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Maps of Quaternary sediments and features in Austria and neighbouring countries at the scales of 1:500 000 and 1:1 500 000

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Abstract

Today´s landscape and morphology of Austria is markedly affected by erosional and sedimentary processes active during the Quaternary. Particularly, large glaciers have shaped the landscape of the Eastern Alps. The presented maps at the scales of 1:500 000 and 1:1 500 000 aim to visualise areas, where deposition or erosion in different stages of the Quaternary prevailed. The maps (free download available) were generated with ArcGIS software using available map sheets at larger scales (1:50 000, 1:200 000). No additional field work has been conducted. The most obvious observation is that an extensive cover of Quaternary sediments predominantly occurs in the northern Alpine foreland, especially outside of Austria.

The maps show that large glacier tongues of the Middle to Late Pleistocene glaciations (Günz, Mindel, Riss and Würm) existed in the northern and southeastern alpine foreland. In the east, hardly any signs of glacial coverage are visible due to later fluvial cannibalisation of features partly deposited in narrow valleys. Bordering terminal moraines, extensive, terraced fluvial deposits occur within and around the Alps showing that river courses partly changed during the Pleistocene. Aeolian sediments often accompany these sediments, but also cover huge areas in the Vienna and Tulln Basin and the Little Hungarian plain. The distribution of large rockslide events shows that they mainly formed in glacially covered areas as a result of rock destabilisation after glacier retreat. Additionally, the map shows that the alpine foreland is subject of inhomogeneous uplift since the Neogene. For example, between Salzburg and Munich, wide areas are covered by Pleistocene deposits, whereas to the west of Munich and in Upper Austria, recent rivers incised deeper into Neogene sediments.

1. Introduction

Overview maps in general are very useful to get a quick overview on a region, to see what happened in the past and future predictions might be possible (Rupp et al., 2011). Quaternary maps in particular are very important in terms of climate change. For instance, they show the distribution of large landslides in the past endangering infrastructure and settlements and based on this, areas susceptible for future landslides might be identified (van Westen et al., 2008). Additionally, in times where energy is getting a more and more precious resource and the transport with fossil fuel is problematic, areas comprised by sediments serving as mineral resources for construction could be detected closest to their need (Pulselli et al., 2008). Furthermore, in terms of nuclear waste deposits, Quaternary maps are vital to reconstruct not only the behaviour of glaciers in the past (Seguinot et al., 2018), but maybe where they might flow again in the future. So far, geological overview maps of the Geological Survey of Austria neglected (with few exceptions like

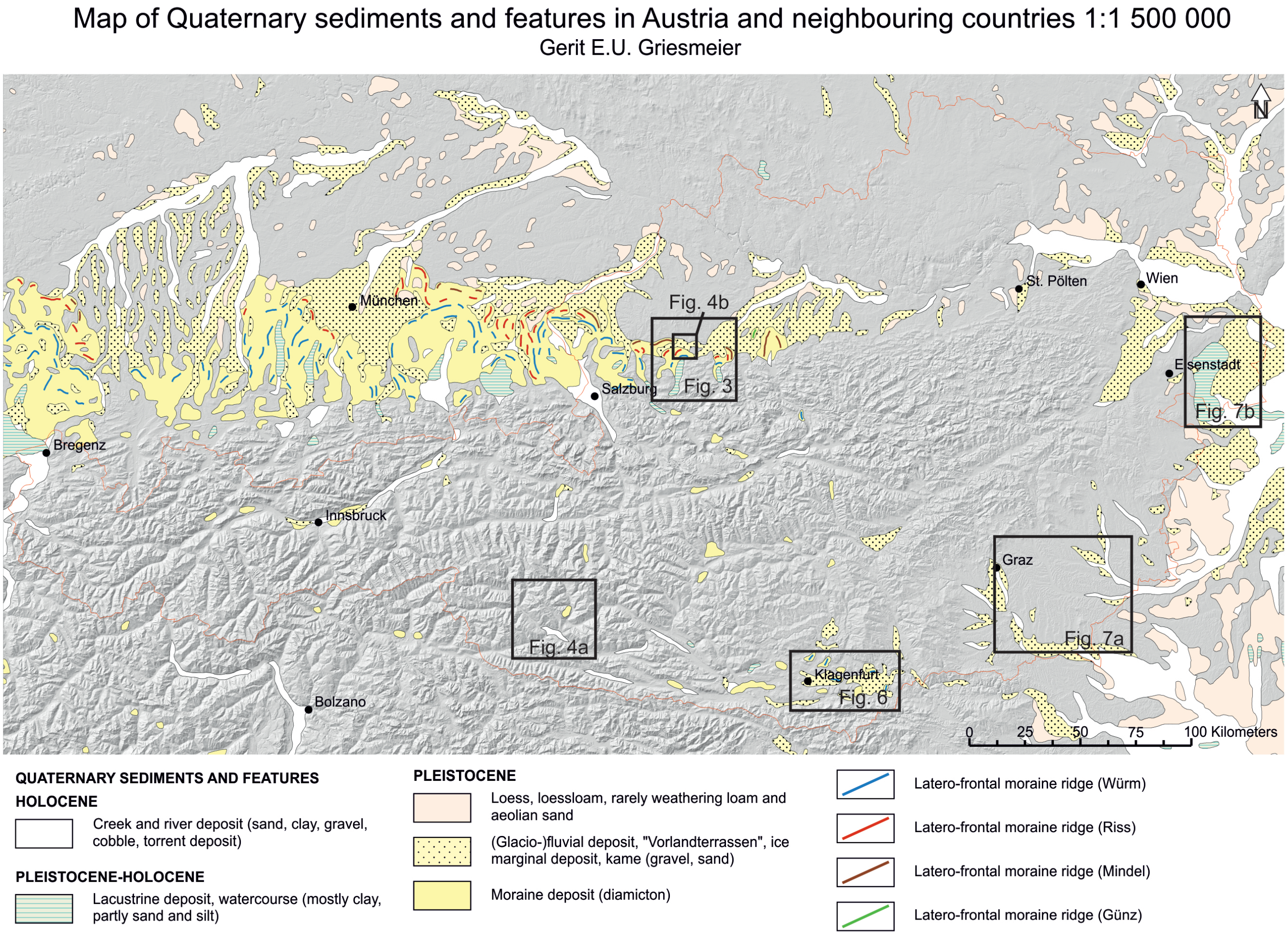

Figure 1: Overview map 1:1 500 000. Locations of several subfigures are shown.

e.g. Vetters, 1933) the sediments and landforms formed during the Quaternary. The presented maps at the scales of 1:500 000 and 1:1 500 000 (supplementary Figs. S1, S2) aim to close this gap. Both presented maps (Figs. 1, S1, S2) show the general distribution of Quaternary deposits in Austria and neighbouring countries. Special focus is set on large glaciations, which significantly shaped the Alpine topography and on the sediments and features produced during these times. For that reason, deposits of smaller extent were omitted or subsumed with other deposits for a better understanding of the overall picture. Furthermore, the maps serve as base for reconstructing paleorivers and glacier extents helping to deduce paleogeographic reconstructions during a specific time period. For example, the map of van Husen (1987) showing the ice extent and river courses during the Würm Glacial could be re-drawn (Fig. 2) using the ice extent on the new overview map 1:500 000, at least in areas, where moraine ridges are abundant (Fig. 2a). In addition to the map of van Husen (1987), small patches of basal till outside of the alpine-wide ice network served as base to identify areas, which were covered by local glaciers. Supplementary to the presented map 1:500 000 (Fig. S1), by using modern laserscan images, the ice extent shown in Figure 2 could also be checked more precisely especially in the area of arêtes and peaks and at local glaciers and this was adapted accordingly (Fig. 2b). The distribution of (glacio-)fluvial deposits, "Niederterrasse" (lower terrace) of the presented map 1:500 000 (Fig. S1) shows where rivers were draining (proglacially covering much broader areas than today) and this could be complemented (Fig. 2). In areas north of the extent of the map of van Husen (1987), the distribution of recent fluvial sediments on the presented map 1:500 000 (Fig. S1) served as base for river courses, assuming that they did not change since the Last Glacial Maximum (LGM).

2. Geological framework and concept of the compiled maps

During the Quaternary, large areas of Austria were significantly affected by processes associated with glacial maxima. This insight was delivered by the paleontologist Louis Agassiz, who is considered to be the founder of the ice age theory. In July 1837, as president of the Swiss Society of Natural Sciences, he did not present fossil fishes from Brazil as expected, but focused on facetted and scrachted pebbles in the Jura mountains (Imbrie and Im-

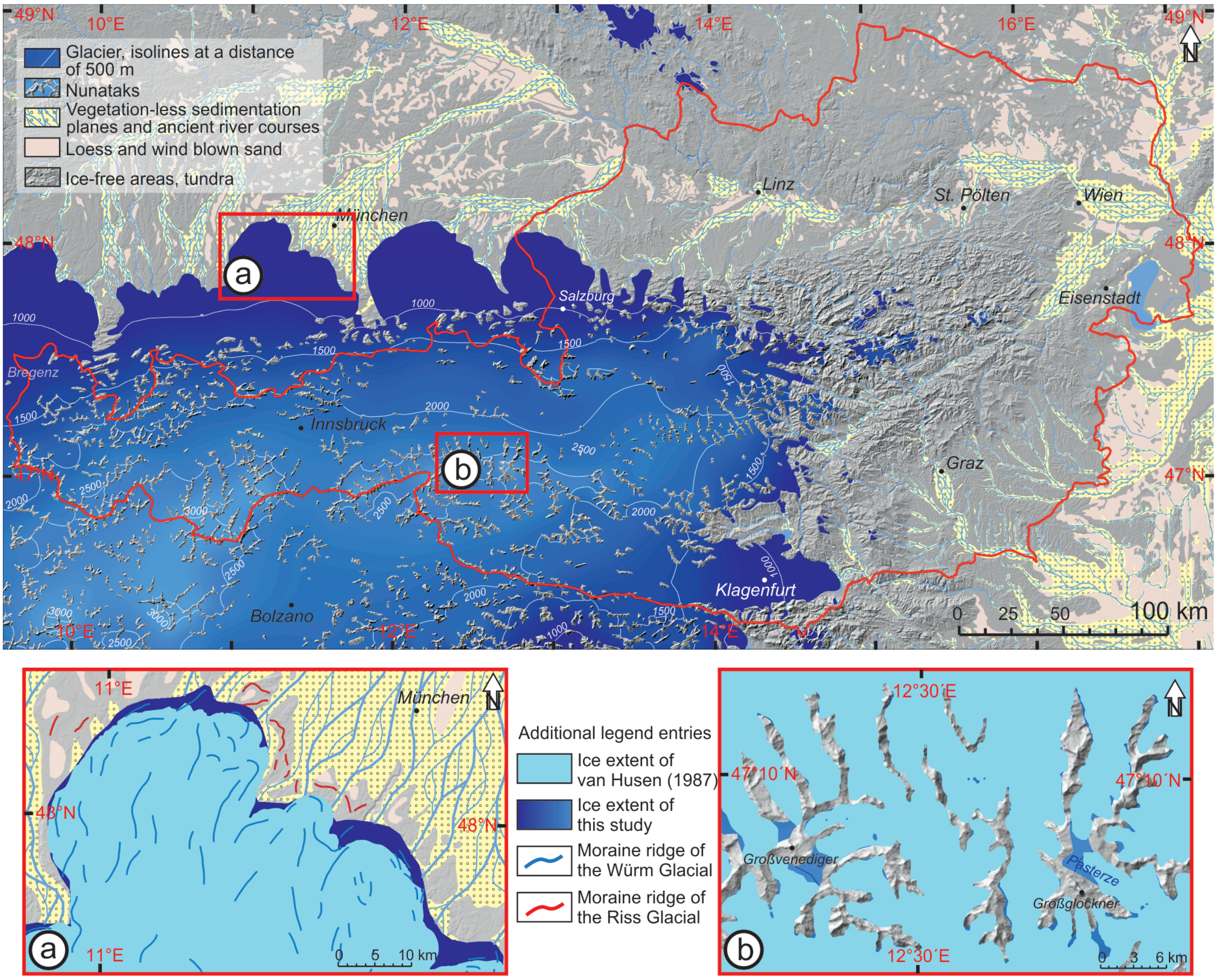

Figure 2: Glacial extent during the Last Glacial Maximum of Austria and surroundings. Glacial extent and contour lines modified after van Husen (1987). Rivers outside the Alps modified after van Husen (1987) and complemented with modern topography, polygons ("Niederterrasse" and Holocene creek and river deposits) of the presented map (1:500 000) and recent river courses. **(a)** Inlet in the area of München showing the new drawn ice extent in comparison with the ice extent of van Husen (1987). The blue moraine ridges of the Würm Glacial (of the presented map 1:500 000) clearly show that the ice extent of van Husen (1987) is underestimated. **(b)** Inlet around the Hohe Tauern mountain range. At the ice extent of van Husen (1987), e.g. the Pasterze Glacier is ice free. Adaptions like this have been made throughout the whole map extent.

brie, 1979). However, he drew a rather catastrophic picture of a huge carapace of ice covering the whole Alps including mountain peaks. By the time, this view developed more and more towards today´s understanding. In Austria, Richter (1900) and Penck and Brückner (1909) served as pioneers in terms of Quaternary geology and their research is still used as reference for Quaternary studies in general today. Their special attention was given to paleo snowlines (equilibrium line between accumulation and ablation area of a glacier) in comparison to modern snowlines and glaciofluvial sediments in proglacial areas, whose weathering conditions hint at their relative age. In this context, the term „glacial series“ was defined, where a perfectly preserved glacial advance is characterised from proximal to distal by a tongue basin, drumlins, terminal moraines and glaciofluvial outwash gravel in the glacier forefield (Penck and Brückner, 1909). At the presented maps (Figs. S1, S2), special attention was given on depicting this glacial series whenever possible, because it clearly shows the glacier extent through time (Fig. 3). However, this is only nicely recognisable in the Alpine foreland, where large glacier tongues fed by major Alpine valleys (e.g. Inn valley, Salzach valley) reached giant extents as so called piedmont glaciers. In contrast, the Enns glacier, for example, reached its maximum extent within the Alps in a narrow valley. Because of a lack of space and the cannibalisational effect of rivers, the preservation potential in such areas is rather low. Nevertheless, the glacial series is preserved rudimentary and depicted as such.

Today, we distinguish four major glaciations in Austria, which are globally correlatable. They are called after rivers

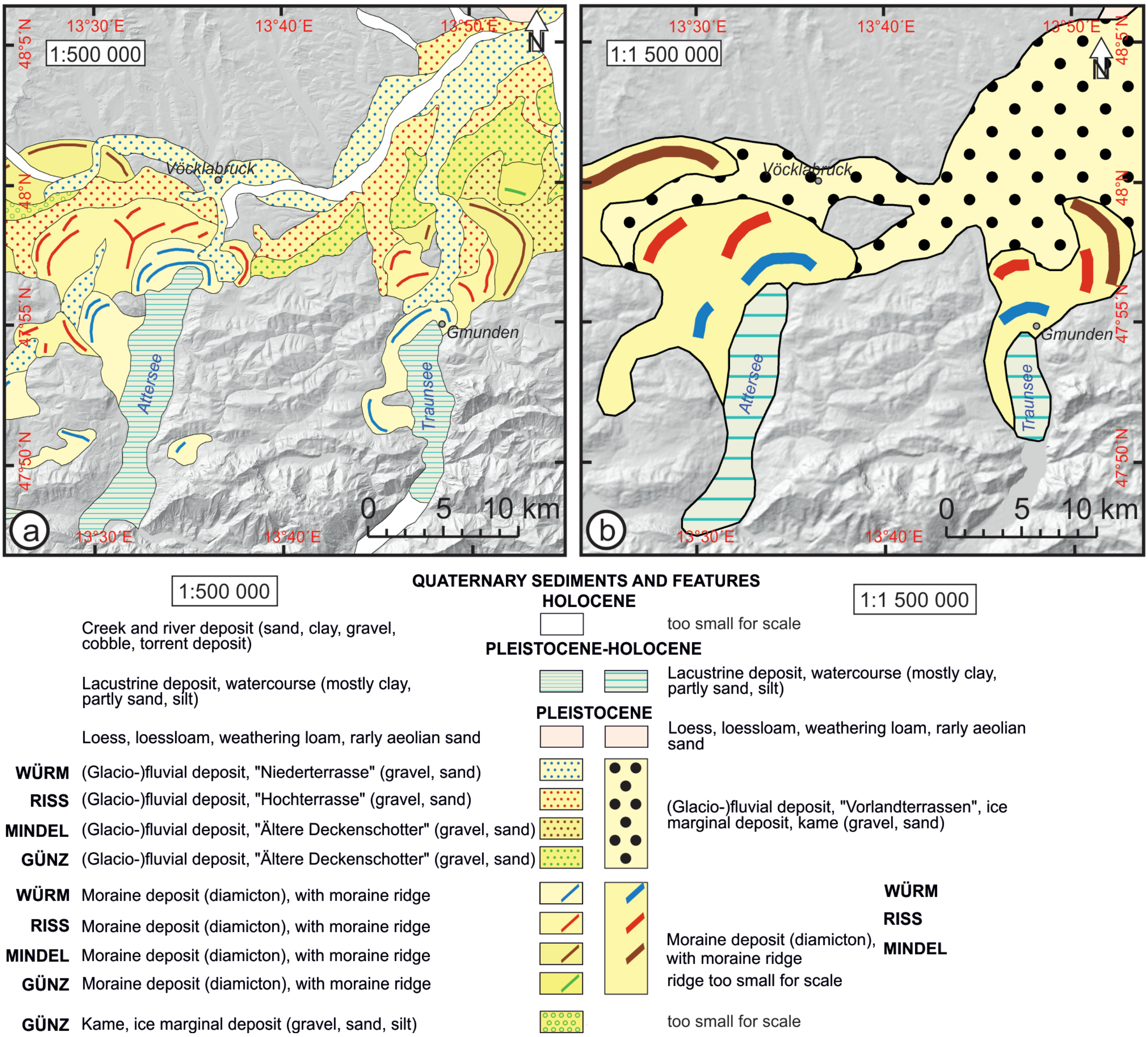

Figure 3: Example of the glacial series as depicted on both maps showing the same extent. **(a)** Example of the map at a scale of 1:500 000. All four major glaciations are shown by moraine ridges and associated outwash gravel. Very typically, the tongue basins are filled with lakes (Attersee on the left and Traunsee on the right). **(b)** Example of the map at a scale of 1:1 500 000. Note that less distinctions could be made and only three glaciations are visible. Note that the maps are not in their original scale, therefore some polygon boundaries are partly angular.

in Bavaria, from old to young: Günz, Mindel, Riss and Würm (Penck and Brückner, 1909; van Husen and Reitner, 2011). Initially, they were only stratigraphically sorted from old to young without age constraints. Today, age data and correlation with data from ice cores and marine isotope stages deliver much more precise age information. Even though the age dating of moraine ridges and sediments (burial and exposure dating with cosmogenic nuclides, optically stimulated luminescence; Ivy-Ochs et al., 2022 and references therein), revolutionized the Quaternary research, it is still challenging to date the major glacier streams, especially older ones. Too often, the associated deposits were eroded or reworked. The following age constrains should give an overall impression of the age of the four glaciations (Raymo, 1997; Reitner, 2022): Günz (MIS 16): ~676–621 ka, Mindel (MIS 12): ~478–424 ka, Riss (MIS 6): ~191–130 ka, (Late) Würm (MIS 2): ~29–12 ka. The correlation for the Günz and Mindel Glacials is, however, tentative as no absolute ages exist so far. After the Last Glacial Maximum, the glaciers step-wisely retreated in high mountainous areas, which is documented by individual glacier halts. In the 1:1 500 000 map none of these stages are marked. In the 1:500 000 map four of these stages are considered: The extent of the Gschnitz Stadial, Egesen Stadial, an Early Holocene Stadial and the “Little Ice Age” around 1850 could be differentiated (Fig. 4a). Regarding the first three mentioned stages, only few markers are present on the map, because the aim was to mark

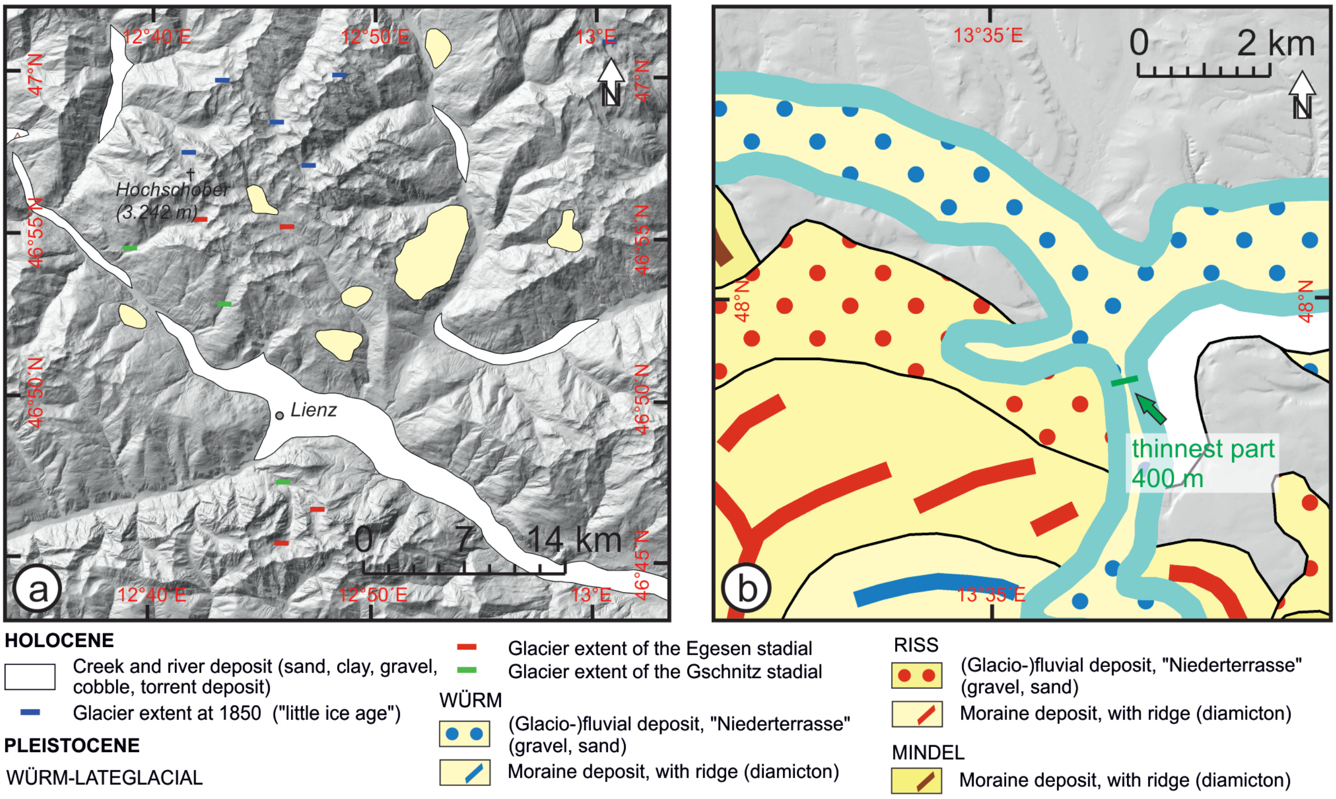

Figure 4: **(a)** Different markers presenting Late glacial stillstands. Most of them are dated, some interpolated (Reitner et al., 2016). "Little Ice Age" extent after Groß and Patzelt (2015). Green markers: Gschnitz Stadial, red markers: Egesen Stadial, blue markers: "Little Ice Age". **(b)** Zoomed in section of the map 1:500 000. Reference scale is set respectively and one polygon is selected. The blue outlines do not touch each other in the narrowest part of the polygon, which is an easy way to check the minimum width of 400 m. Note, the scale of the depicted map is not 1:500 000 anymore, it is zoomed in (scale bar on top of the map).

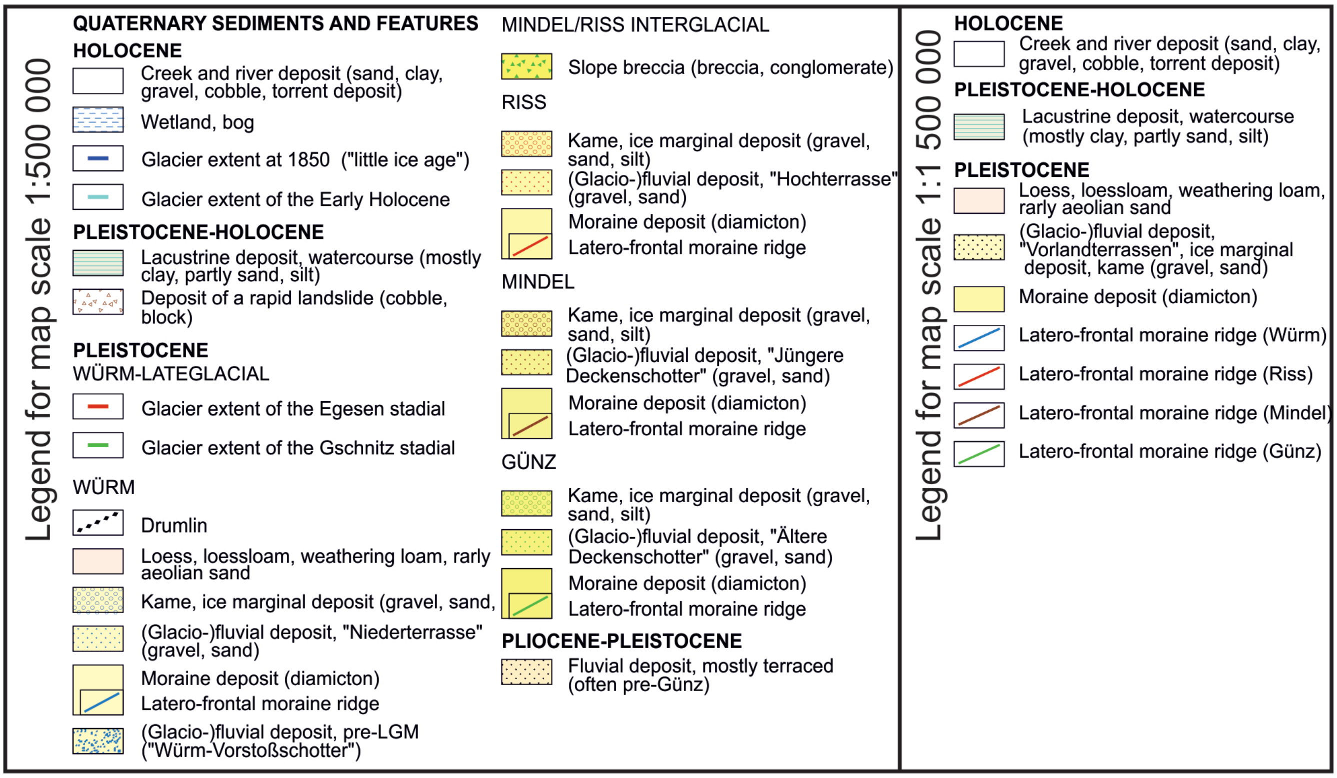

Figure 5: Legends of both presented maps.

only locations, where the age is confirmed via numerical dating. The Gschnitz Stadial, around 17–16 ka (Ivy-Ochs et al., 2006), represents the first phase of glacier re-advance after the breakdown of the Alpine-wide transection glacier complex of the LGM. This was followed by the Egesen Stadial, around 13–12 ka (Ivy-Ochs et al., 2006; Reitner et al., 2016), where glaciers did not reach as far as during the Gschnitz Stadial, but they typically left multiple moraine ridges. Only few findings are reported for the Early Holocene Stadial around 10–11 ka (Braumann et al., 2020, 2021; Moran et al., 2016), but they are clearly separable from the Egesen Stadial moraines. The “Little Ice Age”, having reached its maximum extend around 1850, documents the last distinct glacial advance phase. It is more or less restricted to high mountain ranges (e.g. Hohe Tauern, Zillertal, Stubaital, Ötztal, Silvretta and Verwall Alps and other mountain ranges in the Italian and Swiss Alps). On the map, reconstructed glacier extents of the “Little Ice Age” were taken from Groß and Patzelt (2015) and depicted as markers. In comparison to Late glacial Stadials, much more markers of the “Little Ice Age” occur on the map. However, this circumstance is simply because more information on the latter is available compared to the Late glacial and Early Holocene Stadials.

Not presented on the map are rock glaciers, especially because there are simply too much of them and their extent is too small to be depicted at the map scales (Kellerer-Pirklbauer et al., 2012; Wagner et al., 2020) and secondly, there is still debate about the distinction between debris-covered glaciers and rock glaciers (Janke et al., 2015).

3. Maps used for the compilation

It is important to note that no field work was conducted, the presented maps (Figs. 1, S1, S2) are only based on available geological maps, mostly at different map scales. Following maps were used (all web-links were checked in March 2024):

- Austria: Map series of the GeoSphere Austria 1:200 000 (Burgenland: Pascher et al., 1999; Niederösterreich: Schnabel et al., 2002; Oberösterreich: Krenmayr et al., 2006; Salzburg: Pestal et al., 2005; Steiermark: Flügel and Neubauer, 1984) where available. Otherwise: map sheet Vorarlberg 1:100 000 (Oberhauser et al., 2007), map series 1:50 000 (GeoSphere Austria, 2024)
- Germany: Geologische Karte von Bayern 1:500 000 (Doben et al., 1996)
- Switzerland: Geologische Generalkarte der Schweiz, Blatt 8 Engadin 1:200.000 (Christ et al., 1964) and Geological Map of Switzerland 1:500 000 (Geological Institute, University of Bern and Federal Office for Water und Geology, 2005)
- Italy: Map series 1:100 000 (Italian Institute for Environmental Protection and Research, 2024)
- Slovenia: Götzl et al. (2007)
- Croatia: Hrvatski geološki institute (2009)
- Hungary: GIS Service 1:200 000 (Magyarország felszíni földtana, 2024)
- Slovakia: General Geological Map of the Slovak Republic (Bezák et al., 2011)
- Czech Republic: WMS Service 1:50 000 (Česká *geologická* služba, 2024; date of compilation: march 2021)

4. Methodology

Both maps were drawn in ArcMap (Version 10.8) using the geographic coordinate system GCS_MGI with the local Lambert_Conformal_Conic projection (WKID: 31287 Authority: EPSG). For the exact position of large river deposits and other topographic characteristics, next to geological maps also digital elevation models (10 m resolution in Austria, 25 m resolution in neighbouring countries) were used. Very small deposits, which could not be mapped at the intended scale, but which are of interest for the glacial history of Austria, were depicted as markers (for example: Late glacial glacier extents). Maps used for compilation were generalised based on the following rules in order to avoid inconsistencies in terms of polygon and line size: In the 1:500 000 map polygons have a minimum area of 0.45 km^2 and their minimum width is roughly 400 m. Line features have a minimum length of 600 m. In the 1:1 500 000 map the area is at least 4.5 km^2 and the minimum width in the range of 1.2 km. Line features are at least 2.3 km long. Where polygons were overlapping at maps used for the compilation, the newer geological information was used and the plausibility was briefly checked with laserscan images.

5. Description of the legend

In the following chapter, all legend elements are described briefly and reasons for the subsumption of specific lithogenetic and geomorphologic units are explained. All entries are related to the larger scaled map at the scale of 1:500 000. In the smaller scale map, only a selection of these entries is present, but the descriptions are equivalent. The legend entries are ordered chronostratigraphically as depicted in Figure 5.

5.1. Holocene

Creek and river deposit (sand, clay, gravel, cobble, torrent deposit): Deposits in channels including large alluvial fans. Especially at large channels, a broad base developed, which is frequently flooded. In these areas, it is dominated by fine grained sediments. Within the Alps, depending on the river gradient, coarser grained bedload and torrent deposits additionally occur.

Wetland, bog: In areas, where lakes silt up and on top of impermeable sediments (e.g. basal till), wetland areas or bogs developed. Their spatial extent is largest in ancient piedmont glacier basins in the Alpine foreland (e.g. at Chiemsee).

Glacier extent at 1850 (“Little Ice Age”): During the “Little Ice Age", reaching the maximum around 1850 in the Eastern Alps, high-altitude glaciers peaked again. Some of them left impressive marginal moraine ridges. The extent of this glaciation phase is documented by Groß and Patzelt (2015) and depicted as markers on the map. Their occurrence is restricted to the western part of Austria. Modern (based around the year 2000) equilibrium line altitude (ELA) values range between 2400 m and 2900 m depending on the altitude of the catchment areas of the glaciers (Lichtenecker, 1938). For earlier glacial stadials, usually the ELA depression value (δELA) is used to indicate how much the ELA was lowered in comparison to the "Little Ice Age".

Glacier extent of the Early Holocene: Following the Egesen Stadial, high altitude glaciers reached another peak in the Early Holocene, around 10–11 ka (Braumann et al., 2020, 2021; Moran et al., 2016). Only few findings are reported by now and all of them are located in the westernmost part of the map. δELA values are in the range of 100–120 m (Moran et al., 2016).

5.2. Pleistocene-Holocene

Lacustrine deposit, watercourse (mostly clay, partly sand and silt): Lacustrine deposits are fine grained sediments deposited in a water column. Due to the scales of the maps, also coarser grained delta sediments can be included. Most lakes have at least a small amount of typical lacustrine deposits below the water column. Some exceptions might exist and therefore the term "watercourse" additionally appears in the legend. Most of the lakes in the map section formed after melting of the ice in glacially shaped and partly overdeepened valleys (e.g. Attersee, Traunsee, Wörthersee). An exception is Neusiedlersee, it formed in an unglaciated environment mostly by tectonics and deflation (Draganits et al., 2022; Neuhuber et al., 2024).

Deposit of a rapid landslide (cobble, block): The term combines all landslides, which occurred by gravitationally driven, fast movement of rock material. Mostly, they consist of cobbles and blocks, have a volume of >1 million m^3 and are the result of slope instability after the retreat of the glaciers. 18 of these deposits are mapped, the landslides of Dobratsch in Carinthia and Köflach in the Ötz valley are particularly impressive. Most of the depicted landslides are investigated in detail (e.g. Prager et al., 2008; Ostermann and Prager, 2014).

5.3. Pleistocene

Glacier extent of the Egesen Stadial: The Egesen Stadial describes a phase of glacial stabilization in the Younger Dryas (~13–12 ka; Ivy-Ochs et al., 1996; Reitner et al., 2016). This glacial maximum and its implication on climate is of great importance for the understanding of the glacial history during the Quaternary. It is presented as few markers on the map (e.g. near Lienz in the Schober mountains and Lienzer dolomites; in the Verwall mountains). At present, not many locations, where glaciers existed during the Egesen Stadial, are proved, therefore not many of these markers are depicted. Nonetheless, it seems important to show the climate deterioration during the Younger Dryas, where known. δELA values very greatly and are commonly in the of 200–400 m (Ivy-Ochs et al., 2023a)

Glacier extent of the Gschnitz Stadial: After the breakdown of the large transection glacier complex covering the Alps and massive ice retreat, glaciers advanced again around 17–16 ka ago (Ivy-Ochs et al., 2006). Generally, the climate was much cooler than today, therefore some glaciers could advance far down in secondary valleys (e.g. in the Gschnitz valley, Schober mountains). δELA values are usually in the range of 600–700 m (Maisch, 1982; Ivy-Ochs et al., 2023b). Only a few glacial remnants of the Gschnitz Stadial are dated and studied in detail (e.g. Ivy-Ochs et al., 2006; Reitner et al., 2016).

Drumlin: Single drumlins are often too small to be depicted on the map, therefore drumlin fields are delineated. They are a typical feature of diverging ice bodies, like in piedmont lobes in the Alpine foreland or in broadening longitudinal valleys (Kamleitner et al., 2024).

Loess, loessloam, rarely weathering loam and aeolian sand: During cold phases, fine grained sediments were blown out from vegetation-less gravel bodies in the fluvial forefield of glaciers and deposited as loess in adjacent regions. Depending on wind properties, these deposits can reach several meters in thickness. Commonly, the sediment is rich in carbonate and the grainsize is in the order of clay or silt, which weathers to loessloam. Loess and loessloam extensively occur in the Tulln and Vienna Basins and the Little Hungarian plain. On the maps, also weathering loam and aeolian sand were put into this category, which are of subordinate importance. These mostly occur in the Bohemian massif and in Bavaria, Germany.

Kame, ice marginal deposit (gravel, sand, silt): Massive kames and ice marginal deposits were formed during the glacial maxima and during the recessional phases of the glaciers, respectively. Either, the sediments were deposited in subglacial caves or at the ice margin as terrace bodies. The latter especially occur at the valley mouth of already ice free secondary valleys, where the main valley was still occupied by a large stagnant ice body (Reitner, 2007). In the Alpine foreland, in the area of large Pleistocene piedmont glaciers, but also in the terminal area of the Drau glacier, these sediments occur frequently. Lithofacially, they are not differentiable from sediments in the proglacial area, therefore a conceptual model was established to separate both lithogenetic units. Up valley of the particular terminal moraines, the deposits were attributed as kames or ice marginal deposits, in the glacier forefield, however, as (glacio-)fluvial deposit (see below; Fig. 6). This is adapted for all glaciation phases.

*(Glacio-)fluvial deposit, "Niederterrasse" (Lower terrace) – "Hochterrasse" (Higher terrace) – „Jüngere Deckenschotter" (Younger sheet gravel) – „*Ältere *Deckenschotter" (Older sheet gravel) (gravel, sand):* Glaciofluvial deposits are de-

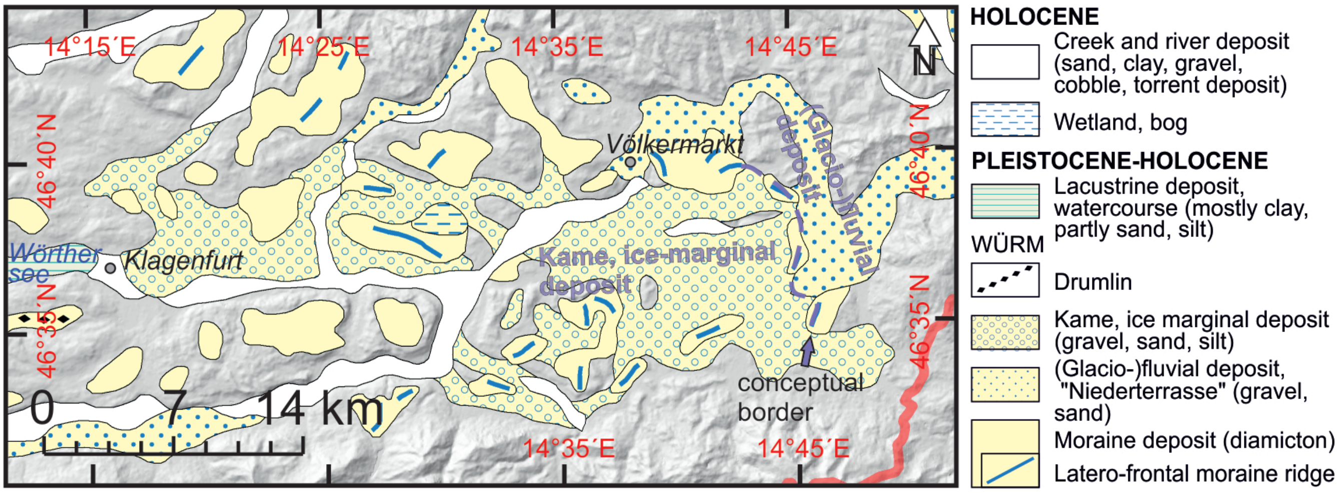

Figure 6: Example of the conceptual separation of "(glacio-)fluvial deposit" and "kame, ice-marginal deposit". Map 1:500 000 in the area east of Klagenfurt.

fined to be directly related to meltwater from glaciers (Neuendorf et al., 2005). Because meltwaters and waters with no relation to glaciers mix further away from ice streams, both lithogenetic units (glaciofluvial and fluvial) are combined on the map to avoid problems separating them. The terms „Niederterrasse, Hochterrasse, Jüngere- und Ältere Deckenschotter" are well established in the Alpine environment and are associated with the four major glaciations after Penck and Brückner (1909). Therefore, on the map, these additional terms are still used. On the geological map sheet Oberösterreich 1:200 000 (Krenmayr et al., 2006) sediments were not always differentiated in detail and generalizing terms like "Tiefere Terrassensedimente i. A." occur in the legend. In order to integrate them into the concept of overview maps, the map sheets at a scale of 1:50 000 (GeoSphere Austria, 2024) were used as additional information source. In that sense, "Tiefere Terrassensedimente i.A." are interpreted as "Jüngere Deckenschotter" and "Höhere Terrassensedimente i.A." as "Ältere Deckenschotter". In some areas (e.g. Alm- and Krems valley) "Weiße Nagelfluh" is mapped on the map sheet Niederösterreich 1:200 000 (Schnabel et al., 2002). This term describes whitish conglomerates, which are supposed to have been deposited in the cold phase between the Günz- and Mindel Glacials. The "Weiße Nagelfluh" is overlain by the "Graue Nagelfluh" (grey conglomerates), which is associated with the Mindel Glacial ("Vorstoßschotter"; van Husen and Reitner, 2011). The extent of these deposits is too small (already hardly visible at the map of Upper Austria 1:200 000; Krenmayr et al., 2006) for the presented maps (Figs. S1, S2), therefore they were put together with "Jüngere Deckenschotter". The gravel body of Rechnitz is associated with the Mindel Glacial according to the explanatory notes of map sheet 138 Rechnitz (Herrmann and Pahr, 1988) and therefore mapped as "Jüngere Deckenschotter" as well.

Moraine deposit (diamicton): Moraine deposits are one of the most prominent glacial remnants and extensively preserved in the Alpine foreland. There, large valley glaciers transformed into piedmont glaciers and deposited basal till at their base, which is largely preserved. Since these sediments comprise lots of fine grained particles, which have a water damming effect, wetlands or up silted lakes may occur along with them. The maximum extent of the glaciers is often marked by latero-frontal moraines, which can be temporally differentiated due to their grade of weathering and therefore their associated basal till deposits can be assigned to different glaciation phases. The timing of basal till deposits within the Alps cannot be constrained. Most of them are probably deposited by the last glaciation. Even though there may be single exceptions at the fringe of the Würm coverage as depicted in Figure 2, all basal till deposits within the Alps are assigned to the last glaciation for simplicity reasons.

Latero-frontal moraine ridge: Latero-frontal moraine ridges are widely preserved in the Alpine foreland. They reach several tens of meters in height and are depicted with line signatures.

(Glacio-)fluvial deposit (gravel, sand), pre-LGM ("Würm-Vorstoßschotter"): These deposits can be found below basal till of the LGM and were probably beginning to be formed closely before the large valley glaciers developed and began to mobilise lots of sediment. For simplicity reasons, deposits from the Early and Middle Würm are subsumed with sediments from the Late Würm (typical "Würm-Vorstoßschotter" – translated to "advance gravel"), which for example are well investigated in the Inn valley (Starnberger et al., 2013). In that area, the sediment pile documents a timespan between 120 ka and 45 ka BP, where in the Inn valley more than 200 m were aggraded. In the Enns valley extensive pre-LGM sediments are known at Gröbminger Mitterberg (Griesmeier et al., 2021; Le Heron et al., 2023). Parts of them were probably de-

posited shortly before the LGM. Similar pre-LGM sediments occur in Carinthia and the Alpine foreland.

Slope breccia (breccia, conglomerate): The term describes massive breccia and conglomerate bodies, which were formed as debris deposits on slopes before the LGM. Slope breccia is commonly known from the Inn valley ("Höttinger Brekzie"; Penck, 1921; Obojes and Spötl, 2004), but also from the Enns valley. Characteristically, these deposits crop out above the modern valley floor and are in some cases over- or underlain by basal till. There is no direct age constrain, but it is assumed that they were deposited during an interstadial or interglacial (Obojes and Spötl, 2004).

5.4 Pliocene-Pleistocene

Fluvial deposit, mostly terraced (often pre-Günz): Especially in the eastern Alpine foreland (e.g. Styrian Basin, Slovenia), fluvial deposits occur, which cannot easily be assigned to a glaciation phase. Either because the catchment area of the rivers was not glaciated or maps did not differentiate between different terrace bodies (especially in Hungary, Slovenia and Italy). Therefore, it was decided to merge these deposits. For more details, see also the discussion below.

6. Discussion

6.1. What can be observed by simply looking at the maps?

In the following, the first (subjective) impression one can have when simply looking at the maps will be outlined. Subsequently, these impressions are discussed and it will be shown that the first glance can sometimes be deceiving.

One of the first impressions, when looking at the presented maps (especially 1:500 000; Fig. S1), is that the Alps are relatively scarce concerning Quaternary sediments, whereas all deposits are distributed in the surroundings. Looking at the glacial extent of the four glaciation phases and their related terrace bodies, it seems that older glaciations left their traces further north than the younger ones and that their associated fluvial outwash plains cover larger areas. Furthermore, large piedmont glaciers occurred only in the northern Alpine foreland (and southern Alpine foreland outside of the presented map extent), especially in Bavaria. In contrast, the Styrian Basin was never glaciated. Glaciers, which could have reached it, died within the Alps in narrow valleys (e.g. Mur glacier). Only a few terrace bodies suggest sedimentation during the Pleistocene. The Vienna Basin is characterised by broad, flat plains, where modern and ancient rivers and their associated fluvial sediments prevail. This is contrasted by downcutting rivers, which can be observed in Bavaria and Upper Austria. The interplay between these two processes (sedimentation vs. erosion) can also be observed along the northern Alpine fringe. For example, in the westernmost part of the map downcutting dominates, near Munich a vast plain filled with "Niederterrasse" is abundant indicating deposition and in Upper Austria again downcutting is evident. Furthermore, the distribution of loess, which was blown out from sparsely vegetated glacier forelands, is worth mentioning. Its deposition seems to be restricted to the surroundings of the Alps. Commonly, it occurs alongside fluvial deposits and as small patches in the Bohemian Massif. In contrast, the vast plains of the Vienna Basin or the Little Hungarian plain are covered by extensive amounts of loess.

6.2. Are the Alps empty of sediments?

Even though, the Alps seem to be quite empty in terms of Quaternary sediments on the maps, this is not the case. Put simply, it is a scale problem. In fact, most of the valley slopes and floors are covered by Quaternary sediments (see also geological maps at the scale of 1:50 000 at GeoSphere Austria). Firstly, the overall extent is too small for depicting them on the presented maps (Figs. S1, S2) and secondly, the sediment thickness often reaches only a few meters and rarely tens of meters. Nonetheless, the abundance of Quaternary sediments is of great importance for humans as they serve as raw material for construction, water storage and easily reworkable base for agriculture. Additionally, humans are often more aware of the sediments within the Alps because of their susceptibility to landslides (e.g. debris flows) endangering their life and belongings. However, on the map, the general trend that, in terms of volume, the Alps are more prone to erosion, whereas the Alpine foreland acts as huge sediment trap for their erosional products, is intended to be prominently shown.

6.3. The four glaciations

The fact that older glaciations (e.g. Günz) left their traces further north than younger ones (e.g. Würm) in the northern Alpine foreland (Fig. 3) is probably misleading. This observation suggests that ice stream was larger in terms of volume during earlier glaciations. There is no evidence that overdeepenings were less deep during earlier glaciations (e.g. Mindel Glacial). Buechi et al. (2017, 2018) show that basins are at a similar dimension at least since the Riss Glacial. However, for earlier glaciations like the Mindel and Günz Glacials, it cannot be ruled out that the ice streams partly used other pathways than during the last glaciation (van Husen, 2004).

Uplift and incision limiting accommodation space could also be a controlling factor. As shown by the distribution of quaternary sediments in the northern alpine foreland, it is evident that it is subject to uplift during the Pleistocene (see also chapter 7.1). This is also observed in the Bohemian Massif, where rivers deeply incised since the Pliocene (Ziegler and Dèzes, 2007; Pánek and Kapustová, 2016; Wetzlinger et al., 2023).

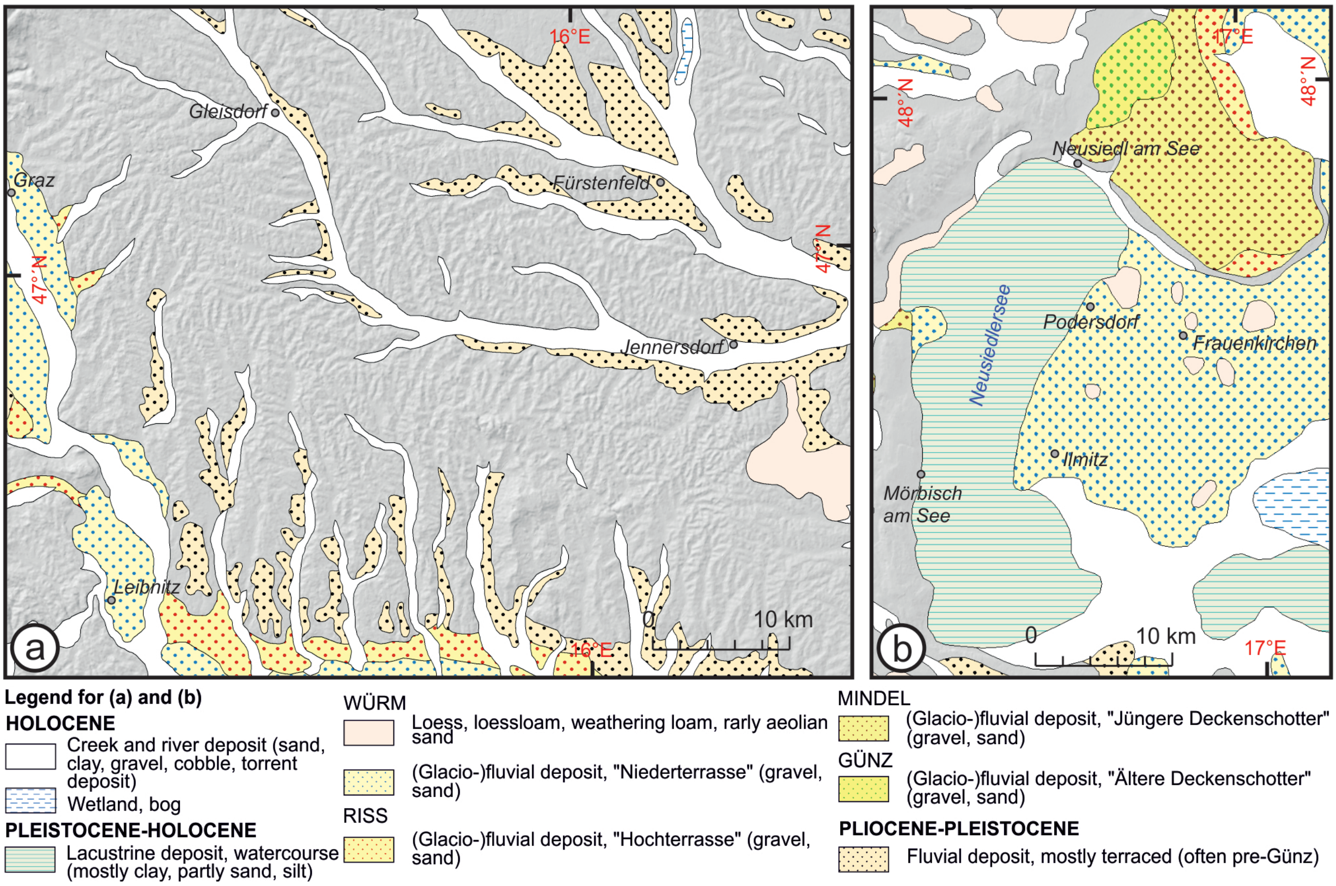

Figure 7: **(a)** Detail of the Styrian Basin. Only along the Mur river, terrace bodies can be assigned to different stadials. The other terrace bodies along rivers with no glacial hinterland during the LGM had to be merged to fluvial deposits in general. **(b)** Neusiedlersee and the terrace bodies around. Even though the lake already existed during the LGM (Draganits et al., 2022; Neuhuber et al., 2024), the sediment body east of it is dated to 75–102 ka and therefore assigned to the Würm Glacial.

6.4. Fluvial sediments in the Styrian Basin

The interpretation of Quaternary deposits in the Styrian Basin is problematic, since rivers draining it, were not fed by glaciers (with few exceptions like Mur and Drau rivers). Investigating the timing of terrace formation was challenging by the time geological maps were drawn in this area (maps of the GeoSphere Austria). Age dating was not possible at that time and since then no attempts were made to the knowledge of the author. Therefore, the correlation of terrace bodies with different glacial phases was leading different authors to different relative age correlations.

On the geological map sheet Burgenland 1:200 000 (Pascher et al., 1999), terrace bodies are assigned to several glaciations, whereas on map sheet Steiermark 1:200 000 (Flügel and Neubauer, 1984) distinction was only made between “Niederterrasse” and older terrace bodies. In the explanatory notes to map sheet Burgenland, Schönlaub (2000) assigns many terrace bodies to Günz or pre-Günz age. However, it is not easily comprehensible which legend entries are specifically referring to which age. In the overlapping area of the map sheets Burgenland and Steiermark, some of the terrace bodies are interpreted as Günz/pre-Günz or “Niederterrasse”, respectively. So there is a lot of inconsistency. Winkler-Hermaden (1955) describes different terrace bodies in detail, however, maps in his article differ from each other. Furthermore, Winkler-Hermaden (1955) claims that lots of these terrace bodies were formed during interstadials. This is in contrast to conclusions of Penck and Brückner (1909). In summary, this leads to the conclusion that the Styrian Basin is not investigated and understood well enough. Therefore, several terrace bodies of various ages were subsumed. Only few exceptions are presented, where there seems to be agreement (e.g. “Niederterrasse” near Graz and Leibnitz; Fig. 7a).

6.5. Terrace bodies at Neusiedlersee

On geologic maps (Pascher et al., 1999; Fuchs, 1985) east of the Neusiedlersee (Lake Neusiedl), terrace bodies are depicted as “Seewinkelschotter” attributed to the Würm Glacial. However, in the explanatory notes to mapsheet 79 Neusiedl am See – 80 Ungarisch Altenburg (1:50 000; Häusler, 2007), these sediments were investigated in terms of petrology and geomorphology and the author came to the conclusion that they should be attributed to the Riss Glacial (Hochterrasse). Furthermore, Neusiedlersee probably already existed during the LGM (Draganits et al., 2022; Neuhuber et al., 2024). Therefore, the extended fluvial sediments next to the lake cannot be of the same age. Recent age dating shows that the gravels were deposited around 102 ka and 76 ka (Zámolyi et al., 2017). This coincides with the Early Würm Stadial. Since at the map 1:500 000, Early Würm sediments are not distinguished, the "Seewinkelschotter" are attributed to the Würm Glacial (Fig. 7b).

6.6. Can loess tell us something about the paleo wind direction?

Loess occurs very extensively in the East, mainly in the Little Hungarian plain and in the Vienna Basin in the northeast. In contrast, in the Bohemian Massif, there are only few patches of loess. However, the distribution of loess might have changed since its initial deposition, because of later erosion, especially in hilly terrain (e.g. Mühlviertel, Waldviertel). Secondly, the maps used for compilation might be incomplete concerning loess, since in the past, it was often ignored during mapping and is therefore significantly underrepresented on the maps. For example, in the Wienerwald area (Flyschzone), loess sequences of several metres thickness have been found recently (own observations; S. Ćorić and H. Gebhardt, oral communication). Additionally, in the Northern Calcareous Alps, loess layers have also been described recently (Gild et al., 2018).

Actually, the most studied loess sequences in Austria are located in the northern Alpine foreland (van Husen and Reitner, 2011 and references therein; Terhorst, 2013). All loess sequences summed up cover a time span of the whole Quaternary. According to Buggle et al. (2008), the chemistry of loess can be traced towards its source area and accordingly, the paleo wind directions can be derived. This cannot be seen by simply looking at the maps. However, the larger amount of loess for example at the eastern side of the Bohemain Massif points to westerly wind directions and a sheltering effect of the topographic high. As detailed studies show (Sebe et al., 2015), there seems to be a topographic control of the air flow and its indirect expression by deposition of loess on the lee sides.

7. Conclusion

The presented maps (Figs. S1, S2) show a compilation of Quaternary sediments and features at the scales of 1:500 000 and 1:1 500 000. Both maps (including the GIS data) are available at the data repository of the GeoSphere Austria (see above) for free. The focus of the maps is to prominently show where sedimentation and erosion prevails and especially to depict the distribution of sediments left by four major glaciations (Günz, Mindel, Riss and Würm). During intense study of the maps, some questions might occur, which are discussed and their outcome is briefly summed up:

- Older glaciations were not necessarily larger in terms of ice volume than younger ones, as suggested by their traces in the alpine foreland, but uplift limiting accommodation space probably had a great input.
- Fluvial outwash gravel is easily assignable to the different glaciations in the northern foreland, whereas in the Styrian Basin, radiometric age dating to constrain their timing of deposition is still necessary.
- The distribution of loess can give hints on the paleo wind direction, but detailed studies are additionally required.

8. Map download

The data of both presented maps (Figs. S1, S2) are stored at the Data Repository Tethys of the GeoSphere Austria: https://doi.org/10.24341/tethys.230. They can be downloaded for free as geopackage. Additionally, bitmaps of both, the 1:500 000 and 1:1 500 000 maps are available as supplementary material Figs. S1, S2 to this paper, respectively.

9. Remark

Hint for drawing: When the reference scale in ArcMap is set to 1:500 000 or 1:1 500 000, respectively, while drawing, the minimum width of the polygons can easily be checked in the following way: When the colour of a selected polygon ("scale selected features" must be checked in ArcMap) is still visible between the two outlines, then it is wide enough (Fig. 4b).

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