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Effects of deglacial sedimentation pulse, followed by incision: A case study from a catchment in the Northern Calcareous Alps (Austria).

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Abstract: In the 'Giessenbach' catchment (Northern Calcareous Alps, NCA), a thick sedimentary succession accumulated during to shortly after deglaciation. The catchment is located on faulted and jointed Triassic dolostones. Up-section, the Quaternary succession consists of: (a) redeposited till with index clasts of the Last Glacial Maximum (LGM), (b) pebbly alluvium supplied from the dolostone substrate, (c) fluvial deposits veneering terraces, and (d) large scree slopes. Today, the pre-LGM upstream half of the Giessenbach course is a dry, elevated valley filled by deglacial to Holocene sediments. The present Giessenbach stream shows a convex longitudinal profile, with a bedrock gorge in its lower reach; the gorge was probably blocked by dead ice when deglacial sedimentation started. Aside of glacially-shaped surfaces and former nunataks, the present catchment morphology is characterized by: (a) mass-wasting deposits derived from a pulse of rapid deglaciation and, after slope stabilization, by (b) stream incision. Strong sedimentation was favoured by the structurally deformed dolostone substrate that weathers under copious production of clastic material. In the NCA, records of similar histories from rapid, deglacial sedimentation to prolonged post-glacial incision are widespread.

Auswirkungen starker spätglazialer Sedimentation, gefolgt von Erosion: Eine Fallstudie aus den Nördlichen Kalkalpen (Österreich)

Kurzfassung: Im Einzugsgebiet des 'Giessenbaches' (Nördliche Kalkalpen, NKA) lagerte sich eine mächtige Sedimentabfolge während bis wenig nach dem Zerfall des hochglazialen Eispanzers ab. Das Einzugsgebiet liegt auf gestörten, geklüfteten triassischen Dolomitgesteinen. Die quartäre Abfolge besteht aus, (a) aufgearbeitetem Till mit Leitgeschieben des Letzten Glazialen Maximums (LGM), (b) alluvialen Kiesen, die vom Dolomitgesteins-Untergrund gespeist wurden, (c) Decklagen von Flusssedimenten auf Terrassen, und (d) grossen Schutthalden. Die ehemalige (Vor-LGM) obere Hälfte des Giessenbach-Laufs ist noch heute ein trockenes, erhöhtes Tal das wesentlich durch spätglaziale bis holozäne Sedimente verfüllt ist. Der heutige Giessenbach zeigt ein konvexes Längsprofil mit einer Klamm im Unterlauf; diese Klamm war wahrscheinlich teilweise durch Toteis versperrt während die Sedimentation der Eiszerfallsphase bereits eingesetzt hatte. Außer glazial überformten Felsflächen und ehemaligen Nunatakkern ist die heutige Morphologie des Einzugsgebiets im wesentlichen bestimmt durch (a) einen ‚Schub' sehr rascher Sedimentation vom Eiszerfall bis ins ?frühe Spätglazial, gefolgt von (b) Hangstabilisierung durch Bewachsung, und Einschneiden von Gerinnen. Die rasche Sedimentation wurde durch den Untergrund aus tektonisch verformtem Dolomitgestein gefördert, das unter reichlicher Schuttbildung abwittert. Ähnliche Verläufe von rapider Sedimentation vom Eiszerfall bis zum Spätglazial hin zu einem längeren Zeitabschnitt vorwiegend mit Einschneiden von Gerinnen sind in den NKA weit verbreitet.

Keywords: *Alps, deglacial, paraglacial, Eastern Alps, late glacial, sedimentation, erosion*

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1 Introduction

In the Alps, thick proglacial sediment accumulations in valleys blocked by advancing ice streams are described in different studies (e. g., Fliri 1973; Van Husen 1977, 2000; de Graaff 1996; Gruber et al. 2011). The proglacial deposystems were characterized by high sediment accumulation rates chiefly as a result of climatic deterioration, hillslope stripping and associated increase in physical weathering (Van Husen 1983). Similarly strong intramontane sedimentation was associated with decay of the ice streams of the Last Glacial Maximum (Van Husen 1997; Müller 1999; Hinderer 2001). The deglacial 'sedimentation pulse' and its impacts on sediment distribution, morphology and drainage, however, are little documented to date. Most deglacial deposystems such as rock glaciers, alluvial fans, valley fans, talus slopes and lakes today are abandoned or in a state of low activity, and in many cases undergo erosion (Reitner 2007; Sanders, Ostermann & Kramers 2009; Sanders & Ostermann 2011). For a short valley within the NCA, based on seismic surveys, Schrott et al. (2004) conclude that post-LGM alluvial fans and talus slopes comprise the largest sediment storage in that valley, and that this should be similar in comparable valleys. Except for active talus slopes today located typically higher than about 1800–2000 m a.s.l. in the present NCA, most alluvial fans and scree slopes mainly began to accumulate during deglacial time (Sanders, Ostermann & Kramers 2009; Sanders & Ostermann 2011). At many sites within the NCA, the deglacial sediment bodies are

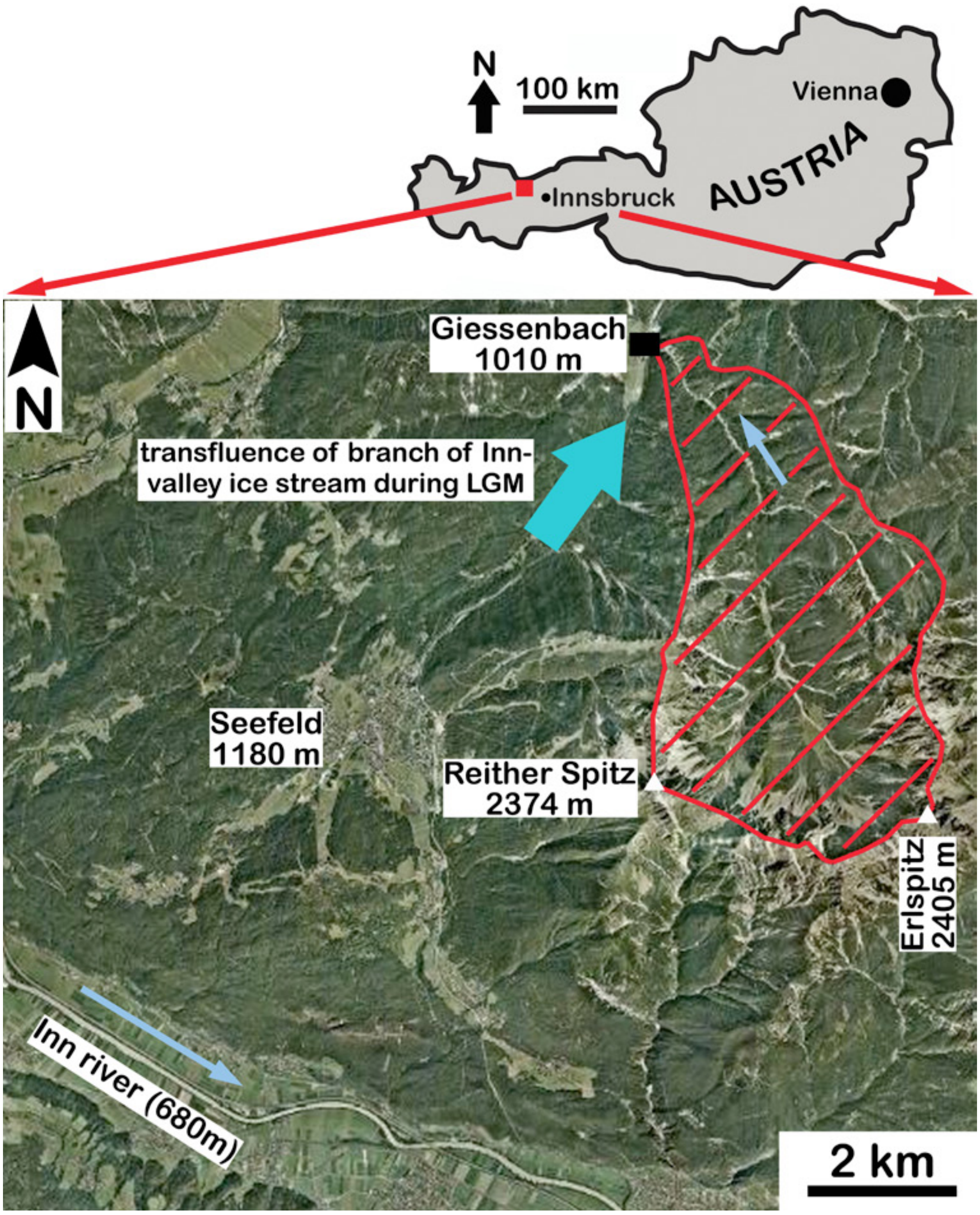

Fig. 1: Above: Position of investigated area in Austria. Below: Satellite image of catchment (red cross-hatch) and its surrounding area (source: Google Maps). During the Last Glacial Maximum, the Inn valley hosted a major ice stream. Part of the ice stream flowed towards the North over the low rock ridge in the area of Seefeld village and also affected the investigated drainage area.

Abb. 1: Oben: Lage des Untersuchungsgebiets in Österreich. Unten: Satellitenbild des Einzugs-Gebiets (rote Kreuzschraffur) und seiner Umgebung (Quelle: Google Maps). Während des Letzten Glazialen Hochstandes verlief im Inntal ein mächtiger Eisstrom. Ein Teil des Eises floss über den niederen Felsrücken im Bereich des Dorfes Seefeld nach Norden und beeinflusste damit auch das hierin betrachtete Einzugs-Gebiet.

well-preserved or are still only partially removed by later erosion.

In the Eastern Alps, the Last Glacial Maximum (LGM; 24–21.1 ka, Preusser 2004) was followed by rapid collapse of ice streams down to about 50% of LGM ice volume. This, early late glacial ice decay‘ (ELGID) is bracketed to 21.1–19 ka BP (Van Husen 2004). Due to its distinct sedimentary records, the ELGID now can be distinguished as a separate post-glacial episode (Reitner 2007; Ivy-Ochs et al. 2009). Upon debuttressing from pleniglacial ice cover, small glaciers supplied from local catchments in the NCA advanced for a short period of time, before retreating, too (Reitner 2007). The ELGID was followed by the late glacial that, in present terminology, would last from ~19 ka to the onset of the Holocene. The late glacial was characterized by stadial-interstadial cycles with progressively smaller outreach of valley glaciers (Van Husen 2004; Ivy-Ochs et al. 2009). Herein, in analogy to other studies of glacial to post-glacial deposits on land and in the sea (e.g., Hein et al. 2010; Bard et al. 1996), the term ‚deglacial‘ is used as an umbrella for sediments accumulated between the end of the LGM to the start of the Holocene; the term thus comprises both the ELGID and the late glacial as outlined. Over the past ten years or so the term ‘paraglacial’, defined as ‘processes directly conditioned by glaciation’ (Church & Ryder 1972), has seen a renaissance. Today, catastrophic rockslides and

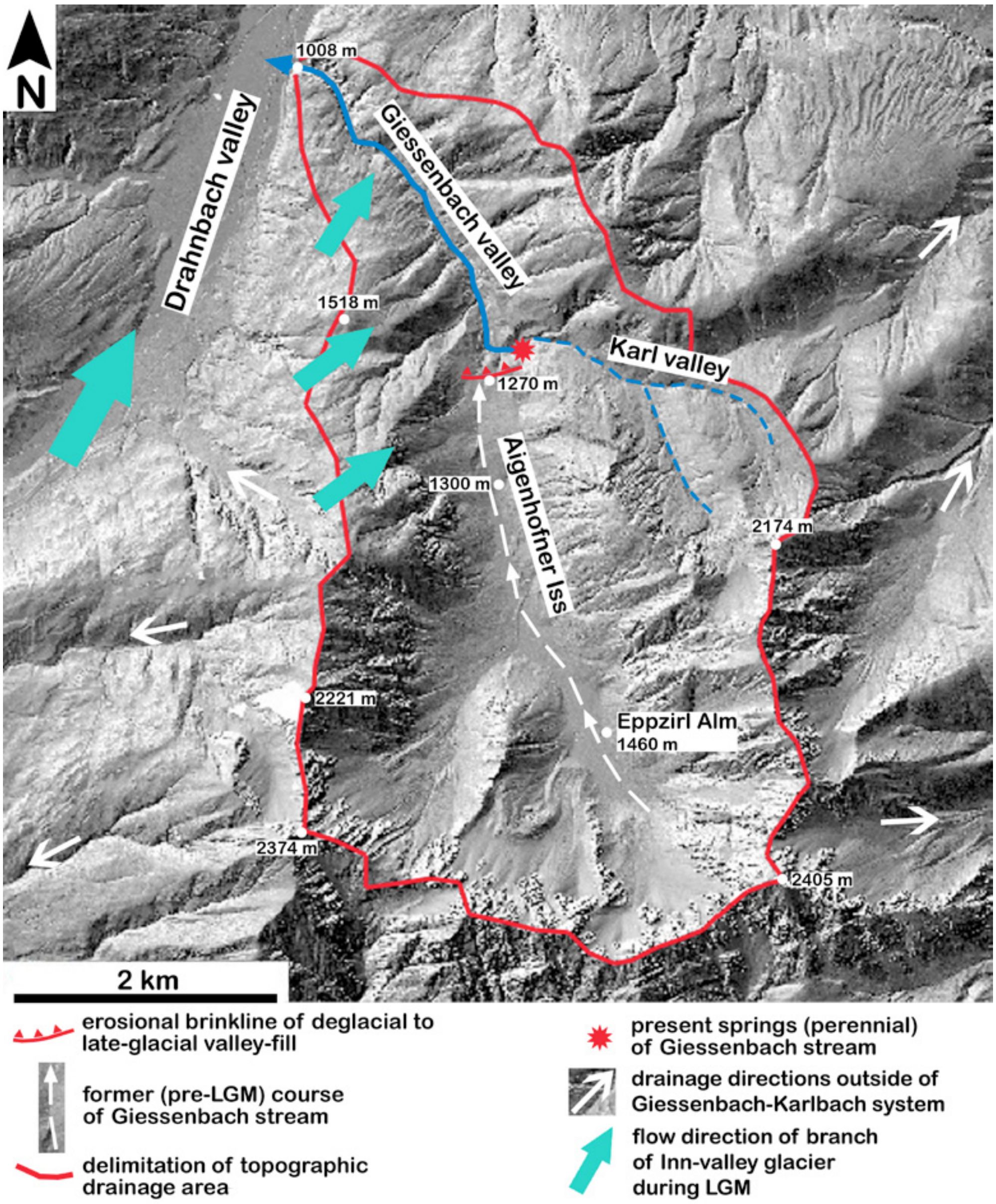

Fig. 2. Laserscan image with topographic drainage area of Giessenbach-Karl valley system (source: www.tirol.gv.at). Gießenbach is a perennial stream that originates from several adjacent springs. Karlbach is ephemeral, and water-run only after heavy rains and/or during prolonged foul weather. The larger, upper part of the drainage area of Gießenbach is a dry valley filled by sediments (Aigenhofner Iss to Eppzirl Alm). The valley-fill terminates along an erosional brinkline towards present Giessenbach.

Abb. 2: Laserscan des topographischen Einzugsgebiets des Giessenbach-Karltal systems (Quelle: www.tirol.gv.at). Giessenbach ist ein perennialer Fluss der aus mehreren benachbarten Quellen entspringt. Der ephemerale Karlbach ist nur nach Starkniederschlägen und während langer Schlechtwetter-Phasen wasserführend. Der längere, obere Teil des Einzugsgebiets des Giessenbachs ist ein Trockental, das von Sedimenten verfüllt ist (Aigenhofner Iss bis Eppzirler Alm); diese Sedimentfüllung endet scharf an einer Erosionskante und einem Steilabfall zum heutigen Giessenbach.

slow deep-seated gravitational mass movements occurring more than 10–15 ka after glaciation are subsumed as paraglacial phenomena (Ballantyne 2002; Kellerer-Pirklbauer, Proske & Strasser 2010). Paraglacial sedimentation, that is, mainly reworking of glacial deposits through debris flows and alluvium, starts immediately after ice retreat at site (Church & Ryder 1972; Ballantyne 1995; Curry & Ballantyne 1999). With respect to alluvial systems, however, a termination of paraglacial sedimentation can be hardly defined because it is a gradual fadeout in space and time, superposed by stadial-interstadial cycles (Orwin & Smart 2004; cf. Tunnicliffe & Church 2011). Therefore, the sedimentation patterns described in the present paper are preferrably characterized as deglacial rather than paraglacial. In this paper, an example of deglacial sedimentation is described that presently has a profound influence on the morphology and hydrology of a typical NCA catchment. Rapid deglacial sedimentation was followed by linear erosion, resulting in complicated stratigraphic and geomorphic patterns. The results are discussed in relation to similar, widespread deglacial deposits in the NCA.

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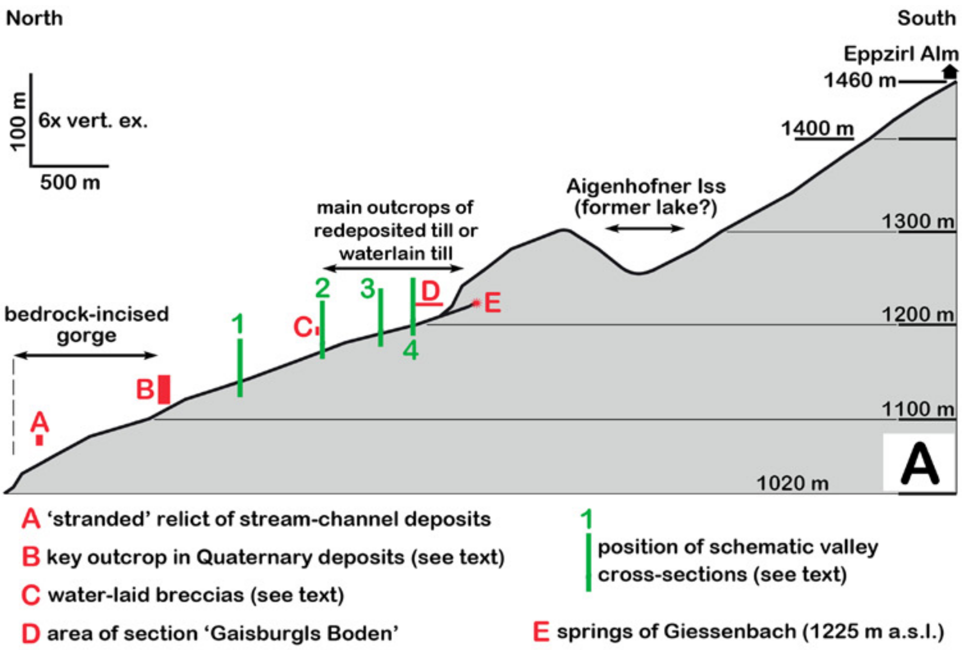

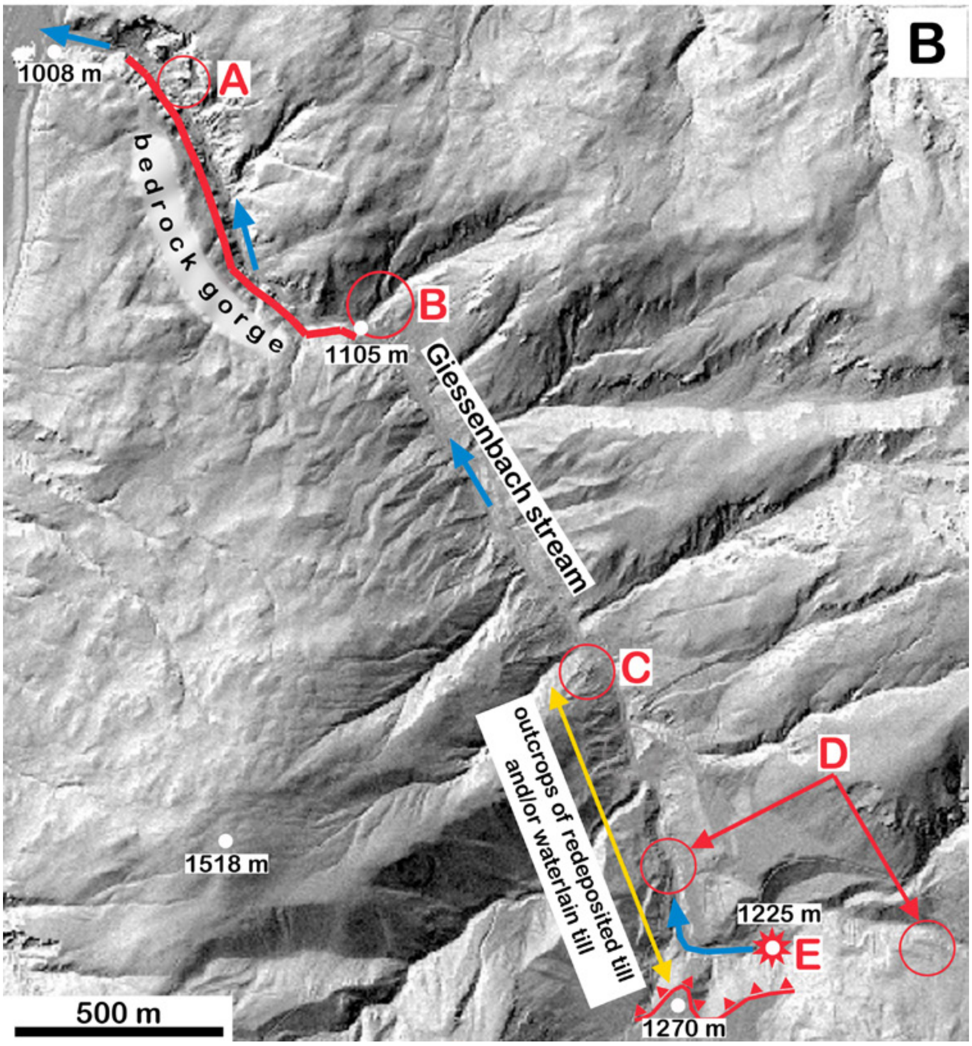

Fig. 3. A. Longitudinal section through Giessenbach valley to Eppzirl Alm (cf. Fig. 1). Note (a) overall convex longitudinal stream profile, (b) knick in stream profile in the distal reach of the bedrock gorge, and (c) the ‚swell' of valley-fill deposits. B. Laserscan image (source: www.tirol.gv.at) of present Giessenbach course, with features labeled A to E as in subfigure A above.

Abb. 3. A. Längsschnitt durch das Giessenbachtal bis zur Eppzirler Alm (vgl. Abb. 1). Beachte, (a) das konvexe Längsprofil, (b) den Profilknick im distalen Abschnitt der Klamm, sowie (c) die ‚Schwelle' aus Talfüllungs-Sedimenten. B. Laserscan (Quelle: www.tirol.gv.at) des heutigen Giessenbach-Laufes, mit den wichtigen Stellen A bis E wie in Subfigur A erläutert.

2 Setting

The NCA are part of the Upper Austroalpine structural unit of the Eastern Alps, and consist of stacked cover-thrust nappes dominated by Triassic platform carbonates (e.g., Neubauer, Genser & Handler 1999; Schmid et al. 2004). The rock substrate of the studied area (Fig. 1) consists of a thick, folded and faulted succession of Upper Triassic dolostones (Hauptdolomit unit). The Hauptdolomit accumulated in banktop environments of a large carbonate platform (Brandner 1984). In the specific area, the Hauptdolomit contains intercalated packages a few tens of meters in thickness of black shales and limestones of an oxygen-deficient intra-platform basin (Seefeld Formation; Donofrio, Brandner & Poleschinski 2003). During Alpine folding and faulting, in the relatively low-tempered portions of the thrust-nappe stack, the Hauptdolomit reacted brittlely and was subject to dense jointing; as a result, it typically degrades under copious production of scree (Sanders, Ostermann & Kramers 2009).

During buildup of the LGM, a bedrock swell with an altitude of about 1100–1200 m ('Seefeld Sattel') was overridden by a northward flowing branch of the Inn-valley ice stream; this branch then advanced northward along present Drahnbach valley (Fig. 1). Transfluence of Inn-glacier ice, across the low rock ridge between Giessenbach valley and Drahnbach valley, is recorded by the presence of index clasts (see below) (Fig. 2). In the investigated area, the reconstructed ice surface of the LGM was located between about 2100–2200 m a.s.l.; as a result the southern, higher crest of the topographic drainage area, with summits between about 2200 to 2400 m a.s.l. (Fig. 2), comprised a crescent-shaped nunatak (Van Husen 1987, 2004). The deposits of the LGM Inn glacier are characterized by three types of index clasts: (a) dark-green garnet amphibolites and eclogites derived from the Engadin area along the uppermost reach of the Inn; (b) granites with green-coloured feldspar, derived from the Julier massif also along the uppermost reach of the Inn valley, and (c) light-green to whitish, diablastic garnet amphibolites rich in feldspar; this latter lithology originated from Alpine retrograde metamorphism of Variscan eclogites, and is derived from source areas in the Oetztal-Stubai basement unit only about 70 km upstream of the area considered herein.

The exposed Quaternary succession along the Gießenbach-Karlbach drainage system (Fig. 2) is up to at least about 100–120 m in cumulative thickness, and consists of distinct units to be described herein. For sake of communication, the most significant units are mentioned beforehand; they include, (1) a basal interval of redeposited glacial till with index clasts of the LGM, overlain by (2) a thick succession of alluvial gravels accumulated from a braided-stream system, and (3) comparatively thin intervals of fluvial deposits (rich in index clasts of LGM) that veneer terraces incised into the deposits mentioned above. In its upper and middle reaches, Giessenbach stream runs on a sediment bed (from about 1100 m a.s.l.). The lower reach is a bedrock gorge (Fig. 3). Today, the Gießenbach stream is supplied by several perennial springs emerging in a small area at 1225 m a.s.l. (Fig. 3). The springs emerge along the top of the lowermost stratigraphic unit (1) mentioned above; elsewhere, this level is also characterized by numerous seepages. Conversely, Karl valley is water-run only during and closely after rainstorms. The Giessenbach valley abuts a very steep erosional slope of a valley-fill composed mainly of stratigraphic units (1) and (2) (Fig. 3A). The top of this valley-fill is situated at about 1270 m a.s.l. (Fig. 2, Fig. 3B). Above 1270 m, the valley is floored by talus slopes, and at approximately 1250–1260 m a.s.l. a subhorizontal plane is present that comprises an ephemeral pond during spring and summer (Aigenhofner Iss; Fig. 2, Fig. 3A); as outlined below, the Aigenhofner Iss may have been filled by a lake during the early deglacial interval. Still higher up, the valley is filled by a valley-fan, scree slopes, and fossil rock glaciers (Fig. 2, Fig. 3A).

3 Methods

The area was investigated during repeated field visits over an interval of eleven years; this reduced bias from seasonally-changing outcrop conditions as typical of unlithified sedimentary successions. Isohypsed satellite orthophotographs and laserscan images (both down to 1/1.000), provided free by the federal government of Tyrol (www.tirol.gv.at), improved precision in mapping and altitude leveling of outcrops. Columnar sections, documentation of key outcrops, and consideration of geomorphic features supported reconstruction of the deglacial to interglacial history of the considered area. Cut slabs and thin sections of a few lithified intervals within the Quaternary succession supplemented description and interpretation of facies. X-ray powder diffractometry used to determine the mineralogical composition of fine-grained deposits was undertaken on a Bruker-AXS D8 diffractometer with Bragg-Brentano geometry, CuKα radiation at 40kV and 40mA acceleration voltage, with parallel-beam optics and an energy-dispersive detector. The data was collected between 2 and 70° 2θ, with a step size of 0,02° 2θ and a detecting time of four seconds per step. Crystalline phase identification was achieved with the program Eva.Ink and the PDF4 data base 8.0.113 of ICDD. The x-ray spectra of two samples were analysed with the programs DIFFRAC PLUS (phase identification) and TOPAS (quantitative assessment).

4 Sedimentary facies

4.1 Description

The sedimentary facies, their composition and interpretation are summarized in Tables 1 and 2. Along Giessenbach, between approximately 1170 to 1230 m a.s.l., the stratigraphically deepest exposed deposits include two facies types: facies 1 consists of unlaminated and unbedded carbonate-rich silt to -mud that locally contains scattered, disorientated clasts of metamorphic rocks and/or of carbonate rocks (Fig. 4A–D, Tab. 1). The carbonate rock clasts are derived from the Hauptdolomit unit and the Seefeld Formation, and typically range from coarse-sand to medium gravel size; locally, clasts of cobble size are present (Fig. 4B). Rounding of the carbonate-lithic clast fraction is highly variable (Fig. 4A–D). Carbonate rock clasts may show surfaces with scratch marks (Fig. 4B, inset). Clasts of metamorphic rocks

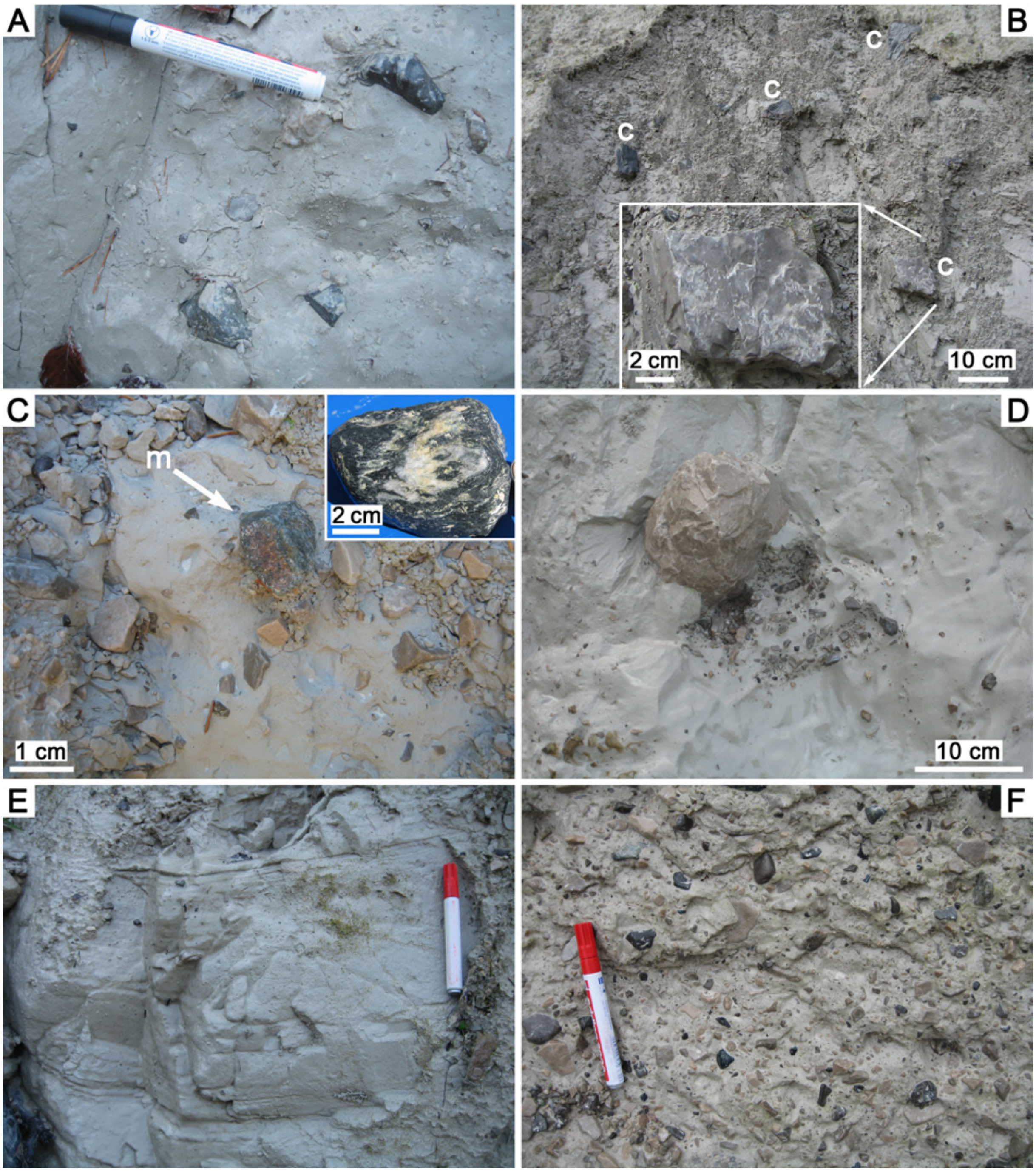

Fig. 4. A. Diamict with disordered, subangular clasts of carbonate rocks. The groundmass of the diamict is a dolomud to -silt with a few percent of siliciclastic material (Table 2). Left bank of Gießenbach, 1195 m a.s.l. Pen is 14 cm long. B. Diamict with angular coarse gravels to cobbles (some labeled with c) derived from the Hauptdolomit unit and the Seefeld Formation. Inset shows clast surface with scratch marks. Left bank of Giessenbach, 1210 m a.s.l. C. Diamict rich in carbonate rock clasts, and with a clast of metamorphic rock (shown by arrow labeled m). Inset shows clast of amphibolite excavated from the same location. Right bank of Giessenbach, 1210 m a.s.l. D. 'Cluster' of carbonate rock clasts, floating in a matrix of carbonate-rich mud to -silt. Left bank of Giessenbach, 1215 m a.s.l. E. Interval of faintly parallel-laminated, carbonate-rich mud to -silt. Left bank of Giessenbach, 1215 m a.s.l. F. Diamict of disordered carbonate-rock fragments (from Hauptdolomit unit) and fragments of metamorphic rocks derived by pleniglacial drift. Matrix is a dolomud to -silt with a few percent of siliciclastic material (see Table 2). Left bank of Gießenbach, 1185 m a.s.l. Pen is 14 cm long.

Abb. 4. A. Diamikt mit disorientierten Bruchstücken aus Karbonatgestein. Die Grundmasse ist ein halbverfestigter Dolomitschlamm von Ton- bis Siltkorngrösse mit wenigen Prozent an siliziklastischem Material (Tabelle 2). Linkes Ufer des Giessenbaches, 1195 m über NN. Stift ist 14 cm lang. B. Diamikt mit angularen Klasten von Grobkies- bis Stein-Grösse (einige mit c markiert), die aus der Hauptdolomit Einheit und der Seefeld-Formation stammen. Das eingesetzte Bild zeigt Schurfmarken an der Oberfläche eines der Klasten. Linkes Ufer des Giessenbaches, 1210 m über NN. C. Diamikt mit vielen Klasten aus Karbonatgestein sowie einem Klasten aus Metamorphit (Pfeil m). Das eingesetzte Bild zeigt einen Klasten aus Amphibolit, der an dieser Örtlichkeit aus dem Diamikt geborgen wurde. Rechtes Ufer des Giessenbaches, 1210 m über NN. D. Lose Ansammlung von Karbonatgesteins-Klasten, die in einer Matrix aus halbverfestigtem Dolomitschlamm von Ton- bis Siltkorngrösse schwimmt. Linkes Ufer des Giessenbaches, 1215 m über NN. E. Lage aus undeutlich parallel-laminiertem, halbverfestigtem karbonatreichem Schlamm bis Silt. Linkes Ufer des Giessenbaches, 1215 m über NN. F. Diamikt aus disorientierten Karbonatlithoklasten (aus der Hauptdolomit-Einheit) und Fragmenten von Metamorphiten von hochglazialer Drift. Die Grundmasse ist ein halbverfestigter Dolomitschlamm von Ton- bis Siltkorngrösse mit wenigen Prozent an siliziklastischem Material (siehe Tabelle 2). Linkes Ufer des Giessenbachs, 1185 m über NN. Stift ist 14 cm lang.

Tab. 1: Prevalent facies types along Gießenbach stream. Facies types of minor significance and/or minor extent are described in the text only, or in figure captions. Facies of outcrop B (see Fig. 3) are described in Table 3. See text for description of index clasts of Inn glacier of Last Glacial Maximum.

Tab. 1: Vorwiegende Faziestypen entlang des Giessenbachs. Faziestypen von geringerer Bedeutung und/oder Ausdehnung werden im Text oder in Figurenbeschriftungen behandelt. Die Fazies des Aufschlusses B (siehe Abb. 3) werden in Tabelle 3 gesondert beschrieben. Siehe Text für die Beschreibung der Leit-Lithologien des Inn-Gletschers des Letzten Glazialen Maximums.

Facies number Designation	Description	Interpretation of sediment Interpretation within sequence of events	Remarks
#1 Diamicton with sparse lithoclasts to unbedded, carbonate-rich silt to mud	Unbedded, unlaminated carbonate silt to mud, locally with floating, disoriented lithoclasts of carbonate rocks and few clasts of metamorphic rocks (e. g. index clasts of LGM, garnet amphibolite, amphibolite, quartzite). Some lithoclasts show polished and striated surfaces. Deposit lacks: (a) shear bands, (b) vertical joints. Intercalated interval (few dm in thickness) of banded carbonate silt to mud (facies 1a, see text).	Interpretation A: Subaerial, paraglacial redeposition of glacial till of LGM by mudflows (facies 1) and cohesive debris flows (facies 2) OR: Intepretation B: Facies 1 and 2 represent a waterlain till associated with a late-glacial local-sourced glacier. Level of postulated lake had to be located at least at about 1225–1230 m a.s.l.	Facies 1 and 2 are: (a) vertically associated with each other, (b) similar in mineralogical composition of their matrix (see Tab. 2). Unit composed of facies 1 and 2 exposed in upper reach of Gießenbach valley between about 1170–1230 m a.s.l. (Fig. 3, Fig. 9)
#2 Diamicton rich in lithoclasts (typically clast-supported)	Unbedded to faintly stratified, clast- to matrix-supported gravelly deposits with a matrix of carbonate silt to mud. Lithoclasts include local-derived carbonate rocks and metamorphic rocks from glacial drift (e. g. index clasts of LGM, amphibolite, garnet mica schist);. Some lithoclasts show polished, faceted and striated surfaces. Deposit lacks: (a) shear bands, (b) vertical joints, (c) 'overcompaction', (d) clasts fractured at point contacts.		
#3 Stratified alluvial gravels	Stratified, clast-supported gravels of angular to subrounded clasts of carbonate rocks. Indistinct strata dip subhorizontally to about 5-15° down-valley, and are typically 10-30 cm in thickness. Clasts of metamorphic rocks (including index clasts of LGM) are rare but persistently present throughout. Matrix is a carbonate-muddy sand of carbonate-rock fragments, with scarce siliciclastic grains. Locally, this facies is lithified into breccias (facies 3a) contained within.	Sheet-flow deposits of braided stream dominated by carbonate gravels. After a first phase of reworking of till and/or deposition of waterlain till ahead of a local-sourced glacier (facies 1+2), massive shedding of scree from local bedrock hillslopes started, perhaps in addition to continued redeposition of basal till. Combined with a probably elevated base-level as a result of decaying Inn-valley ice stream (see also text), this led to strong aggradation along Gießenbach valley.	Facies 3 comprises the majority of sediment volume along Gießenbach valley Stratified alluvial breccias: see Fig. 5A to 5D
#3a Alluvial breccias	Of identical characteristics than facies 3, but lithified by: (a) fringes of micrite and/or (b) thin fringes of calcitic dog tooth spar, and/or (c) by lithification of carbonate-muddy matrix	Localized lithification of alluvial gravels in a meteoric-vadose to essentially phreatic environment (Sanders, Ostermann & Kramers 2010)	
#4 Cohesive debris-flow deposits	Layers up to a few decimeters thick of angular to subrounded clasts of carbonate rocks, with a matrix of cohesive carbonate mud to carbonate-muddy lithic sand; typically clast-supported. Rare clasts of metamorphic rocks (including index clasts of LGM). Intercalated in lower part of successions composed of facies 3	Deposits of cohesive debris flows	Facies of minor significance with respect to volume
#5 Gravelly to bouldery fluvial deposits rich in LGM index clasts	Stratified, clast-supported, gravelly to bouldery deposits composed of subequal amounts of: (a) very well-rounded gravels to small boulders of metamorphic rocks (including index clasts of LGM), and (b) subangular to well-rounded gravels to cobbles of local carbonate rocks. Clast imbrication of a(p,t)b(i,p)-type common. This facies comprises veneers a few decimeters to about 2 meters in thickness atop terrace surfaces (at different levels) alongside the present Gießenbach and Karlbach streams.	Fluvial deposits of re-incision phase of Gießenbach-Karlbach streams, down to their present level Sheet-flow deposits (terrace veneers) and channel deposits Represents the late-glacial to Holocene state of Gießenbach-Karlbach drainage system.	A relict patch of this facies is present on a strath terrace of Gießenbach stream near the exit of the bedrock-incised gorge (outcrop A in Fig. 3).

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such as garnet amphibolite, amphibolite, mica schist and gneiss are rare and confined to a few matrix-supported layers. The clasts of metamorphic rocks are in the coarse sand- to medium-gravel size range; a single amphibolite clast of coarse gravel size was found (Fig. 4C). Locally, lithoclasts are present in matrix- to clast-supported ‚clusters' floating in the diamict (Fig. 4D). At 1210 m a.s.l., near the base of outcrop on the orographic right bank of Giessenbach, an interval about 30 cm in thickness of banded, carbonate silt to -mud is intercalated into the diamict (facies 1a; Fig. 4E, Tab. 1). Throughout the interval of facies 1, no evidence for ‚overcompaction', vertical jointing and shear bands was found. Facies 2 is represented by clast- to matrix-supported diamicton rich in clasts of metamorphic rocks, in addition to abundant carbonate rock clasts derived from the local drainage area (Fig. 4F, Tab. 1). Clast rounding ranges from angular to well-rounded. Most of the carbonate rock clasts are of subangular shape. In facies 2, clasts with striated surfaces are relatively common. Facies 2 is locally intercalated into facies 1, but mainly comprises the upper part of the interval composed of both facies 1 and 2. In both facies, stratification surfaces are absent or only faintly expressed. Where visible, stratification dips with a few degrees downvalley; no steeply inclined bedsets were observed. With respect to mineralogical composition the fine-grained matrices of facies 1 and 2 are closely similar: aside of a percentage of ~80–91 wt% dolomite, some 9–20 wt% consist of silicic minerals such as muscovite, chlorite and albite (Tab. 2). The intercalated interval of banded carbonate silt to -mud (Fig. 4E) contains slightly less of muscovite, quartz and chlorite than the diamict facies (Tab. 2).

Over most of Giessenbach valley, above facies 1 and 2, a thick succession ('alluvial succession') is present that is composed angular to subrounded gravels of carbonate rocks from the local drainage area, and an accessory but persistent content in clasts of metamorphic rocks, including index clasts of the LGM. The succession consists of two types of facies (Tab. 1): facies 3, represented by stratified gravels with openwork fabric or with a matrix of carbonate mud to winnowed, carbonate-lithic sand; clasts prevalently are arranged with their [a,b]-plane subparallel to stratification, but downstream-imbricated clast fabrics of (a)p,(b)i type are present, too. In outcrop C (cf. Fig. 3), the stratified gravels of facies 3 became locally lithified into breccias to conglomeratic breccias (=facies 3a; Tab. 1). The breccias are of identical composition, fabric and texture than their unlithified host deposits, including a low but persistent content of LGM index clasts (Fig. 5A, 5B). The breccias are lithified by: (a) thin fringes of micritic cement, and/or (b) thin fringes of dog tooth spar and, subordinately, (c) by lithification of carbonate mud (Fig. 5C). Rounded interstitial pores within a matrix of lithified carbonate mud may be fringed by micrite and/or dog tooth spar (Fig. 5D).

Facies 4 is closely similar in lithoclast fractions and clast sorting to the former one, but contains a matrix of carbonate mud; facies 4 commonly is clast-supported, but clasts are disoriented and no clast fabrics are obvious (Tab. 1). Finally, facies 5 is present as veneers a few decimeters to a few meters in thickness atop terraces incised into the older deposits (facies 1 to 4). Facies 5 consists of roughly equal amounts of gravels to boulders of metamorphic rocks (including index clasts of the LGM) derived from glacial drift, and of carbonate rocks from the local drainage area. In this facies stratification, clast support, and downstream imbrication of clasts (fabrics of (a)p,(b)i type) up to cobble or small boulder size are common; the matrix typically is a winnowed carbonate-lithic sand.

In outcrop B (Fig. 3), above 1105 m a.s.l. along the right flank of a ravine at the right bank of Giessenbach, a succession containing a record of the LGM is present. In this outcrop, six distinct depositional units G1 to G6 were distinguished. For characterization of depositional units, the reader is referred to Figure 6 and Table 3. By inference, the depositional units terminate in onlap onto the rock substrate a few tens of meters towards the north, where the incised bedrock gorge starts (Fig. 3). Conversely, about 20–25 meters towards the south, starting with the left (southern) flank of the incised ravine, outcrops are dominated by facies 3 to 5 as prevalent in the middle reach of Giessenbach valley (cf. Fig. 3).

4.2 Facies interpretation

Both facies 1 and 2 accumulated subsequent to the LGM. This is indicated by the presence of clasts of metamorphic rocks transported within the pleniglacial Inn glacier, combined with an absence of 'overcompaction', vertical joints and shear bands. As mentioned, the siliciclastic fractions of the fine-grained sediments of facies 1 and 2 are characterized by muscovite, chlorite and albite. Because each of these minerals is readily eradicated by chemical weathering (Berner & Berner 1996), this supports the hypothesis that the origin of the sediment fraction is from pleniglacial drift. The features of facies 1 suggest that it accumulated mainly from subaerial mudflows supplied by paraglacial redeposition of basal till. In facies 2, the prevalence of clast support combined with: (a) the presence of a matrix of silt to mud, and (b) the disoriented embedding of clasts indicates that it accumulated from cohesive debris flows. In consequence, the interval of faintly banded silt to -mud (facies 1a, Fig. 4E, Tab. 2) intercalated into facies 1 may record an ephemeral small lake or pond. An interpretation of facies 1 in terms of subaerial paraglacial mudflows is compatible with the intercalated layers of facies 2. Observations of melting glaciers in Norway show that redeposition of glacial till proceeds immediately after deglaciation at site, resulting mainly in debris flows and mud flows (Ballantyne & Benn 1994; Curry & Ballantyne 1999).

Alternatively, facies 1 and 2 together may represent a waterlain till of a Late glacial local-sourced glacier that debouched into an ice-marginal lake (cf. Reitner 2007). This glacier may have filled the former upper part of the drainage area from Gaisburgls Boden to Eppzirl Alm (Fig. 3). A local glacier that advanced immediately after decay of pleniglacial ice cover at site would redeposit glacial till inherited from the immediately preceeding ice cover. Both, *subaqueous* mudflows and rapid suspension fallout of mud and stones from the base of glaciers facing into proglacial lakes are common. The lack of vertical jointing and shear banding, the disoriented embedding of clasts, and the intercalated interval of banded silt in facies 1 are all com-

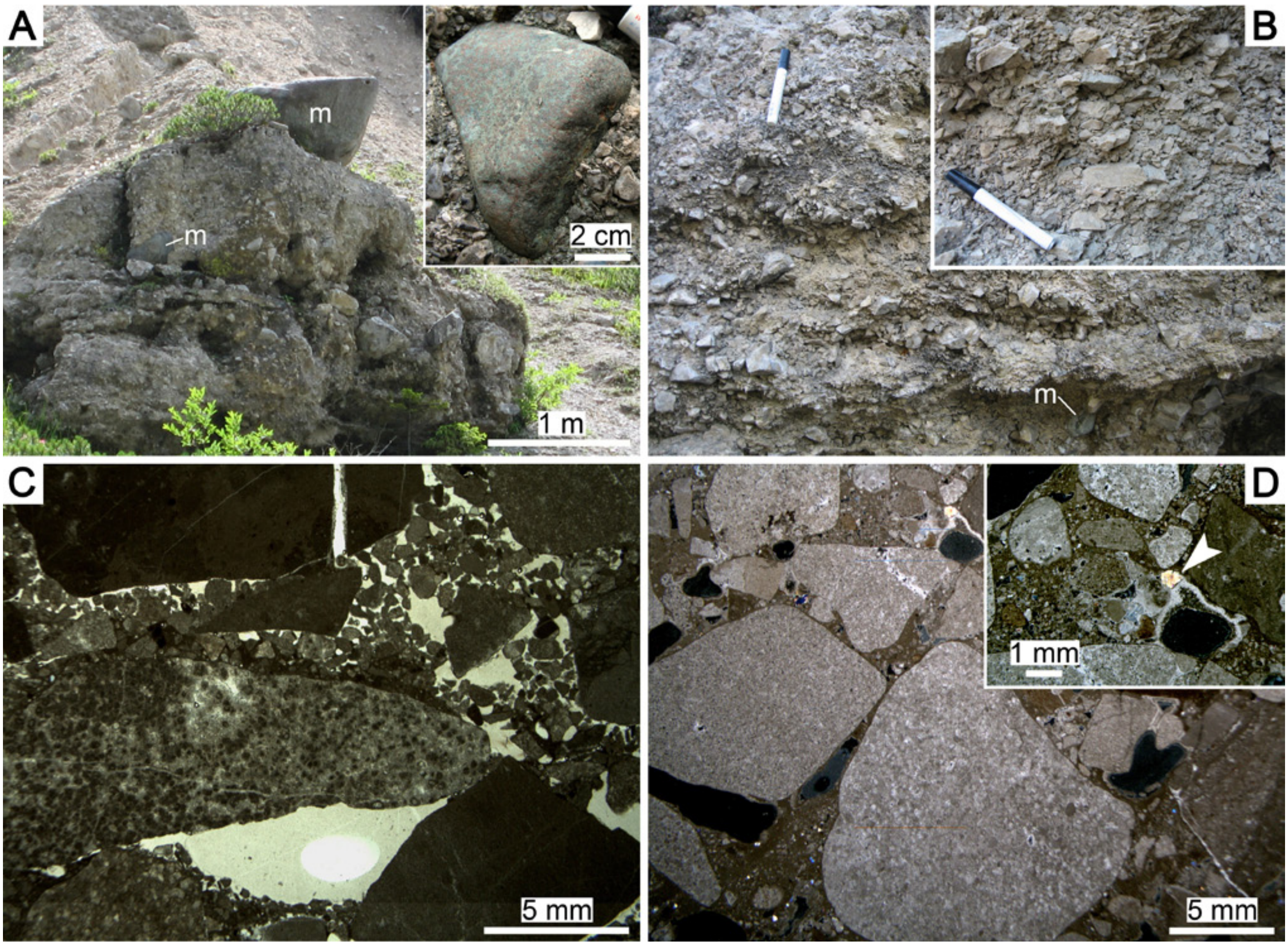

Fig. 5. A. Lithosome of breccia produced by local cementation of stratified alluvial gravels (facies 3; see Table 1). The breccia consists of clasts from the Hauptdolomit unit and of a few gravels to small boulders of metamorphic rocks (marked with ‚m'). Note gently-dipping stratification. Inset shows clast of garnet amphibolite, an index lithology of the Inn-valley ice stream of the Last Glacial Maximum (see text), embedded in the breccia. Outcrop C, 1185–1190 m a.s.l. (cf. Fig. 3). B. Detail of breccia shown in Fig. 5A. Note faint stratification, local downstream-imbricated clast fabrics, and composition mainly of angular clasts of Hauptdolomit and a few clasts of metamorphic rocks (labeled ‚m'). Pen is 14 cm long. C. Thin section of breccia shown in Fig. 5A. The interstitial pores of the breccia contain winnowed carbonate-lithic sand to silt cemented by very thin fringes of micrite or calcite spar. Parallel nicols. D. Thin section of breccia shown in Fig. 5A. This sample shows a matrix of carbonate-lithic silt with a few silt- to sand-sized grains of siliciclastic material (labeled by arrowtip 1 in inset photo). Note rounded pores clad by thin fringes of dog tooth spar. Crossed nicols.

Abb. 5. A. Brekzienkörper, entstanden durch örtliche Zementation geschichteter alluvialer Kiese (Fazies 3, siehe Tabelle 1). Die Brekzie besteht aus Klasten der Hauptdolomit Einheit und einigen wenigen, kies- bis block-großen Metamorphit-Klasten (mit ‚m' angezeigt). Beachte die sanft einfallende Stratifikation. Das Kleinbild rechts oben zeigt einen Klasten aus Granat-Amphibolit, einem Leitgestein des Inntal-Eisstroms des Letzten Glazialen Hochstands (siehe Text), eingebettet in die Brekzie. Aufschluss C, 1185–1190 m über NN (vgl. Abb. 3). B. Ausschnitt der Brekzie von Abb. 5A. Beachte die undeutliche Stratifikation, örtliche Dachziegellagerung von Klasten, und die Zusammensetzung vorwiegend aus angularen Klasten aus der Hauptdolomit-Einheit und einigen wenigen Klasten von Metamorphiten (‚m'). Stift ist 14 cm lang. C. Dünnschliff der Brekzie aus Abb. 5A. Die Zwickelräume sind mit ausgewaschenem karbonat-lithischem Sand bis -Silt gefüllt, der durch sehr dünne Säume von Mikrit oder Kalzisparit verfestigt ist. Parallele Nicols. D. Dünnschliff der Brekzie aus Abb. 5A. Diese Probe enthält eine Grundmasse von karbonat-lithischem Silt mit einigen silt- bis sand-großen Körnern von siliziklastischem Material (angezeigt durch Pfeilspitze 1 im Kleinbild oben rechts). Beachte die gerundeten Poren, die mit dünnen Säumen von Hundezahn-Zement ausgekleidet sind. Gekreuzte Nicols.

patible with waterlain till (Menzies & Shilts 2002; Wood et al. 2010). The local interbedding of facies 1 and 2 might even result from subaqeous deposition in a ‚till delta' (cf. Dreimanis 1995; Benn & Evans 2010); this, however, can not be tested due to limited outcrop. An interpretation of facies 1 as a waterlain till implies that the level of a hypothetical ice-marginal lake was at least about 1225–1230 m a.s.l. (cf. Fig. 9). The morphology of the rock substrate would allow for a lake level at this altitude. However, because no corresponding interval is exposed farther down valley, the potential down-valley extent of that lake cannot be assessed. A narrow, elongate ice-marginal lake would receive copious sediment (chiefly reworked till and scree) not only from the front of a late-glacial ‚Giessenbach glacier', but also from the very steep mountain flanks alongside. With respect to the interpretation of facies 1 and 2 in Giessenbach valley, I see no unequivocal criteria to differentiate between an interpretation in terms of: (a) subaerially redeposited pleniglacial till, and/or (b) deposition as a waterlain till ahead of a local glacier that advanced shortly after decay of the pleniglacial ice cover.

Facies 3 and its lithified equivalent (facies 3A) represents alluvial gravels. In this facies, no lenticular channel-fills (cf. Sanders, Ostermann & Kramers 2009) were observed. Instead, the facies is characterized by low-dipping, more or-less constant stratification without major verti-

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Tab. 2: *Mineralogical composition of facies 1 and of the fine-grained matrices of facies 2 (see Tab. 1), determined by X-ray diffractometry.*

Tab. 2: *Mineralogische Zusammensetzung der Fazies 1 und der feinkörnigen Matrix von Fazies 2 (siehe Tab. 1), bestimmt mit Röntgen-Diffraktometrie.*

Sample # Altitude a.s.l.	**#1 1165 m**	**#2 1170 m**	**#3 1180 m**	**#4 1190 m**	**#5 1200 m**	**#6 1210 m**	**#7 1210 m**
Facies (cf. Tab. 1)	#2	#2	#1	#2	#1	#1a	#1a
Dolomite	87.0	79.9	81.2	76.3	80.5	91	91
Calcite	3.9	2.9	4.3	3.5	3.6	3	4
Muscovite	3.5	5.7	6.1	4.5	4.8	2	1
Albite	2.5	4.4	2.8	5.5	4.1	< 1	< 1
Chlorite	0.7	3.0	2.5	5.7	2.3	< 2	2
Quartz	2.4	4.1	3.1	4.5	4.7	< 2	2
Total carbonate minerals:	90.9	82.8	85.5	79.8	84.1	~ 94	~ 95
Total siliciclastic minerals:	9.1	17.2	14.5	20.2	15.9	~ 6	~ 5

Tab. 3: *Characterization and interpretation of units G1 to G6 in Figure 6.*

Tab. 3: *Charakterisierung und Deutung der Einheiten G1 bis G6 in Abbildung 6.*

Depositional unit Interpretation	**Characterization**	**Remarks**
Unit G1 Pre-LGM talus slope	Faintly stratified deposit of angular gravels derived exclusively from Hauptdolomit; strata dip with about 25-30° (cf. Fig. 6); deposit shows openwork layers, vertically changing with layers more rich in a matrix of winnowed carbonate-lithic sand to silt	Overlain by unit G2 along a truncation surface
Unit G2 Basal till of LGM	Diamicton of fine-grained, compacted, grey matrix rich in clasts of rounded, polished and faceted metamorphic rock fragments including index clasts of LGM Inn glacier	–
Unit G3 Diamicton formed by redeposition of basal till of LGM, mixed with lithoclasts derived from local rock cliffs	Diamicton of light-grey matrix rich in: (a) clasts of rounded, polished and faceted metamorphic rock fragments including index clasts of LGM, and (b) angular gravels to small boulders of clasts of Hauptdolomit.	–
Unit G4 Fluvial deposits of re-incision phase	Clast-supported gravelly to cobbly deposit of: (a) well-rounded clasts of metamorphic rocks (including index clasts of LGM), and (b) subrounded to well-rounded gravels to cobbles of Triassic carbonate rocks (Hauptdolomit unit, Seefeld Fm); matrix is winnowed lithic sand	G4 overlies the other deposits along a surface that dips steeply towards Giessenbach stream (Fig. 6)
Unit G5 Post-glacial talus slope	Stratified deposit of angular gravels to small boulders derived from Hauptdolomit unit; rare clasts of metamorphic rocks are present, too; strata dip with about 30° towards the valley	Downlaps onto unit G4
Unit G6 Veneer of hillslope colluvium/ hillslope creep deposit; topped by forested soil	Veneer, up to about 1 meter thick, of isolated lithoclasts and 'stringers' of clasts embedded in brown to blackish, sandy to silty groundmass rich in particulate organic matter	–

cal or lateral change in mean grain size. The characteristics of facies 3 suggest deposition from episodic, shallow flows (sheet flow; Galloway & Hobday 1983) in an aggrading braided stream. A braided-stream setting for facies 3 is also supported by the fact that it comprises successions tens of meters in thickness that had previously filled the valley at a much higher level than present (see section 5. below). Facies 4, in turn, represents deposits of cohesive debris flows. These deposits seem to be more common in the basal part of the alluvial succession, but do not comprise a major fraction. Finally, facies 5 building terrace veneers of gravelly to bouldery deposits rich in well-rounded clasts of metamorphic rocks is interpreted as deposition from a perennial, or quasi-perennial, ancestral Giessenbach stream that incised progressively deeper into the older Quaternary deposits. For the interpretation of depositional units G1 to G6 in outcrop B, the reader is referred to Table 3. In the following section, significant morphological features of the considered drainage area and their relation to facies and their relative stratigraphic position is described.

5 Morphostratigraphy

In the lowest part of Giessenbach valley, an erosional relict about 15 m in width comprising a gravelly to cobbly stream-channel deposit rich in index clasts of the LGM

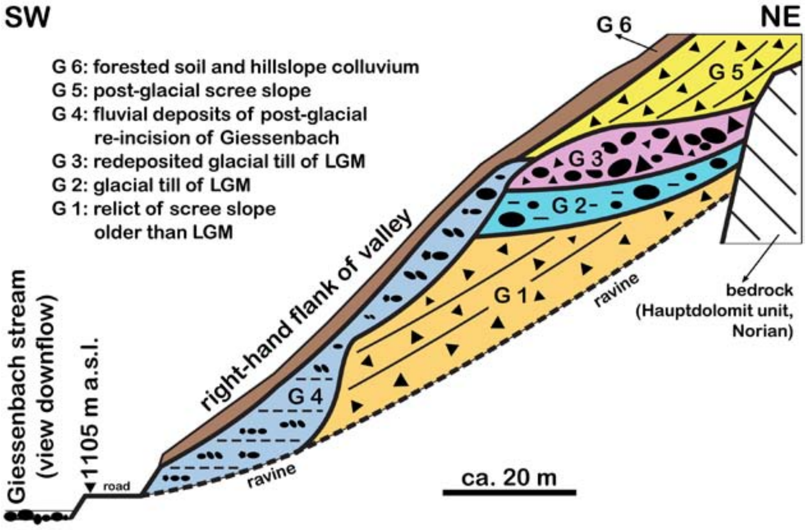

Fig. 6. Scheme of outcrop B (see Fig. 3) in a ravine at right bank of Giessenbach. See Table 3 for further characterization and interpretation of depositional units G1 to G6. Horizontal distance roughly to scale; vertical scale exaggerated.

Abb. 6: Schema des Aufschlusses B (siehe Abb. 3) in einer Rinne rechtsseitig des Giessenbaches. Siehe Tafel 3 für weitere Charakterisierung und Deutung der Ablagerungs-Einheiten G1 bis G6. Horizontale Entfernung grob maßstäblich; vertikal versteilt.

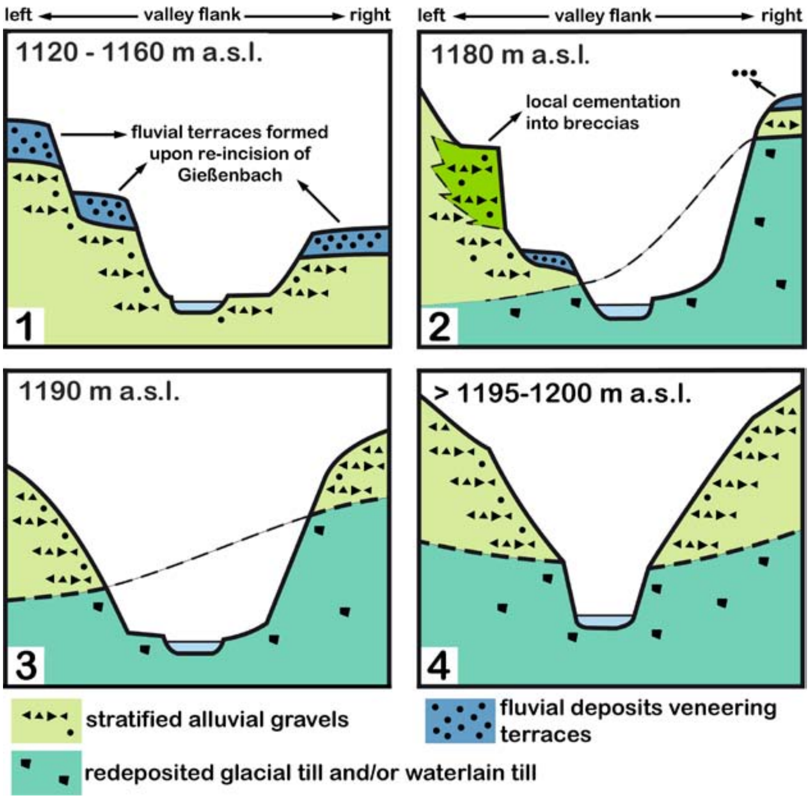

Fig. 7. Schematic cross-sections of Gießenbach valley at different locations a.s.l. (see Fig. 3A for positions). See text for description and discussion.

Abb. 7: Schematische Querschnitte des Giessenbach-Tals bei verschiedenen Höhen über NN (vgl. Abb. 3A für Lagen). Siehe Text für Beschreibung und Erörterung.

is 'stranded' directly on Hauptdolomit bedrock, about 25 meters above the present floor of the gorge (outcrop A in Fig. 3). At this location, the gorge is most narrow, consisting essentially of a bedrock channel about 1 meter in width incised into Hauptdolomit. In the middle reach of Giessenbach valley, outcrops are represented by thick packages of alluvial gravels and debris-flow deposits (facies 3 and 4), and by terraces veneered by fluvial deposits rich in LGM index clasts (facies 5) (Fig. 7, section 1). In the upper part of the present Giessenbach valley, above approximately 1180 m a.s.l., exposures along both valley flanks indicate that the contact between facies 1 and 2 and the overlying unit of alluvial gravels and debris-flow deposits (facies 3 and 4) is a three-dimensional surface (Fig. 7, sections 2 to 4).

In the upper part of the present Giessenbach valley a system of terraces is well-identifiable in laserscan images (Fig. 8A). Field inspection of the surface named 'Gaisburgls Boden' (ca. 1260 to 1290 m a.s.l.; Fig. 8A) yielded scattered clasts of metamorphic rocks as well as of Lower Triassic red beds (Verrucano or Alpiner Buntsandstein) derived by glacial drift from distant source areas, in addition to abundant carbonate-rock clasts derived from the local drainage area. On the opposite, right-hand side of Giessenbach valley, another large surface is present between about 1270 to 1300 m. a.s.l., at nearly the same level. This latter surface also is littered with gravels to cobbles of glacial drift (metamorphic rocks, red beds). The roadcut indicates that the major part of the sediment is again represented by carbonate-rock clasts from the local environs. This surface terminates

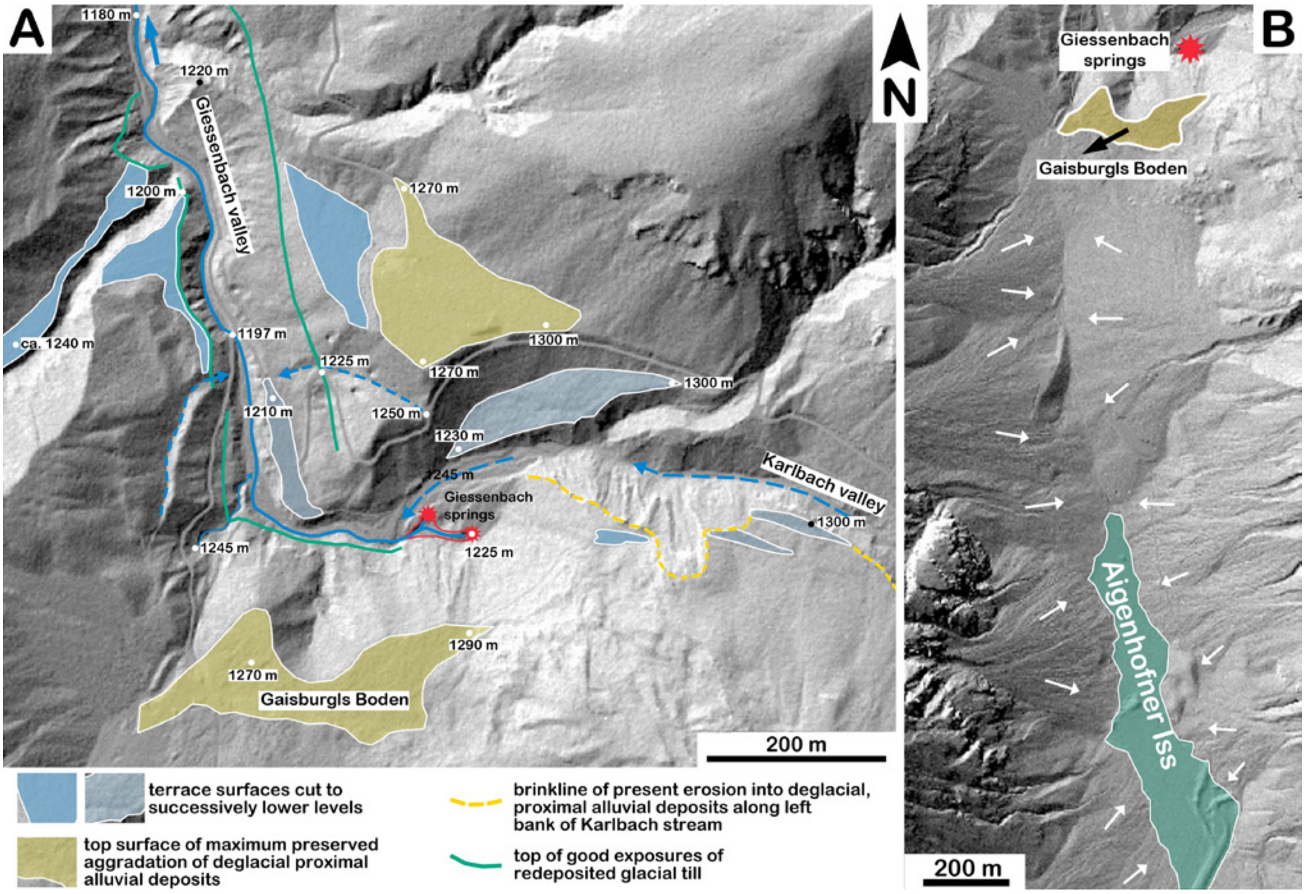

Fig. 8. A. Laserscan of upper reach of present Gießenbach (source: www.tirol.gv.at). On both valley sides, large terraces (light yellow; 'Gaisburgls Boden', and its opposite equivalent) are present between 1270 to 1300 m a.s.l.; these represent the highest and oldest terraces. Down slope along the valley flanks, lower-lying terraces (light blue hues) are present that step down up to a few meters above the present level of Giessenbach. The top of the unit of facies 1 and 2 (Tab. 1) can be placed at 1225 to 1230 m altitude (green line). B. Up-valley of the terrace Gaisburgls Boden, large scree slopes have shed onto the aggraded, raised floor of the dry valley (compare Fig. 3A). Farther up-valley, a vegetated remnant of a subhorizontal plane (Aigenhofner Iss; green hue) is preserved between prograding scree slopes; this plane may record a former lake.

Abb. 8. A. Laserscan (Quelle: www.tirol.gv.at) des Oberlaufs des heutigen Giessenbaches. Auf beiden Talseiten finden sich zwischen 1270 m bis 1300 m über NN grosse Terrassen (hellgelb; ‚Gaisburgls Boden', und seine gegenüberliegende Entsprechung); diese bilden die höchstgelegenen und ältesten Terrassen. Hangabwärts finden sich an den Talflanken bis wenige Meter über der Sohle des heutigen Giessenbachs weitere Terrassen (hellblaue Farbtöne). Die Oberkante der Einheit aus Fazies 1 und 2 (Taf. 1) tritt zwischen 1225 bis 1230 m über NN auf (grüne Linie). B. Talaufwärts der Terrasse Gaisburgls Boden wurden große Schutthalden über den erhöhten Boden des Trockentals geschüttet (vgl. Abb. 3A). Weiter talauf findet sich der bewachsene Rest einer fast söhligen Talfläche (Aigenhofner Iss; grüner Farbton) zwischen vorbauenden Schutthalden; diese fast söhlige Fläche könnte auf einen verlandeten See zurückzuführen sein.

sharply against scree slopes that, today, are abandoned and completely forested; the scree slopes do not show evidence for a knick in the distal part of slope or erosion along their toe. In addition to the described two large surfaces, a system of smaller terraces (surfaces shown in blue hues in Fig. 8A) is identified in lower positions. These latter terraces are veneered by fluvial deposits of facies 5. From the highest terraces to the lowest, and down to the present stream bed, the fluvial facies overall becomes richer in clasts of metamorphic rocks relative to carbonate-rock clasts; in addition, cobbles to boulders of metamorphic rocks become gradually more common: whereas these are comparatively rare in the alluvial gravels (see Fig. 5A), the present stream bed is rich therein.

Schematically summarizing deposits and stratigraphic relations in the upper part of Giessenbach valley into a composite section results in a thickness of the deglacial to early late-glacial succession of more than some 100–120 meters (Fig. 9). It is obvious that the deglacial deposits represent the major sediment body in this valley. The cohesive nature of the redeposited glacial tills probably lowered the rate of headward erosion of Giessenbach, to result in the distinct ‚blockade' of the upper half of the former Giessenbach valley by sediments. The springs of Giessenbach are characterized by perennial shedding of an estimated few hundreds of liters per second in total. Today, the springs discharge a few meters higher than the present bed of Karlbach, from a comparatively young, but vegetated terrace of gravelly to cobbly alluvial deposits. Up-valley of Gaisburgls Boden, shedding of large talus slopes from both valley flanks resulted in a local inversion of gradient, down to Aigenhofner Iss at about 1260–1270 m (Fig. 8B). Today, Aigenhofner Iss is characterized by an ephemeral pond falling dry during autumn and during longer fairweather periods in summer. Today, talus slopes downlap and prograde over the fine-grained ephemeral-lacustrine deposits that floor Aigenhofner Iss.

6 Interpretation and discussion

The segmentation of Giessenbach valley into: (a) a lower reach with a bedrock gorge of high gradient, and (b) a moderately steep middle to upper reach with bedload channel is a common in the NCA; Giessenbach valley, however, differs from many other valleys in that its former upper half (i. e., Gaisburgls Boden to Eppzirler Alm) is still clogged by a sedimentary succession at least a few tens of meters in thickness. By analogy to the outcrops along the present Giessenbach stream, it is assumed that at least the stratigraphically lower part of the valley-fill consists mainly of deposits of the deglacial phase. In the upper part of the valley, however, below cliffs of Hauptdolomit, large scree slopes added significantly to total sediment volume. Taking into account that Giessenbach does not receive major input from tributaries along its course, the overall convex shape of the longitudinal valley profile (Fig. 3A) indicates that the stream is off geomorphic equilibrium. The convex profile is probably related to, both, the increase in mean channel gradient and the knick associated with the bedrock-incised gorge in the lower reach.

To explain the sheer thickness of the stratified alluvial gravels, three hypotheses can be forwarded: (1) sediment delivery was so rapid that drainage could not keep pace, resulting in aggradation of the valley floor; (2) Giessenbach valley was blocked by decaying ice in the trunk valley; and (3) some combination of these two. The entire drainage area is situated on Hauptdolomit. Because of its dense joining, the Hauptdolomit weathers quite easily and represents an efficient source of scree. Thus, under conditions of fresh deglacial exposure, copious sediment delivery from the Hauptdolomit by physical weathering can safely be assumed. Standing at the location of the ‚stranded' relict of stream-channel deposits (outcrop A in Fig. 3), and projecting a gravelly stream bed with a gradient of about 5° down-valley may suggest that the nearby trunk valley (cf. Fig. 2) was filled by at least some 60–80 meters of sediment. Today, along both flanks of Drahnbach valley, there is no evidence for relicts of a valley-fill of this height. North and south of the debouch of Giessenbach valley, the only record of the LGM along the right flank of Drahnbach valley is represented by relicts of a veneer of basal till directly above Hauptdolomit substrate. In addition, laserscan images do not show an alluvial fan, or relicts thereof, of required size connected to the debouch of Giessenbach gorge; instead, the stream enters into Drahnbach valley along the top of an alluvial fan (now largely blocked by buildings) with the apex at about 1015 m a.s.l. The stream-channel deposits (now preserved as relict) were probably adjusted to an intermittent base-level provided by dead ice in the trunk valley.

In the upper reach of Giessenbach valley, the three-dimensional shape of the transition between redeposited tills and overlying alluvial deposits (Fig. 7) may in part represent an ‚original' surface of differentiated relief. During rapid deglacial mass-wasting of till down valley flanks, a differentiated small-scale topography expectably formed. On the other hand, downslope creep of the thick sedimentary packages upon fluvial incision may have produced, or amplified, the three-dimensional aspect of the contact. Laserscan images, however, do not show evidence for sig-

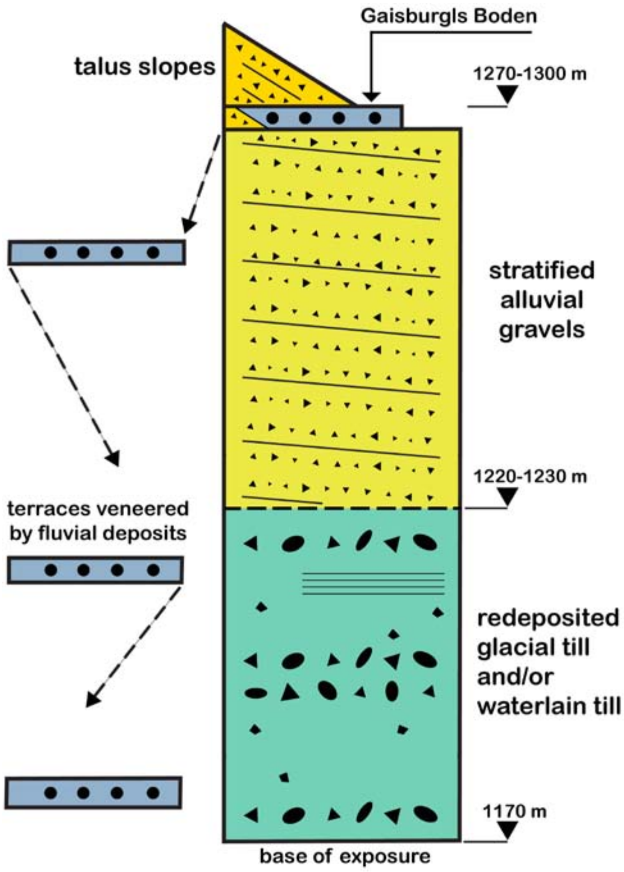

Fig. 9. Composite section of depositional units along Giessenbach valley from 1170 m a.s.l. up to the top of maximum sediment aggradation in this area ('Gaisburgls Boden', 1270–1300 m a.s.l., and its equivalent on the right-hand side of valley, see Fig. 8A).

Abb. 9: Zusammengesetztes Profil der Ablagerungs-Einheiten im Giessenbach-Tal von 1170 m über NN bis zum Dach der höchsten Sediment-Aggradation in diesem Bereich (‚Gaisburgls Boden', 1270–1300 m über NN, und seine Entsprechung auf der rechten Talseite; siehe Abb. 8A).

nificant slow gravitational mass-wasting after deposition of the alluvial gravels; it is thus assumed that the contact between the redeposited tills and the alluvial sediments is largely original. Alternatively, the onset of deposition of alluvial gravels may have been associated with local erosion of the redeposited till. This, in turn, would imply a sharp vertical contact between redeposited tills and overlying alluvial gravels, in contrast to a vertical transition as suggested.

As described, along the uppermost part of Giessenbach stream two opposite terraces between 1270–1300 m a.s.l. were identified (Fig. 8A). These two terraces are interpreted to indicate the maximum preserved sediment aggradation; at that time, the valley had a comparatively wide and plane, high-positioned floor with a braided stream system. For the surface at the right side of the valley, the observation that the scree slopes do not show knicks or erosional brinklines along their toes strongly suggests that they downlap the terrace over a limited distance (Fig. 9). The ‚blue' veneers in Figure 7, section 1, represent younger terraces formed during a later stage of fluvial re-incision. The increase in both relative percentage and mean diameter of clasts of metamorphic rocks with progressively lower posi-

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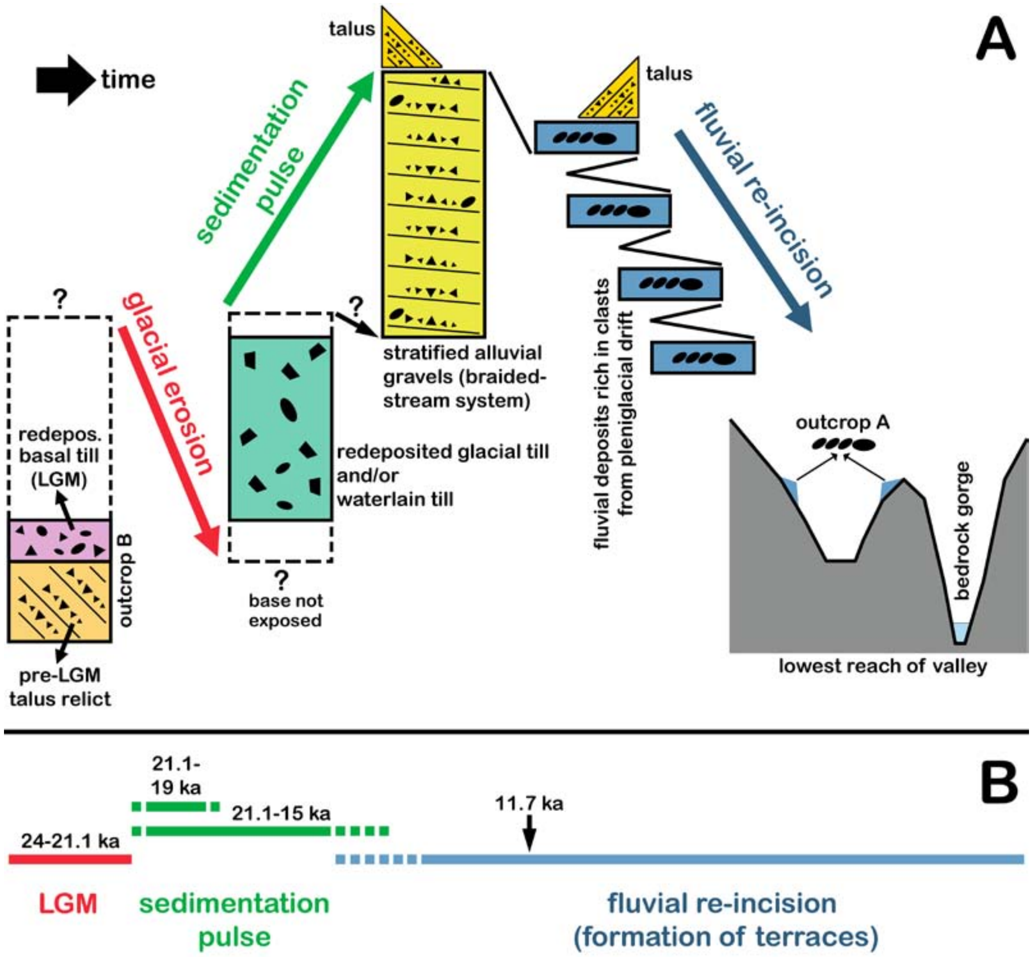

Fig. 10. Summary of geohistory as recorded along present Giessenbach stream. A. Most sedimentation took place during to shortly after decay of pleniglacial ice at the site, and probably lasted into, but faded during, the late-glacial interval. B. Possible time spans of events. For the sedimentation pulse that gave rise to the valley-fill, two time spans may be estimated, a short one from 21.1–19 ka, and a long one from 21.1–15 ka; in either case, the calculated rates of sediment accumulation are very high. See text for further discussion.

Abb. 10: Gesamtschau des geologischen Geschehens entlang des heutigen Laufes des Giessenbachs. A. Sedimentation fand hauptsächlich während bis knapp nach dem deglazialen Eis-Zerfall statt, und dauerte bis ins Spätglazial, währenddessen sie ausklang. B. Mögliche Zeitspannen der Geschehnisse. Für den Sedimentations-Schub, der die Talfüllung bildete, können zwei Zeitspannen geschätzt werden, eine kurze von 21.1–19 ka sowie eine lange von 21.1–15 ka; in beiden Fällen ergeben sich sehr hohe gerechnete Sediment-Akkumulationsraten. Siehe Text für weitere Erörterung.

tion of terraces indicates that the metamorphic clasts became relatively enriched during fluvial re-incision; enrichment is caused by four factors: (1) clasts of crystalline rocks are of higher specific weight than carbonate-rock clasts; (2) up to at least cobble size, clasts derived from glacial drift are commonly better-rounded than carbonate-rock clasts; (3) many crystalline clasts are of cobble to small-boulder size, i. e. larger than the *gros* of the carbonate-clastic material; and (4) except for schists, relative to carbonate clasts, crystalline clasts disintegrate extremely slowly by (a) frost action, (b) impact of bedload and suspended grains, and (c) due to abrasion in bedload transport. Repeated over thousands of flood cycles, these differences typically result in relative enrichment of crystalline rock clasts. The perennial shedding of the Giessenbach springs suggests that they are supplied from a comparatively large drainage area. In addition, their unusal location relative to the local level of ephemeral Karlbach suggests that these springs represent part of the subsurface drainage of the upper part of the Giessenbach catchment that today is clogged by sediments.

There is no evidence in surface outcrops for significant volumes of pre-LGM deposits in the Giessenbach catchment; the talus relict G1 preserved below the basal till of the LGM (= unit G2, Fig. 6) represents the only sediment accumulated before the LGM. The deglacial to Holocene history of the Giessenbach-Karl valley drainage system can thus be summarized as shown in Figure 10. Subsequent to glacial erosion during the LGM, during and immediately after decay of the pleniglacial ice cover, glacial till was redeposited from valley flanks. This partly overlapped with, and was followed by deposition of alluvial gravels and debris flows. Significant aggradation of alluvial deposits was probably favoured by: (a) high rates of physical erosion of glacially-weakened, unvegetated mountain-flanks freshly stripped of glacial ice, and (b) perhaps also by partial blocking of the exit of Giessenbach valley by dead ice (see above). The time spans and rates of sediment aggradation, however, can only be crudely estimated. It is not established when reforestation started in the considered area. The Inn valley about 12 km towards the south was permanently ice-free from ~17.4 kyr cal BP over most of its extent, and became reforested at about 15 ka BP (Van Husen 2000, 2004). On the other hand, due to the prolonged presence of stagnant, dead ice within the Inn valley (former Bühl ‚stadial' of Penck & Brückner 1909; now interpreted as dead ice of the ELGID; Van Husen 1997, 2004; Ivy-Ochs et al. 2005; Reitner 2007), reforestation of the Inn valley may have been retarded relative to other areas. Colonization of the Giessenbach catchment with shrubby vegetation thus might have already started at about 19–17 ka BP (compare maps of late-glacial ice extent in Van Husen 2000, 2004). In the Giessenbach drainage area, redeposition of glacial till followed by aggradation of gravelly alluvium may be bracketed to between 21–19 ka BP to 17–15 ka BP, or between 6 ka (21–15 ka) to 2 ka (21–19 ka) in duration. Taking the altitude difference between the highest terraces (Fig. 8A) and present Giessenbach as a proxy for total aggradation, the mean sediment aggradation rate is calculated as 8.3 mm/a ('minimum') to 25 mm/a ('maximum'). An accumulation rate of 8–25 mm/a is one to two orders of magnitude higher than deglacial denudation rates of Alpine catchments as deduced from sediment volume (see Müller 1999; Hinderer 2001). At least to a large part, this disparity results from the much larger scale in space of the cited studies relative to the present one (compare Tunnicliffe & Church 2011). The aggradation rate 8–25 mm/a, however, is: (a) in the same range of accumulation rates deduced for historical paraglacial accumulation of debris cones following glacial retreat (Ballantyne 1995), (b) in the same range of the highest documented denudation rates of individual catchments in orogens (up to 5–18 mm/a; Hovius et al. 1997; see Norton et al. 2010, for rates of 3–7.6 mm/a of denudation by debris flows and rockfalls in tributary catchments of the upper Rhone since the last deglaciation at site), (c) in the same range of high rates of rock cliff retreat (Hétu & Gray 2000), and (d) in the same range of high rates of talus accumulation in the NCA (Sanders & Patzelt 2011); overall, this correspondence of rates may suggest that the estimate of deglacial sediment accumulation rate in the Giessenbach catchment is roughly correct. It is also possible that some of the low-lying terraces along Giessenbach were produced by minor aggradation during stadials (e. g., Gschnitz stadial, > 15.4 ka; Egesen maximum, ~ 12.4–12.3 ka; Kerschner & Ivy-Ochs 2008), but there is no positive evidence for this.

In the NCA, the upper reaches of many catchments are aggraded valleys with a comparatively wide, gently-dipping floor, in some cases with an abrupt transition from valley floor to cliffs (depending on the rate of scree shedding). In addition, due to gradient reversal in longitudinal valley profile (cf. Fig. 3A), lakes or ephemeral ponds and/or disappearance of streams by percolation may occur; overall, however, gradient reversals are relatively rare. The described case study from Giessenbach shows that rapid deglacial sedimentation can be of lasting and profound impact on the morphology and hydrology of intramontane catchments. A similar development from rapid deglacial to late-glacial aggradation followed by abandonment, vegetation, and linear erosion is observed for many scree slopes of the NCA (Sanders & Ostermann 2011).

7 Conclusions

(1) The post-LGM development of the Giessenbach catchment was characterized by: (a) a deglacial aggradation phase with rapid sediment accumulation, followed by (b) an incision phase dominated by fluvial erosion.

(2) The aggradation phase records redeposition of glacial till from hillslopes, and/or deposition of waterlain till ahead of a local-sourced late-glacial glacier. (Re)deposition of till was followed by rapid accumulation of pebbly alluvium supplied from the local rock substrate. During the incision phase, in turn, down-stepping terraces formed while scree slopes became progressively stabilized.

(3) The springs supplying the present Giessenbach stream emerge from within the deglacial sediment succession about half way along the pre-LGM extent of the valley. The upper half of the pre-LGM course of Giessenbach is still a dry, elevated, wide-floored valley with an ephemeral pond. The sedimentary succession that fills or blocks the upper half of the former stream course mainly accumulated from deglacial to late-glacial time.

(4) Along its actual extent, Giessenbach stream shows a convex longitudinal profile with a bedrock gorge in the lowermost reach. Within the gorge, an erosional remnant of fluvial deposits (with LGM index clasts) on a bedrock terrace well-above the present floor suggests that the canyon was blocked by dead ice during ice decay.

(5) Because of their large volume and incomplete erosion, deglacial deposits still coin the morphology and hydrology of the Giessenbach catchment. Similarly thick deglacial sediment bodies, and a corresponding influence on surface runoff, are common in catchments of the Northern Calcareous Alps.

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