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Field Trip Post-EX-3

Sediment-landform associations of major glaciations in the North Alpine Foreland

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Introduction

The Alpine Foreland gives a qualitative impression on the tremendous erosive and depositional impact of large Piedmont glaciers. Glaciers of this size and kind, warm-based, entering the foreland of an (active) mountain range are globally almost inexistent during Interglacials.

One of the best modern examples is represented by the Malaspina Glacier/Alaska. Glaciers of similar size and dynamics entered the North Alpine Foreland during glacial maxima of at least the Middle Pleistocene where the global climate experienced an intensification of glacial cold periods (100 kyr world; e.g. Head and Gibbard, 2015). The tremendous impact of Quaternary glaciers on the Alpine Foreland was already discussed and summarized by Penck and Brückner (1909) providing the basis for interpretating complex stratigraphic glacial and glaciofluvial settings. The knowledge on the dynamics of major ice-lobes has recently largely expanded through progress in dating techniques and the increasing amount of comprehensive geodata, much reflecting anthropogenic activities within and along the Alpine range. A major outcome was for example to recognize that the full glacial expansion of each glacial maximum was much shorter than previously thought, covering few thousand years only (e.g. Wirsig et al., 2016). This view underlines the extreme dynamics driving landscape reorganization during these short periods.

The special setting of the North Alpine Foreland reflecting a slightly uplifted soft sedimentary basin (Alpine Molasse) provides ideal conditions for landform preservation and glacial modification. Non-glacial erosion is focused along few incised Danube tributaries leaving glacial and glaciofluvial sediments of several glacial maxima largely uneroded. Specifically, the slightly decreasing size of the Salzach Glacier Lobe with successive glacial maxima offers the opportunity to explore topographic and sedimentary features of glacial origin far exceeding the age of the LGM (Fig. 1).

This field excursion guides to some key features of the Salzach Glacier Lobe essential to understand glacial, glaciofluvial and associated postglacial processes associated with the impact of repeated foreland glaciations.

Stops are aligned to cover the temporal succession of processes, from ice built up to the period of maximum ice expansion and to ice wastage at the onset of global climate relaxation. Landforms and topographic features cover three glacial maxima. The excursion, finally, guides to sites of postglacial landscape evolution reflecting the dynamics triggered by warm periods in subsequence to glacial maxima (Fig. 1).

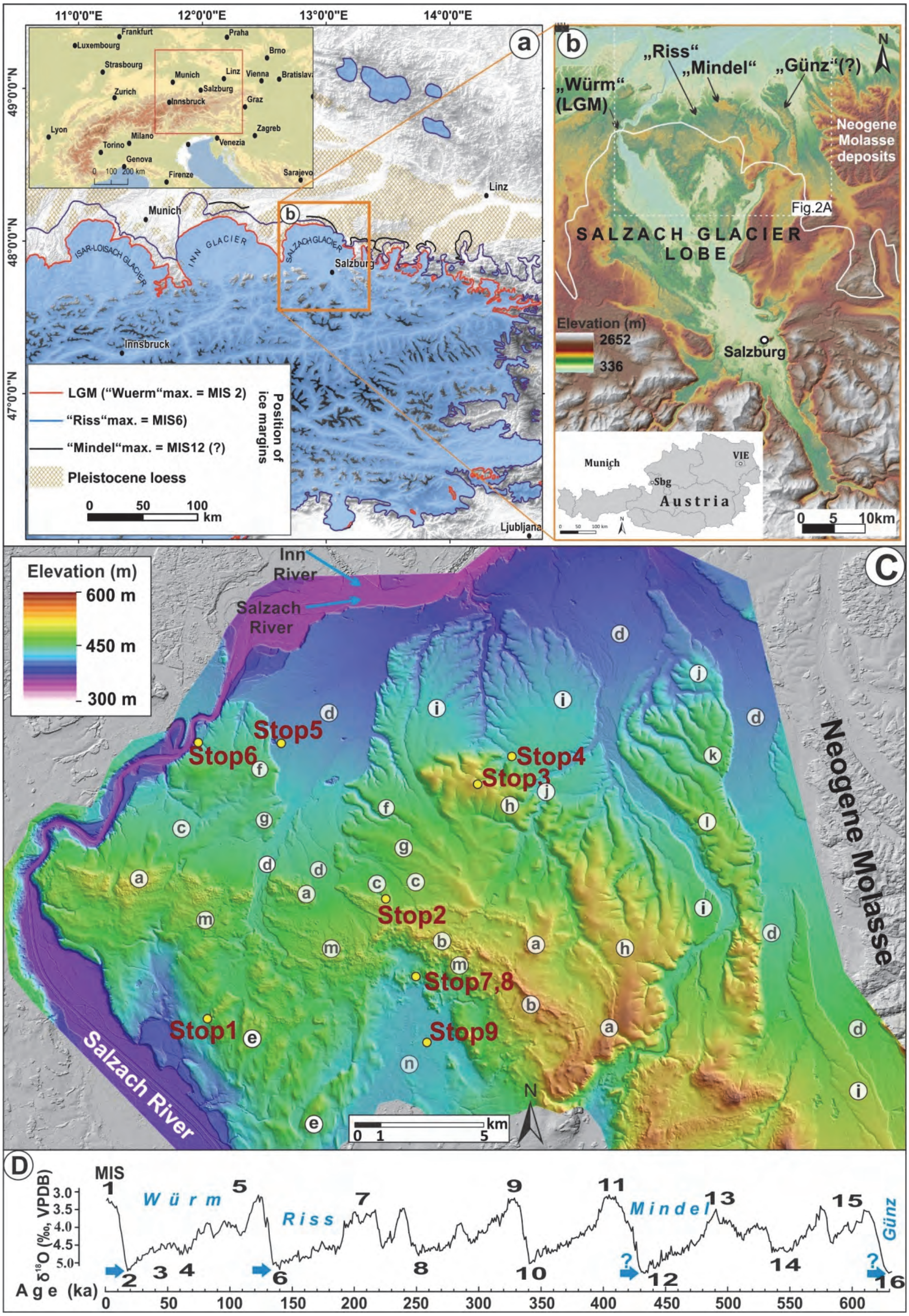

Fig. 1:
a) Extent of the Salzach Glacier Lobe (SGL) in the North Alpine Foreland during full-glacial periods of the last glacial maximum (LGM, "Würm", MIS 2), the penultimate glacial maximum ("Riss", MIS 6) and the antepenultimate maximum ("Mindel", MIS 12?).
b) Topography formerly covered by the SGL. Miocene Molasse preserved east of the major north alpine lobes. DEM bases on NASA's SRTM (90 m; for details see Farr and M. Kobrick, 2000). Modified from Salcher et al., 2015.
C) Topographic overview and locations of planned stops at this field trip. Abbreviations denote Quaternary landforms referring to the repeated glacial impact of this area. (a): LGM (Würm, MIS 2) terminal moraine 1 (max. extend); (b): LGM terminal moraine 2; (c): LGM, upper outwash "obere Niederterrasse" with sub-terrace levels; (d): LGM, lower outwash "untere Niederterrasse" with sub-terrace levels; (e): tunnel channels of subglacial drainage system (LGM); (f): Riss terminal moraine 1 (max. extend); (g): Riss terminal moraine 2; (h): Riss outwash, "Hochterrasse" (undifferentiated); (i) Mindel terminal moraine; (j): Mindel outwash "Jüngere Deckenschotter" (undifferentiated); (k): Günz terminal moraine, (l) Günz outwash "Ältere Deckenschotter" (undifferentiated); (m) LGM ice wastage deposits; (n) Peat bog (Ibmer Moor)
DEM resolution is 10 m (resampled from airborne LiDAR).
D) $\delta^{18}O$ stack of Lisiecki and Raymo (2005) indicating Marine Isotope Stages (MIS) and tentative correlation with Alpine major glaciations (Würm, Riss, Mindel sensu Penck and Brückner, 1909; Raymo, 1997; van Husen and Reitner, 2011). Note that the periods of glacial foreland coverage were only a short fraction of a glacial, limited to maximum cold phases (i.e. MIS 2, 6, etc). The short periods of (suggested) ice expansion into the east Alpine foreland are marked with blue arrows.

Stop 1: Pit "Döstling", the advancing period of the Salzach Glacier Lobe

Gravel pit Döstling (Fig. 2) is situated at the eastern Salzach valley slope giving insights into the thick pile of glacial and glaciofluvial sediments. Well distinguishable units have a total thickness of 30 meters in the outcrop. The *upper* and the *lower unit* is built up by coarse-grained fluvial sediments and the *middle unit*, separating those two, comprises basal till. Deposition of coarse-grained fluvial sediments is interpreted to originate from a bedload dominated stream ("braided river") but regularly providing flow depths large enough for effective sorting (e.g. cross-bedded strata). The interfingering of the fluvial succession (*lower unit*) with the heavily consolidated basal till on top indicates that these sediments were deposited in the forefield of the advancing Salzach Glacier Lobe. Abundant sediments released by meltwaters of the advancing glacier largely filled the Salzach Valley and were subsequently overridden by the ice (till cap). Derived luminescence ages (Salcher et al., 2015) suggest that sediments of the *lower unit* (and thus including the interfingering basalt till) were already deposited during the penultimate glaciation (Riss, MIS 6) and left uneroded by the LGM glacier. Even though no absolute ages are available from the *upper unit*, a clearly younger age is suggested from the lower weathering intensity. Sediments are interpreted to represent the glacial outwash of the advancing stage of the subsequent glaciation (LGM). The LGM glaciation rather provided the modification of this thick glaciofluvial sediments of the penultimate (and older) sediments into streamlined bedforms (Fig. 2a; Salcher et al., 2010; Weinberger, 1952).

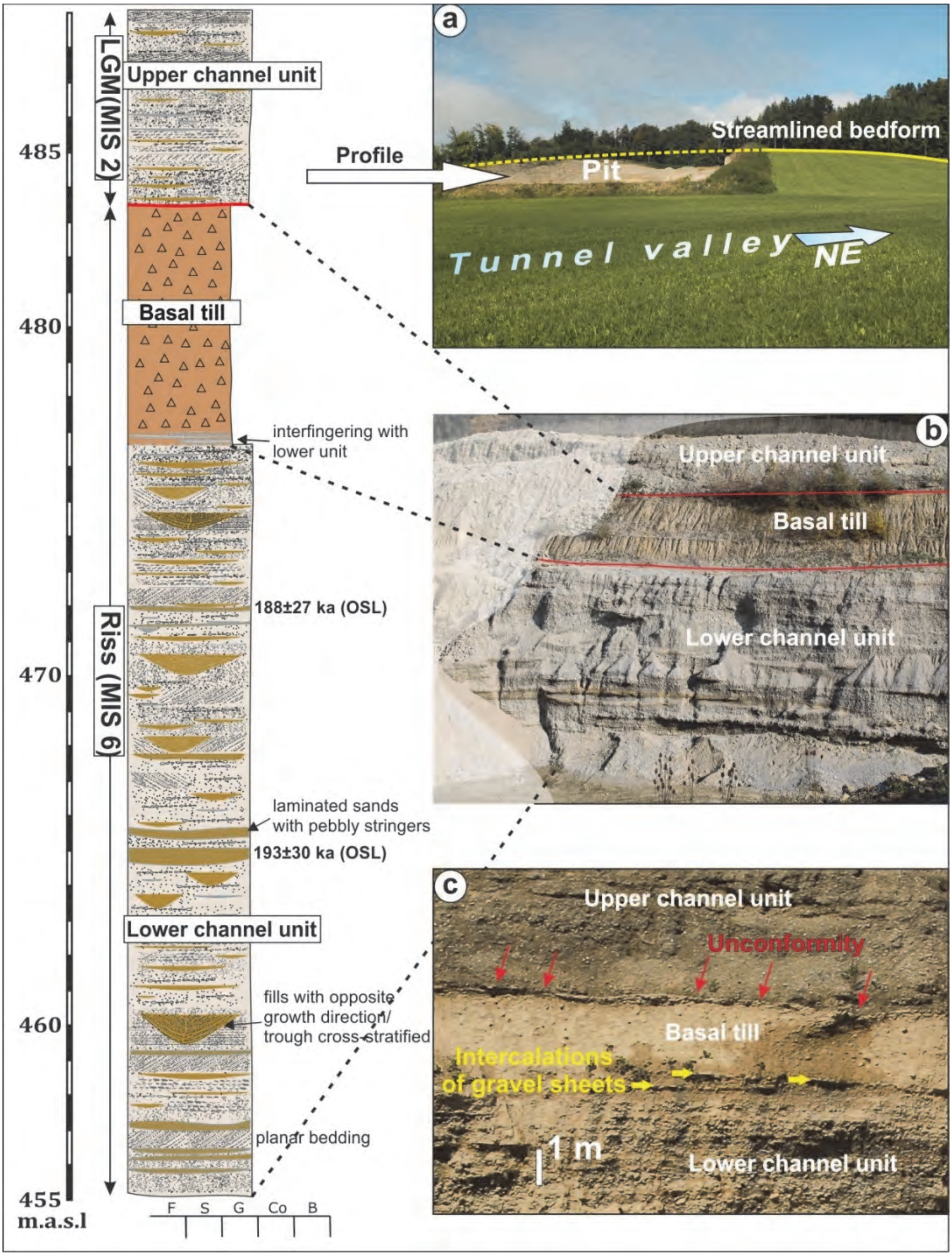

Fig. 2: Geological Profile (left) representing the advancing period of the Rissian (MIS 6) Salzach glacier. Glaciofluvial sediments are capped by basal till (b and c). Basal till is unconformably overlain by glaciofluvial gravels of the LGM (Upper channel unit, (b and c)). The outcrop is located in a streamlined bedform (a) referring to a postdepositional modification by glacial processes (potentially LGM).

Stop 2: Gravel pit "Pfaffinger", Maximum position of the LGM glacier and evidence for the glacial series (Penck and Brückner, 1909)

We park just some hundreds of meters south of the gravel pit "Pfaffinger" and walk across the terminal moraine of the most extensive advance of the LGM Salzach Glacier Lobe to reach the outcrop (Fig. 3). The outcrop is situated within fluvial outwash associated with the terminal moraine representing the most extensive advance of the Salzach glacier during the LGM (Fig. 4). Glacial landforms of the penultimate glacial maximum (Riss/MIS 6) are situated directly north of it. The outcrop shows a succession of three coarse-grained, massive units all dominated by the sheetflood facies with only slight variations in structure.

The *lowest sheetflood* unit is separated from the *middle unit* by a ca. 3 to 4 m thick layer of *basal till*. While the there is a clear unconformity between the *basal till* and the *middle sheetflood unit* above, the transition from the *lower sheetflood unit* to the *basal till* is indistinct and marked by gravel sheets intercalated into the till. Similar to the situation observed at the outcrop "Döstling", this lower sheetflood unit is interpreted to reflect ice proximity and the subsequent overriding by the glacier leaving basal till. The rare occurrence of laminated fines on top of the basal till may point to uncoupling of the ice from the bed, giving rise to melt-out till formation. The stratigraphic context and luminescence ages suggests that these units represent the penultimate glaciation (Riss/MIS 6). If not eroded, the top decimetres of the *middle sheetflood* unit appears altered into a brownish to dark reddish paleosol. This paleosol may also form distinct wedge-shaped structures (up to ~3 m) referring to periglacial wedges (i.e. ice wedge casts). Just below paleosol formation, gravelly sediment often appears conglomerated. The *upper sheetflood unit* is separated by a sharp unconformity from the middle sheetflood unit. The absence of any weathering of the *upper sheetflood unit* well agrees with the derived LGM age. The clear decrease in thickness is related to the surface slope of the outwash. The intensively weathered paleosol can therefore be attributed to the Riss-Würm Interglacial period (Eemian), potentially also forming during later interstadials (e.g. MIS 3).

The three distinct sheetflood units are interpreted to reflect high-energy, supercritical sheetflows. These non-channelized horizontal bedload sheets are considered to represent deposits of shallow flash floods relating to the upper flow regime (Miall, 1977; Todd, 1989; Blair and McPherson, 1994). These supercritical sheetfloods are typical for building up slopes of alluvial fans (Nemec and Postma, 1993; Blair and McPherson, 1994) or similar features associated with a glacier, such as ice contact fans or ramps (Benn and Evens, 1998; Krzyszkowski and Zielinski, 2002).

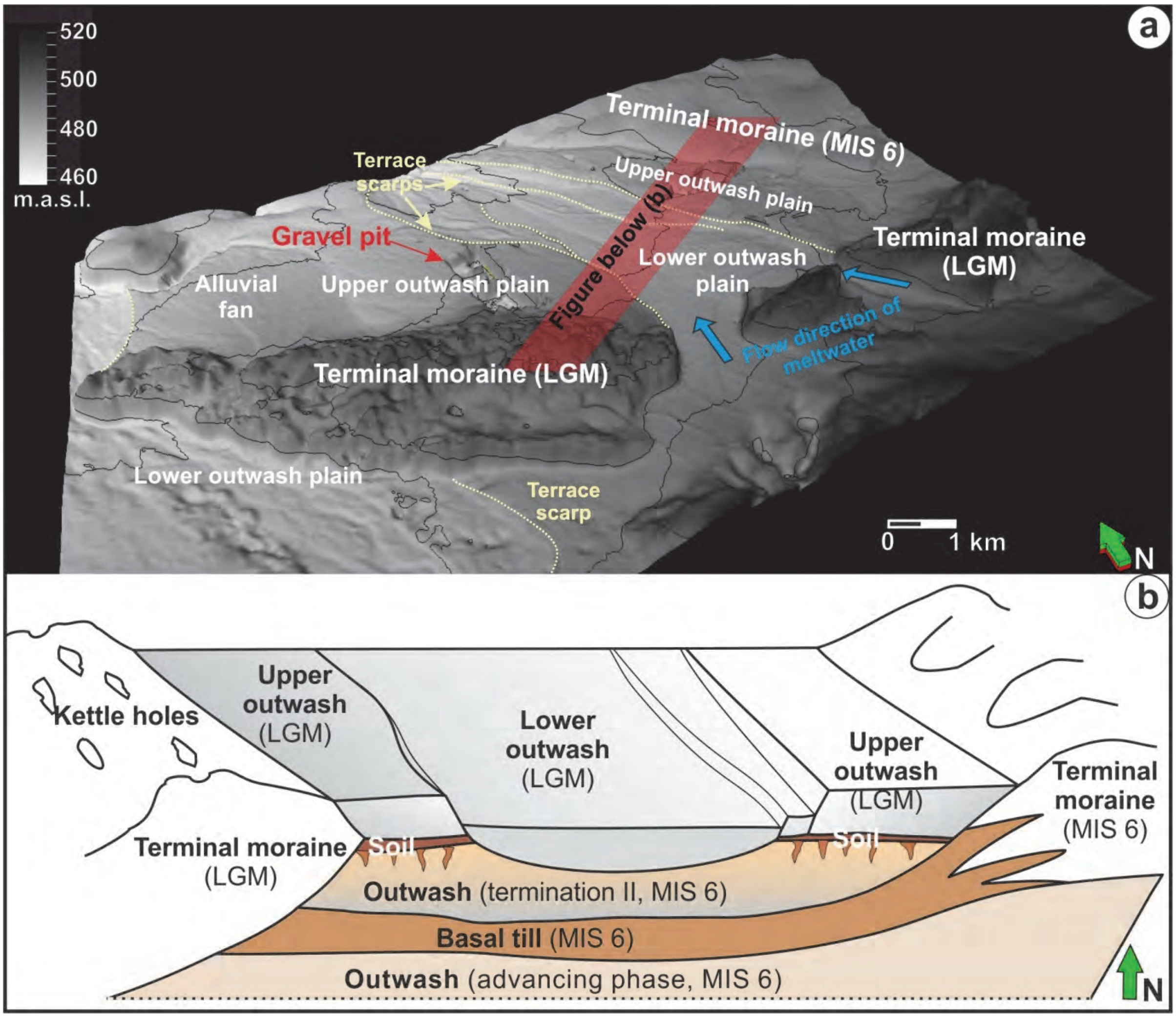

Fig. 3:

a) Topography near the terminus of the Salzach Glacier Lobe. The gravel pit ("Pfaffinger") is situated within outwash associated with the terminal moraine of the most extensive position of the LGM (terminal moraine 1; see also Fig. 2). The lower outwash plain is associated with the more proximal LGM terminal moraine. The red bar denotes the geological 3D profile shown in (b). DEM resolution is 1 m. DEM by courtesy of the Government of Upper Austria.

b) Sketch illustrating the stratigraphy of LGM/Würmian (MIS 2) and Rissian (MIS 6) deposits. Outwash gravel deposited during the advancing stage of the Riss period was later overridden by the glacier as indicated by the basal till. Later, during ice collapse at the end of the Riss period (termination II) outwash was deposited on top of the basal till. These sediments were subjected to intense soil forming processes (last interglacial) and occasionally covered by loess. The sketch is in well accordance with Penck and Brückner's (1909) glacial series model. Modified from Salcher et al., 2015.

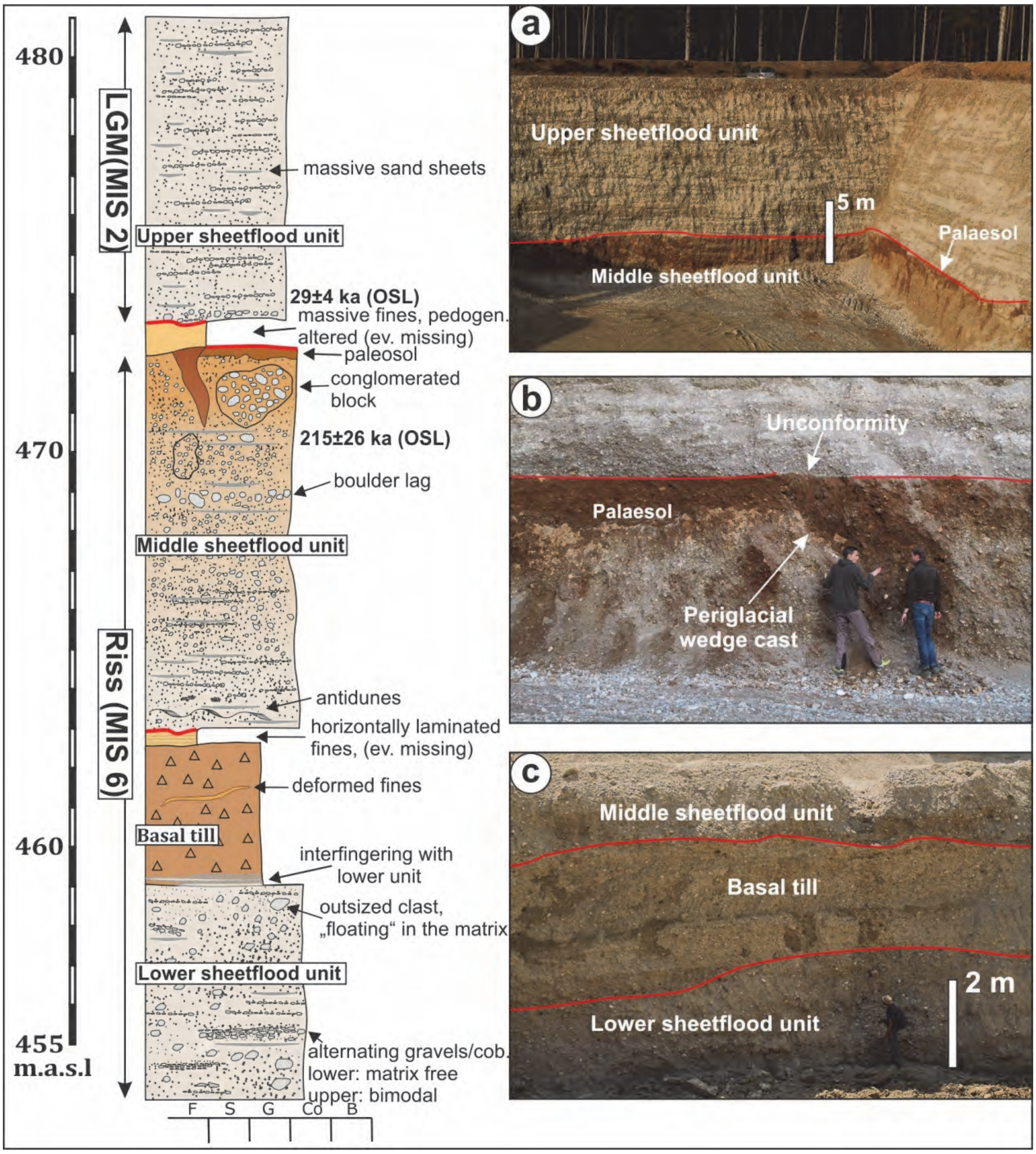

Fig. 4: Gravel pit "Paffinger" (see Figs. 1 and 3 for location and geological context). Profile shows the sequences development near the terminus of the Salzach Glacier. Glaciofluvial sediments deposited at the steep slopes of the former ice margin. They typically involve sheetflood sediments referring to shallow flash floods associated with the upper flow regime. Modified from Salcher et al., 2015.

Stop 3: Mindel terminal moraine

The Mindel glaciation (MIS 12 (?)) is considered to generally reflect the most extensive glaciation in the North Alpine Foreland of the Eastern Alps (e.g. van Husen, 2000). Only at some few spots some minor deposits might reflect an even earlier glaciation ("Günz"). However, if preserved, Mindel terminal moraines often appear very impressive exceeding the width and height of younger moraines (i.e. Riss and Würm) by far (Fig. 5a). So far there is still no clear absolute age constraint is available from deposits related to the Mindel glaciation. Tentatively, deposits are considered to represent the MIS 12 (e.g. Raymo, 1997; van Husen, 2000). Note that the classical stratigraphy (i.e. Günz, Mindel, Riss, Würm) applied for Quaternary deposits of the East Alpine Foreland (Bavaria and Austria) is not applicable to deposits of the West Alpine foreland.

Stop 4: Glaciofluvial outwash of the Mindel glaciation ("Jüngere Deckenschotter")

Glaciofluvial sediments relating to glacial deposits of the Mindel glaciation are referred to as "Jüngerer Deckenschotter" in the older literature. These glaciofluvial gravels commonly appear as erosional remnants with restricted spatial extend and typically characterized by a high degree of cementation (representing conglomerates). Pipe-like weathering structures ("Geologische Orgeln") in between conglomerates are also typical (e.g. van Husen and Reitner, 2011) but not obvious in this outcrop (Fig. 5b). Both, the high degree of cementation and intense weathering are a function of time and also the relatively high content of carbonate clasts (potentially acting as source for dissolution and subsequent carbonate precipitation). Thick loess deposits on top, which may be intercalated by paleosols are also characteristic features on top of the Deckenschotters (here, landform gradient and degree of dissection prevents formation/preservation).

The outcrop (Fig. 5b) shows coarse-grained sediments including features of the upper flow regime (antidunes, plane beds). The sedimentary setting well reflects a dynamic ice marginal environment as already indicated by the topographic context in adjacency to the Mindel terminal moraine. The outcrop situated in a hollow seems at least to be partly natural. This is for example suggested by the occurrence of a cave (total length c. 20 m), recently discovered by mining activities in the gravel pit about 200 m to the west.

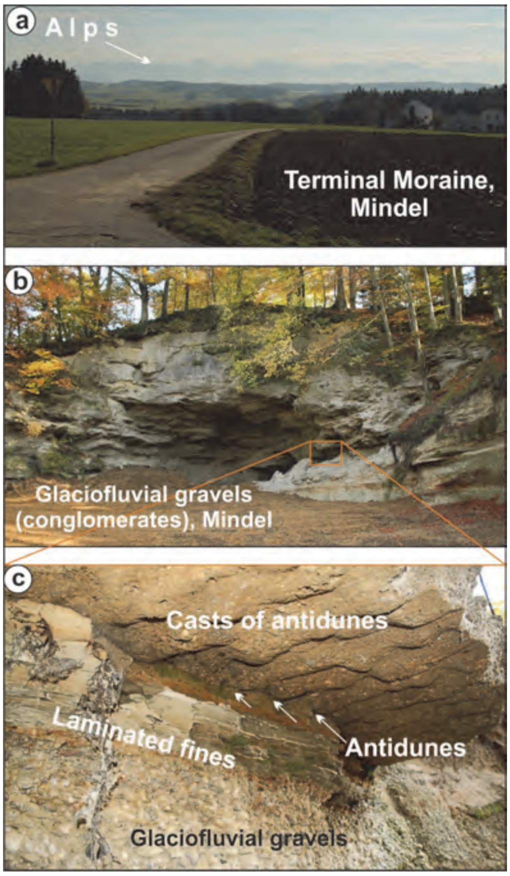

Fig. 5: Deposits relating to the Mindel glaciation.
a) View from the Mindel terminal moraine (MIS 12?) towards south (Alps).
b) Glaciofluvial gravels ("Höhere Deckenschotter") associated with the Mindel stage moraine. Sediments are commonly intensively conglomerated. Ice proximity is underlined by features of the upper flow regime (c).

Stop 5: Sediments and topography along Salzach Glacier's main drainage

The gravel pit (Fig. 6a) is situated within the main meltwater route of the Salzach Glacier and represents thick glaciofluvial deposits of homogenous, horizontally bedded sandy gravels to cobbles. The outwash is associated with the LGM glacier, which was a bit less extensive than the one of the penultimate glaciation (Riss maximum, MIS 6; see also Figure 1 for differences in extent). As a consequence, Rissian deposits in the pathway of the LGM outwash were reworked (eroded). The erosional scarp slightly west of the outcrop marks the Rissian terrace ("Hochterrasse") which was left as erosional remnant.

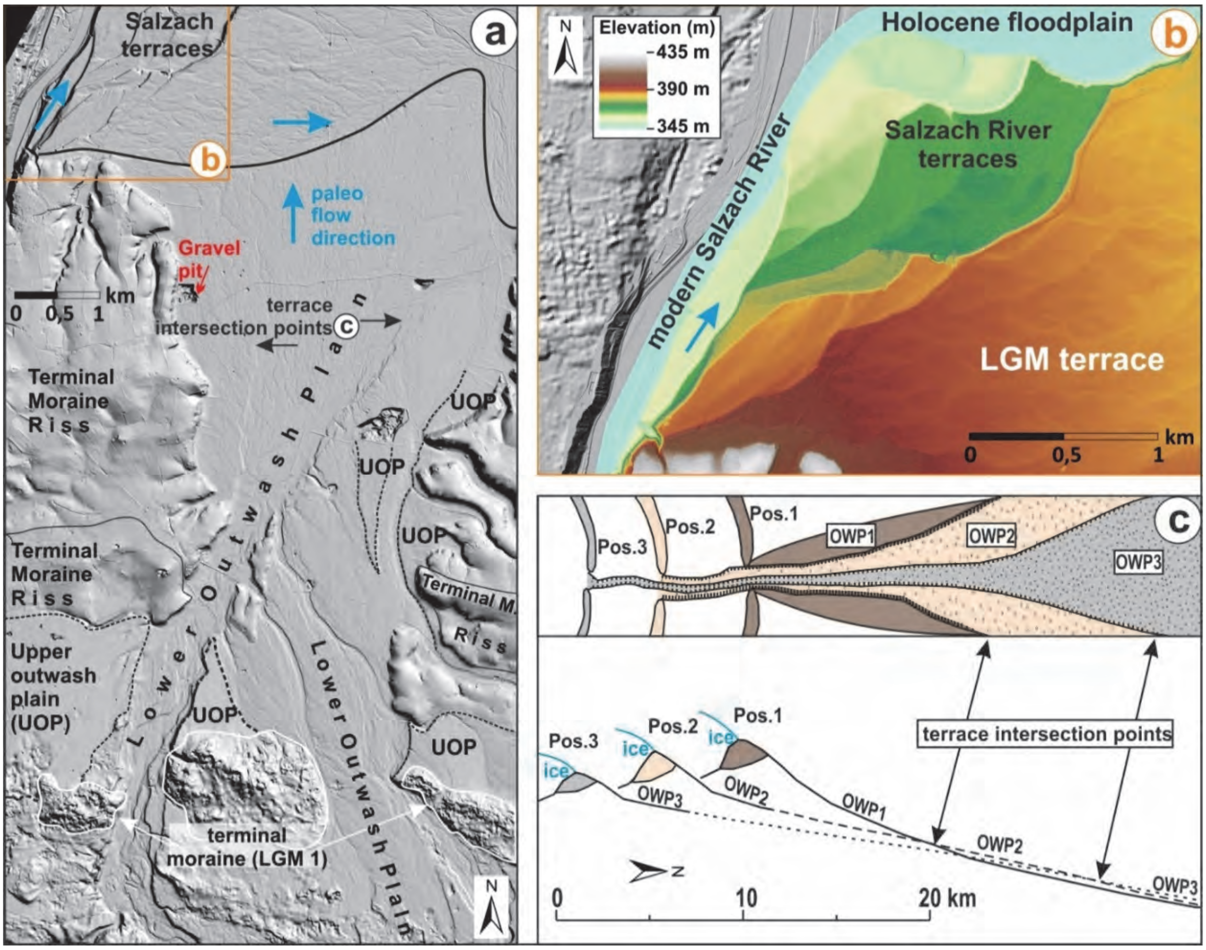

Fig. 6:

a) Fluvial outwash morphology along the Salzach Glacier's main drainage. Different terrace levels of a glacial period arise from glacier retreat and associated lowering of the glacier's drainage. Black arrows (a) mark the intersection points showing the transition from stream dissection (no accommodation space) to outwash formation (accommodation space): See c) for the conceptual model (modified from Troll, 1926 and Schreiner, 1997). Note the multiple sinks (kettle holes) in the terminal moraines (LGM 1) reflecting the incorporation of dead ice.

b) Terraces remnants distributed over an elevation range of c. 100 m demonstrate the dramatic incision of the Salzach River associated with glacial collapse. Note the change in river planform and flow direction from the top terrace level (braided, W-E directed) to lower levels (meandering, SW-NE). 0,5 m DEM by courtesy of the Government of Upper Austria.

Figures 6a and c highlight a typical, but rarely preserved (and detected) topographic feature of outwash related to different stages of glacier stabilization (Fig. 6c, Pos. 1, 2, 3). Drainage lowers with the slightly receding LGM glacier forming outwash of slightly different slopes. Outwash associated with the most extensive terminal moraine is the steepest, outwash associated with sediments from a more southern positions have a lower slope. This phenomenon leads to the apparent crossing of terraces (Troll, 1926) reflecting the change in accommodation space.

Stop 6: Ice collapse and fluvial incision

This Stop is located at Ach in the opposite to the Burghausen castle (Germany). Burghausen sits on glaciofluvial sediments of the LGM impressively showing the contrast in stream flow elevation and characteristics of the Salzach River between full glacial and present interglacial conditions (modern Salzach level). On the eastern river side numerous preserved terrace steps mark the successive incision of the river at the onset of deglaciation (Termination I, Fig. 6b). Glacier retreat was probably very rapid and glaciers were already at inner alpine positions at around 17--18 k.a. (e.g. Ivy-Ochs et al., 2004, Starnberger et al., 2011). Timing (and average rate) of fluvial incision into outwash (Fig. 6a) is however not fully clear but was likely not completed with the onset of the Holocene. The modern stream level is just above the Neogene bedrock suggesting that the incision of the cold stage sediments has largely ceased. Note the change in paleoflow direction and river planform. At the LGM outwash is N-S directed and shows a braided pattern (as already indicated by outcrop data). With full retreat of the glacier into the Salzach Valley, flow direction was W-E directed suggesting the strong influence of the Paleo-Inn River (modern confluence is few km to the north). Still, the stream appears bedload dominated (braided). Further, terraces suggest modern flow direction S-N to SSW-NNE and meandering planforms.

Stop 7: Ice wastage and associated landforms (Termination 1)

Ice collapse induces the formation of specific landforms such as kettle basins and hummocks (e.g. Eyles et al., 1999). The intensified melting process increases sediment release and promotes the local deposition of fluvial, gravitational and lacustrine sediments on or within the stagnant ice body. In accordance, landforms typically incorporate a large variety of sediments often associated with steep slopes and short topographic wavelengths (Fig. 7a). Kame-deltas of limited extend are common features proofing the existence of short-lived lakes (Figs. 7b, c). They formed between the ice margin and e.g. the terminal moraine incompletely filling some local basins. Importantly, the surface of the topset highlights the elevation of former lake levels at a given time of ice collapse. Kame deltas at multiple altitudes can therefore help to understand processes of ice collapse.

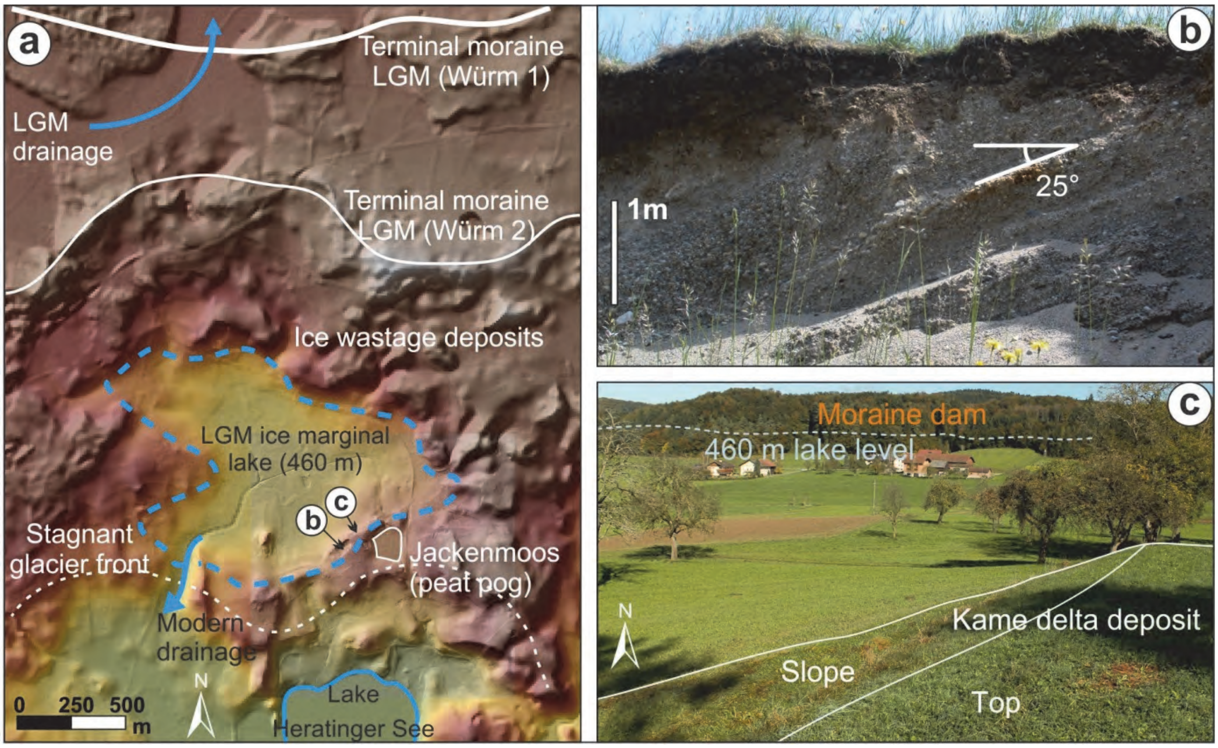

Fig. 7:
a) Strongly undulating topography typical for an environment associated with the melting of a stagnant glacier. DEM by courtesy of the Government of Upper Austria.
b) Foreset of a local kame delta deposit. See a) for location.
c) The kame delta marks the elevation of a short-lived ice marginal lake, locally dammed by moraines. The presence of dead ice leads to the formation of kettles. These sinks may later turn in the tiny peat bogs (Jackenmoos, see Fig. 8). Modified from Götz et al., 2018.

Stop 8: The formation of kettle holes and its importance for postglacial processes. The Jackenmoos Kettle.

The full detachment of ice fragments from the glacier ("dead ice") is a common process at a glacier's terminal position. Naturally, the formation of dead ice is promoted when ice melting accelerates (ice collapse). If bodies of dead ice are incorporated into sediments, melt out of ice can result in characteristic topographic concave forms ("kettle-holes"). Kettle-holes or kettles are often appearing in larger fields with numerous kettles side by side. They are especially prevalent in terminal moraines (Fig. 6a) or associated with ice wastage ("kame and kettle topography"). In rare cases kettles can turn into (small) lakes, if there is e.g. some water inflow and the underlying material is suitable to prevent drainage (e.g. be provided by fine material through slope wash). Through lateral or vertical terrestrialisation these lakes can turn into kettle-hole mires (Fig. 8a). The given example shows a large kettle hole structure which has been completely horizontally grown by a floating peat mat ("floating mat terrestrialisation"). The result is the existence of an overgrown body of water. The contrast between the floating mat, the water body and the underlying material can also be beautifully discriminated by subsurface resistivity sections (Fig. 8b). The unusual high resistivity of the water body is a function of lower mineralization (i.e. surface water, with absence of mineralization through e.g. groundwater flow).

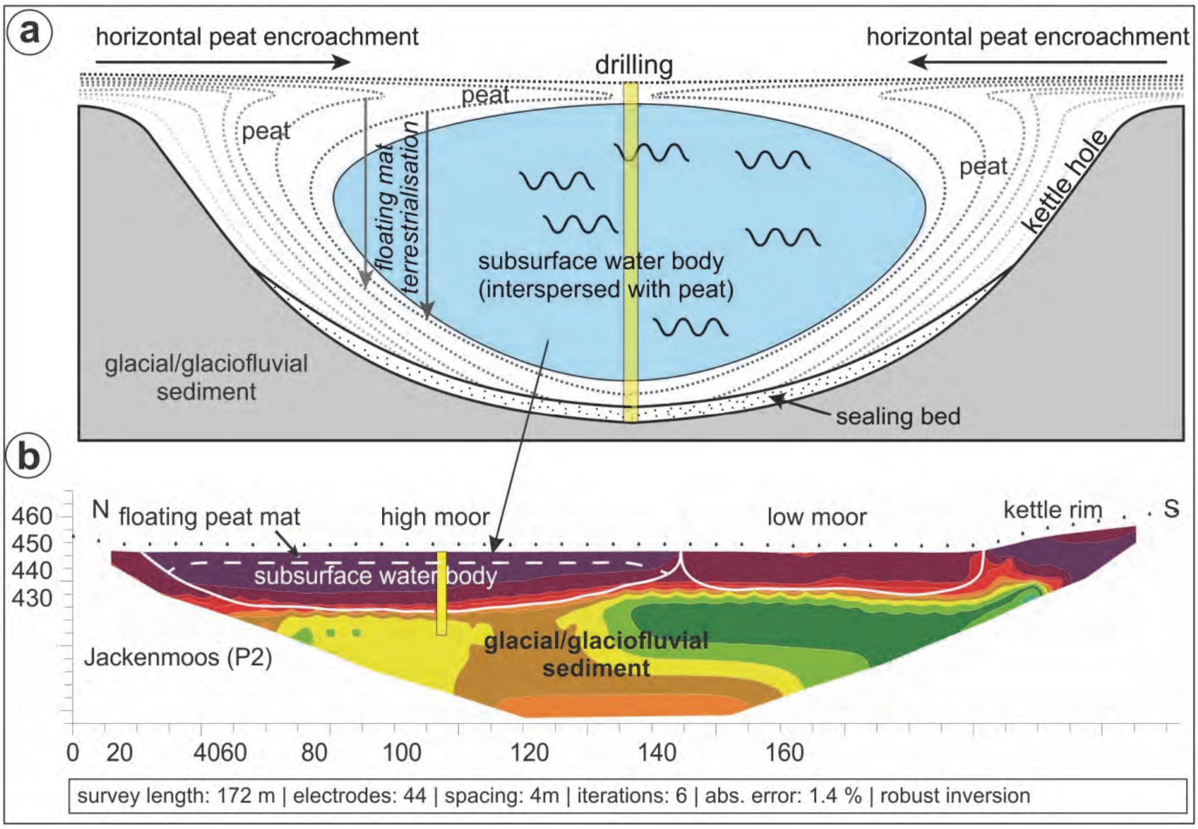

Fig. 8: Modified concept of peat formation in kettle-hole mires using results of the Jackenmoos peat bog.

a) The model (i) modifies the concept of floating mat terrestrialisation after Gaudig et al. (2006). The location of the core drilling core is highlighted as yellow bar.

b) Subsurface resistivities of ERT section crossing the Jackenmoos. Interpretation is indicated. Modified from Götz et al., 2018.

Stop 9: Peat bog "Ibmer Moor" – Natural trail

The "Ibmer Moor" is the largest peat bog area in Austria. The natural trail gives a quick overview on some relatively undisturbed parts of the largely destroyed peat bog. While the peat bog of the southern part (Salzburg area) was completely exploited (and thus destroyed) the northern part remained better preserved (Upper Austria; Fig. 9). Large parts of this northern part formed through Late Glacial to Holocene terrestrialisation of a lake left after deglaciation. The absence of significant drainage basins and minor water depth of few meters only promoted this process, which was largely completed at around 8000 yrs B.P. However, two smaller residual lakes remained resisting this terrestrialisation process (Lake Heratinger See and Leitensee, Fig. 9).

Very fine lake sediments reflect the absence of significant influx into the basin after deglaciation. Climate relaxation is indicated by lake marl deposition often present below the peat.

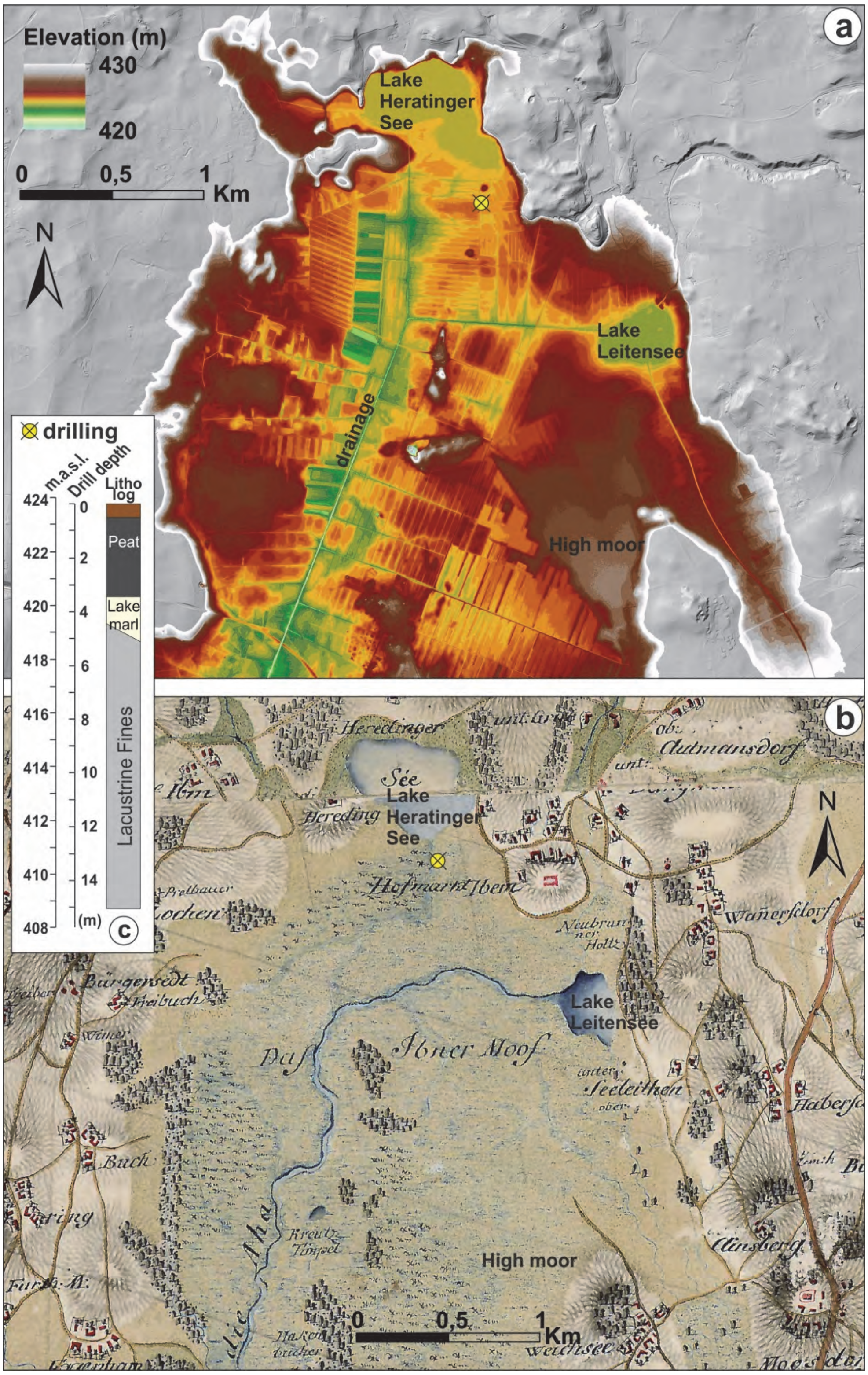

Fig. 9: Peat bog Ibmer Moor. a) DEM with 0.5 m ground resolution shows the major anthrophogenic overprint through dewatering (long linear features from artificial lake drainages) and peat exploitation (rectangular features by peat cutting). 0.5 m DEM by courtesy of the Government of Upper Austria. B) First Military Survey (Josephinische Landesaufnahme; 1775–1777) showing approximately the same area as above (A) but with largely undisturbed environment. Note the natural drainage system and difference to A. Map is from https://mapire.eu. c) Drill log showing the Postglacial to Holocene stratigraphy just south of Lake Heratinger See (yellow circle in A and B).

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