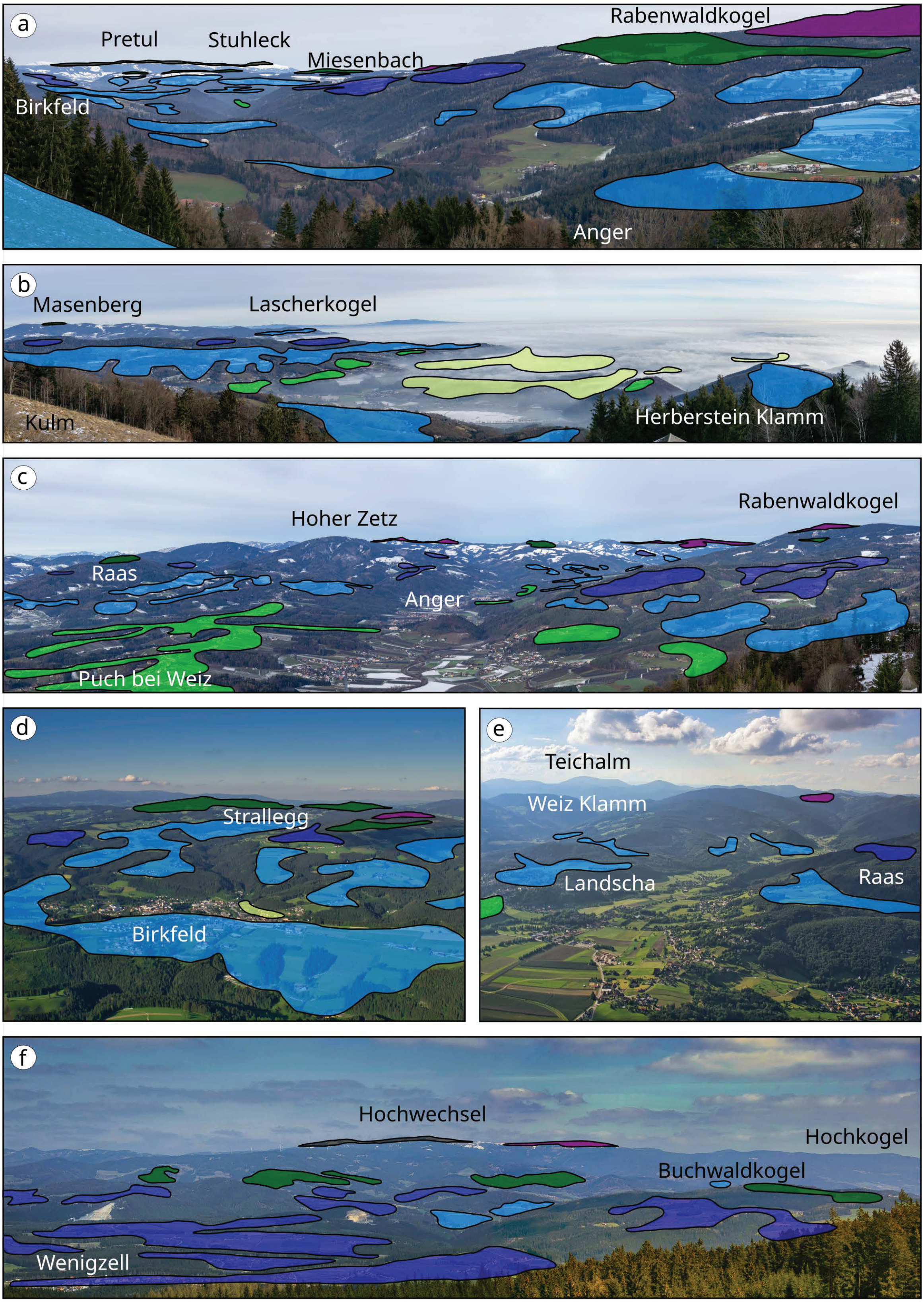

Figure 4: Field photographs of mapped low-relief surfaces. (a) View from Anger to Birkfeld. (b) The Styrian Basin with the L0 low-relief surfaces at the basin-orogen transition as seen from the Kulm mountain. (c) View from the Kulm in north direction up the Feistritz valley overlooking the L0 surfaces at Puch near Weiz as well as the low-relief strath terraces of the L1 level at the foothills of the Raasberg. (d) Aerial photo of the Birkfeld Basin with the lower Arbesbach and Miesenbach catchments in the background. (e) Aerial photo of the Landscha level (L1) type locality at the outflow level of the Fladnitzbach and the Weiz Klamm in the background. (f) Low-relief surfaces of the upper Lafnitz catchment (L2 level) near Wenigzell. Colour coding: beige =Terrace level, light green = Low-relief level L0, light blue = Low-relief level L1, blue = Low-relief level L2, green = Low-relief level L3, magenta = Relict landscape L4, dark grey = Relict landscape L5.

river, north of Anger at elevations of ~600 m and south thereof at elevations ~560 m.

The ***Trahütten level*** is named after the type locality Trahütten in the Koralm at an elevation of ~1000 m and is sometimes referred to as the 1000 m landscape (Legrain et al., 2014), although elevations in the study area can be somewhat lower. This level marks the first occurrence of widespread cave formation in the Mur valley. The highest and oldest level of the Drachenhöhle was dated to ~4 Ma and correlates to the Trahütten level by Wagner et al. (2011), contradicting the proposed late Pannonian age by Winkler-Hermaden (1957).

The ***Hubenhalt level*** bears its name from a low-relief surface between the north-western part of the Passail Basin and the Teichalm along a ridgeline at an elevation of ~1200 m. This level correlates with the Teichalm base which is of the same elevation but interrupted by the Teichalm topography surrounding it. In the study area east of the Anger-Piregg Fault this level can be traced along the ridge containing the Feistritz valley where it is observable as very gentle mountain peaks between the catchments of the Pöllauer Saifen, Lafnitz and Feistritz river (Fig. 4). North of Fischbach at the Alpl pass this level stretches from the landscape surrounding the Teufelstein (1498 m) to the shoulders of the Wechsel mountain. According to Winkler-Hermaden (1957) the Hubenhalt level formed in middle Pannonian times.

The ***Wolscheneck level*** is the second oldest level within the relict landscapes of the region. According to Wagner et al. (2011) and Stüwe and Hohmann (2021) it can be found at elevations between ~1250–1350 m. Winkler-Hermaden (1957) proposed an early Pannonian age to this levels. In the work of Stüwe and Hohmann (2021) the Wolscheneck and the Koralm level were unified because the distinction between those levels is difficult due to prolonged erosion history compared to the lower levels and possible tectonic dissection. Notable occurrences of this level can be found at the Schöckl summit and the summits surrounding the Teichalm. In the Vorau Basin and between Birkfeld and Vorau the local relief is remarkably low (Fig. 4).

The ***Koralm level*** is the highest level recognised by Winkler-Hermaden (1957) who proposed a late Sarmatian age for these relict landscapes. Wagner et al. (2011) found that these levels should be found at elevations of ~1550–1850 m but did not recognise them in the Grazer Bergland. Here, the Wechsel (1743 m) and Pretul (1656 m) and Stuhleck (1782 m) mountains and their ridge lines are attributed to this level (Fig. 4). Winkler-Hermaden (1957) interpreted the Koralm level as the oldest level throughout the Eastern Alps between elevations of ~1300–3000 m (Masenberg-Dachstein), thus recognising increasing elevation towards the source area.

3. Data and Methods

Relatively flat, perched surfaces above the rivers base level can, within the right tectonic framework, be inter-

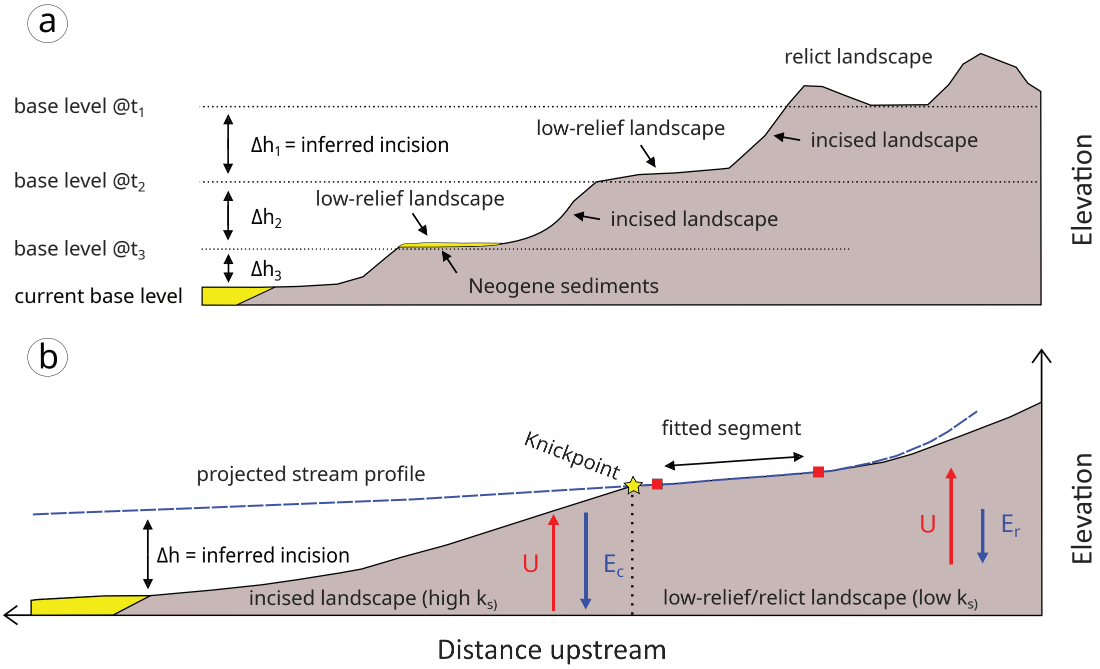

Figure 5: Conceptual model of a landscape responding to tectonic uplift. (a) A set of low-relief surfaces is perched above the current base level. Each level of low-relief surfaces serves as a marker for base level at the time and discrete phases of uplift (U). The relict landscape on top reflects the oldest topography of the study area. (b) Projected river profile (for a single timestep) of a river in a landscape responding to tectonic uplift (U) by an upstream migrating knickpoint at an increased rate of erosion (E_c). The river is projected from a segment in the upper portion of the river (with low k_{sn} values) which has not yet experienced increased erosion E_c. The projected profile represents the pre-uplift local base level. Projection segment boundaries are marked with red squares and represent low k_{sn} portions of low-relief and relict landscapes that erode with lower erosion rate (E_r) as compared to the incised landscapes. by subtracting the erosion rate of the relict landscape above the knickpoint, E_r, from the rock uplift rate U.

preted as remnants of pre-existing landscape (Clark et al., 2006), but the terminology often varies. Here we use the terms "planation surface", "elevated low-relief landscape" and "strath terrace" more or less synonymously to describe relicts of former base levels (Fig. 5). In contrast, with the term "incised landscapes" we refer to the more recent topography below the uplifted pre-existing landscape. Incised landscape has typically steeper slopes (for mapping typically ≥20°), but may also gradually merge from one pre-existing landscape to another when only slow erosion processes are working and abundant sediment cover is present.

To map elevated low-relief landscapes a combined approach of topographic analysis of a digital elevation model (DEM) and field mapping of landforms was chosen. Mapping was conducted from vantage points overseeing large parts of the study area and was assisted by hillshade relief printouts and a handheld GIS for reference. Topographic and numerical analysis of river profiles was performed on a 10 m resolution airborne laserscan (LIDAR) DEM (geoland.at). Digitizing of field mapping sheets and further DEM-aided mapping was performed within a QGIS 3.22 project (QGIS Development Team, 2009). For this purpose, local relief, slope and the normalised steepness index, k_{sn}, the concavity index Θ, as well as the normalised parameter χ (Perron and Royden, 2013) were calculated using Topotoolbox (Schwanghart and Scherler, 2014) and algorithms included in QGIS 3.22. Topographic swath profiles and projected river profiles were also produced with the Topographic Analysis Kit (TAK) (Forte and Whipple, 2019). Published geological maps were incorporated in the GIS and used to extract the Neogene sediments and river terraces (Fig. 3) (e.g. those published by Geological Survey of Austria as well as Flügel et al., 1990; 2011; Matura and Schuster, 2014; Mandl et al., 2001; Herrmann et al., 1992; Moser, 2016; Kreuss, 2016; Flügel, 1969; Flügel and Maurin, 1958; Flügel and Neubauer, 1984; Schnabel et al., 2002).

3.1 River network analysis

Rivers in tectonically active landscapes incise into the underlying bedrock or consolidated sediment deposits as long as the river's capacity to transport sediment is greater than the actual sediment load. This is then called a detachment-limited regime and applies to most rivers in the non-glaciated parts of the Alps (Robl et al., 2017), at least outside the Pleistocene glaciations. In a detachment-limited regime, equilibrium is reached when a river erodes at the same rate at all points of the channel. This is then called a graded river profile. Divergence from this equilibrium profile can be exploited to identify river segments subject to tectonic activity and can be observed as breaks in slope, called knickpoints, in the river profile (Wobus et al., 2006). Rivers that flow across (multiple) low-relief relict landscapes and younger incised landscapes are likely to retain such knickpoints that separate equilibrated and non-equilibrated sections (Fig. 5). River profiles can thus be used as an additional tool to identify relict landscapes.

To identify knickpoints in the analysed catchments we follow other studies of relict landscapes in the Eastern Alps and use a simple model for fluvial incision that relates erosion rate E to slope S and catchment area A (as a proxy for water flux) by: $E = K A^m S^n$ (e.g. Howard and Kerby, 1983; Whipple and Tucker, 1999). Therein, K is an erodibility constant which incorporates information about erosive properties of the riverbed and the exponents m and n describe the relative contribution of slope and water flux to erosion, i.e. to the incision process (Kirby and Whipple, 2012). For graded rivers, where E is a constant along the channel, this can be written as $S = k_s A^{-\theta}$ (Hack, 1957; Flint, 1974), in which the constant $k_s = (E/K)^{(1/n)}$ is called the steepness index and $\theta = m/n$ is called the concavity index (Wobus et al., 2006). Using slope and catchment area as measured from the DEM, it is therefore easily possible to use a linear regression of this data in a double-logarithmic space of A against S to derive k_s and θ. For better comparison of k_s values between different river segments and across different catchments, we use common practise and use a dimensionless reference concavity index $\theta_{ref} = 0.5$ and fit for k_s only. This is then called the normalized steepness index k_{sn} (Kirby and Whipple, 2012).

3.2 River profile projection

A distance-elevation profile of a river can be used to investigate the topographic state of its corresponding mountain range (Wobus et al., 2006). Knickpoints can be identified as breaks in slope along an elevation-distance profile. This is reflected in a higher steepness index (k_{sn}) and higher erosion rate below the knickpoint and a lower steepness index and lower erosion rate above. The landscape above the knickpoint is correlated with the relict or low-relief landscape, whereas the lower part correlates with the younger incised landscape. By downstream-projecting of an equilibrated segment of the upper part of a river (above a knickpoint), the amount of surface uplift Δh from the current base level in the time Δt can then be inferred (Kirby and Whipple, 2012) (Fig. 5). This was done by fitting manually chosen selected channel segments that appear to be in equilibrium (i.e. they have more or less constant k_{sn}) with a least-square linear fit in χ-space fixed at a base level of 300 m elevation using the SegmentProjector function in TAK (Forte and Whipple, 2019). Since knickpoint migration is also sensitive to changes in lithology (Kirby and Whipple, 2012), extra care was taken by comparing knickpoints to geological maps. Δh of the elevation of the downstream projected fitted segment above base level was then interpreted as the amount of uplift above base level that occurred since the formation of the low-relief surface on which the projected equilibrium channel segment lies.

4. Results

The geomorphological map of the Fischbach Alps is presented in Figure 6. Throughout the study area low-relief surfaces are generally found below elevations of ~1300 m. These low relief surfaces concentrate on discrete elevations with steep sections in between so that discrete levels can be discerned that suggest genetic linking. A total of six discrete levels were mapped.

4.1 The six mapped low-relief levels

The lowest low-relief level L0 (light green colour on Fig. 6) was mapped at a mean elevation of 537 ± 45 m throughout the study area. It can be found near the Raab outflow into the Styrian Basin as well as on two relatively small low-relief surfaces just below the low-relief surfaces at Landscha. In the Feistritz catchment it is observable between Puch bei Weiz and Anger, were a continuous, ~5 km long elongated surface can be found (Fig. 4). From Birkfeld, to the entering of the Feistritz channel into the subbasin of Anger, the L0 surfaces can be found as the lowest level in the bedrock hillsides of the meandering Feistritz valley reaching ~600 m elevation at Birkfeld. In the Pöllau basin this level is harder to distinguish from the terraces level near the town of Pöllau and was mapped from elevations of ~450–600 m. About 5 km north-west of Pöllau Nebert (1952) mapped terraces at a location where the L0 level was mapped in this work (Fig. 6). From the Pöllau Basin the L0 level can be traced by occasional surfaces occupying the lowermost foothills of the Masenberg and near the town of Lafnitz at both sides of the Lafnitz river. Interestingly, no low-relief surfaces of this level can be found in the catchment of the Feistritz river. At the town of Friedberg and at the south and west margins of the Bucklige Welt, low-relief surfaces of the L0 level can be distinguished from the higher L1 level. A general observation is that the L0 level can be observed both on the lower foothills of the orogen (sometimes on sediment covered bedrock) and on the Sarmatian-Pannonian sediments of the Styrian Basin where erosion and base level lowering formed the Riedel landscape that is recognized throughout Styrian Basin.

The second lowest level (light blue colour on Fig. 6) above the river terraces is called L1 and occurs at 670 ± 75 m mean elevation. It is the lowest level that is observed as straths on a greater scale and can be followed from

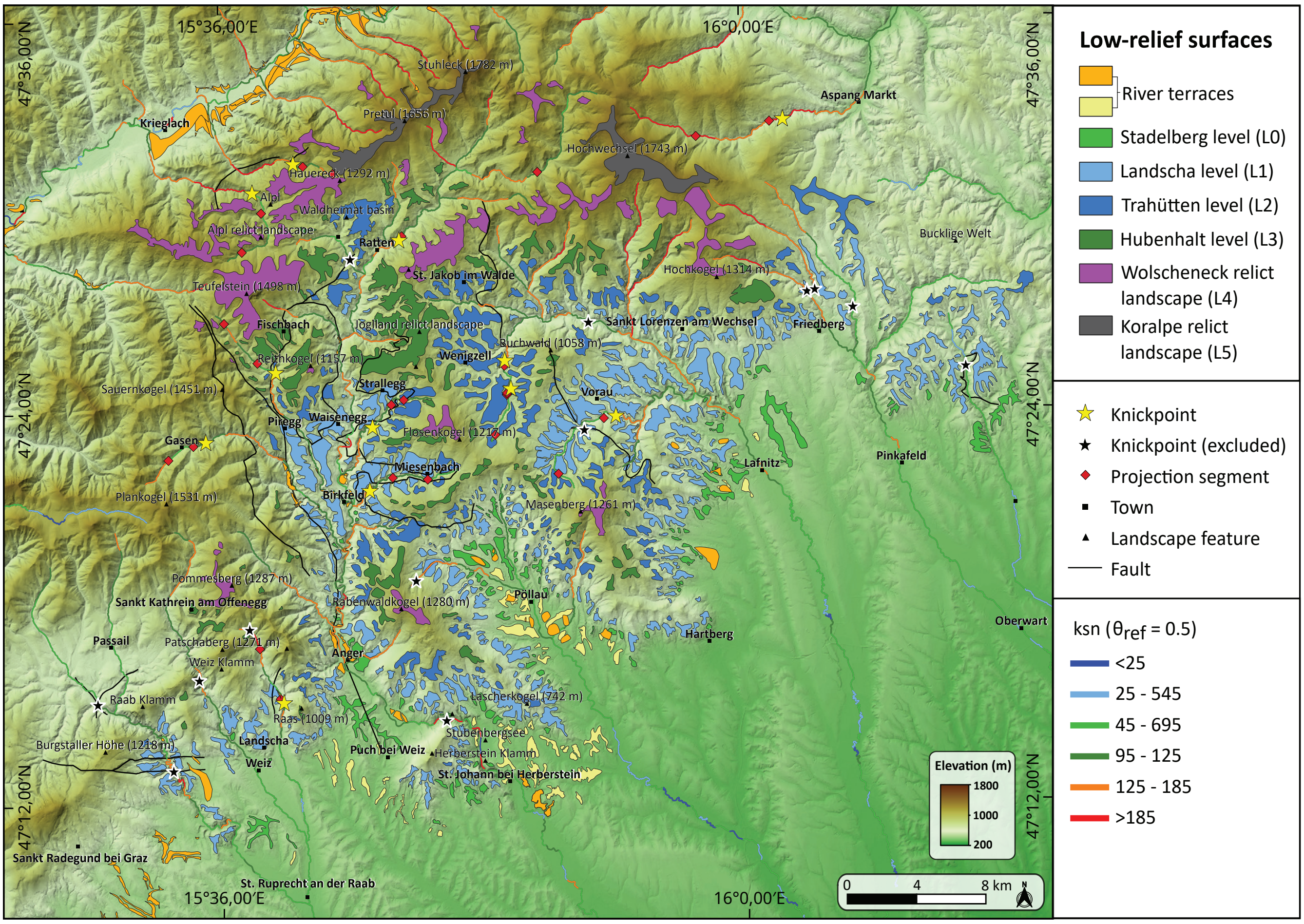

Figure 6: Geomorphological map of the greater Fischbach Alps. The abbreviation k_{sn} is the normalised steepness index (see methods section): The term "projected segment" with the red diamond symbol shows channel sections that are used for fitting as explained in the text. Excluded knickpoints are also discussed in the text.

the strath terraces close to the Styrian Basin to the intramontane basins at Birkfeld and Vorau. Of those strath terraces, the ones of the Raab river below the Raab Klamm, and the terraces at the outflow level of the Weizbach and Fladnitzbach, are the most remarkable. Here the base level is around 150 m lower than the low-relief surfaces. From the transition from the Styrian basin to the mountainous topography, this level can be traced to the Birkfeld subbasin and further upstream to St. Kathrein am Hauenstein where elevations of mapped surfaces range from ~700–850 m in the upper reaches of the tributary catchments. Along this stretch of the Feistritz river the mapped surfaces and the slope of the channel are about 0.5°. In the Birkfeld and Vorau basins the L1 level sits on top of Neogene sediments (likely of Karpatian age, Matura and Schuster, 2014). Given the long time since deposition and the easier erodibility of the sediments it is likely that the initial low-relief was possibly tens or even hundred(s) of meters higher, compared to the current elevation. Evidence for this can be found in the tributaries of the Waisenbach and Miesenbach where the mapped L1 level increases in elevation with distance from the Feistritz river. In the Lafnitz catchment, at the southern foothills of the Hochkogel, different sublevels of the L1 level were mapped. The higher level (~700 m) is located on bedrock whereas the lower mapped level (~600 m) is located on Neogene sediments which are more likely to have eroded quicker and gradually decline in elevation towards the Styrian Basin and Lafnitz outflow level. Similar to the Feistritz catchment, the Lafnitz river displays perched low-relief surfaces along the main river some 15 km upstream from the outflow level. From the Vorau basin to the foothills of the Hochkogel and to the Bucklige Welt the L1 level can be traced as a nearly continuous low-relief surface.

Level L2 lies above the L1 level at elevations of 830 ± 65 m (darker blue on Fig. 6). It constitutes the next highest level of low-relief surfaces. This level is predominantly found in the central parts of the study area and only a small fraction of the mapped surfaces can be found close to the Styrian Basin where this level can be found at elevations of ~700–800 m for example at the Lascherkogel north-east of the Stubenberg Lake and on the foothills of the Masenberg, between Hartberg and the town of Lafnitz. Along the Feistritz river this level varies considerably in elevation ranging from elevations of ~700 m towards the Styrian Basin to ~900 m in the Neogene Waldheimat Basin near St. Kathrein am Hauenstein with a relative base level drop of ~200–300 m. In the Birkfeld Basin and in the upper catchments of the Miesenbach and Arbesbach, the L2 level is constrained to lie below the bedrock lithology of the Joglland relict landscape (L3 level) and the L1 level, which is mapped on sediment deposits ~150–200 m below. It is therefore possible, that the L2 level was the paleo-surface of the Birkfeld Basin sediment filling that has since been eroded to form the lower L1 level (Fig. 7). In the Lafnitz catchment the L2 level is found in the upper foothills of the Hochkogel and Hochwechsel from Friedberg to St. Jakob im Walde and in the catchment of the upper Lafnitz near Wenigzell. Here the level can be found at elevations of ~800–900 m where the lower bound is owed to the Neogene sediments in the centre of the catchment. It is possible that erosion contributed to the removal of sediments (≤ 50 m). The low-relief surfaces near the base level of the upper Lafnitz and around the town of Wenigzell are nonetheless mapped to the L2 level and not to a lower level because of negligible difference in relative elevation. The highest recognized level of low-relief surfaces in the Bucklige Welt is the L2 level, which can be found between ~800 and ~900 m elevation and which represents smooth ridgelines and peaks that withstood fluvial dissection and drainage reorganisation.

Level L3 (dark green on Fig. 6) lies at a mean elevation of 995 ± 59 m and represents also a distinct landscape

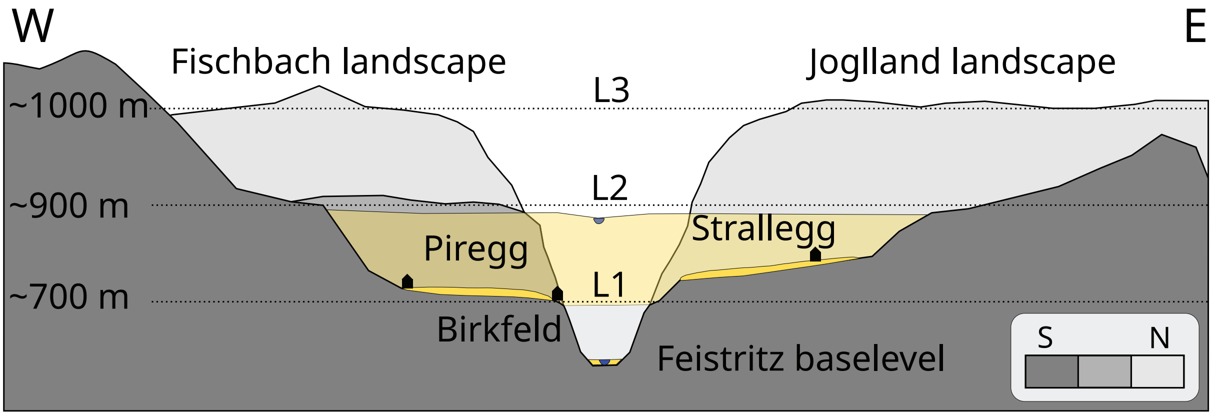

Figure 7: Schematic west-east transect of the Birkfeld Basin showing mapped levels (L1, L2, L3), proposed eroded Neogene sediments (shaded yellow) and remnants thereof (bright yellow). According to this model up to ~200 m of Neogene sediment could have been eroded over a time of approximately three million years in the Middle to Late Pannonian. Grey-shading from light to dark grey represents three different transects of the topography across the Feistritz river during the formation of L3, L2 and L1, respectively. Dark grey = west-east transect at Birkfeld Basin today, middle grey = west-east transect between Piregg and the Fischbach landscape during L2, light grey = west-east transect through the Fischbach and Joglland landscape during formation of L3.

River	Lat (°N)	Lon (°E)	Outlet Elevation (m)	A (km²)	Mean Elevation (m)	Slope (°)	Mean Relief ± σ (m)	k_{sn} (θ = 0.5)	θ	$θ_{up}$	Knickpoint Elevation	Inferred Incision Δ h
1. Feistritz	47.1962	15.8362	350	480	939 ± 254	19 ± 10	598 ± 124	111 ± 155	0.47	0.48	761; 415*	89
2. Gasenbach	47.3312	15.6925	531	65	983 ± 196	26 ± 10	666 ± 71	122 ± 37	0.62	0.91	798	248
3. Waisenbach	47.3533	15.7006	560	39	1009 ± 201	19 ± 10	553 ± 134	107 ± 37	0.51	0.63	819	246
4. Naintschbach	47.2915	15.6853	483	26	917 ± 181	27 ± 10	691 ± 66	148 ± 51	0.45			
5. Pfaffenbach, Reithbach	47.5247	15.7823	845	25	1256 ± 202	22 ± 10	760 ± 106	138 ± 58	0.85			
6. Hirschbach	47.4712	15.7111	714	23	1015 ± 139	16 ± 7	540 ± 75	99 ± 28	0.62		748*	
7. Miesenbach	47.3531	15.7017	561	21	897 ± 123	12 ± 7	487 ± 51	85 ± 35	0.22	0.34	630	209
8. Arbesbach	47.3691	15.6918	575	19	901 ± 127	13 ± 8	459 ± 62	86 ± 24	0.44	0.52	711	247
9. Lafnitz	47.3836	16.0031	420	268	864 ± 225	15 ± 9	533 ± 168	99 ± 59	0.32		570*	
upper Lafnitz	47.4481	15.8343	627	45	876 ± 103	11 ± 7	423 ± 66	65 ± 32	0.29	0.51; 0.75	747*; 698	212*; 131
10. Voraubach	47.4087	15.9635	464	62	768 ± 127	12 ± 8	438 ± 95	72 ± 32	0.4	0.54	653; 602*	91
11. Schwarze Lafnitz	47.4384	15.9154	534	42	1121 ± 266	20 ± 9	769 ± 119	172 ± 72	0.71			
12. Weißenbach	47.4482	15.8469	615	25	1019 ± 175	21 ± 9	641 ± 88	132 ± 38	0.55			
13. Waldbach	47.4489	15.8351	628	19	931 ± 113	16 ± 8	468 ± 41	91 ± 32	0.4			
14. Raab	47.1717	15.6168	400	184	782 ± 203	17 ± 11	522 ± 168	77 ± 49	0.47		588*;499*	
15. Weizbach	47.2075	15.6325	450	55	881 ± 231	21 ± 12	630 ± 124	110 ± 54	0.63		578*	
16. Fladnitzbach	47.2188	15.6465	470	18	890 ± 187	23 ± 10	638 ± 64	106 ± 47	0.68	0.66	882*;590	38
17. Pinka	47.3830	16.1178	400	128	759 ± 223	15 ± 8	423 ± 157	77 ± 54	0.69			
upper Pinka	47.4209	16.0933	452	68	855 ± 254	14 ± 8	513 ± 171	97 ± 64	0.67		592*;588*;524*	
18. Schäffernbach	47.4206	16.0949	452	49	680 ± 82	16 ± 8	313 ± 17	57 ± 21	0.38			
19. Willersbach	47.3164	16.2080	322	33	517 ± 112	13 ± 9	238 ± 72	44 ± 20	0.5		496*	
20. Pöllauer Saifen	47.2393	15.8977	330	121	650 ± 204	12 ± 7	515 ± 159	74 ± 43	0.68		821*	
21. Pitten	47.7348	16.2220	300	413	754 ± 276	17 ± 9	516 ± 198	93 ± 60	0.66	0.54	666	121
22. Mürz	47.5492	15.5297	600	611	1104 ± 251	25 ± 14	762 ± 172	115 ± 70	0.54			
23. Stanzbach	47.4924	15.4312	558	86	992 ± 214	25 ± 10	699 ± 106	122 ± 56	0.68			
24. Freßnitzbach	47.5449	15.5473	612	44	1125 ± 187	20 ± 10	610 ± 140	126 ± 55	0.26	0.6	930	209
25. Pretulbach	47.5728	15.6313	640	21	1152 ± 235	24 ± 11	765 ± 69	152 ± 52	0.66			
26. Traibach	47.5591	15.5924	623	19	1119 ± 198	20 ± 11	602 ± 91	130 ± 62	0.37	0.53	1036	231
27. Fröschnitzbach	47.6195	15.7913	824	18	1178 ± 160	25 ± 9	710 ± 89	118 ± 25	0.53			

Table 1: Summary of catchment statistics for the analysed catchments. Latitude and Longitude indicate outlet coordinates. The asterisk symbol in the “knickpoint elevation” column marks knickpoints that were excluded from further analysis.

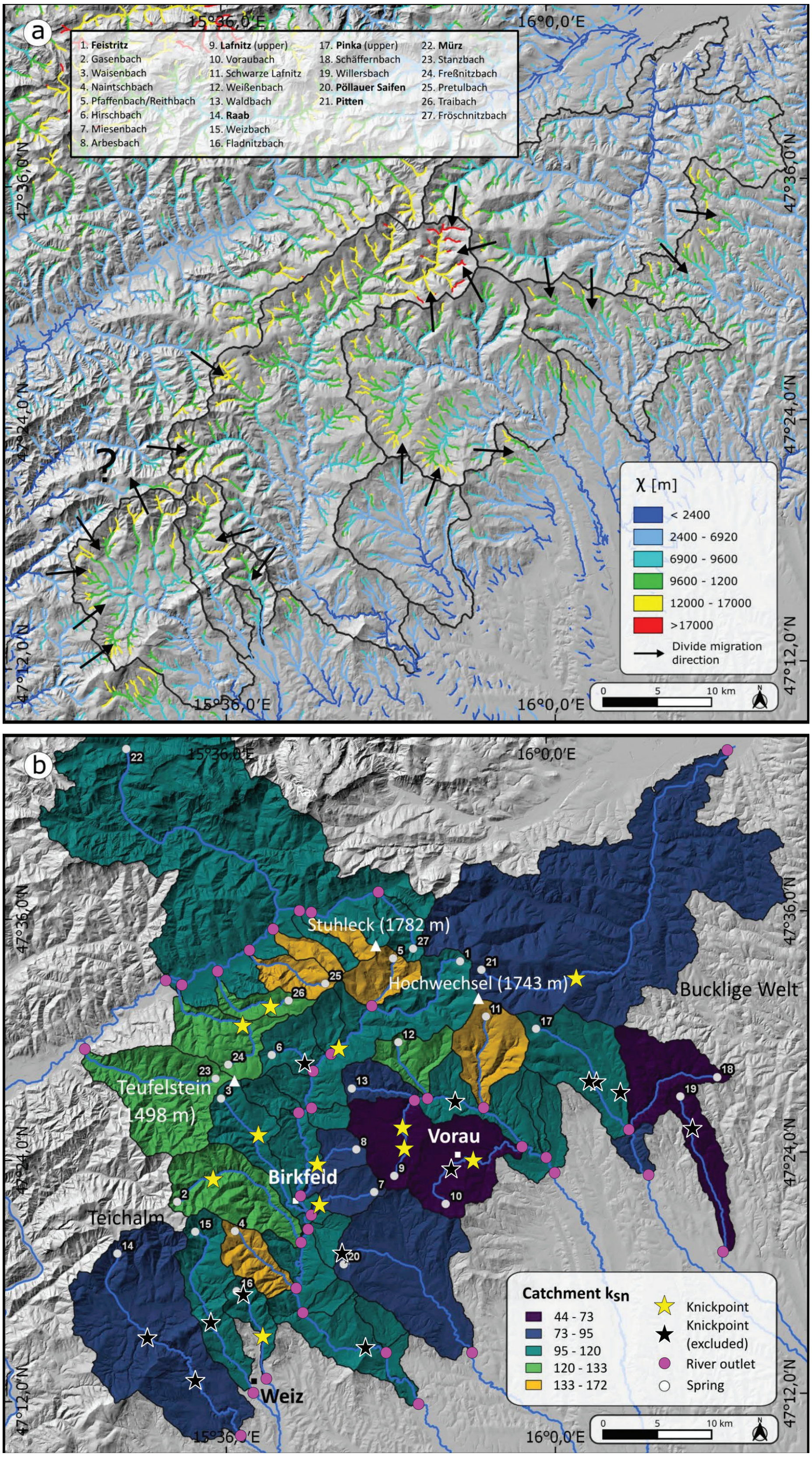

Figure 8: Geomorphic metrics of river channels in the region. (a) χ-map of the study area showing the drainage divide movement (black arrows). Following the approach of Willett et al. (2014), χ-maps can be used to determine whether two divides are in steady state or disequilibrium. Lower χ-values represent the "aggressor"- catchment moving towards the "victim"-catchment with higher χ-values. χ-values were calculated from a 300 m base level and averaged over 500 m segments with an algorithm implemented in TAK by Forte and Whipple (2019). (b) Map of catchment-wide averaged k_{sn} of the analysed catchments. k_{sn} can be used to identify catchments that are unusually steep and are either interpreted to represent a response to uplift or different lithology. See Table 1 for names of numbered rivers and a comprehensive collection of catchment statistics. The upper Lafnitz and upper Pinka were analysed separately from the main river catchment.

with low-relief. The low-relief surfaces belonging to this level are perched ~100 m above the L2 level and covers in part vast areas between the highest ridges and peaks of the relict landscape R2 level along the Feistritz watershed to the Lafnitz, Pöllauer Saifen and Raab catchments. The most notable location is the Joglland relict landscape north of Stralleg and the Fischbach landscape south of the Teufelstein. Along the ridgelines, mapping of this level may represent intermediate or transient surfaces between the L2 and R1 level as they mark local elevation maxima but are not high enough to meet the criteria for the R1 level which is located at an elevation of ~1200 m.

The relict landscape L4 (magenta on Fig. 6) represents an intriguing set of different topographies at a mean elevation of 1248 ± 101 m: At ~1150 m the Alpl relict landscape and the low-relief surfaces of the Eggberg mark the base of this relict landscape. These surfaces are very flat and easily recognizable in the field and on a slope map (Fig. 2). However, in contrast to lower levels L4 often bears considerable topography within this level (see also Schuster et al., 2015). While the Eggberg surfaces are the local elevation maximum, the Alpl relict landscape is dissected by the Freßnitzbach and smaller streams. Low k_{sn} values in the upper reaches of the Freßnitzbach can be seen on Figure 6. What can be called "old topography" related to L4 are the smooth peak areas between the watersheds of the Feistritz, Pöllauer Saifen and Lafnitz catchment, for example the Rabenwaldkogel, Flosenkogel and the Masenberg between the Feistritz valley and the Weizbach catchment. These peaks and their surrounding can be found at elevations just under 1200 m everywhere south of the Teufelstein mountain. From the Teufelstein north- and eastwards, the study area changes to a noticeably more mountainous topography where peak elevations, within the mapped level, range between ~1300 m and ~1500 m but a smooth landscape character nonetheless persists. The prominence of the Teufelstein led Schwinner (1935) to term this landscape the "Teufelstein-Landschaft". Towards the Hochwechsel this level is observed as ridgelines and mountain shoulders within the Lafnitz catchment. Here the mean elevation of this level is around 1300 m and 1500 m.

The relict landscape L5 level (darkest gray on Fig. 6) constitutes the highest and oldest landforms recognized in the Fischbach Alps and are often related to orthogneis lithologies. While we discern it here separately, earlier authors have seen these landforms as part of the L4 landscape. In the study area the peaks of the Pretul-Stuhleck and the Hochwechsel mountains are mapped to this level and can potentially be correlated to the highest peaks of the Teichalm and to the type locality in the Koralm. From the two mapped polygons that cover the continuous ridge lines of these two mountains (Fig. 6) a mean elevation of 1567 ± 31 m was calculated while the peaks reach elevations of almost 1800 m. This level is characterized by smooth topography with greater variation in slope than the lower levels.

4.2 River profile analysis

In order to support the attribution of mapped low-relief surfaces to discrete levels and ultimately allocate these levels a genetic significance, a morphological analysis of the river in the study region was made (Fig. 8; Tab. 1). For this, the region was somewhat arbitrarily divided into 7 major and 29 minor catchments. Figure 8 shows the catchment averaged k_{sn} as well as the χ values of the catchments and Table 1 summarises the geomorphic metrics. The difference in χ across drainage divides can be used to predict their migration directions and some of these are marked with arrows on Figure 8a. For example, the Lafnitz catchment and the upper Pitten catchment migrate towards the upper Feistritz catchment because of their higher χ. Likewise, the Pitten catchment migrates towards the Pinka catchment as well as incorporating the remaining Bucklige Welt drainage area. In the Teichalm area and in the Passail Basin the χ-analysis is not conclusive as it suggests that the Teichalm relict landscapes drainage divide migrates towards the headwaters of the Teichalm.

The k_{sn} values and channel profiles were used in connection with geological maps to select channels that characteristically represent the region and show knickpoints that are unrelated to lithological contrasts or anthropogenic changes. In particular, we selected 10 channels that are shown in Figure 9. It may be seen that all 10 channels bear knickpoints that appear to be related to some of the mapped levels as shown in the green and blue bars, respectively (Fig. 9). As such, it appears plausible that the knickpoints separate areas of geomorphic equilibrium in the low-relief relict landscapes above, from disequilibrium sections in the incised landscapes below (as schematically shown in Fig. 5). We have therefore used the channel projection method explained above to infer the amount of uplift between the individual phases of low-relief landscape formation.

The Feistritz main river and its three tributaries Miesenbach, Waisenbach and Gasenbach display knickpoints at different elevations (Fig. 9). The projection from the Feistritz section above the knickpoint at Ratten yields an incision of only 89 m (Fig. 9). However, projection of the upper Miesenbach river yields an incision of ~209 m with the projected segment being at about the elevation of the highest reaches of the L0 level. To the west of the Anger-Piregg Fault, the Waisenbach and the Gasenbach river show knickpoints at 819 m and 798 m, respectively. Projection of a section in the upper Waisenbach river yields an incision of 246 m correlating with the L1 level. Correspondingly, the Gasenbach river yields a very similar inferred incision of 248 m also correlating with the L1 level. Because of their Klamm-regions, the Raab and Weizbach river were promising candidates to display knickpoints. However, interestingly, both rivers do not have knickpoints in the Klamm areas (see also Stüwe and Hohmann, 2021). Only the Raab river hosts two knickpoints but interpretation of projected segments is not

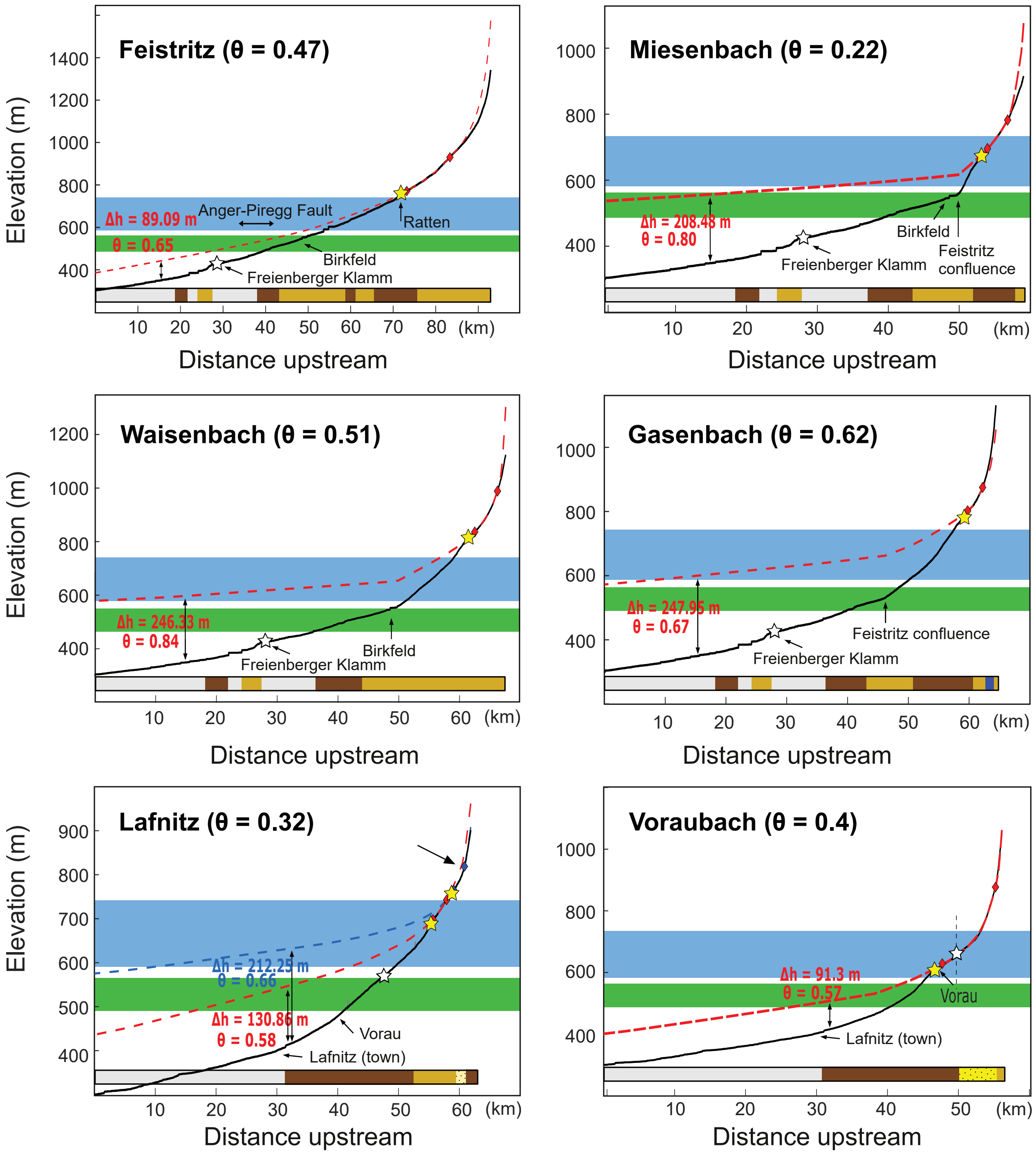

Figure 9: Channel profiles of 10 selected rivers in the Fischbach Alps (see Tab. 1 and Fig. 8 for location). Each plot shows the channel profile (black line), extracted knickpoints (yellow stars) and some geographic locations for reference. Note that the knickpoints were extracted based on the fitting of data in a slope-catchment area plot (see methods section) and may therefore not always be visible in the shown channel profiles. Inferred equilibrium segments above knickpoints are marked with the red or blue diamonds and fitted projected equilibrium channel profiles are shown by red and blue dashed lines. The violet, blue and green bars show the elevation range of the mapped low-relief landscapes. θ is the concavity index. The colour-codes bar at the bottom of each plot shows the simplified geology (using the colour scheme of Fig. 3) so that the correlation of knickpoints with geology can be evaluated. See text for details.

done because their position coincides with mapped faults (Fig. 9).

Two segments of the upper Lafnitz river were projected (Fig. 9). The lower mapped knickpoint is in the vicinity of a minor fault zone further downstream (Fig. 6). The best projection for the segments which lie on the low-relief landscape near Wenigzell yields an inferred incision of 212 m (above the higher knickpoint) and 131 m (above lower knickpoint) correlating with the L1 level and the L0 level, respectively. Two knickpoints were identified on

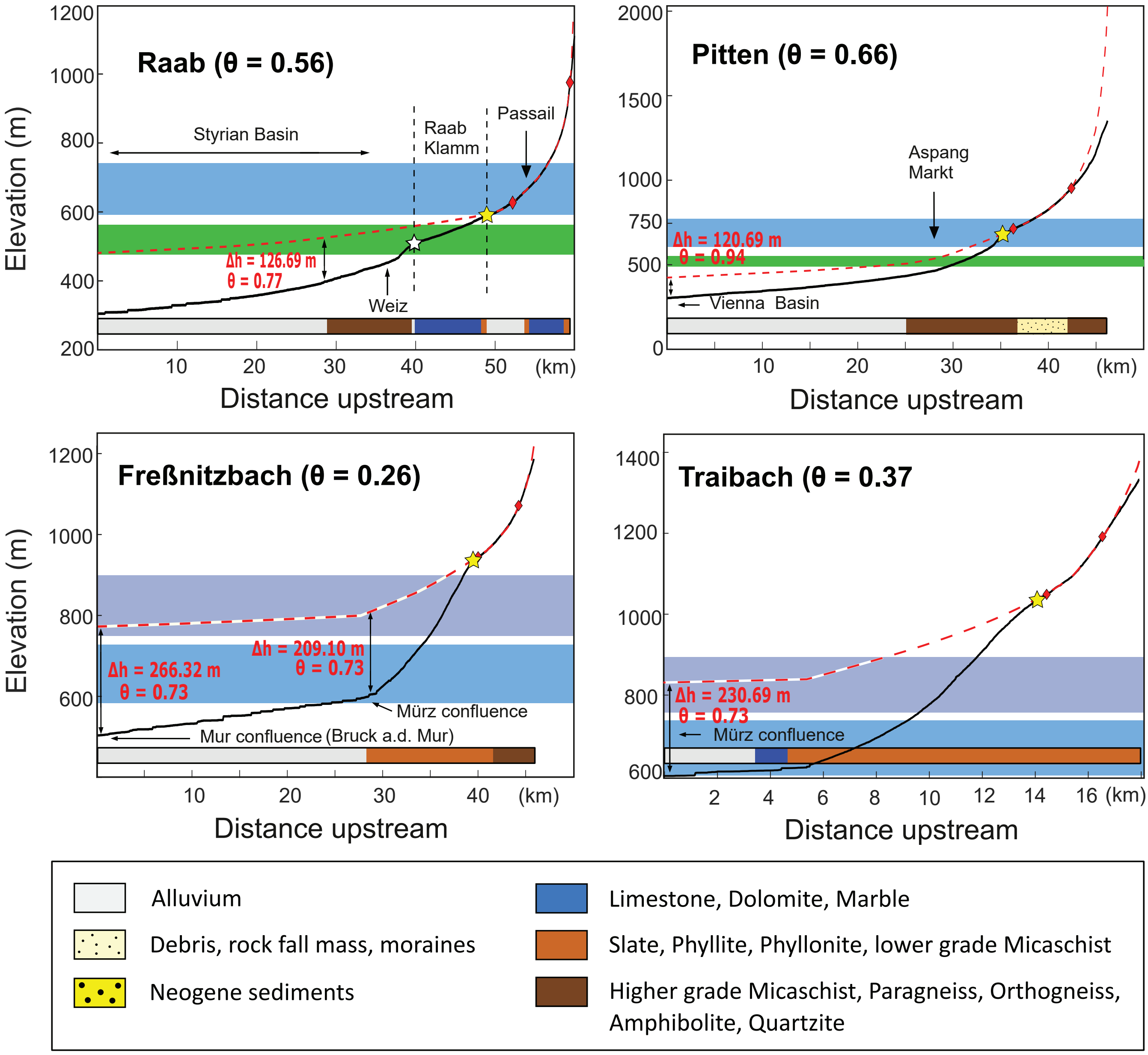

Figure 9: continued

the Voraubach river profile. Projection of a segment lying on the low-relief landscape of the Vorau Basin yields an inferred incision of 91 m correlating with the L0 level. The upper knickpoint was not considered because a fault was observed at the location. The projected profile is somewhat bend downwards (Fig. 9) and might reflect perturbation caused by the knickpoint above. Nevertheless, the profile projection indicates that the migrating knickpoint is from the L0 level.

The Pitten river drains towards the Vienna Basin and was analysed to interpret if the Styrian Basin and the Vienna Basin may have responded differently to an uplift signal. The profile projection of the Pitten river yields an inferred incision of 121 m with respect to the base level of the Vienna basin at 300 m which can be correlated to surfaces below the L0 level. Of the analysed rivers of the Mürz catchment, only the Freßnitzbach and the Traibach display notable knickpoints and equilibrium segments. The knickpoints at 930 m and 1036 m elevation are both located below the Alpl low-relief landscape and are also in the vicinity of a fault line of unknown kinematics (Schuster et al., 2015). In the Freßnitzbach a segment was fitted that is located in the Alpl relict landscape but is not directly related to the surface as the river already incised some 200 m into the relict landscape. Segment projection for the Freßnitzbach yields an inferred incision of 209 m which is in agreement with the elevation of L2 above base level. For reference with the Freßnitzbach a segment was projected yielding a similar inferred incision of 231 m (Freßnitzbach = 209 m) with respect to the Mürz confluence at ~600 m. The projected profile correlates with the L2 level.

4.3 Swath profile analysis

Four topographic swath profiles were prepared in order to investigate the different topographic peculiarities of the Fischbach Alps (Fig. 1a, 10). The profile in Figure 10a shows a transect roughly along the Feistritz river from the Styrian Basin to the Mürz valley. A nearly unperturbed mid-section of the Feistritz river is clearly visible but a knickpoint at km 35 is also visible. This knickpoint can also be seen in Figure 9. Swath transect Figure 10b shows the remarkable Teichalm relict landscape which is characterized by a mean topography of ~1300 m and a relief of ~900 m. Figure 10c shows the topographic swath profile crossing the Alpl and Joglland relict landscapes and the Wenigzell and Vorau basins representing the L4, L3, L2 and L1 level, respectively. Swath profile analysis along the transect of the Schöckl-Patschaberg ridge line yields a minimum incision of ~400 m for the western part of the study area (Fig. 10d). This is a comparatively conservative estimate since relict landscapes can be found well above 1000 m. Summarizing the results from swath profile analysis the amount of incision in the Fischbach Alps and the surrounding regions (e.g. Teichalm) can be estimated to ~400–900 m.

5. Discussion

The results from the landform mapping and river profile analysis reveal six discrete levels of low-relief surfaces and relict landscapes at elevations between ~500 m and ~1600 m (summarised in Fig. 11) and three generations of knickpoints at ~1000 m, ~800 m and ~650 m, indicating a discontinuous uplift history interrupted by stagnation phases during which the levels formed. Some of the knickpoints appear to correlate with the mapped L3, L2 and L1 levels, respectively. However, others do not and projection results of the river profile analysis show that many knickpoints may not relate to the level at the same elevation. Thus, it is necessary to discuss the relationship of knickpoints and low-relief surfaces before relating them to a particular genetic level.

5.1 Correlation of knickpoints and mapped levels

Knickpoints in channels are not stationary but migrate upstream and vanish once the river reached a new geomorphic equilibrium during erosion over time. However, the elevated low-relief surfaces that formed during that time are preserved and are not affected by consecutive incision events. Therefore, knickpoints are likely to be located at higher elevations than the corresponding low-relief landform. Moreover, they may be located at different elevations for different channels, depending on their relative erosion rate as given by their k_{sn}. As such, the comparison of knickpoint elevations with the mapped low-relief landscapes is difficult. However, equilibrium channel sections above a given knickpoint can be projected and compared to a mapped landform because their equilibrium remains undisturbed. For example, the Gasenbach and Waisenbach have knickpoints at ~800 m but the reconstructed profiles from equilibrium sections above them correlate with present elevations of the L1 level which is about 670 m (Fig. 9). Furthermore, the knickpoints of both rivers are located in river beds around 100 m below the next highest mapped level – an observation that holds true for many of the analysed rivers (see incised river gorges in Figs. 2, 6). Incidentally, in the Birkfeld Basin the L2 level can be found at ~900 m elevation, roughly 100 m above the knickpoint. This suggests that the complex relationship between knickpoints and their associated mapped levels stems from waves of migrating knickpoints.

The knickpoint in the upper Feistritz river at the town of Ratten (Fig. 9) is located at 761 m elevation. The projected profile of the section above yields an inferred incision of 89 m which would correlate the knickpoint to the terrace level. For this level the knickpoint elevation is too high and perturbation due to mass movement or multiple smaller knickpoints forming an extensive knickzone would better explain the occurrence of a knickpoint at this location. The Lafnitz river features two knickpoints in its upper reach at 747 m and 698 m elevation (Fig. 9). Of these two, the upper knickpoint correlates with the knickpoints of similar elevation and inferred incision (~212 m) in the Feistritz catchment, placing it in the L1 level. The slightly lower knickpoint is just not high enough to be placed in the L1 level but also not exactly in the 650 m range to be placed in the L0 level. Based on the inferred incision (~131 m) calculated from the picked segment below the upper knickpoint, it should be placed in the L0 level. The low-relief surfaces near Wenigzell are placed in the L2 level and probably formed in a similar way as the Birkfeld Basin (Fig. 7) but on a smaller scale. Here the low-relief landscape is mapped as a continuous L2 level where the L1 level is not exposed, because of slower erosive capacity in the upper reach, compared to the Birkfeld Basin. The analysed knickpoint in the Voraubach is placed in the L1 level based on segment projection. The inferred incision of 91 m agrees with the lower bound of the L1 level at the outflow of the Lafnitz, but with respect to the observed incision (L1 mean elevation minus Styrian Basin mean elevation), as shown in Figure 11, close to double the amount of incision is expected. This gives rise to the problem of comparing mean elevation values over tens of kilometres in north-south direction. Mapped surfaces are observed to increase in elevation in upstream direction as can be seen in Figure 11 and so comparing surface elevations in the lower or upper margin of the elevation range can cause too high or too low Δh-values.

5.2 Correlation of known low-relief surfaces in the Eastern Alps

With the analysis above, the mapped levels and their related knickpoints in channels (often located at somewhat higher elevations) can now be related to the known surfaces at the eastern margin of the Alps and sum-

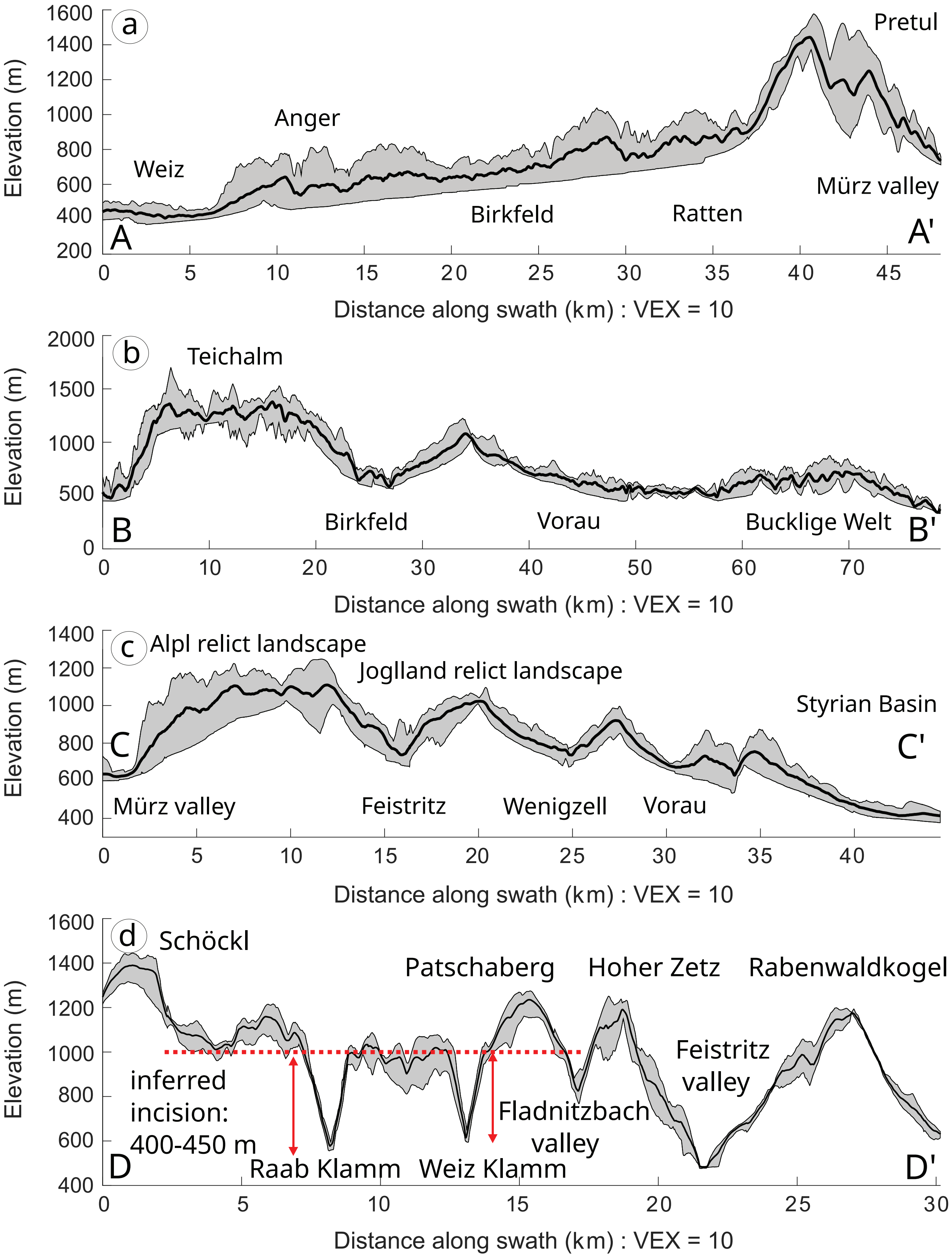

Figure 10: Swath profiles depicting the topography of the study area with ten times vertical exaggeration. Profiles (a)–(c) show the low-relief landscapes of the Birkfeld Basin, Vorau Basin, Wenigzell Basin and the Bucklige Welt. Profile (d) shows a transect of the Schöckl-Patschaberg ridge line which is separating the Passail Basin from the Styrian Basin. Here the minimum incision of the study area was found to be ~400 m. Black line = mean elevation, grey shading = min-max values, swath width 2500 m (Profile (d) = 500 m). See Figure 1 for profile locations.

marised in earlier sections of this paper (see also summaries of Winkler-Hermaden, 1957 and Wagner et al., 2011) (Fig. 11). In the study area the L0 level is correlated with the Stadelberg level as both are predominantly mapped at the orogen-basin transition towards the Styrian Basin and on the Riedel landscape in the northern parts of the Styrian Basin. The mean elevation of ~530 m agrees with previous mapping results from Wagner et al. (2011) and Stüwe and Hohmann (2021) in the Grazer Bergland. In the Gurktal Alps, Bartosch and Stüwe (2019) recognized the same level at higher absolute elevations, but at a similar relative elevation with respect to the current base level.

The mapping results of the L1 level near Weiz are consistent with prior mapping results from the Weizer Bergland of Flügel and Maurin (1958) who attributed these surfaces to the Hochstraden-level. The level is therefore likely to be between 3 and 4 my in age (Wagner et al., 2011). Zonal statistics of the mapped polygons show that the mean elevation is somewhat lower than in the study of Wagner et al. (2011) and Stüwe and Hohmann (2021) while low-relief surfaces of the same level upstream are mapped about ~50 m lower. Comparison of the elevation brackets from mapped surfaces and published reference surfaces, the L1 level correlates best with the Landscha level. It is important to note that the sedimentation of the Fladnitzbach, Weizbach and Raab at the outlet level likely conceals or prevented a deeper river bed that may have formed during the outwash of the Passail Basin sediments. The Ilzbach base level between the Fladnitzbach and the Anger subbasin is ~50 m lower compared to the outlet elevation of the above mentioned rivers. The correlation within error to low-relief surfaces across the Lavanttal Fault in the Gurktal Alps is possible but surface elevation is skewed towards higher values (Bartosch and Stüwe, 2019).

The higher levels (L2 and L3) are here discussed together. L2 was mapped at 830 ± 65 m elevation and would topologically be related to the Trahütten level. Compared to the previously published elevation bracket for the Trahütten level of ~950–1100 m by Stüwe and Hohmann (2021) no definitive correlation can be made, however the mapping results agree better with the earlier results of Wagner et al. (2011) where surfaces of this level were mapped at elevations of ~860–960 m. As such, the L2 level can be seen as an eastward extension of the Trahütten level. The L3 level was mapped here about 100 m lower at a mean elevation of 995 ± 59 m compared to the Hubenhalt level at 1060–1160 m in Wagner et al. (2011) and ~1200 m in Stüwe and Hohmann (2021). Since the Hubenhalt level is traceable through various mountain peaks from the Grazer Bergland to the Fischbach Alps we attribute the L3 level to the Hubenhalt level. Paleo-surface L3 in the Gurktal Alps (Bartosch and Stüwe, 2019) appears to better correlate with our mapping results from the L3 level and the Hubenhalt level according to Wagner et al. (2011).

The highest mapped levels (L4 and L5) are best attributed to the Wolscheneck and Koralm relict landscapes respectively, as they are the uppermost level that is recognized. Winkler-Hermaden (1957) counted all landforms and surfaces over roughly 1600 m (including the Stuhleck and Wechsel mountains) to the highest Koralm level which is in good agreement with the results from Wagner et al. (2011) and Stüwe and Hohmann (2021), consolidating evidence for pre-existing topography (Frisch et al., 1998) in the Eastern Alps. Bartosch and Stüwe (2019) report systematically higher elevations for their paleo-surface levels L2 to L4 in the Gurktal Alps which they correlate to the Landscha level, the Trahütten level and the Hubenhalt level. This can possibly be related to the activity of the Lavanttal Fault.

Given the plausible correlations presented above, uplift and erosion rate of the region and incised landscape can be estimated using published ages of the low-relief landscapes in other regions. Overall, erosion rates of the low-relief surfaces to the Trahütten level, Landscha level and the Stadelberg level are comparably high in the Gurktal Alps and the Fischbach Alps. In both regions, more than 500 m of uplift and incision occurred within the Pliocene in the last 4–5 Ma. This age is fixed by a geochronological age for the formation of the Drachenhöhle on the Trahütten level (Wagner et al., 2010), but this age was already estimated by Winkler-Hermaden (1957) and is now confirmed by more geochronological evidence (Stüwe et al., 2024). Over time, a trend of decreasing erosion rates is recorded in the surface uplift history of the Fischbach Alps and the Gurktal Alps (Bartosch and Stüwe, 2019). For the Koralm relict landscape above 1000 m Legrain et al. (2014, 2015) found that the onset of incision was between 3–5 Ma with a surface uplift of up to 500 m. The mean erosion rate of 137 ± 15 m/ky reflects the average erosion rate of the younger and slower (below 3 Ma) erosion regimen of terraces levels and the higher erosion rates of the Stadelberg level (Fig. 11). Interestingly, the ages for uplift and erosion are consistent with both cosmogenic nucleide-derived erosion rate estimates in the region on a 10^4 year time scale (Dixon et al., 2016) and low temperature geochronological ages that document exhumation and cooling from apatite and zircon fission track ages that reflect a 10^6– 10^7 year time scale. Hejl (1997), Wölfler et al. (2012; 2016) and van Gelder et al. (2020) found that the Eastern Alps experienced late-Neogene uplift event which is further supported by sediment budget analysis by Kuhlemann (2007) and detrital apatite fission track ages in the North Alpine Foreland Basin by Kuhlemann et al. (2006).

5.3 A model for uplift of the Fischbach Alps

The correlation of the mapped levels with surfaces of established age now allows to infer aspects of the young surface uplift history of the Fischbach Alps. Wagner et al. (2011) proposed that the Styrian Block acted as a coherent unit during the Pliocene uplift history. The Styrian Block encompasses the entire region east of the Lavanttal fault and south of the Mur-Mürz fault including the mountain-

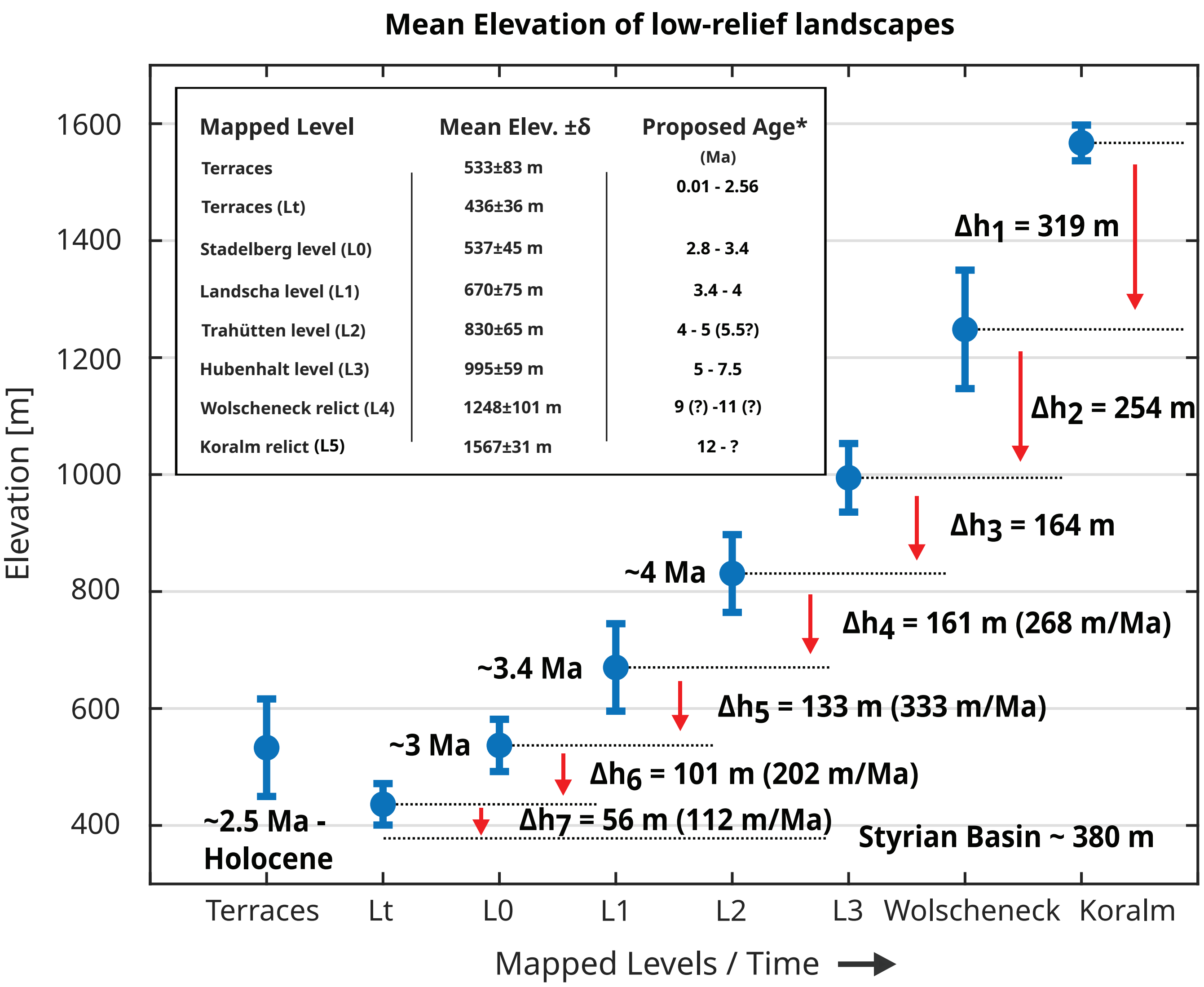

Figure 11: Synopsis of mapped low-relief surfaces and relict landscapes. The incision (*Δh*) between the surfaces was calculated as the difference of the mean elevation of 2 subsequent levels. The proposed ages of level formation in the inset, denoted with an asterisk, are taken from Wagner et al. (2011) and Winkler-Hermaden (1957).

ous regions and the Styrian basin with the topographic difference between Styrian basin and the surrounding mountain mainly being a consequence of the different erodibility of the rock. Nevertheless, Wagner et al. (2011) suggest that the Styrian Block was tilted about 1–2° in southwards direction in the late Pliocene. This interpretation is consistent with observations of Schuster et al. (2015) on the interfingering of Pannonian sediments with Neogene sediments or on potential northward draining valleys. This all indicates that the region, prior to the uplift inferred here, was a hilly low-lying landscape during the Pannonian (i.e. about 7–12 Ma). It is however not clear whether the subsequent tilting occurred as a whole or if only sub-units fragmented and the tilting was not uniform throughout the area. In this context, the Anger-Piregg Fault is of special interest because it marks an abrupt change of two very different nappe stacks and relief (Fig. 2) (Schuster et al., 2015). More importantly, it marks considerably different preservations of low-relief landscapes to the west and east of it (Fig. 6). Schuster et al. (2015) presented no conclusive evidence for the sense of shear of this fault, but inferred an east-side down movement, based on the occurrence of gneisses of the Strallegg complex on the L2 surface. This is consistent with more low-relief landscapes being preserved to its east, and may be related to a stronger southward tilting of the Styrian block in its western part than its eastern part. Tilting of the entire region to the south with more southwards tilting west of the Anger-Pieregg fault is also suggested by the channel profiles of the south draining river, because their orographic gradient parallels the tilt: While the Raab and Weiz show only marginal knickpoints despite their crossings of the Klamm regions, the rivers further east like the Feistritz show no knickpoints. Indeed, based on the river profile analysis of the Feistritz and the relatively wide alluvial plains within the steep valley it is plausible to suggest that the Feistritz is in geomorphological equilibrium. This is consistent with other south draining rivers like the Mur itself (Robl et al., 2008b; Stüwe and Hohmann, 2021).

Southward tilting of the Styrian Block south of the Mürz valley implies that the northern slopes of the Teufelstein-Landschaft into the Mürz valley experienced relatively young exhumation during the southward tilting of the region south of it. This is supported by several lines of evidence. For example, (i) for the Mürz catchment two tributaries (Freßnitzbach and Traibach) display notable knickpoints in their upper reaches which record the migrating knickpoint wave into the Alpl relict landscape which is correlated with the L4 level. Although the difference in elevation is ~100 m, the knickpoints at 930 m and 1036 m document an inferred incision of ~220 m to the local base level of ~600 m, which is substantially higher than the incision of all south draining rivers. (ii) Channel profiles (Fig. 9) show a notable difference in shape and position of the knickpoints compared to all other analysed rivers is apparent and there are no low-relief surfaces to be found on the slopes towards the Mürz valley. In the Mürz valley itself. (iii) Sachsenhofer et al. (2001) reported coal seams that are tilted upwards into a near vertical position near the southern valley margin, which is in support of a south-side-up motion along the Mürz valley. Tilting of the Styrian Block and increased erosion along the Mürz valley may have closely interacted with the capture event of the paleo-Mürz by the antecedent river Mur (Dunkl et al., 2005; Stumpf and Stüwe, 2019).

6. Conclusion

The Interpretation of the findings from landform mapping and river profile analysis in the Fischbach Alps allows to make the following conclusions:

- Mapping of low-relief surfaces and relict landscapes reveals six discrete levels (excluding fluvial terraces levels) at elevations between ~500 m and ~1600 m. Additionally, three generations of knickpoints at ~1000 m, ~800 m and ~650 m were detected. The mapped levels can be correlated with known levels in adjacent regions in the surroundings of the Styrian Basin.
- In general, the mapping results are in good agreement with Wagner et al. (2011) and Stüwe and Hohmann (2021) although low-relief surfaces in the southern Fischbach Alps are somewhat lower, which could be explained by slightly different erosive settings in the Passail Basin and the much larger catchment with the peri- and paraglacial history of the Mur river. Correlation with the four mapped low-relief surfaces in the Gurktal Alps (Bartosch and Stüwe, 2019) yields comparable results for the lowest level. Higher levels are skewed to higher elevations.
- The Fischbach Alps have experienced base level lowering and incision of up to 800 m in response to tectonic uplift after the formation of the Wolscheneck and Koralm relict landscapes. Swath profile analysis of the Raab and Weizbach Klamm yields a minimum incision of ~400–450 m since the formation of the Hubenhalt level.
- The onset of increased erosion, as a consequence of tectonic uplift, can be approximately constrained by comparing the presented results with areas where the lower Stadelberg (L0) level, Landscha (L1) level and the Trahütten (L2) level have been dated. From this comparison it can be concluded, that uplift started sometime prior to the Hubenhalt or Trahütten level formation between 4–7 (?) Ma or possibly even later. This observation is consistent with sediment budget analysis (Kuhlemann, 2007) and with erosion rate estimates of Dixon et al. (2016). As the suggested uplift is younger than the apatite fission track dating (Hejl, 1997; Wölfler et al., 2016; van Gelder et al., 2020) from various regions in the Styrian block, their variation across different regions does not impinge on our model.
- The formation of low-relief surfaces cannot be explained by a simple Piedmonttreppen model alone. Southward tilting of these surfaces as part of the Styrian Block between 1–2° could be the reason that surfaces of the same level can be found at higher elevations upstream and lower elevations at the outlet level than in other regions of the Styrian Block.

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References

Balogh, T., Ebner, F., Ravasz, C., 1994. K/Ar-Alter tertiärer Vulkanite der südöstlichen Steiermark und des südlichen Burgenlandes. Jubiläumsschrift 20 Jahre Geologische Zusammenarbeit Österreich-Ungarn 2, 55–72.

Baran, R., Friedrich, A., Schlunegger, F., 2014. The late Miocene to Holocene erosion pattern of the Alpine foreland basin reflects Eurasian slab unloading beneath the western Alps rather than global climate change. Lithosphere, 6/2, 124–131.

Bartosch, T., Stüwe, K., Robl, J., 2017. Topographic evolution of the Eastern Alps: The influence of strike-slip faulting activity. Lithosphere, L594.591

Bartosch, T., Stüwe, K., 2019. Evidence for pre-Pleistocene landforms in the Eastern Alps: Geomorphological constraints from the Gurktal Alps. Austrian Journal of Earth Sciences, 112/2, 84–102.

Clark, M.K., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., Tang, W., 2006. Use of a regional, relict landscape to measure vertical deformation of the Eastern Tibetan Plateau. Journal of Geophysical Research: Earth Surface, 111/3.

Dertnig, F., Stüwe, K., Woodhead, J., Stuart, F. M., Spötl, C., 2017. Constraints on the Miocene landscape evolution of the Eastern Alps from the Kalkspitze region, Niedere Tauern (Austria). Geomorphology, 299, 24–38.

Dixon, J.L., von Blanckenburg, F., Stüwe, K., Christl, M., 2016. Glaciation's topographic control on Holocene erosion at the eastern edge of the Alps. Earth Surface Dynamics, 4/4, 895–909.

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.

Dunkl, I., Demeny, A., 2997. Exhumation of the Rechnitz Window at the border of the Eastern Alps. Tectonophysics, 272, 197–211.

Flint, J.J., 1974. Stream gradient as a function of order, magnitude, and discharge. Water Resources Research, 10/5, 969–973.

Flügel, H.W., 1969. Geologische Wanderkarte des Grazer Berglandes 1:10 0000. Geologische Bundesanstalt, Wien.

Flügel, H.W., Hötzl, H., Neubauer, F., 1990. Geologische Karte der Republik Österreich 1:50 000 – GK134 Blatt Passail. Geologische Bundesanstalt, Wien.

Flügel, H.W., Maurin, V., 1958. Geologische Karte des Weizer Berglandes 1:25 000. Geologische Bundesanstalt, Wien.

Flügel, H.W., Neubauer, F. R., 1984. Geologische Karte der Steiermark 1:20 0000, Geologische Bundesanstalt, Wien.

Flügel, H.W., Nowotny, A., Gross, M., 2011. Geologische Karte der Republik Österreich 1:50 000 – GK164 Blatt Graz. Geologische Bundesanstalt, Wien.

Forte, A.M., Whipple, K.X., 2019. Short communication: The topographic analysis kit m(TAK) for TopoToolbox. Earth Surface Dynamics, 7/1, 87–95.

Frisch, W., Kuhlemann, J., Dunkl, I., Brügel, A., 1998. Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. Tectonophysics, 297/1–4, 1–15.

Frisch, W., Kuhlemann, J., Dunkl, I., Székely, 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, 90/3, 500–518.

Gradwohl, G., Stüwe, K., Robl, J., Liebl, M., 2023. Topography and landscape evolution of the Alps. In: Rosenberg C. and Bellahsen N., (eds.) Geodynamics of the Alps 1, Wiley, ISBN 978-1-78945-116-0, 115–147.

Gradwohl, G., Stüwe, K., Liebl, M., Robl, J., Plan, L., Rummler, L., 2024. The elevated low-relief landscapes of the Eastern Alps. Geomorphology, in print.

Gross, M., Fritz, I., Piller, W.E., Soliman, A., Harzhauser, M., 2007. The Neogene of the Styrian Basin – Guide to Excursions. Joannea Geologie und Paläontologie, 9, 117–193.

Hack, J.T., 1957, Studies of longitudinal stream profiles in Virginia and Maryland, U.S. Geological Survey Professional Paper, 294-B, 45–97.

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

Herrmann, P., Mandl, G., Matura, A., Neubauer, F., Riedmüller, G., Tollmann, A., 1992. Geologische Karte der Republik Österreich 1:50 000 – GK105 Blatt Neunkirchen. Geologische Bundesanstalt, Wien.

Howard, A.D., Kerby, G., 1983. Channel changes in Badlands. Geological Society of America Bulletin, 94/6, 739–752.

Kirby, E., Whipple, K.X., 2012. Expression of active tectonics in erosional landscapes. Journal of Structural Geology, 44, 54–75.

Kreuss, O., 2016. Geologische Karte der Republik Österreich 1:50 000 – GEOFAST136 Blatt Hartberg. Geologische Bundesanstalt, Wien.

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., Székely, B., Dunkl, I., Kázmér, M., 2002. Post-collisional sediment budget history of the Alps: tectonic versus climatic control. International Journal of Earth Sciences, 91, 818–837.

Kuhlemann, J., Dunkl, I., Brügel, A., Spiegel, C., Frisch, W., 2006. From source terrains of the Eastern Alps to the Molasse Basin: Detrital record of non-steady-state exhumation. Tectonophysics, 413, 301–316.

Legrain, N., Dixon, J.L., Stüwe, K., Blanckenburg, F., Kubik, P.W., 2015. Post-Miocene landscape rejuvenation at the eastern end of the Alps. Lithosphere, 7/1, 3–13.

Legrain, N., Stüwe, K., Wölfler, A., 2014. Incised Relict Landscapes in the Eastern Alps. Geomorphology, 221, 124–138.

Mandl, G.W., Nowotny, A., Rockenschaub, M., 2001. Geologische Karte der Republik Österreich 1:50 000 – GK104 Blatt Mürzzuschlag. Geologische Bundesanstalt, Wien.

Matura, A., Schuster, R., 2014. Geologische Karte der Republik Österreich 1:50 000 – GK135 Blatt Birkfeld. Geologische Bundesanstalt, Wien.

Mey, J., Scherler, D., Wickert, A.D., Egholm, D.L., Tesauro, M., Schildgen, T.F., Strecker, M.R., 2016. Glacial isostatic uplift of the European Alps. Nature Communications, 7, 1–9.

Molnar, P., England, P., 1990. Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?. Nature, 346, 29–34.

Moser, M., 2016. Geologische Karte der Republik Österreich 1:50 000 – GEOFAST165 Blatt Weiz. Geologische Bundesanstalt, Wien.

Nebert, K., 1952. Die pliozäne Schichtfolge in der Pöllauer Bucht (Oststeiermark). Jahrbuch der Geologischen Bundesanstalt, 95/1, 103–118.

Perron, J.T., Royden, L., 2013. An integral approach to bedrock river profile analysis. Earth surface processes and landforms, 38/6, 570–576.

QGIS Development Team, 2009. QGIS Geographic Information System, Open-Source Geospatial Foundation. http://qgis.osgeo.org.

Robl, J., Stüwe, K., Hergarten, S., Evans, L., 2008a. Extension during continental convergence in the Eastern Alps: The influence of orogen-scale strike-slip faults. Geology, 36, 603–606.

Robl, J., Hergarten, S., Stüwe, K., 2008b. Morphological analysis of the drainage system in the eastern alps. Tectonophysics, 460, 263–277.

Robl, J., Hergarten, S., Prasicek, G., 2017. The topographic state of fluvially conditioned mountain ranges. Earth-Science Reviews, 168, 190–217.

Sachsenhofer, R., Kuhlemann, J., Reischenbacher, D., 2001. Das Miozän der östlichen Norischen Senke. Arbeitstagung Geologische Bundesanstalt Neuberg an der Mürz.

Schnabel, W., Fuchs, G., Matura, A., Roetzel, R., Scharbert, S., Krenmayr, H.G., Egger, H., Bryda, G., Mandl, G.W., Nowotny, A., Wessely, G., 2002. Geologische Karte von Niederösterreich 1:20 0000. Geologische Bundesanstalt, Wien.

Schuster, R., Nievoll, J., Rupp, C., Ćorić, S., Ilickovic, T., 2015. Neogene Sedimente und Landschaftsentwicklung im Umfeld der Kartenblätter GK50 Blatt 103 Kindberg und 135 Birkfeld, Arbeitstagung 2015 Mitterdorf im Mürztal, 127–143.

Schwanghart, W., Scherler, D., 2014. Short Communication: TopoToolbox 2 – MATLAB based software for topographic analysis and modelling in Earth Surface Sciences. Earth Surface Dynamics, 2/1, 1–7.

Schwinner, R., 1935. Zur Geologie von Birkfeld. Mitteilungen des Naturwissenschaftlichen Vereins für Steiermark, 72, 67–100.

Sternai, P., Sue, C., Husson, L., Serpelloni, E., Becker, T.W., Willett, S.D., Faccenna, C., Di Giulio, A., Spada, G., Jolivet, L., Valla, P., Petit, C., Nocquet, J.-M., Walpersdorf, A., Castelltort, S., 2019. Present-day uplift of the European Alps: Evaluating mechanisms and models of their relative contributions. Earth-Science Reviews, 190, 589–604.

Stumpf, S., Stüwe, K., 2019. Aspekte der morphologischen Entwicklung des Murtales zwischen Bruck und Graz. Eine Augenstein Provenienz Studie. Mitteilungen des Naturwissenschaftlichen Vereins für Steiermark, 149, 63 – 81.

Stüwe, K., Gradwohl, G., Robl, J., Plan, L., Fabel, D., Stuart, F., 2024. The rapid surface uplift of the Eastern Alps. Evidence from cosmogenic nucleides and mapping of elevated low relief surfaces. EGU 24-6089 (Abstract).

Stüwe, K., Hohmann, K., 2021. The Relic Landscapes of the Grazer Bergland: Revisiting the Piedmonttreppen Debate. Austrian Journal of Earth Sciences, 114, 46–65.

Untersweg, T., 1982. Morphologische Studien im Schöcklgebiet (Grazer Bergland). Mitteilungen des Naturwissenschaftliche Vereins für Steiermark, 112, 109–125.

Van Gelder, I.E., Willingshofer, E., Andriessen, P.A.M., Schuster, R., Sokoutis, D., 2020. Cooling and vertical motions of crustal wedges prior to, during, and after lateral extrusion in the Eastern Alps: New field kinematic and fission track data from the Mur-Mürz fault system. Tectonics, 39/3.

Van Husen, D., 1997. LGM and late-glacial fluctuations in the Eastern Alps. Quaternary International 38–39, 109–118.
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, 295/1–2, 159–169.
Wagner, T., Fritz, H., Stüwe, K., Nestroy, O., Rodnight, H., Hellstrom, J., Benischke, R., 2011. 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, 134/1–2, 62–78.
Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs, Journal of Geophysical Research: Solid Earth, 104/B8, 17661–17674.
Willett, S.D., 2010. Late Neogene Erosion of the Alps: A Climate Driver?. Annual Review of Earth and Planetary Sciences, 38/1, 411–437.
Willett, S.D., McCoy, S.W., Perron, J.T., Goren, L., Chen, C.-Y., 2014. Dynamic reorganization of river basins. Science, 343/6175, 1248765-1-1248765-9.
Winkler-Hermaden, A., 1957. Geologisches Kräftespiel und Landformung, Springer Vienna.
Wobus, C., Whipple, K.X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., Sheehan, D., 2006. Tectonics from Topography: Procedures, Promise, and Pitfalls. Geological Society of America, 55–74.
Wölfler, A., Stüwe, K., Danišík, M., Evans, N.J., 2012. Low temperature thermochronology in the Eastern Alps: Implications for structural and topographic evolution. Tectonophysics, 541–543, 1–18.
Wölfler, A., Kurz, W., Fritz, H., Glotzbach, C., Danišík, M., 2016. Late Miocene increasing exhumation rates in the eastern part of the Alps – implications from low temperature thermochronology. Terra Nova, 28/5.

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