The Relic Landscapes of the Grazer Bergland:
Revisiting the Piedmonttreppen Debate

Kurt Stüwe and Konstantin Hohmann
Institut für Erdwissenschaften, Universität Graz, Universitätsplatz 2, 8010 Graz, Austria
* Corresponding author: kurt.stuewe@uni-graz.at
Received: 30.3.2021, Accepted: 11.6.2021

Abstract
The Grazer Bergland is a mountainous region at the eastern end of the Alps that escaped glacial erosion in the Pleistocene and thus preserves low-relief landforms that are relics of the earlier uplift history. These relic landforms may reflect a Piedmonttreppe that formed during a series of stages of a wide-reaching Pliocene uplift event that interacts with the landscape evolution, but this model is not uniquely accepted for the region. In order to test this model and for a future better correlation of the paleosurfaces with those mapped in other regions, it is important to benchmark these relic landforms. We do so by presenting a geomorphic map of the Bergland region over some 600 km2. We describe the well-known levels Stadelberg/Zahrerberg- (at 540 – 700 m a.s.l.), Kalkleiten/Hochstraden- (at 700 – 850 m a.s.l.), Trahütten- (at 950 – 1100 m a.s.l.), Hubenhaust- (at 1200 m a.s.l), as well as Wolschenegg- and Kor- (at 1200-1720 m a.s.l.) levels and correlate their distribution in space and time. Fluvial channels between segments of the relic surfaces have knickpoints that correlate with the planation surfaces, which is in strong support of the Piedmonttreppe model. Our analysis results in a model that interprets the course of the Mur river to be the product of a river piracy event near Peggau at the time of the planation of the Trahütten level (about 4 Ma), diverting the paleo-Mur from an eastwards course along the Mürz valley in direction Vienna, towards Graz. Thereafter, the Mur remained antecedent with respect to the uplift of the surrounding massifs resulting in massive base level drop for many tributaries, like the Mixnitzbach or Rötschbach. The resulting knickpoints have since migrated upstream to cause successive minor river capture events, for example the Rötschbach capture at Kesselfall. We also show that the presence of lower levels in the Passail Basin is best interpreted in terms of the more efficient erosion of basin sediments that filled a Miocene half graben north of the Schöckl ridge and analyze the two major drainages of the region, the Raab and the Weizbach.

1. Introduction
During the Pleistocene glaciations periods, the eastern end of the Alps was never covered by a continuous ice sheet (van Husen, 1997). It is thus unique in the Alps for preserving landforms that are relics of the pre-Pleistocene uplift history of the range (e.g. Legrain et al., 2014). These relic landscapes include a series of planation surfaces that have historically been interpreted as a Piedmonttreppe (Winkler-Hermaden, 1955 and references therein), according to a concept first proposed by Penck (1924). The concept interprets the step-shaped arrangement of low-relief landforms like strath terraces or benches in the landscape in terms of remnants of peneplains that are preserved during successive uplift stages, with the highest landform representing the oldest relic. The concept was first suggested as an explanation for geomorphological features in the Black Forest of Germany (Penck, 1925) and later for the south Swedish dome (Lidmar-Bergström et al., 2017 and reference therein) and Winkler-Hermaden (1957) used morphological mapping in the Grazer Bergland to propagate this concept for the eastern end of the Alps.

Ever since its original formulation, the concept of Piedmonttreppen was discussed and sometimes refuted (e.g. Spreitzer, 1932; 1951; Gellert, 1933; Lidmar-Bergström et al., 2017), predominantly in contrast to alternative models that explain the stepwise arrangement of low-relief surfaces in terms of lithological control or tectonic dissection. This discussion was also conducted about the low-relief surfaces at the eastern end of the Alps. For example, Untersweg (1982) and others (e.g. Ebner et al., 1985 and references therein) recognized characteristic basement lithologies and cover sequences of supposedly Pannonian gravels to recur on several different planation levels. They used such observations to argue for tectonic dissection of uplifted landforms rather than a Piedmonttreppe. However, Untersweg (1982) did not recognize discrete faults between the different supposedly dissected planation levels and admitted to the possibility that the gravel coverage may not be of Pannonian
The Relic Landscapes of the Grazer Bergland: Revisiting the Piedmonttreppen Debate

The advent of digital elevation models in the new Millennium has now resulted in a new generation of geomorphological studies that allow a modern discussion of this concept (e.g. Wobus et al., 2006; Robl et al., 2015). In the Eastern Alps, relic landscapes that may form a Piedmonttreppen have recently been described in modern studies from the Calcareous Alps (Frisch et al., 1998), the Gurktal Alps (Bartosch and Stüwe, 2019), the Niedere Tauern (Dertnig et al., 2017), the Koralpe (Legrain et al., 2014), the Grazer Bergland (Wagner et al., 2011), or the Fischbach Alps (Hohmann and Stüwe, 2019; Schuster et al., 2015). Their existence is consistent with orogen-scale morphological data that the Alps are geomorphologically pre-mature (Hergarten et al., 2010) and many of the surfaces described in these studies can, in fact, be correlated with those from other areas. This correlation appears to suggest a substantial long wavelength (>300 km) uplift event of at least some 500 m that may have affected much of the eastern end of the Alps and the surrounding basins in the Pliocene (e.g. Legrain et al., 2015). In terms of this model, the different planation surfaces may in fact represent relics of a Piedmonttreppen. Because of the apparently wide-reaching extent of this uplift and its hitherto unknown dramatic contribution of this young event to the total uplift of the Alps, it appears timely to benchmark the planation surfaces that define this Piedmonttreppen.

In this paper we present a geomorphological map for some 600 km² of the Grazer Bergland region (Fig. 1) with the aim of providing a modern, field-based description of the distribution for the most important planation surfaces and their type localities as well as a suggestion for a nomenclature of different geomorphological features. We also use our map to make some interpretation about the paleogeography and paleodrainage networks of the region with particular focus on the Mur and its tributaries, the Weizbach, the Raab, the Passail Basin, as well as the river capture events around the Rötschgraben north of Graz.

2. Geological and geomorphological setting

The Grazer Bergland is a loosely defined region north of Graz. To the north, it reaches to the Breitenau valley and Mixnitz and in the east to the upper Feistritz valley (Fig. 1) (e.g. Paschinger, 1974). It also includes the hilly country west of the river Mur and to the south it is bound by the Styrian Basin. The geographic extent of the Grazer Bergland largely corresponds to the area of the geological unit of the Paleozoic of Graz (Fig. 2). This unit is a thin (about 2 km thick) nappe of Paleozoic rocks that sits on top of mostly Cretaceous (Eoalpine) metamorphic rocks (Gasser et al., 2010). The age of emplacement of the Paleozoic rocks onto the much younger, high grade gneisses is still unclear (Gasser et al., 2010). The Paleozoic rocks include low grade metamorphics and large amounts of carbonates in different nappes and are in part strongly karstified (Middle Styrian karst) (e.g. Bauer and Marke, 2010; Maurin and Benischke, 1992). Stratigraphically, there are at least three sedimentary basins that lie on top of the Paleozoic of Graz: Firstly, there is the Kainach Gosau Basin in the west, which is a late Cretaceous marine basin that lies entirely to the west of the region of interest of this paper. Interestingly, some minor occurrence of probably Gosau-aged conglomerates also exists in the mapping region near Frohnleiten and at Burgstall in the Bärenschützklamm (Gollner and Zier, 1985) (Fig. 2). Secondly, there is the Styrian Basin that bounds the Paleozoic to the south (Fig. 2). It contains a sedimentary sequence of both marine and terrestrial sediments from about 18 - 10 Ma (Kollmann, 1965; Gross et al., 2005; Gross, 2007). Between 16 Ma and 11 Ma, the sequence is mostly shallow marine and thus forms an important benchmarking parameter for the position of sea level of the uplift of the Piedmonttreppen discussed here. The basin merges to the east into the larger Pannonian Basin and it may be considered as the westernmost lobe of this extensional Neogene basin. This Styrian basin has several embayments that reach towards the Grazer Bergland, with the most notable for this study being the Gratkorn Basin in the Mur valley (Gross et al., 2010). Thirdly and finally, there is the Passail Basin that is located between the Hochlantsch massif and the Schöckl massif (e.g. Flügel, 1975). The Passail Basin appears somewhat similar to the intramontane basins further north and hosts a fluvially sequence of Miocene age with coals and up to 16 Ma old sediments at up to 650 m elevation (Fig. 2) (Eberer and Gräf, 1982). It does not appear fault-bound and the current thickness of the basin is at least 90 m (Flügel and Maurin, 1957; Flügel, 1975) and in places even up to 250 m (Mauritsch et al., 1977). The presence of coals indicates that the sedimentary pile may have been much thicker and is now largely exhumed by erosion.

Geomorphologically, the most prominent peaks of the Grazer Bergland include the Hochlantsch (1720 m) and the Schöckl (1445 m). It also hosts enormous karst caves (Drachenhöhle, Lurgrotte, Fig. 3) that have been used to constrain the uplift history (Wagner et al., 2010) and one of the largest internally draining regions (a Polje?) in the Semriach region (Fig. 1). The river Mur crosses the Bergland from north to south. The astonishing absence of a knickpoint at its transition from the basement rocks into the soft sediments of the Styrian Basin near Graz shows that lithology is only a second order parameter to its erosion and that it appears to be a largely antecedent river (Robl et al., 2008). As such, the Mur is likely to have remained at roughly its present day level during much of the rock-uplift history and its channel profile provides an important benchmarking parameter for surface uplift of the surrounding peaks.

Importantly to this paper, the Bergland region hosts substantial areas of low-relief relic surfaces. Indeed, aside from the Fischbacher Alpen, where these relic surfaces
Figure 1: Maps of the study region. (a) Topography of the Graz Bergland with color scheme from orange (300 m a.s.l.) to dark blue at the highest point of the image on the Hochlantsch summit (1720 m a.s.l.). Blue colored streams are those that are used for detailed channel profile analysis in Figs. 9 – 10 with dots at the end of the modelled region. Red colored stream sections are those for which curved swath profiles are presented in Fig. 11. Small numbered red triangles show the view-points of Fig. 6 and Fig. 7. The two small white arrows show the approximate position of the schematic profile shown in Fig. 12. Black dots are settlements and black stars are peaks. (b) Slope map of the same region with green for low-slopes and red for highest slopes and inset showing the location of the study area in the inset.
form an almost continuous surface (Schuster et al., 2015), the Grazer Bergland is probably one of the most contiguous regions of the eastern Alps where these surfaces exist (Wagner et al., 2011). At low elevations these surfaces include a series of distinct terrace groups of Pleistocene age that we will not consider here. However, at higher elevations the relevant surfaces are:

The **Stadelberg/Zahrerberg level** is the lowest and youngest low relief surface that is older than the Pleistocene terraces deposited during the glaciation periods (Wagner et al., 2011). It is named after type locations on the Stadelberg near St. Anna a. Aigen in the Styrian Basin and the Zahrerberg (also called: Zaraberg) west of Klöch (Wagner et al., 2011). It is here referred to as the Stadelberg level (Table 1). Indeed, the low-relief area at Zahrerberg may not be related to this planation level as it may simply reflect the nature of the lava flow (Ingomar Fritz, pers. comm., 2021). In the Graz region, it is located some 180 m to 300 m above the present base level but more generally it may be considered to lie between 540 – 700 m above sea level with the higher end of this range being more appropriate to the Passail Basin (Table 1). It is considered
to be of latest Pliocene age (2.5 Ma according to Wagner et al., 2010; 2011). The level is most clearly recognized in the Styrian Basin where it has efficiently levelled the soft sediments in many places, mostly at elevations around 550 m. In the Bergland region outside the Passail Basin, it is weakly developed along mountain shoulders. On this level as well as above this level there are isolated occurrences of the so-called Eggenberger Breccie (Fig. 3e) and often gravel deposits. The Eggenberger Formation (Gross, 2015) is a slope deposit that was considered by Flügel (1975) to be of Karpatian age (~16 Ma), but other authors indicated that it may be of quite variable age, as it occurs on different levels (Ebner et al., 1985; Gross, 2015). Nevertheless, it is important as it indicates topographic relief at the time of its formation.

The Kalkleiten (or Hochstraden) level is the next higher level. Wagner et al. (2011) described it to lie some 325 - 450 m above the Mur at Graz, but we consider it more generally to lie some 700 - 850 m above sea level in all of the Grazer Bergland (Table 1). Winkler-Hermaden (1957) considered it to be of upper Pliocene age and it was dated to 3.4 Ma by Wagner et al. (2010). It is one of the most important levels of the region as it is high enough to be widespread in the Grazer Bergland region, but low enough to be visible in the Styrian Basin where it correlates with the top of the Stradnerkogel volcano in the Styrian Basin. However, although the contiguous uplift of the Styrian Block as a whole is very plausible, it needs to be said that the Stradnerkogel may be younger than the age of the Kalkleiten level (Balogh et al., 1994; Bojar et al., 2013). Wagner et al. (2011) discussed this and pointed out that the age of the level and the dating of the Stradnerkogel are probably identical within error. Because of its characteristic occurrence it has also been termed “Gebirgsrandflur” or “Balcony of Graz” (Untersweg 1982). It is heavily karstified and it often hosts gravel deposits or red clays that are often mixed with rounded pebbles. Spectacular occurrences are on the Tanneben massif (Fig. 3g) or the type locality at Kalkleiten itself.

The Tragihütten level is the next higher level named after a type locality in the Koralpe, where it also has been called the “1000 m landscape” (Legrain et al., 2014), for it is located generally between 950 - 1100 m above sea level (Table 1). In the Koralpe, it is extremely distinct and can be well observed as breaks in slope along the Weinebene road or along the autobahn across the Pack saddle - often at somewhat higher elevations than in the Grazer Bergland. Due to erosion, the level is not preserved in the Styrian Basin, but its elevation in the Koralpe correlates well with the occurrences in the Bergland of Graz. When it is developed in limestone, it is also karstified, but less than the Kalkleiten level below. The Drachenhöhle near Mixnitz relates to this level (Fig. 3c) and was dated there to be of roughly 4 Ma age (Wagner et al. 2010). Notable occurrences are along the southeast side of Schöckl at 1000 m, at Nechnitz or around the Windhokfogel east of Semriach. The level is not as distinctly plane as the Kalkleiten level, possibly because it contains some paleotopography.

The Hubenhalt level is one of the higher levels in the Grazer Bergland. It is located at around 1200 m above sea level and varies only some 50 m around this elevation. Wagner et al. (2011) suggest about 700 - 800 m elevation of this level above the Mur valley near Graz. The type locality is the Hubenhalt Alm southwest of the Teichalm and Winkler-Hermaden (1957) considered the level to be of middle Pannonian age (around 10 Ma). According to Wagner et al. (2010) it may be only 5 - 7 Ma in age. Wagner et al. (2011) also ascribed the Teichalm surface itself to this level. However, as we recognize another level above the Teichalm, we restrict its occurrence to the flat area around the Teichalm sensu stricto, the Hubenhalt Alm and some other large occurrences, for example the ridge east of Schöckl along the Burgstaller Höhe, and Mt. Hartl (1136 m). Isolated occurrences of gravel and
conglomerates occur at various locations with one of the more prominent being that near Zechnerhube on the Teichalm (Gollner and Zier, 1985).

The **Wolschenegg** and **Kor**-levels are the highest two levels as defined by Winkler-Hermaden (1957) and they are here grouped together, because the higher levels become increasingly difficult to discriminate (see above), possibly because they contain paleotopography or possibly because they are the oldest and therefore most dissected by later erosion. These levels make up the summit plateau of the Schöckl and the hilly country north and south above the Teichalm including the Hochlantsch summit and we group them to occur at elevations between 1200 - 1720 m above sea level (Table 1). The age of these levels is largely unknown, but we will show below that it is plausible that these levels and their paleotopography are relics of the mid-Miocene lateral extrusion phase of the Eastern Alps.

### Table 1: Summary of the Planation surfaces in the Bergland of Graz and their elevation ranges.

<table>
<thead>
<tr>
<th>Level Name</th>
<th>elevation above Mur (after Wagner et al., 2011)</th>
<th>absolute elevation (after Wagner et al., 2011 for 360 m Mur)</th>
<th>elevation a.s.l. proposed here</th>
<th>example locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kor Level</td>
<td>1200 - 1500</td>
<td>1560 - 1860</td>
<td>1200 - 1720</td>
<td>Schöckl, Hochlantsch</td>
</tr>
<tr>
<td>Wolschenegg Level</td>
<td>900 - 1000</td>
<td>1260 - 1360</td>
<td></td>
<td>Hubenhalt, Burgstaller H.</td>
</tr>
<tr>
<td>Hubenhalt Level</td>
<td>700 - 800</td>
<td>1060 - 1160</td>
<td>1200</td>
<td>Summits in Joglland</td>
</tr>
<tr>
<td>Trahütten Level</td>
<td>500 - 600</td>
<td>860 - 960</td>
<td>950 - 1100</td>
<td>Nechnitz</td>
</tr>
<tr>
<td>Kalkleiten Level</td>
<td>325 - 450</td>
<td>685 - 810</td>
<td>700 - 850</td>
<td>Kalkleiten, Tanneben</td>
</tr>
<tr>
<td>Stadelberg Level</td>
<td>180 - 300</td>
<td>540 - 660</td>
<td>540 - 700</td>
<td>Tullwitz</td>
</tr>
</tbody>
</table>

Wagner et al. (2011). The map itself was then drawn by hand in the field using weighted observations from these different sources and was later georeferenced using GIS methods. Final editing of the georeferenced units was done in CorelDRAW 16. Emphasis was placed on mapping with a complete coverage of the map beyond extracting individual planation surfaces. This allowed us to consider the age of incision between specific relic surfaces and ultimately allows a much more complete interpretation of the evolution of landforms in the region.

In this context, this paper pronounces the value of field mapping in geomorphological analysis (Fig. 4). Experience shows that channel profile analysis is best done using quantitative extraction from DEM using numerical methods (for example using the Topotoolbox of Schwanghart and Scherler, 2014), because field work is very limited to recognize channel knickpoints. In contrast, the mapping of planation surfaces is best done with the human eye in the field in combination with slope and topographic map and exclusive mapping using remote sensing data may be somewhat limited. This is predominantly due to the fact that: (a) Relic surfaces may not be plane surfaces, but often contain topography on their own, either because they were later dissected or because of inherited topography. (b) Relic landscapes are often rounded by hillslope diffusion and other processes that are almost impossible to eliminate by digital methods. (c) Relic surfaces are often anthropogenically altered. This concerns particularly small surfaces and is often easy to see in the field. Indeed, because of the above points, we were able to recognize important aspects, for example that the discerning of relic surfaces is increasingly difficult with elevation. This is in support of the hypothesis that older levels are more influenced by subsequent hillslope processes and dissection than younger levels.

3. **Mapping the Grazer Bergland**

Mapping the Grazer Bergland was performed using 20 years of geomorphological observations of the Bergland region, followed by two weeks of focused field work in 2020. The mapping region was chosen as to cover all characteristic landforms of the Bergland and includes parts of the published geological 1:50,000 map sheets Passail (134), Birkfeld (135), Voitsberg (163) and Graz (164), as well as parts of the Geofast sheets Leoben (133) and Weiz (165) (https://www.geologie.ac.at/onlineshop/karten). In addition to field work, the map was made using topographic and slope maps derived from a 10 m resolution DEM (from: www.geoland.at), Google Earth imagery and published information from studies like those of Winkler-Hermaden (1957), Flügel and Maurin, (1957), (1958), Paschinger, (1965), Flügel (1975), Untersweg (1982) and
3.1 The geomorphological map

The principal result of this paper is the geomorphological map shown in Figure 5. The map shows a series of different colors for different recognized landforms. The superimposed dashing indicates inferred erosive decay like rounding of the landform during successive incision and erosion events. The different landforms are from old to young:

- The oldest landform interpreted as the Wolschenegg- or even Kor- level is shown in black. On the map of Fig. 5, this occurs only on the summit plateaus of the Schöckl and on the Hochlantsch/Teichalm (Figs. 6, 7). The landform is extremely distinct as it is characterized by widely undulating hillslopes, surrounded by much steeper slopes. In itself, the landform contains some 300 m of relief so that it can be found between roughly 1400 m and 1700 m above sea level. On the Hochlantsch massif the lower end of this level merges directly into the next level below – the Hubenhalt level. The Hubenhalt level is the mapped at elevations around 1200 m in dark green color. The elevation of this level is fairly tightly constrained, but the level does not occur as frequently as other levels further below. The Trahütten level is recognized around 1000 m as a clear break in slope with low relief surface. One of the most distinct features is that the lower end of this level is substantially rounded, possibly because of later hillslope processes. Below this, there is the Kalkleiten level mapped in light blue. This is a the most distinct level of the Grazer Bergland. Interesting is the somewhat ring-shaped occurrence along the margins of the Passail Basin. The Stadelberg level is the lowest level and is mapped in light green. It makes up the low parts of the Passail Basin and is preserved in low-lying regions in the south of the mapping area. The incised landscapes between different paleosurfaces is mapped in red and it clearly formed at all stages of the landscape evolution with a successively stronger erosion at higher levels around old landforms where it includes erosion of all subsequent stage. However, we will show below that it is this very incised landscape that allows some interesting interpretations about the landscape evolution and different incision stages are illustrated on the map with dashing.

The internally draining region of the Semriach Basin is here mapped as its own landform because it is so distinct. The region has been referred to as a Polje (Maurin and Zöttl, 1959; Bauer and Kellerer-Pirklbauer, 2010), but lithological contacts including non-karstifiable rocks cross the internally draining region (see Fig. 2), so that it is unlikely to be a Polje in the strict sense. Nevertheless, its morphology is obviously related to the formation of the Lurgrotte cave system (Kübeck et al., 2012). The basin also includes some thick gravel deposits of ill-defined age (Gross, 2015 and references therein), but probably belonging to the Kalkleiten level as they are located on the corresponding elevation. The basin forms not a single planation surface, but varies in elevation between the lower reaches of the Kalkleiten level at the Lurgrotte entrance at 641 m elevation and peaks like the Windhofkogel (1064 m) near the Trahütten level. The Lurgrotte cave system itself is known to be located on three distinct levels (Maurin and Benischke, 1992) with the highest being the Kalkleiten level, an intermediate level on the Stadelberg level and the present day active level at groundwater table of the Mur (Kübeck et al., 2012). As such, the age of the Semriach Basin is clearly younger than that of the Kalkleiten level, with the principal landforming process probably being related to the Stadelberg level.

The Pleistocene terraces and later alluvial planes are mapped in yellow and white, respectively. They were mapped (and somewhat simplified) directly from the published geological maps (see list above). Within the mapped region, two distinct terraces are recognized that both belong to the so-called “lower terrace group” of Russian and Würmian glacial age. These are the “Hochterrasse” at somewhat higher elevations and the “Niederterrasse”. Within the mapped region, the largest occurrence of the former is on the northwest side of Frohnlieben. The largest occurrence of the Niederterrasse is at Stübing or on the West side of Mur near the village of Röthelstein. Both terrace types are relics of a transport limited stage of the river Mur during the glaciation periods when the ice cap reached along the Mur as far as Judenburg and the Mur was thus extremely sediment-rich (Robl et al., 2008).

3.2 Observations from and interpretation of the map

The map shows several features that are of importance for the later interpretation of the landscape evolution.
The Relic Landscapes of the Grazer Bergland: Revisiting the Piedmonttreppen Debate

Figure 5: Geomorphological map of the Grazer Bergland. The colors are light green = Stadelberg level; light blue = Kalkleiten level (with green hatching: unsure mapping result); dark blue = Trahütten level; dark green = Hubenhalt level; black = Kor- and Wolschenegg levels; dark yellow = Hochterrasse; light yellow = Niederterrasse; light grey = Alluvial planes; red/orange = incised landscape at all stages between the formation of planation surfaces. Dashed regions indicate geomorphic processes that occurred after the formation of the respective landform. For example, the absence of "incised landscape" (red) and the presence of dashing on the Kalkleiten level between Kalkleiten and Stadelberg surfaces north of Passail indicates erosive rounding of the Kalkleiten level but without enough erosion to produce a mappable region of "incised landscape". Conversely, the dashing within the "incised landscape", for example flanking the Weizbach and Raab gorges indicates a mappable region of slope contrast within the areas mapped as red.

Legend

- Peaks
- Townships
- Groundwater level
- Alluvial planes
- Intermediate Surface
- Planation Surface
- Incised Landscape
- Sectors of incised landscape
- Palaeochannels
- Intermediate level (Kalkleiten)
- Intermediate level (Stadelberg/Zahrern)
- Intermediate level (Stadelberg/Kalkleiten)
- Intermediate level (Hochstrad.)
- Intermediate level (Trahütten)
- Intermediate level (Wolschnegg & Kor)
- Intermediate level (Hubenhalt)
- Intermediate level (Kor- and Wolschenegg)
- Intermediate level (Hochterrasse)
- Intermediate level (Niederterrasse)
- Intermediate level (Alluvial planes)
- Intermediate level (incised landscape at all stages)

Note: The labels and colors on the map represent different geological and geomorphological features of the Grazer Bergland.
Starting with the oldest and highest landform on the Hochlantsch or Schöckl summit, it may be seen on Fig. 5 that the edges of these plateaus are sharp and thus appear rarely overprinted by later hillslope processes (Fig. 6). This was already observed by Schwinner (1935) who referred to this observation as “Kalk-cuesta”. Later erosion appears to have affected the landform by scarp retreat only. This is likely to be due to the fact that the level is the exclusively developed in the two limestone plateaus of the region which are internally draining through their karst channel. Accordingly, the level contains dolines (e.g. Untersweg, 1982) and rare isolated gravel deposits. The most characteristic feature of the Hubenhalt level is that it is so discretely confined to 1200 m elevation. The Trahütten level is the highest level that defines a ring-shaped level arrangement around the Passail Basin (Fig. 6). The Kalkleiten and Stadelberg levels form further concentric rings and are particularly well developed near the Passail Basin, possibly indicating that the soft basin sediments eroded much easier and thus higher levels are only preserved in the basement lithologies of the Paleozoic rocks.

Important observations for the interpretation of the map come predominantly from the incised landscapes mapped in red. In general, this red color implies erosive incision at all stages subsequent to the level below which it is mapped. Thus, the color red below the Stadelberg level means uplift and incision postdate to this level only, while areas mapped in red below the Hubenhalt level could have incised both, directly after formation of the Hubenhalt level or much later, for example postdate to Stadelberg. Some of the different incision stages within the areas colored in red are highlighted by black dashing and will be discussed below. Note, for example, that there are places where there is no red between different levels, for example going south from the Burgstaller Höhe or going south from the Gelderkogel (1195 m) on the north side of the Passail Basin (Fig. 6, 7). In other regions, incised landscape is distinctly mapped between landforms of the different age, for example going north and south from the Wolfsattel (1080 m) between the Raab and Weizkamm. Also note that incised landscape is mapped at most locations between the Wolschenegg and the Hubenhalt levels, but occurs less frequently as a break between levels at lower elevations. This clearly indicates that the higher levels are older with more time for subsequent erosion. Also note the geometry of the incised landscape that widens at the transitions between the Stadelberg and the Kalkleiten level and again between the Kalkleiten and the Trahütten levels inside the Passail Basin but narrows above and below, for example along the Tulwitzt Bach and surrounding streams east of Rechberg (Fig. 6).

In the Raab and the Weizbach, there is an obvious break in slope inside the incised landscape indicating two discernable parts of the incised landscape mapped in red (Fig. 6, 7). We have outlined this region with an additional dashing on the map (Fig. 5). This region forms the gorge regions for the Weizbach and the Raab, but it can be clearly traced for much longer parts up and down stream of the gorges themselves. Clearly these parts indicate that the gorges of both streams may have formed later than some of the stepwise uplift of the planation surfaces and we will discuss its age below.

The alluvial channels are important inasmuch that they indicate that channel profile analysis may need to be considered using transport limited rather than detachment limited erosion models. Channel profile analysis (see below) shows that most channels may be well interpreted using detachment limits models, so that we infer that sedimentation in the study region is not significant. A notable example is the river Mur: Between Bruck an der Mur and Graz, the river flows alternatingly on bedrock and on quaternary deposits without knickpoints (Robl et al., 2008) showing that the channel is largely equilibrium and sedimentation is minor. Wagner et al. (2010) interpreted this alternating bed-rock pattern of the river between Bruck and Graz in terms of incomplete erosion of glacial sediments that were deposited during the transport limited state of the river during glaciation periods, that incompletely removed during detachment limited interglacial periods like today. Interestingly, except for a small bedrock outcropping at the Schlossberg in Graz, the bedrock rapids in the Badl Enge (Fig. 3g) are the last bedrock occurrence in the river (see also Kollmann, 1965). The next downstream occurrence of bedrock in the channel bed occurs after the Mur has joined the Drau and later the Danube at the Iron Gates in the Carpathian arc, some 1000 km downstream of Graz.

4. Discussion

The landforms described in the last section may be interpreted in terms of two end member scenarios of the landscape evolution: They may form what is known as a Piedmonttrepppe reflecting successive stages of uplift of the whole region, or they may be lithologically controlled or even due to tectonic dissection. Both alternative interpretations have been made for the Graz basin, but Untersweg (1982) concluded that the Piedmonttrepppe model is unlikely to hold for a number of reasons mentioned in the introduction to this paper. Here, we have shown that the different relic landscapes can well be correlated across the Bergland region and Wagner et al. (2011) have shown that they do in fact correlate over some 100 km along the Mur river up- and downstream of Graz with only a smooth continuous north and westward rise in elevation above base level. This strongly argues for the Piedmonttrepppe model and observations made by Untersweg (1982) that were used to support a tectonic dissection model need to be discussed. This includes particularly (a) the distribution of Eggenberger Breccia (Fig. 3e), (b) the distribution of Pannonian gravels and (c) possibility of lithological control for the Planation surfaces.

The distinct Eggenberg Breccia (Fig. 3e) occurs on a series of elevations and thus has been used as an argument for tectonic dissection of the area. However, Ebner et al. (1985) suggested that this slope deposit is likely to be only indicative of exiting topography at the time of
formation and may have formed from debris slides at various stages in time (Gross, 2015). Indeed, the occurrence of the Gratkorn embayment of the Styrian Basin near the Schöckl indicates that there was likely to exist some 1000 m of relief at the time of the embayment. Such pre-existing relief actually supports to formation of widespread planation levels on hard basement rocks during subsequent subsidence and later exhumation: If peneplanation did not have to form a completely new surface, but only planate a pre-existing hilly landscape, this may be achieved in much shorter time periods. (b) Conversely, the so-called “Pannonian gravels”, derive their name from Winkler-Hermaden (1957) who considered them as relicts of an up to 800 meters thick sequence of gravels of Pannonian age. However, the age of these gravels is much less well constrained than their name may suggest. For example, Maurin (1952) considered them to be of Pliocene age, which is much more consistent with the interpretation of Wagner et al. (2011) for the uplift history. Although these gravels occur in the Grazer Bergland predominantly at elevations below about 740 m (e.g. Gross, 2015), it needs to be said that gravels of up-to Oligocene age are found in other parts of the Eastern Alps at up to 2500 m surface elevation where they have been termed “Augensteine” (Frisch et al., 2001). As such, the gravel occurrence on different low-relief surfaces of the Grazer Bergland has no bearing on their interpretation as Piedmonttreppen versus being tectonically dissected. Finally, (c) the argument of lithological control for the existence of planation surfaces is easily refuted because the same surfaces can be traced through very different lithologies. Without referring to many examples, we simply refer to a comparison of the geomorphic map on Fig. 5 and the geological map on Fig. 2. It may be seen that many contacts of planation surfaces transect both lithological and tectonic contacts in the region. While all these arguments may or may not be a unique argument, the strongest support for the Piedmonttreppen model comes from channel analysis.

4.1 Channel analysis
Fluvial channels in the Grazer Bergland incise the landscape and, within the Piedmonttreppen model, they separate segments of relictic surfaces on the same elevation that once were a continuous landscape. Thus, they may have knickpoints in their channels that formed during relative base level drop caused by uplift of the adjacent planation surfaces. These knickpoints migrate upwards in elevation with time and thus may be located at somewhat higher elevation than the corresponding planation surfaces. Nevertheless, migrating knickpoints are geomorphological information that is largely independent from the mapping results and thus can be used in support of the Piedmonttreppen model – in particular if the knickpoints are at or slightly above mapped low-relief surfaces.

Knickpoints may be recognized as deviations from geomorphologically equilibrated channel profiles of detachment limited fluvial channels. Such equilibrium channels are characterized by a constant steepness index ks and have a linear relationship on a double logarithmic slope vs. catchment area plot. In practice, the steepness index is often normalized to a constant reference concavity index and is then called ksn. For an explanation of geomorphic channel equilibrium and the definition of steepness index we refer to an abundance of studies, for example Whipple and Tucker (1999), Wobus et al. (2006), Kirby and Whipple (2012), Neely et al. (2017), or more locally, Lontschar and Stüwe (2020), or Bartosch and Stüwe (2019). Figure 8 shows a map of normalized steepness index for the Grazer Bergland. It may be seen that (aside from the obvious high- ksn regions that will be discussed for selected streams below), many streams show increased steepness indices near their head waters, in particular those that drain the Hochlantsch massif to the south or the Schöckl towards the west. Such increased steepness index may arise from an un-proportionally large catchment region for the stream and therefore indicate river piracy events where these streams encroach onto the Hubenhalt and higher levels. This interpretation is independent- and in support of the interpretation from the field mapping that indicates scarp retreat as a main erosion process at these elevations. The Mur has a largely constant steepness index and may therefore be interpreted as a largely equilibrated antecedent river. However, many of the smaller rivers show slight heterogeneities in ksn when they cross planation level boundaries.

For a more detailed analysis we have chosen six channels that reflect a typical spread of regional distribution and characteristic landscapes of the Grazer Bergland. These are the Rötschbach, the Lurbach/Badlgrabenbach system, the Tynrauer Bach and the Mixnitzbach, as well as the two major gorge-forming rivers Weizbach and Raab. For each of these streams, we show the channel profile, the catchment area and the normalized steepness index as a function of channel length on Fig. 9. The data used to calculate the steepness index are shown in the double logarithmic slope – catchment are plots on Fig. 10.

The Tynrauer Bach has a fairly well-equilibrated channel profile with a fairly uniform ksn between 40 - 60. This is shown by the nicely linear relationship of the slope-catchment area data on Fig. 10. Only in the uppermost reaches the steepness index rises somewhat, probably due to minor catchment capture events from the Teichalm plateau. The equilibrated nature is different from most tributaries to the Mur in this region, and is interpreted to the be consequence of the Tynrauer Bach flowing along a major fault. This may have allowed more rapid incision than the other streams or may imply that there was a drainage prior to uplift.

In contrast, the channel profiles of the Mixnitzbach and the Lurbach/Badlgrabenbach and the Rötschbach all show clear evidence for substantial knickpoints that may be correlated with adjacent planation levels (Fig. 5). On the Teichalm, the Mixnitzbach has a well-equilibrated profile on the Hubenhalt level and above (Figs. 9, 10). The enormous knickpoint in the Bärenschützklamm drops down...
from the Hubenhalt level to the present-day level of the Mur. Two weak steps inside the Bärenschützklamm are potentially evidence for knickpoints related to the Trahütten and Kalkleiten levels. Correspondingly, the Badlgrabenbach and the Lurbach are reasonably well-equilibrated above the Kalkleiten level. On the Kalkleiten level on about 700 m they have knickpoints with the Lurbach disappearing into the Lurgrotte cave shortly thereafter. The Badlgraben however, has a noisy profile across the Stadelberg level until it reaches the Mur. The Weizbach and the Raab
are the two major rivers that drain the Passail Basin towards the south into the Styrian basin. Although both rivers form substantial gorges along their course where they break through the Burgstaller Höhe ridge, they appear to be largely antecedent with only minor knickpoints.

The inferred knickpoints are also reflected in valley profiles across the channels discussed above which show smooth wide profiles above and below the knickpoints, but V-shaped steep incisions at the knickpoints (Fig. 11). In summary, it may be said that the dis-equilibrium...
sections (knickpoints) of most streams in the Grazer Bergland may be well correlated with the field mapping results for adjacent planation levels. This is in strong support of the Piedmonttreppe model.

4.2 Geomorphological evolution

Within the Piedmonttreppe model for the planation surfaces of the Grazer Bergland as proposed here, the uplift history may be interpreted if the ages of the relic surfaces are known. Wagner et al. (2010) have used cosmogenic burial ages from siliciclastic sediments in caves as proxies for the age of the planation surfaces and were able to largely support the qualitative age interpretation made by Winkler-Hermaden (1957). They suggested an age of some 4 Ma for the Trahütten level and successive younging of the erosion surfaces towards lower levels. As the levels correlate between the Bergland region and the Styrian Basin, they interpreted the rock uplift in terms of a broad, long wavelength event that affects the entire Styrian block as defined by Wagner et al. (2011) (see also Sachsenhofer et al., 1997). Within this model, the much lower topography in the Styrian Basin is solely the consequence of higher erosion (lower surface uplift, but the same rock uplift as in the Bergland region (see Stüwe and Barr (1998) for definition of uplift terminology) (Fig. 12). This model is also consistent with the origin of low surface topography of the intramontane basins along the Mur-Mürz lineament (Sachsenhofer, 1989).

Within this model, the Pliocene rock uplift around 3-4 Ma affected the entire Styrian Block with substantial surface uplift in the Grazer Bergland, but negligible surface uplift in the Styrian Basin would have caused successive oversteepening of channels draining into the basin in the Grazer Bergland. We propose that the paleo Mur near Graz (which we here term “Kugelsteinbach”) may have originated in a region near Peggau prior to about 4 Ma (near, but at several hundreds of meters elevation above Peggau). This idea is consistent with the idea that the paleo Mur in Upper Styria flowed in the early Pliocene and Miocene from the upper Mur-valley and further along the Mürz valley across the wind gap of the Semmering pass into the Vienna basin (Schwinner, 1935; Dunkl et al., 2006). Within this paleodrainage geometry, the Mürz valley was only later reversed and tributaries to the paleo Mur at Bruck would have flown northward originating in the Frohnleiten region (here termed: “Frohnleiten tributary”) (Fig. 13). We suggest that headward migration of the Peggaubach channel

![Figure 8: Stream power map of the Grazer Bergland. The steepness index was fitted using a reference concavity index Θ_{ref} = 0.45.](image-url)
Figure 9: Channel profiles of important streams of the Grazer Bergland region. The extracted channel segments are delimited by the blue dots at the ends of the blue colored streams on Fig. 1a. The steepness index (ksn) curves below the channel profiles allow a better evaluation of the disequilibrium sections. For the Weizbach and Raab we also show the associated size of the drainage areas along the river profile as they will form part of the discussion section of this paper. The associated double logarithmic slope are plots are shown on Figure 10. The steepness index was fitted for the data on Fig. 10 using a reference concavity index $\Theta_{ref} = 0.45$. This is the value for the concavity index commonly used in the literature (e.g. Kirby and Whipple, 2012).
near Peggau eventually caused capture of Frohnleiten tributary (Stumpf and Stüwe, 2019). This capture event occurred roughly contemporaneously with the uplift of the Semmering at around 4 Ma (as part of the Styrian Block uplift) and thus dramatically increased the amount of water in the river. It thus rapidly became an antecedent river dropping its base level to the present-day level in the Badl Enge region. This idea is supported by the fact that the Mur valley narrows in the so-called Badl Enge and widens north and south of it (Fig. 1). The mapping results presented here support this model for the evolution of the Grazer Bergland and we now present some highlights of this support.

4.2.1. The Mixnitzbach, Lurbach and the Rötschgraben river piracy event:

The Mixnitzbach and the Rötschbach contain the most spectacular knickpoints of the Grazer Bergland and we interpret both knickpoints within the evolution proposed above. We suggest that they formed around 3 Ma due to the sudden base level drop during the Peggaubach-Frohnleiten tributary capture and incision at the Badl Enge to the present day Mur level. The knickpoints of these rivers have since migrated some kilometers into the contributing valleys. Around the time of their initial formation, the uppermost level of the Lurgotte formed, draining the Lurbach – which previously flowed into the lower Rötschgraben valley below the Kesselfall - subsurface to the Mur valley. This river piracy event caused the ridge to fall dry, that now forms the smooth, broad, gravel ridge that separates the Kesselfall from the Semriach Polje along the Semriach road. Shortly thereafter, the headward migrating Kesselfall knickpoint may have captured the creek from the Upper Rötschgraben. This Upper Rötschbach may have drained into the Lurbach before this time, assisting the rapid erosion and subsidence of the Semriach Polje.

4.2.2. The Gratkorn embayment:

The Sarmatian sediments of the Gratkorn embayment present an unresolved problem to the landscape evolution. These sediments contain important vertebrate fossils with inferred evidence for a lagoonal environment of the Paratethys sea (Gross et al., 2010). This evidence for near sea level sedimentation implies the presence of topography of at least the current relief between Schöckl and Gratkorn at this time, unless substantial tectonic motion since the Sarmatian can be shown.

Figure 10: Double logarithmic slope area plots of the channels shown in Figure 9. According to the stream power law of detachment limited channels, linear segments of data in these plots can be interpreted to be in geomorphic channel equilibrium. Fitting of such linear segments for streams at the eastern end of the Alps to determine uplift rates has been shown by Bartosch and Stüwe (2019), Legrain et al. (2014) and several others.

Figure 11: Swath profiles of important streams of the Grazer Bergland. The swath profiles are averaged for near sea level sedimentation implies the presence of topography of at least the current relief between Schöckl and Gratkorn at this time, unless substantial tectonic motion since the Sarmatian can be shown.
Tectonic dissection must have occurred after the Sarmatian around 12 Ma, but before the broad continuous uplift of the Styrian block that we suggest to have started around 5 Ma. Interestingly, it is this very time period from 10 - 5 Ma during which there exists very little sediment record in the Styrian basin except for some minor occurrences of brackish deposits, for example those near Jennersdorf (Gross, 2015). Several authors have suggested tectonic dissection of the Styrian block in this period (Ebner and Sachsenhofer, 1995; Wagner et al., 2011). While our findings of the consistently mappable planation surfaces post 5 Ma are consistent with localized subsidence of the Gratkorn embayment prior to 5 Ma, we see little evidence for vertical displacements that could be responsible for up to 1000 m relief formation.

Without tectonic dissection of the region, there would have been some 1000 m of relief in the Sarmatian (12 Ma) (between the elevations of Gratkorn, today at 400 m a.s.l. and Schöckl summit). Several lines of evidence suggest that such relief at about 12 Ma is also not implausible and help to lessen the need for tectonic dissection with substantial vertical displacements (Fig. 12): For example, the presence of coal in the Passail Basin indicates that some overburden was present. We suggest that - similar to the intramontane basins along the Mur-Mürz valleys (Sachsenhofer, 2000) - this overburden may have been up to about one kilometer, filling the entire topographic depression between the Schöckl and Teichalm levels (Fig. 13). Within this model, the present-day relief is similar to that of the Mid-Miocene and may have been built from tilt blocks that are the product of the Miocene lateral extrusion phase of the eastern Alps (Fig. 12). This model is supported by observations in the Koralpe and Sualpe tilt blocks. It's topography however, was obscured soon after its formation by the sedimentation of the Passail Basin, similar to the formation of the Koralpe and Sualpe tilt blocks. Its topography however, was obscured soon after its formation by the sedimentation of the Passail Basin to its north and the Styrian Basin to its south (Fig. 12). This model is supported by the types of sediments: In the Gratkorn embayment the sediments were probably deposited in a lagoonal environment at the spatial transition from terrestrial to shallow marine sedimentation and in the Passail Basin they are mostly fluviatile. When the Burgstaller Höhe ridge was exhumed, it eventually became exposed enough to be subject to gravitational forces affecting the tilt block, as, for example, may be indicated by the double-crest formation at Wolfsattel, in line with the Karterloch cave fault.

4.2.3. Weiz and Raabklamm:

Weizbach and Raab have surprisingly small knickpoints in their dramatic gorge sections (Fig. 9) and we suggest that these knickpoints are relics of capture events similar in style and age to that of the Badl Enge in the Mur valley, with the area of the Raab- and the Weiz- gorges being a watershed until about 3 Ma. Prior to this time, the Passail Basin itself was probably filled by Miocene sediments of about one kilometer thickness so that the Schöckl plateau was directly connected to the Teichalm and drained towards the west into the Mur (Fig. 12, 13). Indeed, it is possible, that the substantial sediments in the Semriach region are reworked sediments from the Passail Basin from this time. Successive over steepening of the Paleoraab and Paleoweizbach creeks that drained this ridge towards the south may have eventually caused a capture event of rivers that previously drained the Passail Basin to the west. Thereafter, the Passail Basin was rapidly emptied and denuded by the Raab and Weizbach, thereby exhuming the Burgstaller Höhe ridge.

Within this model, the characteristic topographic ridge from Schöckl across the Burgstaller Höhe and Hartl (1136 m), Wolfsattel, Patschaberg (1271) and Zetz (1274 m) is a Miocene tilt block that formed during the formation of the Styrian Basin, similar to the formation of the Koralpe and Sualpe tilt blocks. Its topography however, was obscured soon after its formation by the sedimentation of the Passail Basin to its north and the Styrian Basin to its south (Fig. 12). This model is supported by the types of sediments: In the Gratkorn embayment the sediments were probably deposited in a lagoonal environment at the spatial transition from terrestrial to shallow marine sedimentation and in the Passail Basin they are mostly fluviatile. When the Burgstaller Höhe ridge was exhumed, it eventually became exposed enough to be subject to gravitational forces affecting the tilt block, as, for example, may be indicated by the double-crest formation at Wolfsattel, in line with the Karterloch cave fault.

Figure 12: Schematic summary profile through the Grazer Bergland showing its interpreted geomorphological evolution since the Mid Miocene. The profile is from northwest to southeast, roughly at the position indicated by the small white arrows on Fig. 1. Miocene rocks are in grey, Miocene basin sediments in yellow. Relics of planation surfaces are shown in red. For detailed discussion of this profile, see text.
Kurt STÜWE and Konstantin HOHMANN

The gigantic water increase caused by these capture events for Mur, Raab and Weizbach led to rapid antecedent equilibratiation of these rivers, causing erosive denudation of the Passail Basin to its present-day remnants and forming massive knickpoints in the Mur tributaries at Bärenschützklamm, Kessel, fall or Badlgrabenbach. Headward migration of these knickpoints in the last 2-3 Ma have caused subsequent minor reorganization of drainage networks, for example the capture of the upper Rötschgraben, or the formation of the Semriach Polje causing internal draining of the Lurbach System.

8. Conclusion
From the above, we draw the following conclusions of our study:

• The relic surfaces in the Grazer Bergland can be interpreted as a Piedmonttreppe that records evidence for a wide-reaching Pliocene uplift history that affected the entire Styrian Block. This Piedmonttreppe includes the well-known planation surfaces of the Stadelberg-, the Kalkleiten-, the Trahütten-, the Hubenhalt, as well as the Kor- and Wolschenegg levels, with the latter being more likely a remnant of the Miocene evolution than of the Pliocene uplift history.

• The uplift occurred with little tectonic dissection and the topographic difference between the low lying Passail- and Styrian Basins and the summits of the Grazer Bergland is interpreted solely as the consequence of higher erosion rates of the basins sediments. Within this interpretation, the Passail Basin is the remnant of a basin that once connected the Schöckl and Teichalm plateaus.

• Without differential uplift within the Bergland region, the presence of 12 Ma old lagoonal sediments at Gratkorn (400 m a.s.l.) implies that there was some 1000 m of relief to Schöckl (1445 m) during this time. This Miocene relief was probably the product of the lateral extrusion phase of the Alps and we suggest that the northeast-southwest striking Burgstalle Höhe ridge may be interpreted as a tilt bock related to the formation of the Styrian Basin, similar to the Kor and Sau-Alpe ranges.

• Within the Piedmonttreppe model the geomorphological evolution is interpreted in terms of watersheds at Peggau (for the Mur) in the Raab Klamms (for Raab) and the Weizklamm (for Weizbach) prior to about 4 Ma. These watersheds were broken by south draining paleo-creeks that were oversteepend during the Pliocene uplift causing river piracy of the entire Mur (previously draining across the Semmering to the east), as well as the upper Raab and Weizbach (previously draining the Passail Basin to the west).

Acknowledgements
We thank all the former students that helped us to consolidate the observations and interpretations presented here. T. Bartosch is thanked for his patience with the first author when using standard GIS tools and G. Gradwohl for a partial review of the manuscript. C. Bauer and M. Gross are thanked for careful reviews and Walter Kurz for the professional handling of the manuscript.

References
Flügel H., Maurin V., 1958. Die geologischen Verhältnisse im Raum zwischen der Karstverhältnisse. Steirische Beiträge zur Hydrogeologie, Heft 1/2