Field trip 13

Inner gorge-slot canyon system produced by repeated major base-level changes (Northern Calcareous Alps).

Diethard Sanders[1], Alfred Gruber[2]

[1] Institute of Geology, University of Innsbruck, 6020 Innsbruck, Austria

[2] Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria

1 Introduction

The Quaternary history of valley development of the Alps still is largely unresolved. Overdeepened valleys perhaps are the most prominent features probably related to Pleistocene ice streams, but else, except for models and concepts, little is known about dynamics and time spans involved in valley incision. In contrast to sediments, except where surface exposure dating is applicable, landscape elements (e.g., a graded rocky slope or a bedrock canyon) do not contain a direct record of age, so their age in most cases must be constrained by indirect approaches. With the present methods of age-dating at hand, this is still possible only for comparatively few valleys, or valley reaches. Many Alpine valleys that were passed by pleniglacial ice streams show an inner gorge excavated into bedrock. Previously it was often implicitly assumed that these inner gorges formed after the Last Glacial Maximum. With increasing knowledge about rates of glacial and fluvial erosion, respectively, it emerged that at least most of these inner gorges should have formed over several glacial-interglacial cycles. This is particularly obvious by narrow slot canyons intercalated between upstream–downstream reaches of an older and wider inner gorge, and by abandoned canyon reaches filled with Quaternary deposits (Fig. 1).

In the excursion area near Steinberg am Rofan, a system of inner gorges and slot canyons – both inactive (‚fossil') and active – allows to distinguish major cycles of base-level change during valley formation (Fig. 2). The present streams thus follow an inner gorge–slot canyon system that is of *markedly different ages along different reaches*. From a stratigraphic point of view, the excursion shows that repeated stream epigenesis produces truncation surfaces of extremely differentiated, brusk relief. The results communicated hereunder and the methods of investigation are described in detail in Sanders et al. (2014). Therefore, text will be kept short and emphasis is placed on figures.

The implications of the observations with respect to development of the higher-order stream network and the uplift history of the Northern Calcareous Alps are discussed.

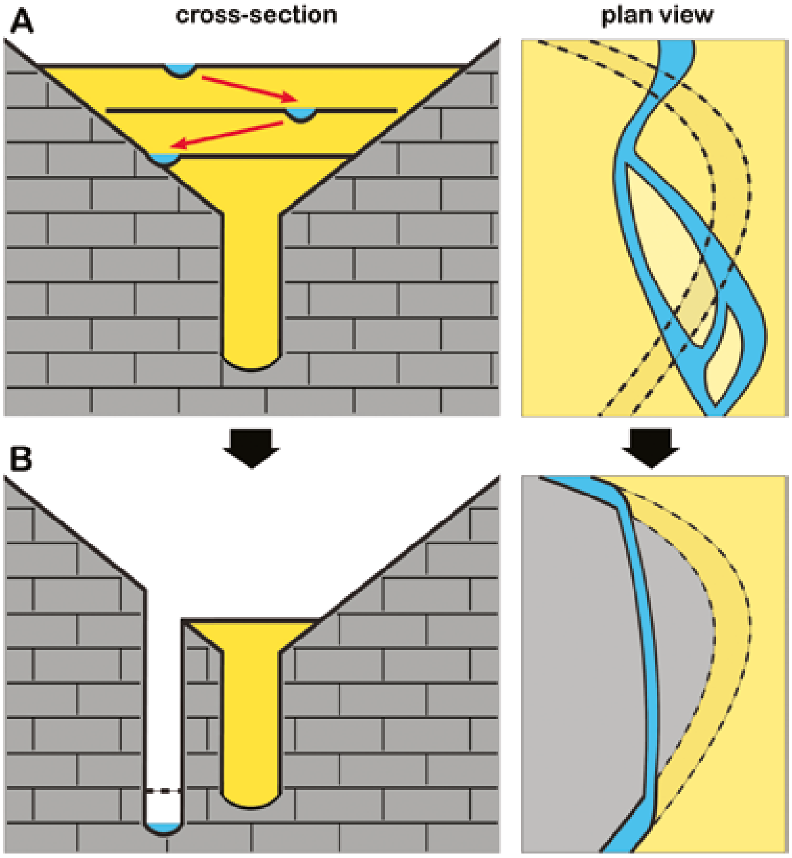

Fig. 1: Scheme of slot-canyon development due to marked base-level rise by sedimentation (e. g., in a proglacial setting, as seen with the excursion).

2 Setting

2.1 General

The Northern Calcareous Alps (NCA; part of the Eastern Alps, see Fig. 2A) consist of a pile of thrust nappes mainly of Triassic shallow-water platform carbonates (e. g., Schmid et al., 2004). From late Paleogene to early Neogene times, large parts of the orogenic edifice became uplifted and exposed. In the Eastern Alps, the development of a simple drainage pattern was precluded by: (a) superposed fold- and fault structures, and (b) Neogene E-W lateral escape of the orogen along large strike-slip faults that trend parallel to oblique to the main crestline (e. g., Ratschbacher et al., 1991); these faults controlled the trend of major trunk valleys at least since ~13 Ma (e.g., Inn valley; Kuhlemann, 2007). The fault-controlled trunk streams provided the major drainage conduits over Pliocene to Quaternary times, but their history still is poorly documented (Robl et al., 2008a,b). In the Alps, major glaciation and glacial shaping of the landscape probably started at 0.87 Ma (Muttoni et al., 2003). The Eastern Alps were subject to at least four major Quaternary glaciations (van Husen and Reitner, 2011). Along advancing Pleistocene ice streams, many tributary valleys at first were blocked and filled by proglacial fluvio-lacustrine successions (e. g., van Husen, 2000; Reitner, 2007). The Last Glacial Maximum (LGM; ~26.5-21 ka; Preusser, 2004; Starnberger et al., 2011) of the Eastern Alps was followed by rapid collapse of ice streams. This ‚early late-Glacial ice decay' (ELGID; ~21 to ~19 ka BP) reduced ice streams to about 50% of LGM volume (van Husen, 2004; Reitner, 2007). The ELGID was followed by the late-Glacial from ~19 ka to the onset of the Holocene at 11.7 ka BP.

2.2 Catchment of Steinberger Ache

Steinberger Ache is a tributary to Brandenberger Ache which, in turn, debouches in the Inn River (Fig. 2). The catchment of Steinberger Ache is largely located on Triassic platform rocks; along the southern fringe of the catchment, Jurassic

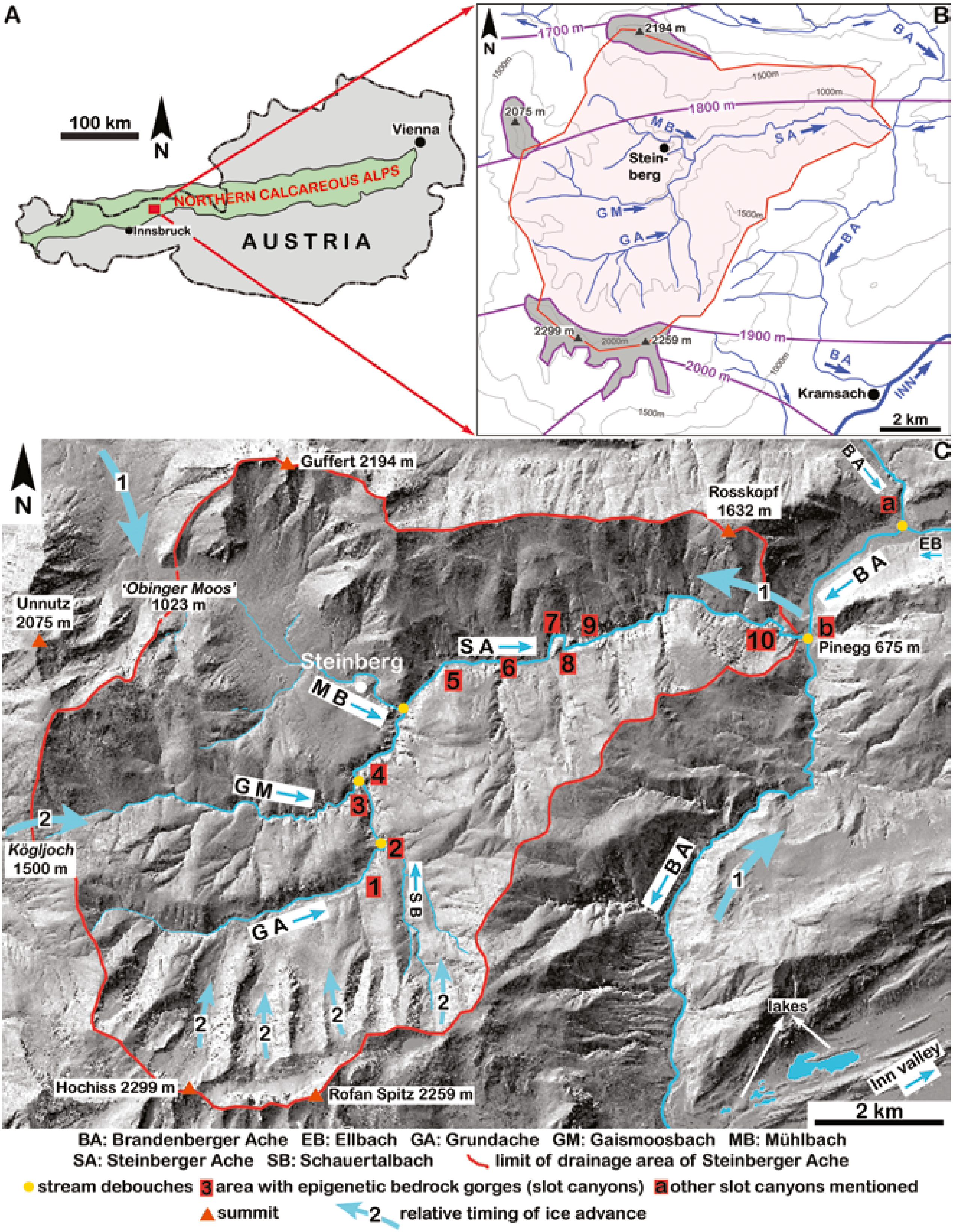

Fig. 2: **A)** Geographic location of study area (red rectangle) in the Northern Calcareous Alps (light green). **B**) Map of Steinberger Ache catchment, with reconstructed ice surface of the Last Glacial Maximum (after van Husen, 1987). During the Last Glacial Maximum, except for three nunataks, the catchment was buried under an overall northward-flowing ice stream. **C**) Laserscan image showing catchment of Steinberger Ache (SA; red outline), and its connection to the trunk valley of the Inn River via Brandenberger Ache (BA).

deep-water limestones and cherts are exposed that are identifiable in the field in pebble-sized clasts. The present course of Steinberger Ache and its main tributaries are characterized by inner bedrock gorges up to 100-150 m wide, changing downstream with slot canyons about one meter to a few meters in width near their base (Fig. 2C). In the western NCA, the late Middle Würmian (MIS 3; 61-29 ka; Martinson et al., 1987) was characterized by a cool climate and a tundra-like vegetation. During the later part of MIS 3, from at least ~36 to 27 ka, thick fluvial and fluvio-lacustrine successions accumulated along the Inn valley and its tributaries. The lower reach of the Inn valley probably was devoid of glacial ice until at least 27 ka BP (Reitner, 2011). Significant fluvial aggradation from ~36 to 27 ka perhaps largely resulted from increased physical weathering and sparse vegetation (Reitner, 2011).

As outlined below, U/Th dating of cement in fluvial deposits of the pre-LGM Grundache stream indicates that an inner bedrock gorge already existed during the late MIS 3 phase, and that this gorge underwent partial infilling from valley-bottom aggradation that may be assigned to this phase. During buildup of the LGM, valley drainage became blocked by advancing ice streams, and a proglacial lake dubbed Lake Steinberg formed (Ampferer, 1905; Horvacki, 1982). Aggradation in Lake Steinberg was punctuated at least once by marked lake-level lowering and fluvial incision. The lake attained a level of at least 1100 m a.s.l. (highest preserved foreset beds), well-above most of the present catchment of Steinberger Ache. The pre-LGM drainage system thus was leveled-out by fluvio-lacustrine sedimentation. In the study area, the reconstructed LGM ice surface ranged from 1900 m a.s.l. in the South to 1750 m a.s.l. in the North, so only the nunataks of Guffert, Unnutz and the northern Rofan summits stood out (Fig. 2B). Subsequent to the LGM, perhaps during the Gschnitz Stadial (~17–15 ka),

Fig. 3: Distalmost slot canyon #10 of Steinberger Ache (cf. Fig. 2C) (not visited on the excursion).

glaciers of East- and North-facing cirques (N slope of Rofan massif, E slope of Unnutz) advanced down to near Obinger Moos (1000-1100 m a.s.l.) and upper Grundache valley (c. 1000-1300 m a.s.l.) (van Husen, 2004; Wischounig, 2006; Gruber, 2008). The glacial advance had led to another pulse of sediment input to the upstream reach of Grundache. There is no evidence that local cirque glaciers nucleated and advanced during stadials subsequent to Gschnitz (Gruber et al., 2011b; cf. Kerschner et al., 2006; Ivy-Ochs et al., 2008).
By analogy with the Inn valley adjacent to the South (Fig. 2C), reforestation in the excursion area may have started at ~16-15 ka BP (cf. van Husen, 2004); in consequence, hillslopes stabilized and the geomorphic regime progressively changed to incision (cf. Sanders and Ostermann, 2011; Sanders, 2012). During the late-Glacial changeover from sedimentation to incision, Steinberger Ache and its tributaries had largely hit again their pre-LGM inner bedrock gorges. Along these older reaches, the re-incising streams cleared out the pre-LGM fluvio-lacustrine succession. Along some reaches, however, the streams 'missed' their pre-glacial course, and a slot canyon was incised. The present course of Steinberger Ache and its tributaries thus is a 'chain' of bedrock canyons formed: (a) before the LGM, changing downstream with (b) slot canyons incised after the LGM (Fig. 2C, Fig. 3).

3 Description of stops

Stop 1: Grundache inner gorge. Explanation of local geology and Quaternary history.

The stream system of Grundache-Steinberger Ache is incised into the southern and central part of a north-vergent, E-W striking anticline mainly of Middle to Upper Triassic shallow-water carbonate rocks. Along the southern fringe of the catchment, the summits of Rofan massif consist of Jurassic lithologies (diverse types of deep-water limestones and marls, cherts).

A few meters upstream of the confluence of Grundache and Mühlbach streams (Steinberger Ache, Fig. 2), the inner gorge of Grundache is approximately 100-150 m in width. Along this reach, the gorge is incised into dolomitized Middle to Upper Triassic shallow-water limestones (Wetterstein dolomite). During folding and thrusting in the Northern Calcareous Alps, these dolostones reacted in brittle style, and became riddled with a dense network of faults and joints.

Here, Grundache shows a channel morphology transitional from plane-bed to pool-riffle type. This present channel status also results from decades of careful development of the stream with an array of run-of-river dams (compare Stop 4). Upstream to Stop 5, the channel is an alluvial channel throughout.

Stop 2: Debouch of Dry Gorge. Walk into the gorge.

Walking upstream Grundache, a first distinct feature is the right-hand debouch of a bedrock gorge that is not waterrun (Fig. 4). This gorge, dubbed Dry Gorge, was inactivated by human action in 1941, to facilitate commercial drift of wood logs along Grundache (see also Stop 4). Walking ‚upstream' Dry Gorge, it is obvious that it is more narrow than the gorge of Grundache stream.

Although inactivated only 75 years past, Dry Gorge is already filled with an impressive amount of scree derived from physical erosion of the canyon walls (Fig. 4A). Because the deeper, shaded parts of the rock walls are moist over most of the year, frost-related weathering may be particularly effective in such a setting.

Upstream, Dry Gorge progressively narrows; the most proximal part is a shady canyon some 50-70 m in depth and ~1.5-2 m in width with a pebbly to cobbly former stream bed (Fig. 4B). The side walls of the canyon are sculpted by undulations with well-preserved smooth surface, excavated by sediment-laden stream vortices. Notwithstanding the inactivation of the gorge in 1941, these observations indicate that this uppermost, narrow part of Dry Gorge must be also geologically very young, i.e. it represents a younger reach incised upon re-activation of a pre-existing older Dry Gorge.

Fig. 4: **A**) Upstream view into the medial reach of Dry Gorge, inactivated in 1941 (75 years ago). Note (a) waterfall tufas (wt) of brooks descending into the gorge, and (b) scree slopes supplied from the gorge cliff. **B, C)** Upstream view (**B**) and downstream view (**C**) onto waterfall knick of the post-glacially incised sector of Dry Gorge, inactivated in 1941.

The upstream termination of Dry Gorge is a bedrock-incised waterfall step (Fig. 4C). It is clear that this step provided a major obstacle to log drifting, which was the reason for the decision to artificially divert drainage to the present Grundache stream (see Stop 4).

Stop 3: View over to Gaismoosbach gorge. Fluvial conglomerates with age-dated cement along Grundache gorge.

Tracking further upstream the course of Grundache, the narrow bedrock canyon of the Gaismoosbach tributary (GM) is seen on the left bank

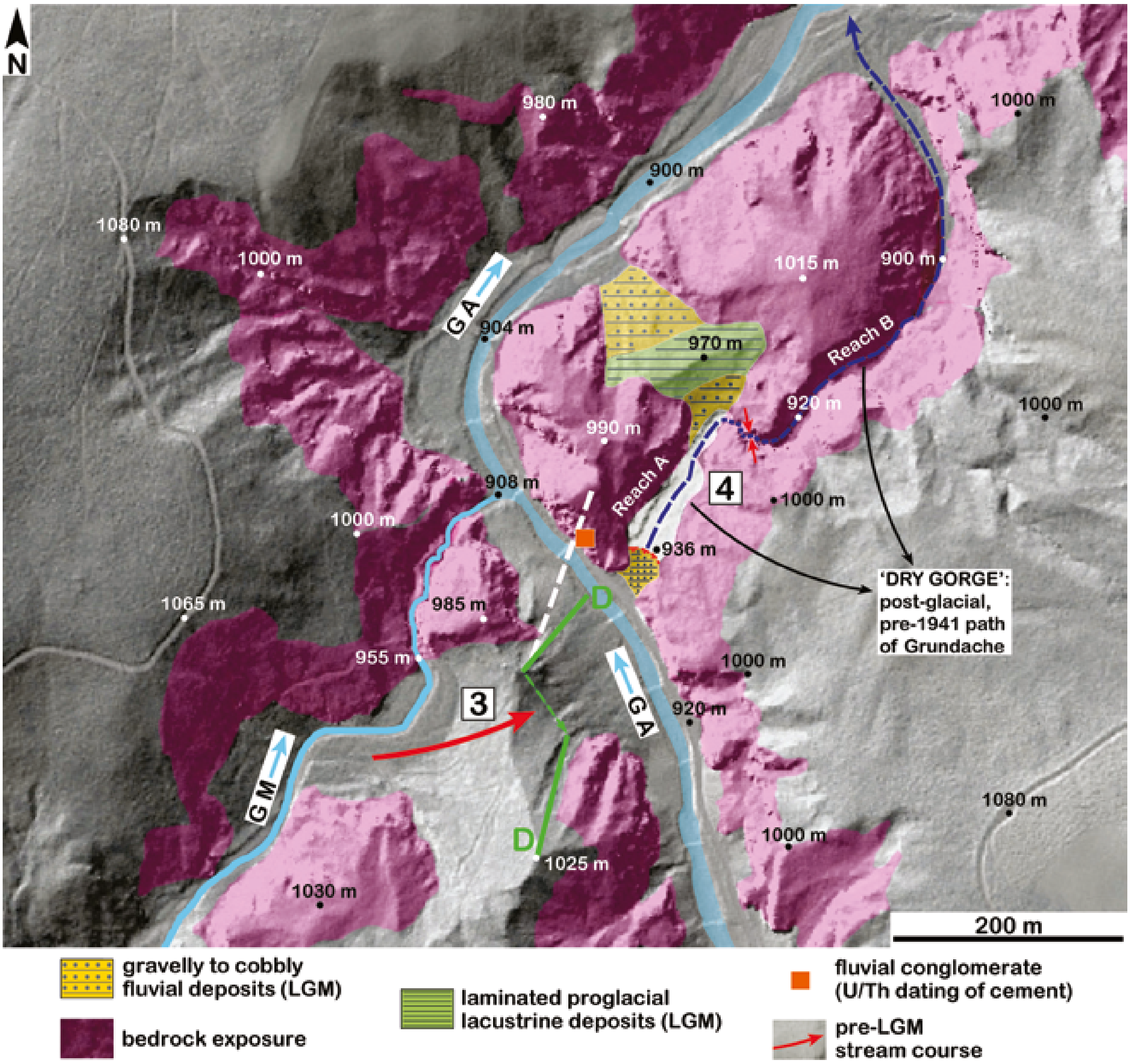

Fig. 5: Map of confluence, at 908 m a.s.l., of Grundache (GA) and Gaismoosbach (GM). The present Gaismoosbach descends over a vertical distance of 45 m within a steep slot canyon with waterfalls and plunge pools. Red arrow: pre-LGM course of Gaismoosbach, through a canyon filled by a proglacial fluvio-lacustrine succession. Dashed white line across Grundache valley shows approximated crest of the natural sediment ridge that up to 1941 had separated the post-glacial routes of GM and GA. The ridge consisted of the same fluvio-lacustrine succession that elsewhere accumulated within the bedrock gorges shortly before the LGM. Before anthropogenic removal of the ridge in 1941, Grundache flowed via a bedload channel (Reach A, light-grey area) into a narrow bedrock slot canyon (Reach B), dubbed Dry Gorge. Red arrows point to a sharp knick with a formerly-active waterfall along reach B. Halfway between Reach A and B, note the bedrock canyon filled with the same proglacial succession as elsewhere. Orange quadrangle: Fluvial conglomerates onlapping the flank of the pre-LGM Grundache canyon. In this conglomerate, isopachous cement fringes were U/Th-dated to an age of 29.7 ± 1.8 ka.

of Grundache (Fig. 5). The Gaismoosbach canyon is some 10-20 m in vertically incised depth only, and consists of a succession of waterfalls and plunge pools; this canyon thus should be significantly younger than the wider Grundache gorge. The pre-LGM course of Gaismoosbach is filled with a proglacial fluvio-lacustrine succession (green labeled section D in Fig. 5).

The right, vertical bedrock flank of Grundache gorge is onlapped by an erosional remnant of stream conglomerates (orange quadrangle in figure). A $^{234}U/^{230}Th$ disequilibrium age of 29.7 ± 1.8 ka of cement from the conglomerate provides *ante quam* ages for: (a) existence of this bedrock flank, and (b) sediment aggradation filling an already existing Grundache canyon.

Stop 4: LGM sediment filling of older Grundache gorge. Walk on post-glacial stream bed (inactivated in 1941) to waterfall knick of Dry Gorge.

A short distance upstream, the left-side bedrock cliff along Grundache gorge sharply disappears, and the left flank consists of a thick Quaternary succession; a similar gap of bedrock flank and change to sediment succession is obvious on the right stream bank (where the excursion is).

Hiking up to the erosional brinkline on the right bank, the outlook exposes:
(1) older, inactive bedrock canyons filled with Quaternary sediments,
(2) fully re-activated canyons (Grundache canyon with its >29.7-ka age flank; see Stop 3),
(3) a partly sediment-filled bedrock canyon that was artifically inactivated in 1941.

Up-section, the Quaternary succession in this area comprises: (a) fluvial deposits that most probably accumulated during rapid stream aggradation in buildup of the LGM (see section 2. Setting); (b) proglacial-lacustrine silts with dropstones of metamorphic rocks derived from drift in large ice streams, and (c) basal till of the LGM.

Ad (3); Partly sediment-filled bedrock canyon artifically inactivated in 1941: The sediment filling that here comprises the right bank of Grundache gorge is topped by an inactivated bed of a braided, gravelly to cobbly stream. Up to 1941, this stream bed was the course of Grundache; it leads directly to the bedrock waterfall step in Dry Gorge (Stop 2).

The solution to the puzzle: To facilitate wood drift, a ridge (cored by Quaternary sediments) that here separated the courses of Gaismoosbach and Grundache was blasted away. In contrast to expectation, the ridge did not consist of rock, but of the Quaternary succession described above. The result was a sudden, tremendous increase in bedload transport that is said to have caused problems out to Pinegg some 10 km farther downstream (cf. Fig. 2). This human interference does not detract from the geohistorical reconstruction of stream development; the blasting of the ridge rather exposed the conglomerates with the age-dated cements!

In the area of stop 4, the geometrical relations and routes of all bedrock canyons and their sediment filling (if present) can only be explained by *three* major cycles of base-level change: (1) Postglacial stream incision, (2) Pre-LGM incision, and (3) at least one preceeding phase of incision of unknown age.

Stop 5: View onto upper Grundache slot canyon and fillings of older valleys. Epigenetic waterfall of Schauertal stream.

Hiking the brinkline of a post-glacial stream terrace, the outlook onto the left bank of Grundache provides an overview of the pro-glacial Quaternary succession that filled the older canyon system (Fig. 8). Note also the width of more than 200 m of the inner bedrock gorge of the pre-LGM Grundache (Fig. 9). After the LGM, Grundache here did not find into its older canyon but incised a new, narrow and steep bedrock gorge sculpted by waterfall steps and plunge pools (Fig. 9).

In the same area, the bedrock canyon of the tributary Schauertal stream also still is clogged with Quaternary sediments (Figs. 9, 10A). The debouch of the pre-LGM precursor to Schauertal stream may have been located at similar level than the

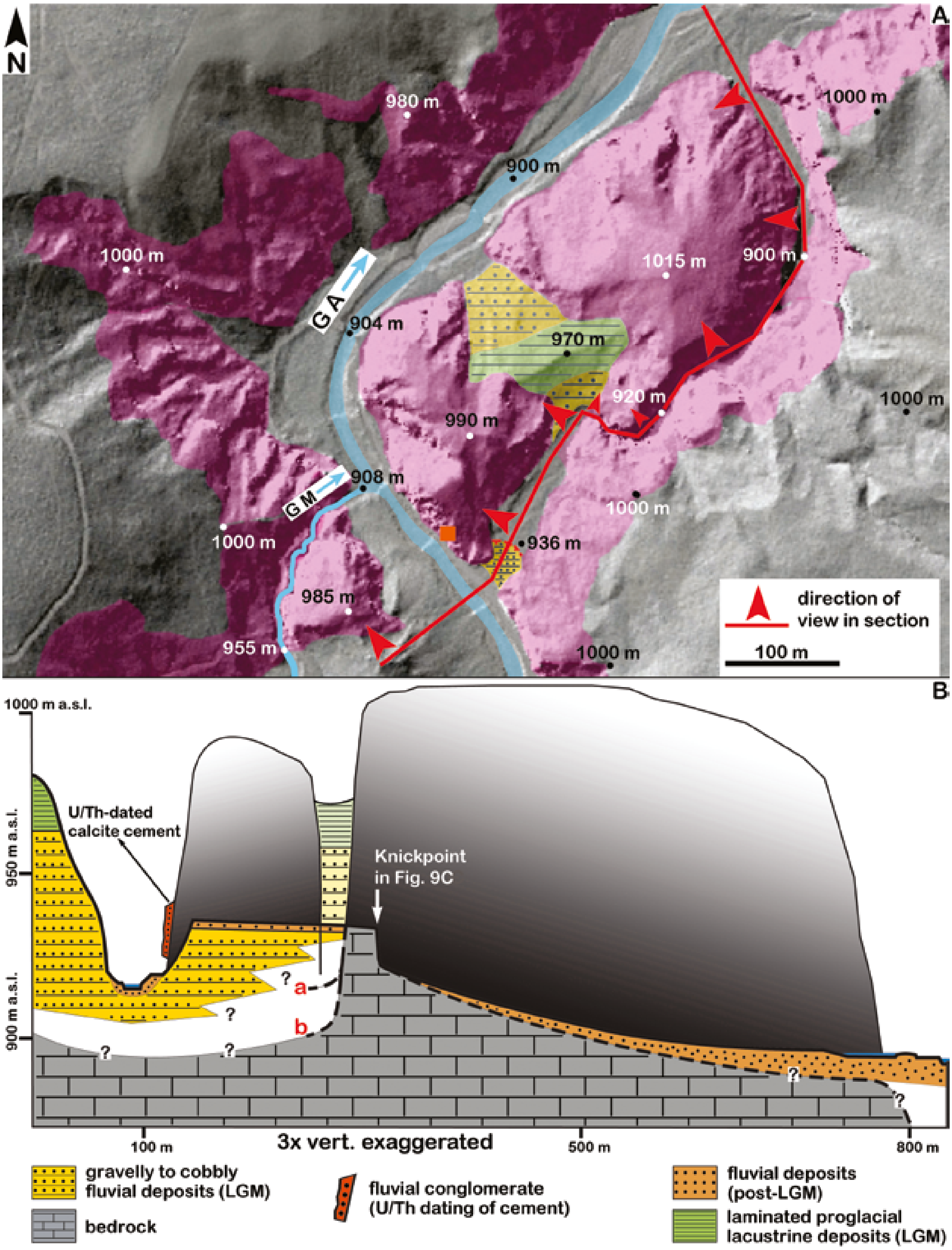

Fig. 6: Plan (**A**) and schematic section (**B**) parallel to Dry Gorge, i. e. along the pre-1941 course of Grundache. The incision of pre-1941 Grundache was anthropogenically halted at a bedrock knick with a formerly-active waterfall. This knick had laterally receded from a presumed initial position near the right flank of Grundache gorge for more than 500 meters. Along the right flank of present Grundache, no bedrock but a succession of proglacial fluvial gravels is exposed. In addition, the two bedrock hills shown shaded-grey are separated by a canyon filled with the same proglacial succession as elsewhere along Grundache. This suggests that the subsurface top of bedrock is located, at least, at the depth of lowest outcrops of the canyon-like breach (line a) or perhaps even deeper (line b). These relations suggest that, both, the sediment-filled canyon and reach A of Dry Gorge are part of a canyon incised before the LGM.

pre-LGM Grundache; i.e. the precursor Schauertal stream may have been graded to the former Grundache level. The *present* Schauertal stream is incised into bedrock along the left gorge flank, from where it cascades down with two waterfalls to merge with Grundache (Fig. 10A).

The situation at Stop 5 shows that proglacial sediment aggradation was high enough to bury and to overstep the entire Grundache-Schauertal stream canyon system, i.e., pro-glacial sediment aggradation completely ‚cleared the memory‘ of stream course.

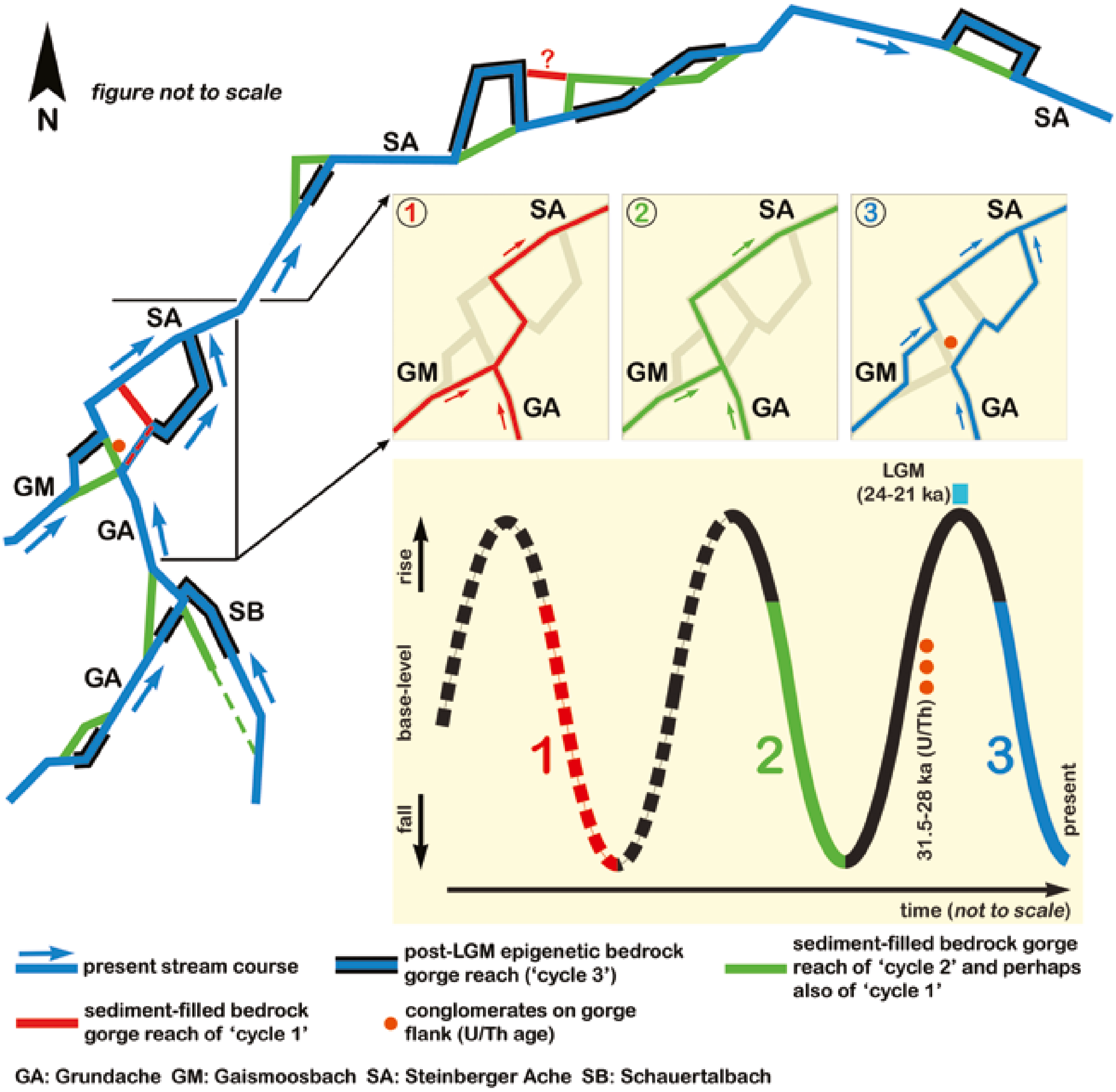

Fig. 7: Summary scheme of stream courses, epigenetic canyons, and relative age of canyon reaches. Stream pattern at Dry Gorge is shown in its pre-1941, natural state. Upper inset figures 1–3 show hypothetical development of stream network in the area of Dry Gorge. Lower inset figure: possible relation of phases of stream incision to major base-level changes, probably mainly related to glacial-interglacial cycles.

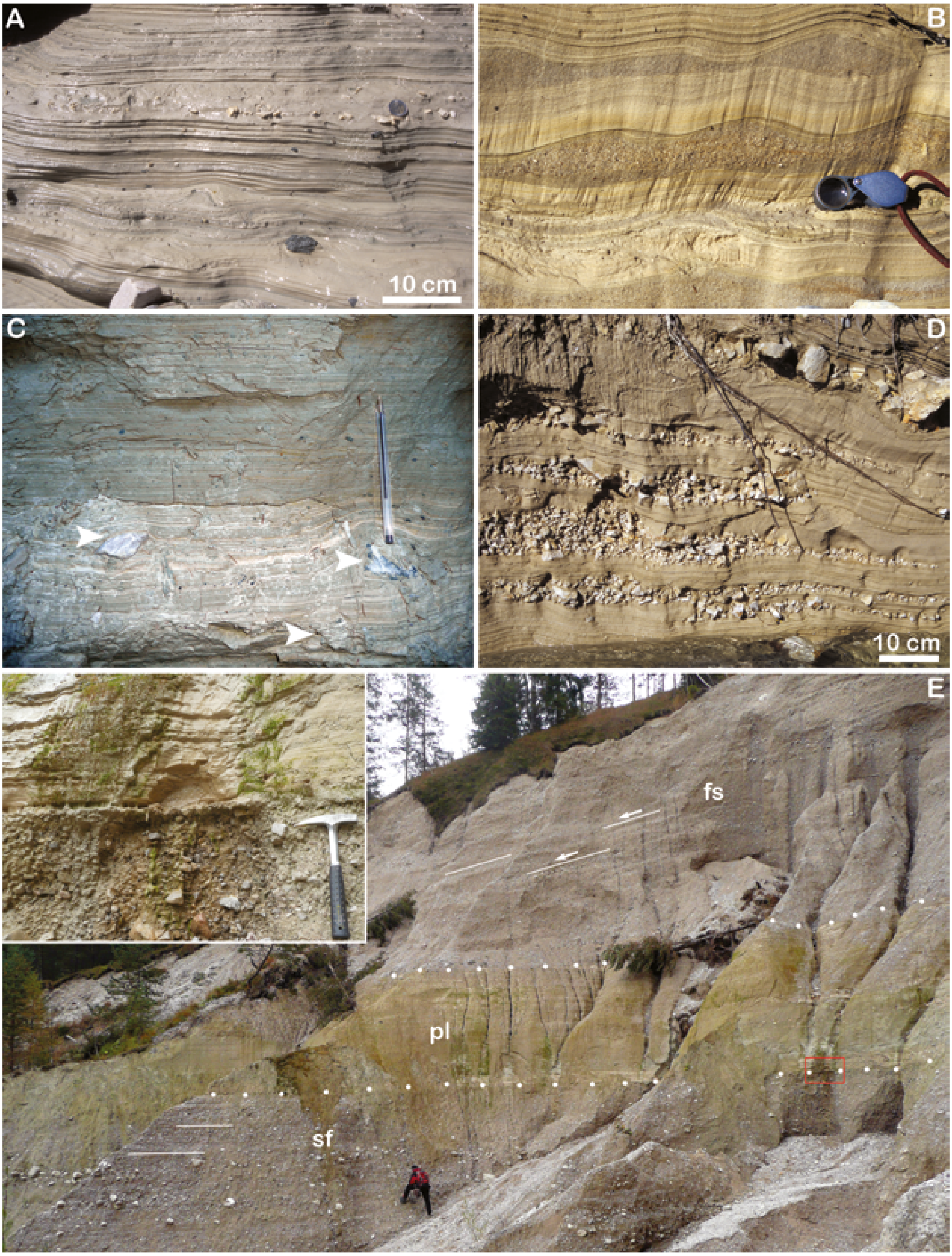

Fig. 8: Quaternary deposits comprising the fill of inner bedrock gorges. **A**) Banded silt with isolated dropstones and dropstone 'trails'. **B**) Banded silt with intercalated, ripple-drift laminated sandy layers showing pinch-and-swell bedding. Field lens for scale. **C**) Banded muddy silt with dropstones (arrowtips) with faceted and polished surfaces. Pencil for scale. **D**) Banded silt with intercalated, stacked lenses of gravels to cobbles derived from an adjacent palaeocliff (red asterisk in Fig. 9). **E**) Lower part of proglacial valley filling, view to southwest. Person stands on gravelly sheet-flow deposits (sf) which are overlain by an interval of banded silts (pl) with dropstones. Up-section, the lacustrine silts interfinger with and are overlain by the foreset (fs) of a Gilbert-type delta. Red rectangle indicates location of inset photo. **Inset:** Detail of sharp contact between gravelly sheet-flow deposits and overlying banded silts.

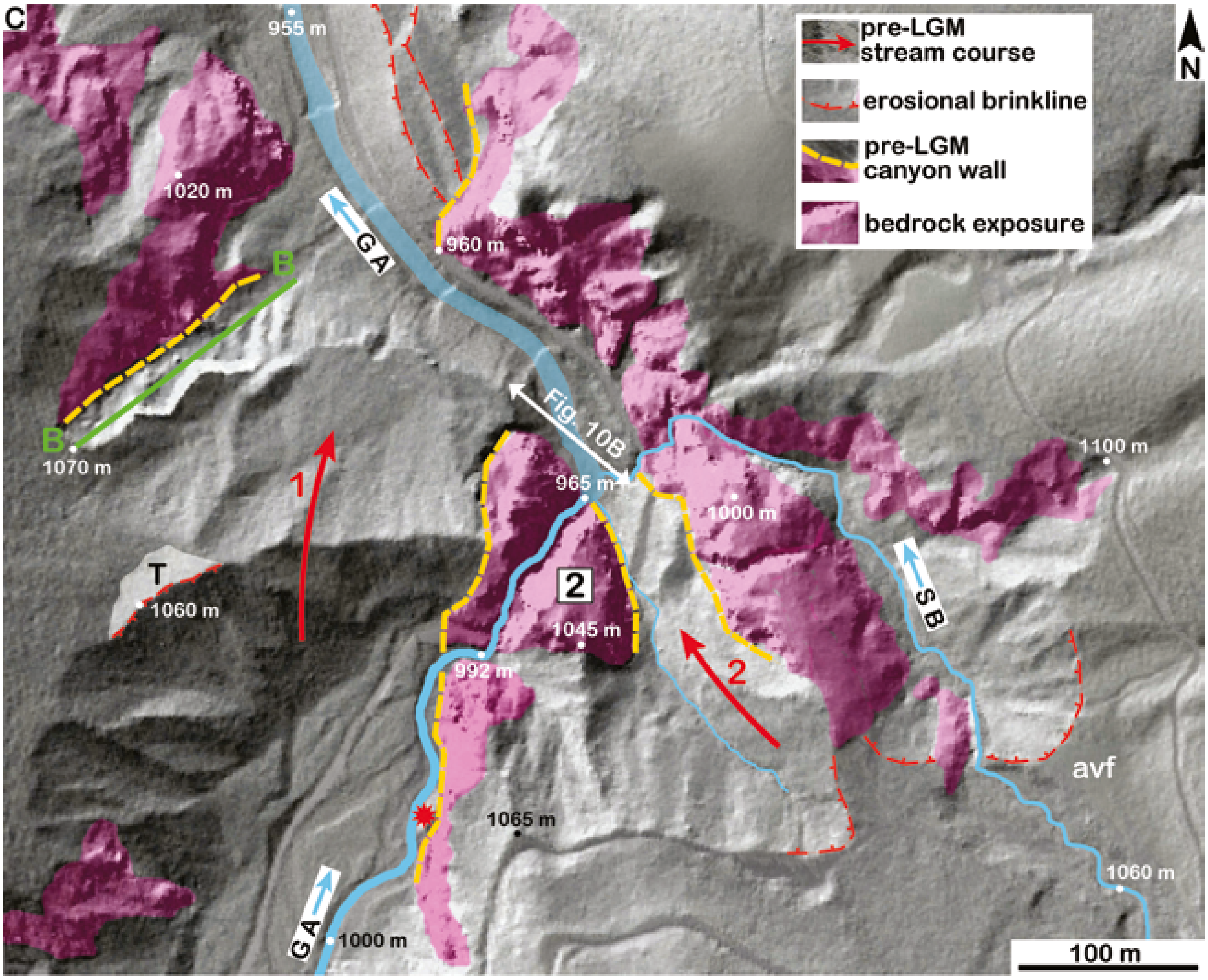

Fig. 9: Map of slot canyon #2 of Grundache (GA), and epigenetic course of Schauertal stream (SB) (cf. Fig. 2C). Dashed yellow lines indicate walls of pre-LGM bedrock canyons. Red arrow 1: pre-LGM course of Grundache. In this area, the pre-LGM Grundache valley was approximately 200 m in width, and flanked by subvertical bedrock walls (dashed yellow lines). The valley became completely filled with a proglacial fluvio-lacustrine succession. Green line labeled B denotes section. During post-glacial re-incision, Grundache cut slot canyon #2 across its former right-hand flank. Along the left bank, a terrace (labeled T) veneered by fluvial gravels rich in clasts of metamorphic rocks (also index clasts of the Inn ice stream) may record a very early stage of post-glacial valley re-incision. Red arrow 2: pre-LGM course of Schauertal stream (SB). Also this old canyon was filled up with proglacial fluvio-lacustrine deposits. During post-glacial re-incision, Schauertal stream excavated a short bedrock gully parallel to the buried canyon. Where the gully merges with the flank of the present Grundache canyon, the stream cascades down a waterfall ~35 m in height. Note also erosional brinkline (barbed dashed red line) delimiting the wide, still-aggraded valley floor (avf) of Schauertal valley.

Stop 6: Proglacial lacustrine deposits of the filling of older Grundache gorge. Old canyon flank, newly exposed. Return to bus.

This stop shows the proglacial-lacustrine deposits that contributed to filling of the older canyon system hands on. Aside of lamination, the lacustrine deposits show: (a) dropstones of metamorphic rocks, (b) thin graded densite deposits, and (c) and levels of scattered angular carbonate rock fragments derived from the local rock substrate (by ice drift or by snow avalanches onto lake ice or directly into lake water).

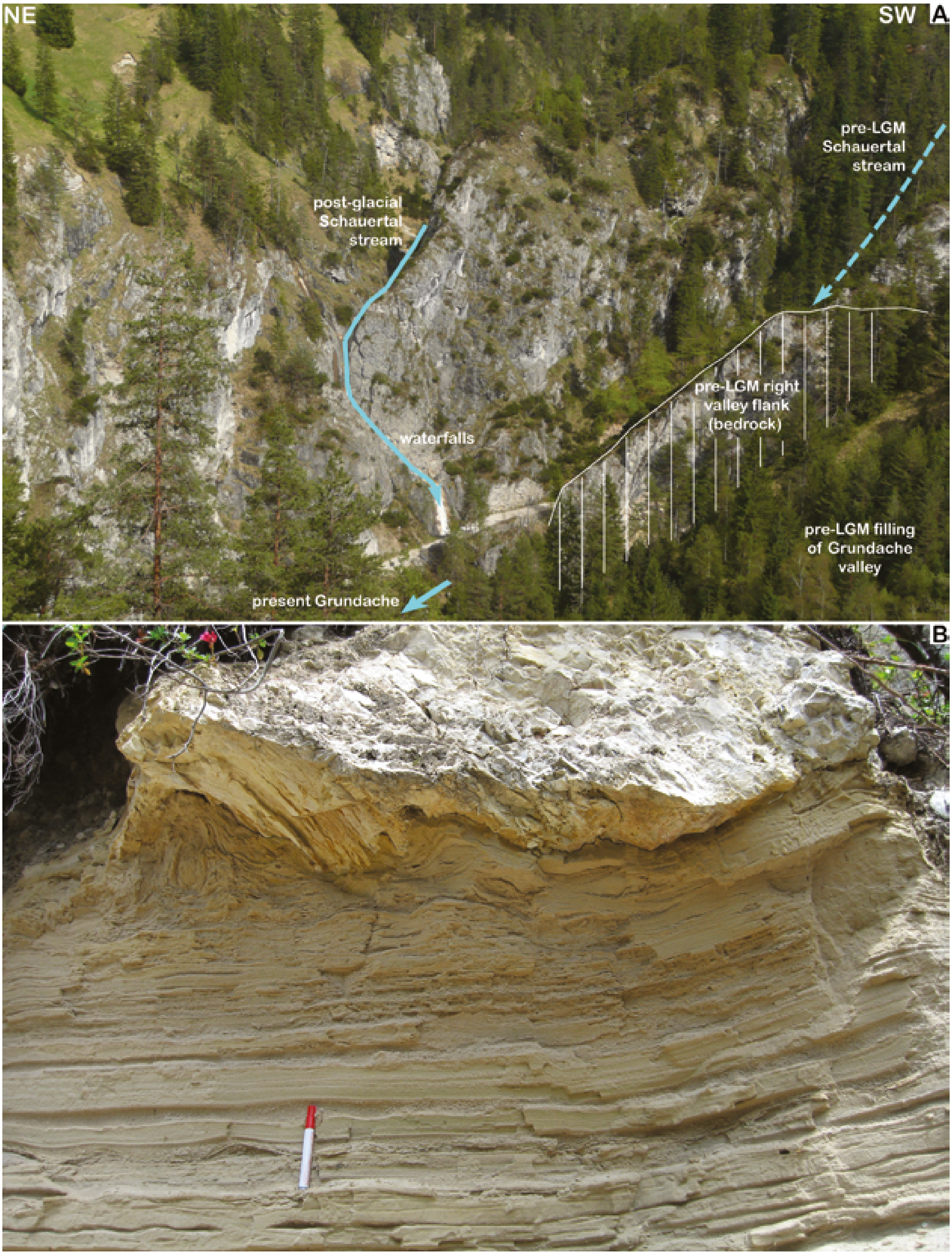

Fig. 10: **A**) View to SE onto epigenetic stream course and waterfall of Schauertal stream. **B**) Outcrop of proglacial-lacustrine succession composed mainly of stacked beds of silt to medium sand with parallel-horizontal lamination and ripple-drift cross-laminasets. The boulder had fallen right from an adjacent, vertical cliff (=pre-glacial right flank of inner bedrock gorge) into the proglacial lake. Note deformed sedimentary lamination underneath the boulder. Pen for scale is 14 cm in length.

The lacustrine succession onlaps a rock cliff of Wetterstein Dolomite that provided part of the former right flank of the pre-LGM Grundache canyon (location: red star in Fig. 9). This cliff thus predates at least the LGM, yet stands high as if geologically very young. In the lacustrine sediments that onlap the cliff toe, small mounds composed of angular clasts and isolated boulders fallen from the directly adjacent rock cliff are intercalated (Fig. 10B).

Upstream of Stop 6, aside of a small slot canyon (slot canyon #1 in Fig. 2C) a few tens of meters in length, no further clear-cut record of longer-term stream development is present. Channel types include alluvial and bedrock channels, and delivery of scree and colluvium from sidehills becomes prevalent.

4 Discussion

One of the main results of the Steinberg study is that different reaches of an inner gorge can be of markedly different age. The base-level changes required for sediment filling of the canyon system followed by re-incision most probably were related to glacial-interglacial cycles. Further processes that can significantly disturb stream systems are: (a) catastrophic rockslides, and (b) tectonism. In the Alps, several rockslides triggered stream diversion and re-incision into bedrock. Conversely, for the considered part of the NCA, at least the present tectonic deformation appears to be too slow to override potential rates of stream incision and slope adjustment (i.e., to become evident in landforms and stream profile). This is supported by GPS-derived displacement vectors that suggest practically no active deformation in the Steinberg area (Caporali et al., 2013).

The incision of the slot canyons manifests the high erosive capacity of steep-gradient streams rich in bedload. It thus may seem perplexing that some reaches of the Grundache-Steinberger Ache canyon system should have been re-activated over three base-level cycles. Why did the successive streams not re-incise in a significantly more random pattern? We suggest four causes: (1) The overall valley shape, with mountain flanks dipping toward the inner gorge, provides a first-order control to steer a re-incising stream to near its former course, and this should apply also to subglacial meltwater of decaying ice-streams. (2) If approaching a lateral bank (e.g., rock) that is more competent than the opposite bank (e.g., loose sediment), channel axes tend to be locked along the competent bank. This helps to ‚trap' a re-incising reach along a pre-existing canyon wall. (3) Only where a re-incising stream is underlain by rock over its entire channel width, bedrock incision could start. Because the early re-incising braided stream system was prone to channel avulsion, the probability for a channel to stay in place long enough for sufficiently deep bedrock channel excavation (which then would tend to remain stable) was relatively low; at the same time, avulsion enhanced the probability for a channel reach to hit a lateral wall of bedrock which may be the flank of an older canyon reach. In combination, these controls might have acted together to guide streams back into their former canyons over most of their extent.

Inner gorge-slot canyon systems are widespread in the NCA, and are particularly common in lower valley reaches closely before debouch into a trunk valley. Because every slot canyon corresponds to an abandoned reach, the (minimum) depth of bedrock incision before excavation of the active slot canyon can be determined by field mapping. It is a common observation that slot canyons of the western NCA are incised to similar depths than the older (pre-LGM) abandoned reaches. Unfortunately, the ages of these abandoned reaches are very poorly constrained. For the Steinberg catchment, a glacio-isostatic rebound (21 ka to present) between some 80-50 m was modeled (Norton and Hampel, 2010). As discussed in detail elsewhere (Sanders et al., 2014), there is no record of this uplift by the post-glacial slot canyons in their relation to the older canyon reaches. In other words, already before the LGM, Steinberger Ache was adjusted to a similar level or perhaps even a deeper one as that of today. As there is hardly a doubt on the phenomenon of post-glacial rebound, our observations thus may suggest that at least parts of the NCA underwent glacial-interglacial isostatic ‚yo-yo' movement, but experienced little net uplift, or even slow subsidence (cf. Höggerl, 2007), over 10s of ka or perhaps longer.

The re-activated older canyon reaches of course are not fully identical to their pre-LGM predecessors; in re-activation, the gorge may be widened by lateral bank erosion, and re-exposed cliffs are subject to physical erosion. Locally, the preservation of canyon walls may be very good, such as the cliff onlapped by the lacustrine sediments of Stop 6. For *pre-LGM* talus slopes, it was documented that in many cases these onlap the toe of rock cliffs still standing high; in other cases, however, fossil talus is partly offset or even completely perched from its present geomorphic setting (Sanders et al., 2009). The coupling of a fossil talus to its geomorphic setting is not a straightforward function of age; it rather results from landscape dissection that may act at highly different rates at different locations. Both, the Steinberg canyon study and the former observations on fossil talus thus highlight that the mountain scenery is a mosaic of landscape elements of different ages.

References

Ampferer, O. (1905): Aus der geologischen Geschichte des Achensees.– Zeitschr. d. Dt. & Österr. Alpenvereins, 36: 1-15.

Caporali, A., Neubauer, F., Ostini, L., Stangl, G., Zuliani, D. (2013): Modeling surface GPS velocities in the Southern and Eastern Alps by finite dislocations at crustal depths.– Tectonophysics, 590: 136-150.

Gruber, A. (2008): Bericht 2006 über geologische Aufnahmen auf den Blättern 88 Achenkirch und 119 Schwaz.– Jb. Geol. Bundesanst.: 148, 277-281.

Gruber, A., Wischounig, L., Sanders, D. (2011): Ablagerungs- und Flussgeschichte während des späten Quartärs im Bereich nördlich des Rofan.– In: Gruber, A. (ed.): Arbeitstagung 2011 der Geologischen Bundesanstalt Blatt 88 Achenkirch, 226-246, Geologische Bundesanstalt, Wien.

Höggerl, N. (2007): Höhenänderungen in Österreich.– In: Hofmann, T., Schönlaub, H.P. (eds.): Geo-Atlas Österreich, 56-57. Böhlau, Wien.

Horvacki, J. (1982): Ablagerungsmodell der Tiroler Bändertone aufgrund sedimentpetrographischer Analysen mit rohstoffkundlicher Bewertung.– 124 p., Unpubl. Ph. D. thesis, University of Innsbruck,.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., Schlüchter, C. (2008): Chronology of the last glacial cycle in the European Alps.– Jour. Quat. Sci., 23: 559–573.

Kerschner, H., Hertl, A., Gross, G., Ivy-Ochs, S., Kubik, P. Q. (2006): Surface exposure dating of moraines in the Kromer valley (Silvretta Mountains, Austria)-evidence for glacial response to the 8.2 ka event in the Eastern Alps?- The Holocene, 16: 7-15.

Kuhlemann, J. (2007): Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Glob. Planet. Change, 58: 224-236.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J. (1987): Age dating and the orbital theory of the ice ages: development of a high resolution 0 to 300.000-year chronostratigraphy.– Quat. Res., 27: 1-29.

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

Norton, K.P., Hampel, A. (2010): Postglacial rebound promotes glacial re-advances–a case study from the European Alps.– Terra Nova, 22: 297-302.

Preusser, F. (2004): Towards a chronology of the Late Pleistocene in the northern Alpine foreland.– Boreas, 33: 195-210.

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

Reitner, J. M. (2007): Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications. Quat. Int., 164-165: 64-84.

Reitner, J. (2011): Das Inngletschersystem während des Würm-Glazials.– In: Gruber, A. (ed.): Arbeitstagung 2011 der Geologischen Bundesanstalt, Blatt 88 Achenkirch, 79-88. Geologische Bundesanstalt, Wien.

Robl, J., Hergarten, S. & Stüwe, K. (2008a): Morphologial analysis of the drainage system in the Eastern Alps.– Tectonophysics, 460: 263-277.

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

Sanders, D. (2012): Effects of deglacial sedimentation pulse, followed by incision: A case study from a catchment in the Northern Calcareous Alps (Austria).– E&G Quat. Sci. Jour., 61: 16-31.

Sanders, D., Ostermann, M. & Kramers, J. (2009): Quaternary carbonate-rocky talus slope successions (Eastern Alps, Austria): sedimentary facies and facies architecture.– Facies, 55: 345-373.

Sanders, D. & Ostermann, M. (2011): Post-last glacial alluvial fan and talus slope associations (Northern Calcareous Alps, Austria): A proxy for Late Pleistocene to Holocene climate change. Geomorphology, 131: 85-97.

Sanders, D., Wischounig, L., Gruber, L. & Ostermann, M. (2014): Inner gorge-slot canyon system produced by repeated stream incision (eastern Alps): significance for development of bedrock canyons.– Geomorphology, 214: 465-484.

Schmid, S.M., Fügenschuh, B., Kissling, E. & Schuster, R. (2004): Tectonic map and overall architecture of the Alpine orogen.– Ecl. Geol. Helv., 97, 93-117.

Starnberger, R., Rodnight, H. & Spötl, C. (2011): Chronology of the Last Glacial Maximum in the Salzach palaeoglacier area (Eastern Alps).– Jour. Quat. Sci., 26: 502-510.

van Husen, D. (1987): Die Ostalpen in den Eiszeiten.– 24 S., Geologische Bundesanstalt, Wien.

van Husen, D. (2000): Geological Processes during the Quaternary.– Mitt. Österr. Geol. Ges., 92: 135-156.

van Husen, D. (2004): Quaternary glaciations in Austria.– In: Ehlers, J. & Gibbard, P. L. (eds.): Quaternary Glaciations-Extent and Chronology, Developments in Quaternary Science 2, 1-13, Elsevier, Amsterdam.

van Husen, D. & Reitner, J. (2011): An outline of the Quaternary stratigraphy of Austria.– E&G Quat. Sci. Jour., 60: 366-387.

Wischounig, L. (2006): Das Quartär bei Steinberg am Rofan (Tirol): Stratigraphie, Sedimentologie und Aspekte der Landschaftsentwicklung.– 105 S., Unpubl. Diploma thesis, University of Innsbruck.

Zeitschrift/Journal: Geo.Alp

Jahr/Year: 2016

Band/Volume: 013

Autor(en)/Author(s): Sanders Diethard, Gruber Alfred

Artikel/Article: Field trip 13 Inner gorge-slot canyon system produced by repeated major base-level changes (Northern Calcareous Alps) 277-292