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Reconsidering the current stratigraphy of the Alpine Lateglacial: Implications of the sedimentary and morphological record of the Lienz area (Tyrol/Austria)

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Abstract: The sedimentary and morphological evidence for Lateglacial glacier fluctuations in the Lienz area provides a strong case against the currently used pentapartite stratigraphic subdivision of the Alpine Lateglacial (ALG; c. 19–11.7 ka) i.e. the timespan between the Würmian Pleniglacial (= Alpine Last Glacial Maximum; AlpLGM) and the beginning of the Holocene. The results of comprehensive geological mapping (including the detection of mass movements) supported by geochronological data and pollen analysis revealed that the ALG- record of the Schobergruppe mountains and the Lienz Dolomites can be subdivided into four unconformity-bounded (allostratgraphic) units which are linked to three climatostratigraphically-defined phases of glacier activity. Delta deposits and till of local glaciers document the phase of ice-decay after the AlpLGM. Between this period and the Bølling/Allerød (B/A) interstadial only one glacier stabilisation with massive end moraines, correlated with the Gschnitz stadial, is evident. Multiple end moraines prove the presence of very active glacier tongues during the Younger Dryas aged Egesen stadial. The ^{10}Be exposure dating of an end moraine, previously attributed to the Daun stadial (pre-B/A interstadial) based on ΔELA values, provided an age of 12.8 ± 0.6 ka indicating it is of Younger Dryas age. This case highlights the pitfalls of the commonly used ΔELA-based stratigraphic ALG subdivision and the subsequent derivation of palaeoclimatic implications. ΔELAs are still considered as a useful tool for correlation on the local scale e.g. in one mountain group with a quite comparable topography and lithology and taking into account the limitations, especially the impact of debris cover. However, our results show that a stratigraphic correlation across the whole Alpine chain via ΔELAs is not a successful approach potentially leading to bias and, eventually, to circular arguments.

Eine Neubetrachtung der aktuellen Stratigrafie des Alpinen Spätglazials: Implikationen aus den sedimentären und morphologischen Belegen des Gebietes um Lienz (Tirol/Österreich)

Kurzfassung: Die morphologischen und sedimentären Belege aus dem Raum Lienz liefern starke Argumente gegen die bisher angewandte, fünfgliedrige Stratigraphie des Alpinen Spätglazials (ALG; ca 19–11.7 ka), dem Zeitraum nach dem Würm-Hochglazial (= Alpines Letztes Glaziales Maximum; AlpLGM). Die Resultate einer flächendeckenden geologischen Kartierung (inklusive Erfassung von Massenbewegungen) unterstützt durch geochronologische Methoden sowie Pollenanalysen zeigen, dass sich die ALG-Abfolgen in der Schobergruppe und den Lienzer Dolomiten jeweils in vier „unconformity-bounded units“ im Sinne der Allostratigraphie untergliedern lassen. Diese belegen drei klimato-stratgraphisch korrelierbare Phasen. Deltasedimente und Grund- bzw. Seitenmoränen von Lokalgletschern dokumentieren die Eiszerfallsphase unmittelbar nach dem AlpLGM. Nach der Eiszerfallsphase und vor dem Bölling/Alleröd (B/A)-Interstadial gibt es nur eine markante Phase der Gletscherstabilisierung, die mit dem Gschnitz-Stadial korreliert wird. Multiple Endmoränenwälle belegen aktive Gletscherzungen in der Jüngeren Dryas während des Egesen Stadials. Eine zuvor dem Daun-Stadial (prä-B/A-Interstadial) aufgrund von Schneegrenzdepressionswerten (ΔELA) zugeordneter Gletscherstand wurde mit ^{10}Be auf 12.8 ± 0.6 ka datiert und entspricht dem Egesen-Maximum. Damit kann gezeigt werden, dass die bisherige Praxis ΔELA-Werte zur stratigrafischen Korrelation über größere Räume zu benutzen nicht nur untauglich ist, sondern letztlich zu Fehlschlüssen hinsichtlich Paläoklima führt. ΔELA-Werte werden nach wie vor als ein nützliches Werkzeug für Korrelationen im lokalen Maßstab betrachtet, so beispielsweise innerhalb einer Gebirgsgruppe mit vergleichsweise ähnlicher Topographie und Lithologie sowie unter Berücksichtigung von Einschränkungen wie z.B. dem Einfluss einer ehemaligen Schuttbedeckung. Jedenfalls zeigen unsere Resultate, dass eine stratigrafische Korrelation mittels ΔELA-Werten quer über die Alpen kein erfolgreicher Ansatz ist, der zu einer Verzerrung der Resultate und schließlich zu Zirkelschlüssen führt.

Keywords: *Late Pleistocene, Lateglacial, Alps, geological mapping, allostratigraphy, climatostratigraphy, exposure dating, palynology, Younger Dryas, deformable bed*

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1 Introduction

The subdivision of the Alpine Lateglacial (ALG), i.e. the glacial phase between the Alpine Last Glacial Maximum (AlpLGM), here used as synonym for Würmian Pleniglacial (Chaline & Jerz 1984, van Husen & Reitner 2011), and the onset of the Holocene has a long history beginning with Penck & Brückner (1909). These authors established three stadials (from old to young): Bühl, Gschnitz and Daun, defined as prominent glacier stillstands in the Inn glacier system during retreat after the Würm glaciation (AlpLGM in modern sense). As is the case for the Alpine Ice Ages (e.g. Würm, Riss), Penck and Brückner's climatostratigraphic terminology has been applied to many other Alpine regions (e.g. in the Maritime Alps; Federici et al. 2016) or serves as a reference for areas outside the Alps (e.g. in the Tatra Mountains; Zasadni & Kłapyta 2016).

Since then the statigraphic terminology evolved further as described in detail by Maisch (1982) and Kerschner (1986). A summary of the 1960s with a partial re-assessment of, but still referring to, the original type localities is given by Mayr & Heuberger (1968) who extended the previous tripartite sequence to five stadials, named (again from old to young) Bühl, Steinach, Gschnitz, Daun und Egesen. Finally, until the 1990s six stadials were in use i.e. Bühl, Steinach, Gschnitz, Senders/Clavadell, Daun (all as pre- Bølling stadials) and Egesen as the equivalent of the Younger Dryas.

While extending the stratigraphic subdivision the meaning of some of the old stadials has been changed considerably irrespective of the original definition with respect to size and with no reference to the original type locality and the relation to previous and younger stadials documented in the original literature. This is especially evident when considering the Egesen stadial, which was first introduced by Kinzl (1929) as an "appendix" of the Daun stadial (as defined by Penck & Brückner 1909) with a comparatively limited ice-extent. Now it is regarded as a synonym for the Younger Dryas glaciation in the Alps with the original extent at the type locality only representing one of the last minor glacier extents during retreat (compare discussion in Kerschner 2009). The same is true for the Daun stadial where eventually a pre–Bølling age was claimed on basis of the work of Heuberger (1966), who defined morphological characteristics in the appearance of Egesen and Daun moraines as a result of considerable age differences, again with no link to the type locality (see also discussion in Kerschner 1978). In this shifting chronology of Lateglacial stadials, equilibrium line altitudes (ELAs) and their difference (ΔELA) to the reference ELA at the last Little Ice Age (LIA) around the year 1850 (ELA_{LIA}; Gross et al. 1977) gained more prominence in stratigraphic definitions as well as for correlative purposes. The main issue here, however, is that this approach relies on an inconsistent reference to type localities.

This overall evolution of further subdivision resulted in two contrasting developments.

ΔELAs associated with other parameters were used for sophisticated models of palaeoclimatic development (e.g. summary in Heiri et al. 2014). On the other hand, the use of Lateglacial stratigraphy for geological maps declined contrary to this increase in stratigraphic terminology. Cornelius & Clar (1935) used the, at that time modern, subdivision for their geological map of an alpine core region in the Hohen Tauern mountain range (Fig. 1). The last recorded application in Austria was done by van Husen (1977, see also 1997) following the Mayr & Heuberger (1968) approach for a thematic map of the whole former Traun Glacier area. Thus, the stratigraphy of the ALG was running into danger of becoming an entirely self-referring academic approach without any further geoscientific basis. Even the use of modern dating approaches, especially exposure dating with cosmogenic isotopes since the mid-1990s that resulted in the type locality of the Gschnitz stadial to be dated to 16.8 ± 1.7 ka (Ivy-Ochs et al. 2006a, recalculated age using 'NENA' Balco et al. 2009), did not affect the importance of the ΔELA approach.

In order to evaluate the stratigraphy established by the 1990s, Reitner (2005, 2007) started to re-investigate the type locality of the Bühl stadial based on geological mapping and sedimentological studies accompanied by palaeogeographic reconstructions. The results demonstrated that this stadial, as well as the Steinach stadial, do not represent the previously claimed chronology of glacial processes and should thus be abandoned. Instead, a phase of (early Lateglacial) ice-decay (with local glacier oscillations) was proposed and has since been accepted (*cf.* Ivy-Ochs et al. 2006b, 2008; Ivy-Ochs 2015). In addition, Klasen et al. (2007) provided a luminescence age of 19 ± 2 ka for deltaic sediments in the corresponding type locality of the phase of ice-decay at Hopfgarten.

Following on from these early results, the present study aims to test the relevance and applicability of the ALG stratigraphy, including a phase of ice-decay, Gschnitz and Egesen stadial in an area around Lienz as mapped for the geological map sheet Lienz (Linner et al. 2013), based on complete mapping of sedimentary and morphological sequences, supported by numerical dating.

2 Study area and geological setting

The study area is located south of the Eastern Alpine main chain (represented here by the Hohen Tauern mountains) in Eastern Tyrol and consists of the Schobergruppe mountains, Deferegger Alps and Lienz Dolomites (Fig. 1). The area is drained by the River Drau and its tributaries with the River Isel as the most prominent one. Only the highest Schobergruppe mountains with peaks reaching just below 3300 m are still glaciated by small cirque glaciers and still show active permafrost at elevations above c. 2500 m (Buchenauer 1990). The Deferegger Alps with elevations of up to 2700 m and Lienz Dolomites with 2770 m only reach considerably lower elevations on the area covered by the map sheet Lienz.

The basement nappes of the Austroalpine Superunit (Schmid et al. 2004) between the Penninic Tauern Window and the Periadriatic fault system represent the tectonic setting for the study area. These nappes are composed of the western part of the Drauzug-Gurktal nappe system in the Deferegger Alps and Lienz Dolomites and the Koralpe-Wölz nappe system in the Schobergruppe mountains. The Schobergruppe mountain chain is made up of mica schist,

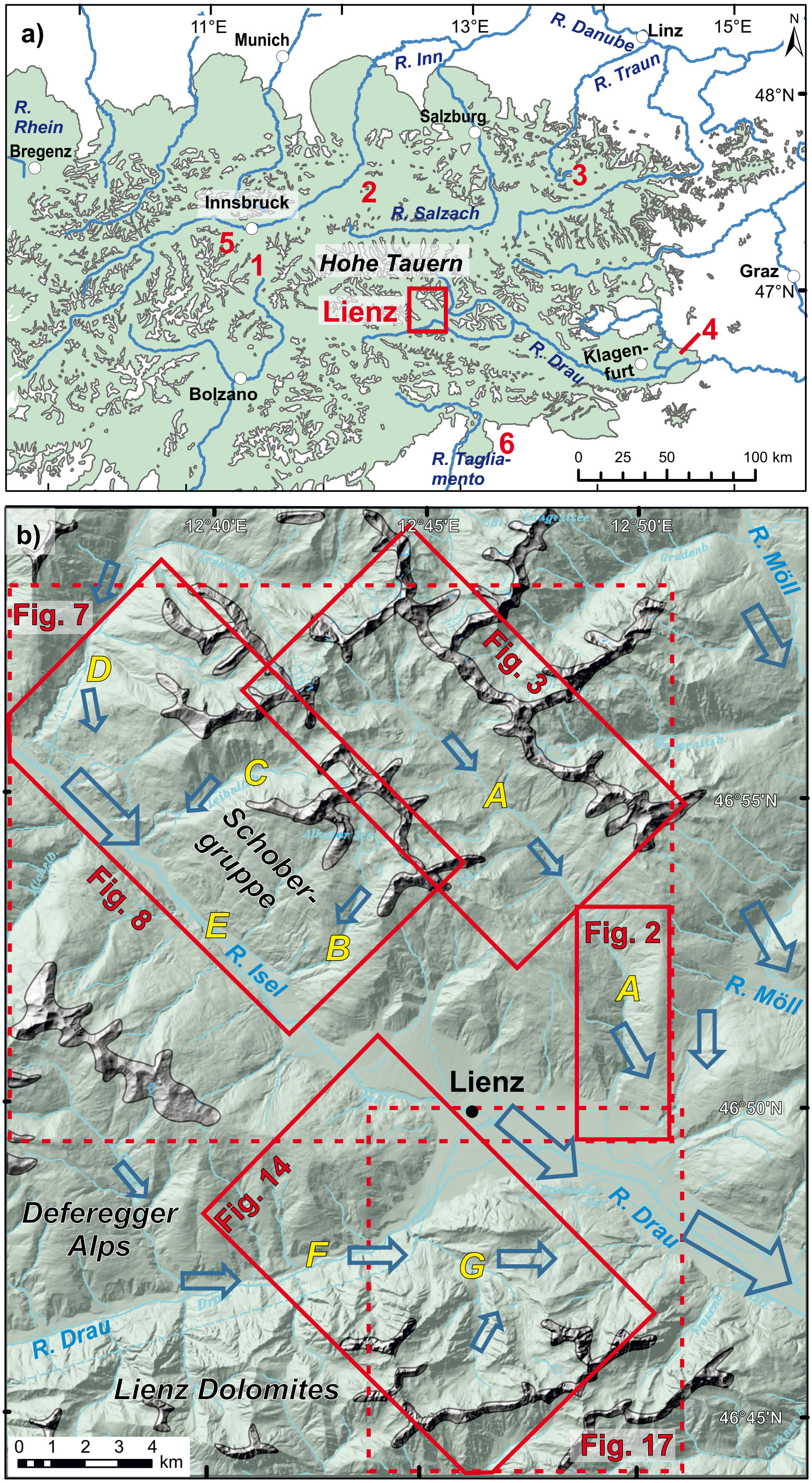

Fig. 1: a) Location of the study area around Lienz in the centre of the Eastern Alps. The AlpLGM ice extent (based on Ehlers *&* Gibbard *2004; in pale green) and important locations mentioned in the text are indicated (1 – Gschnitz Valley, 2 – Hopfgarten, 3 – Rödschitz, 4 – Längsee, 5 – Sellrain, 6 - Tagliamento Glacier).*
b) Map of the Lienz area with the valleys of the study area (A – Debant Valley, B – Daber Valley, C – Leibnitz Valley, D – Kals Valley, E – Isel Valley, F – Drau Valley (Puster Valley), G – Galitzen Valley) and of the corresponding geological maps (red line; in Figs. 2, 3 & 8) and palaeogeographic maps (dotted red line; Figs. 7 & 17). The transparent pale blue area indicates the glacier-covered area during the climax of the AlpLGM with blue arrows showing ice-flow directions. Only the highest peaks (in grey) were nunataka.

Abb. 1: a) Lage des Untersuchungsgebietes um Lienz im Zentrum der Ostalpen. Die AlpLGM-Eisausdehnung (nach Ehlers *&* Gibbard *2004; in Hellgrün) und wichtige, im Text erwähnte, Lokalitäten sind angezeigt (1 – Gschnitztal, 2 – Hopfgarten, 3 – Rödschitz, 4 – Längsee, 5 - Sellrain, 6 - Taglimentogletscher).*
b) Karte der Umgebung von Lienz mit den Tälern des Untersuchungsgebietes (A – Debanttal, B – Daber(-bach)-Tal, C- Leibnitz(-bach)-Tal, D – Kalser (Bach)-Tal, E – Isel-Tal, F – Drautal (Pustertal), G – Galitzen(-bach)-Tal. Die Lage der korrespondierenden geologischen Karten (rote Linie; in Abb. 2, 3 & 8) und der paläogeografischen Karten (rote strichlierte Linie; Abb. 7 & 17) ist dargestellt. Die transparente blassblaue Fläche dokumentiert die von Gletschern bedeckte Fläche während des Höhepuntes des AlpLGM. Blaue Pfeile zeigen die Eisflussrichtung. Nur die höchsten Gipfel (in grau) ragten als Nunataka aus dem Eisstromnetz.

paragneiss eclogite, amphibolite and orthogneiss, (Pestal et al. 2009, Linner et al. 2013). Mica schists, partly phyllonitic, are the dominant lithology of the Deferegger Alps (Linner et al. 2013). The Lienz Dolomites consist of mesozoic sedimentary rocks with dolostone of the Hauptdolomit Formation as the main constituent (Probst et al. 2003). The valleys of the rivers Drau and Isel follow major strike-slip faults, which mainly accommodated the Miocene lateral extrusion of the Eastern Alps relative to the South Alpine Superunits (Mancktelow et al. 2001).

The phase of ice build-up at the onset of the AlpLGM, characterised by a severe climatic deterioration (van Husen & Reitner 2011), are documented by horizontally-bedded gravels and cobbles with a coarsening-upward trend (Mittewald unit in the upper Drau Valley/Puster Valley; Reitner 2016) below a subglacial traction till (Evans et al. 2006). During the climax of the AlpLGM (c. 26–19 ka according to data from the Tagliamento end moraine system, Monegato et al. 2007) the valleys of the rivers Isel and Drau were filled with ice streams as part of the Drau Glacier (Fig. 1b), which was the largest glacier in the south-eastern sector of the Alpine transection glacier complex. The Isel Glacier was the dominant glacier in the study area with an ice surface sloping from 2260 m a.s.l. at the outlet of the Kals Valley to around 2200 m at the outlet of the Debant Valley (Reitner 2003a). On the northern flank of the Lienz Dolomites an altitudinal range of the trimline between the glacially moulded area and the ârete is evident which lies in an comparable altitude and thus above the findings of erratic material in 2040 m a.s.l (Mutschlechner 1956). Glacial overdeepening has been detected by a gravity survey in the broad part of the Drau Valley from Lienz downflow with a depth of up to 500 m below the surface (Walach 1993). Therefore, the onset of major glacial erosion occurred in a classical confluence of Drau, Isel and finally Möll Glacier (Fig. 1), the latter coming from the north via a transfluence pass. In contrast, no overdeepenings are known from the upper Drau Valley, also called Puster Valley, with a V-shaped cross-section.

As a result of glacial oversteepening during the AlpLGM and, to a more limited amount, during the ALG, slopes in crystalline rocks reacted to withdrawal of ice overburden with various types of deep-seated gravitational slope deformations (DSGSDs; e.g. Reitner & Linner 2009). In contrast, rock slides and rock avalanches are known from the northern rim of the Lienz Dolomites (Reitner 2003b, Reitner et al. 2014).

3 Previous work, applied stratigraphic terminology and approach

The core area for establishing a Lateglacial stratigraphy is the southwestern flank of the Schobergruppe mountains between the Kals Valley in the West and the Debant Valley in the East (Fig. 1b). Firstly, the earliest descriptions of Lateglacial moraines, as available from Lucerna (1925) and Klebelsberg (1931 & 1952), can be regarded as cursory, whereas Senarclens-Grancy (1944) presented a map of large parts of this area with moraines defined according to his stratigraphic terminology (see discussion in Buchenauer, 1990). The phase of modern (re-)investigation of the study area began with Buchenauer (1990) who mapped this and adjoining areas geomorphologically in order to reconstruct the glacial and permafrost development from the end of the AlpLGM to the Holocene. With all the detailed geomorphological maps (scale 1:25,000), palaeogeographic reconstructions and the calculation of equilibrium line altitudes (ELAs) and corresponding ΔELAs (difference to the ELA of the last LIA maximum extent around the year 1850), this is a key work for the ALG of the Eastern Alps south of the Alpine main chain with an unprecedented standard of documentation. Based on his mapping results, Buchenauer (1990) defined local stadials (further subdivided by stillstands) as a local reference with defined stratotypes for which he calculated corresponding ΔELAs for the reconstructed palaeoglaciers using the accumulation-area-ratio (AAR-) method, with a value of 0.67 as defined by Gross et al. (1978) for the Alps. The deduced stratigraphic correlation is based on the terminology of the 1980s (summarised in Maisch 1982, 1987; Kerschner 1986) with ΔELAs serving as the major criterion for defining local stillstands and finally for correlation with defined stadials (Table 1). In addition, geomorphological criteria such as the shape (“freshness”) of moraines as an indicator of relative age were applied in stratigraphic assignments. The latter was important especially for the distinction between the glacial landforms of the Daun stadial (pre-Bølling/Allerød interstadial), which were supposed to be more subdued compared to those of the Egesen stadial (Younger Dryas). This morphological approach established by Heuberger (1966) in the Sellrain area (Northern Tyrol) has a possible bias as this morphological differentiation might be only evident in one valley dependent on altitude (*cf.* Kerschner 1978: 29).

As nearly all local type localities defined by Buchenauer (1990) are located in the study area, a re-assessment of the stratigraphy has been done by re-investigating the sedimentary and morphological sequences in two valleys i.e. Debant Valley and Daber(-bach) Valley containing these type localities and applying numerical dating methods to these sites; it is thus possible to discuss the sedimentological and geomorphological findings in the light of accompanied geochronology, a fortuitous situation rarely encountered in the Alps (*cf.* Ivy-Ochs et al. 2009). Likewise, similar successions in neighbouring valleys (Leibnitz(-bach) Valley and Kals Valley) and additional evidence in the Isel Valley, in the Drau Valley and in the Lienz Dolomites can be compared to this dataset.

The specific topographic and geological peculiarities of the aforementioned valleys having an impact on glacial development and preservation of successions (e.g. mass movements) are described in the sections dealing with the geology of the valleys.

4 Methodology

4.1 Fieldwork and stratigraphy

Geological mapping was performed mostly at a scale of 1:10,000, supplemented by mapping at 1:25,000, depending on the area, supported by lithofacies analysis according to Keller (1996). High-resolution LiDAR-images from the TIRIS online map of the Province of Tyrol (www.tirol.gv.at) were only available in the final stage of map compilation.

Tab. 1: The sedimentary stratigraphy with the different (allostratigraphic) units, their lithogenetic attribution in the published map sheet Lienz (Linner et al. 2013) and their climatostratigraphic correlation in comparison to the stratigraphic terminology and correlation used by Buchenauer (1990).

Tab. 1: Die Stratigraphie der Ablagerungen mit den verschiedenen (allostratigrafischen) Einheiten, deren lithogenetische Attributierung in der publizierten Karte Lienz (Linner et al. 2013) und deren klimastratigraphische Korrelation im Vergleich zu der von Buchenauer (1990) verwendeten stratigrafischen Terminologie und deren Korrelation.

Schober Mountains (local terminology)	**Lienz Dolomites (local terminology)**	**Lithogenetic unit [1]**	**Stadials defined by Buchenauer (1990) for the southern part of the Schober Mountains** *(with stratigraphic correlations used therein)*		**Climatostratigraphic subdivisions**	**Chronostratigraphy [2]**	
Debant (DE) unit	Kerschbaumeralm (KA) unit	glacigenic deposit	Lienzer Hütte (L.H.) *(Egesen)* Gaimberger-Alm (G.A.) *(Daun)*	Gartl (*Kromer*, ΔELA 60–90 m, Viehkogel (*Böcktentäli*, ΔELA 105–135 m) L.-H.-Maximum (*Egesen-Maximum*, ΔELA 185–225 m) Hofalm (*Daun II*, ΔELA 240–255 m) G.-A. Maximum (*Daun I*, ΔELA 265–300 m)	Egesen stadial (Younger Dryas)	late	ALPINE LATEGLACIAL (ALG) Würmian Lateglacial
					Bølling/Allerød-Interstadial	middle	
Kunig (KU) unit	Klammbrückl (KB) unit	glacigenic deposit	Kunig *(Senders/Clavadel)* Debant *(Gschnitz)*	ΔELA 405–450 m ΔELA 555–585 m	Gschnitz stadial (Oldest Dryas)	early	
Daber (DA) unit	Gallitzen (GA) unit	glacigenic deposit	(Strassboden, Grossbohn *(Steinach)*)[3]	(ΔELA 640 m, 665 m)[3]	Phase of ice-decay		
Ainet (AI) unit	Ainet (AI) unit	fluvioglacial deposit					
Isel (IL) unit		glacigenic deposit			Würmian Pleniglacial (AlpLGM)		
Mittewald unit		fluvial deposit					

[1] according to to CGI Controlled Vocabulary (2011–12) and Geologische Bundesanstalt Thesaurus (2016). [2] Lateglacial and Pleniglacial according to Chaline & Jerz (1984). The subdivision into early to late is informal. [3] The type localities of Strassboden and Großbohn are in the drainage area of the River Möll outside the study area and are not discussed in this paper.

In the published geological map of Lienz (Linner et al. 2013) the geologic units discussed in this paper are indicated as lithogenetic units, defined on the base of their genesis according to CGI Controlled Vocabulary (2011–12) and Geologische Bundesanstalt Thesaurus (2016). For establishing a stratigraphy as a solid base for further chronostratigraphic correlations these geologic units are informally defined based on Allostratigraphy (according to the North American Stratgraphic Code; North American Commission on Stratigraphic Nomenclature 2005: 1578) in this paper as "… a mappable body of rock that is defined and identified on the basis of its bounding discontinuities." Compared to lithostratigraphy, this stratigraphic approach is the most practicable for many cases in the Alpine Quaternary (see Bini et al. 2004, Monegato & Stefani 2010, van Husen & Reitner 2011, Colucci et al. 2014, Bichler et al. 2016). It allows to distinguish between different (1) superposed discontinuity-bounded deposits of similar lithology, (2) contiguous discontinuity-bounded deposits of similar lithology, or (3) geographically-separated discontinuity-bounded units of similar lithology (North american Commission on Stratigraphic Nomenclature 2005: 1578). However, the geological units are not denoted as alloformations or allomembers, as such a step requires standardised procedures which are beyond the scope of this paper.

4.2 Geochronology

Two samples for surface exposure dating (Ivy-Ochs & Kober 2008) were taken from quartz veins on the top surfaces of two boulders with a gasoline-powered saw. After crushing and sieving to grain size < 1 mm, quartz was purified with selective chemical dissolution (Kohl & Nishiizumi 1992). Be was isolated with several ion exchange separations and pH steps (Ivy-Ochs et al. 2006b). ^{10}Be/ ^{9}Be ratios were measured at the 600 kV TANDY (Christl et al. 2013) at the Laboratory of Ion Beam Physics (LIP) at ETH Zürich against the in-house standard S2007N, which is calibrated to 07KNSTD (Nishiizumi et al. 2007). Measured ratios were corrected for a long-term average full process blank ratio of (3.6 ± 2.6) * 10−15 ^{10}Be/ ^{9}Be. Exposure ages were calculated with the CRONUS-EARTH online calculator (Balco et al. 2008) with a spallation production rate at sea level and high latitude of 3.93 ± 0.19 at / g / a ('NENA'; Balco et al. 2009), 'St' scaling (Stone 2000)). No erosion or snow cover correction was made. This production rate agrees well with results from the Chironico landslide in Ticino, Switzerland (Claude et al. 2014)

One sample of macrofossils (ETH-48227), selected when pollen samples of Pitschedboden (site B-04) were prepared, was submitted to the AMS ^{14}C laboratory at ETH Zürich. This material underwent treatment of acid-base-acid washes (Hajdas

2008) to remove potential contamination with carbonates and humic acids. 2.1 mg of dry clean organic matter, which is equivalent to 1 mg of carbon, was then weighed into tin cups for combustion in an Elemental Analyser and subsequent graphitization (Wacker et al. 2010). Resulting graphite was pressed into aluminium cathodes and the ^{14}C/^{12}C and ^{13}C/^{12}C ratios were measured using the MICADAS dedicated AMS facility of ETH Zürich (Synal et al. 2007). The radiocarbon age was calculated following Stuiver & Polach (1977) using the measured ^{14}C content after correction for standards, blank values and fractionation (δ^{13}C values measured semi-simultanously on graphite). the reported conventional age is 11525±236 BP, $\delta^{13}\mathrm{C}=-19.0\pm1.0$‰. The calendar age of 13470–13260 (95.4%) was obtained using the calibration progam of OxCal v4.2.4 Bronk Ramsey (2013) and the IntCal13 atmospheric curve (Reimer et al. 2013).

4.3 Palynology

Samples for pollen analysis of the drilled core of Pitschedboden (site B-04) have been analysed to constrain the chronology and to test the plausibility of the radiocarbon age. 2 cm^3 of sediment were chemically treated using HF and acetolysis and stored in glycerol. At least 500 pollen grains per sample were counted. A percentage diagram shows the results of the lower part (6.48–5.97 m), which is relevant in the context of the present study, whereas the upper part will be presented elsewhere. For calculation of the percentages, Pteridophytes, water plants and Indeterminanda are excluded from the pollen sum (trees and shrubs (AP) and upland herbs (NAP) = 100%).

5 Debant Valley

The Debant Valley (Figs. 2 & 3), with a length of 17 km, is the longest tributary valley of the River Drau in the Schobergruppe mountains. Its uppermost cirques below the highest peaks in the range of 3053–3242 m a.s.l. are still glaciated. During the last peak of the Little Ice Age around the year 1850 (LIA$_{1850}$) an area of nearly 1 km^2 was covered by glaciers with equilibrium line altitudes (ELAs$_{\mathrm{LiA}}$) between 2680 and 2860 m a.s.l. (cf Buchenauer 1990 for details). With a gently-sloping middle part and steep lower part towards the Drau valley it still exhibits the characteristics of a hanging valley.

5.1 Field evidence

The area stretching from the true left flank of the lowermost part of the valley to the northern Drau Valley flank is characterised by kame terraces made up of sandy gravels unconformably resting on bedrock (Figs. 2 & 4). The most prominent terrace is located around 800 m a.s.l. (150 m above modern valley floor of the Drau Valley) has a gentle

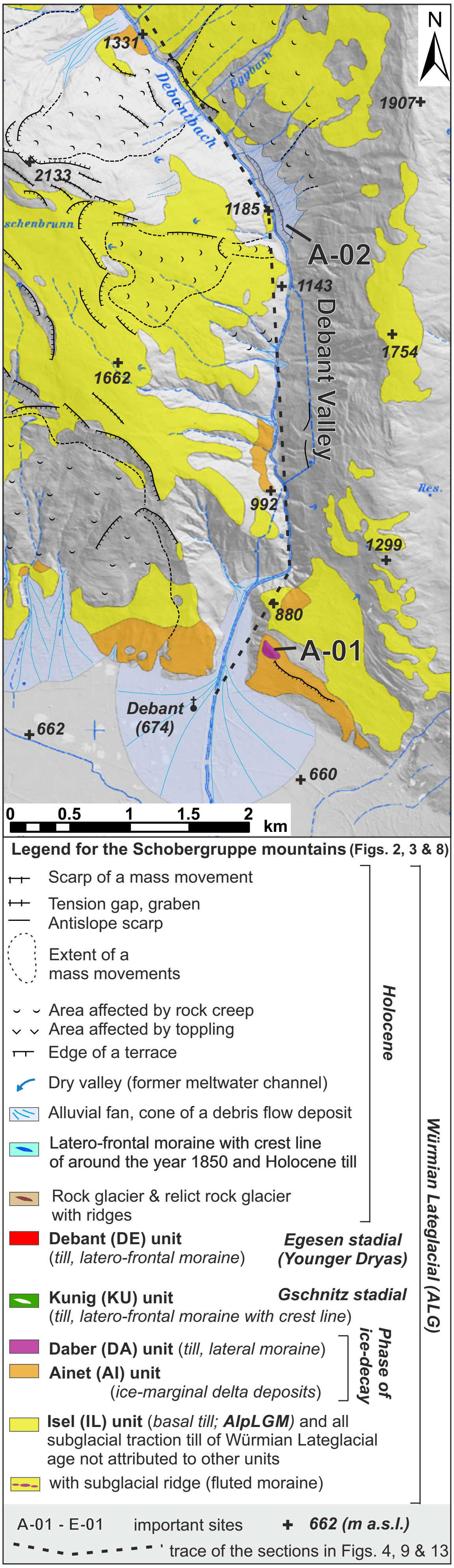

Fig. 2: Map of the lower Debant Valley with Quaternary sediments and important sites (A-01, A-02) with the legend of the Schobergruppe mountains valid for Figs 2, 3 & 9 (shaded relief image from TIRIS online map of the Province of Tyrol: www.tirol.gv.at).

Abb. 2: Quartärgeologische Karte des unteren Debanttales mit den wichtigen Lokalitäten (A-01, A-02) mit für die Schobergruppe (Abb. 2, 3 & 9) gültigen Legende (Hillshade von der TIRIS online Karte des Bundeslandes Tirol: www.tirol.gv.at).

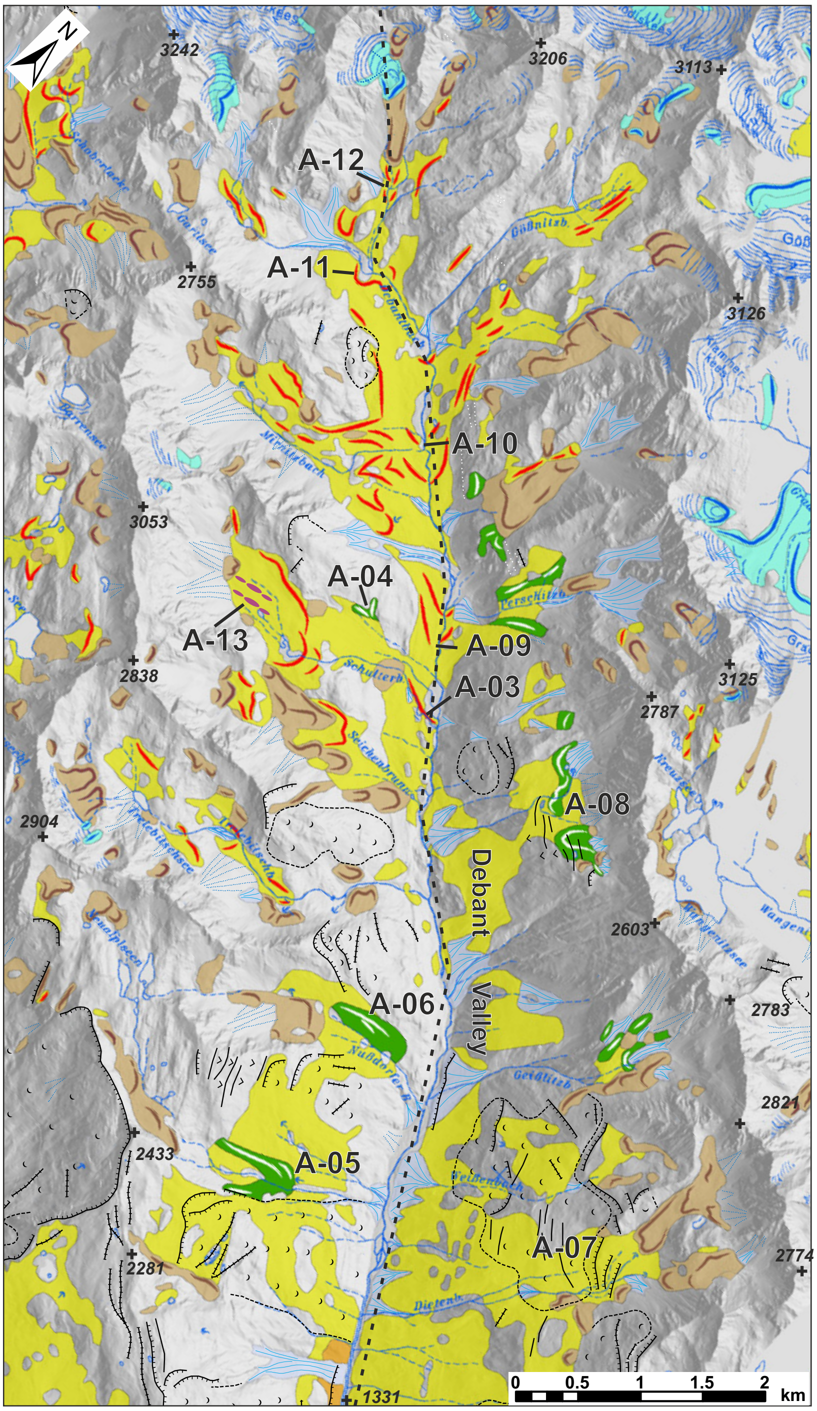

Fig. 3: Map of the middle and upper Debant Valley with Pleistocene sediments and important sites (A-03 to A-13) (shaded relief image from TIRIS online map of the Province of Tyrol: www.tirol.gv.at).

Abb. 3: Quartärgeologische Karte des mittleren und oberen Debanttales mit den wichtigen Lokalitäten (A-03 bis A-13) (Hillshade von der TIRIS online Karte des Bundeslandes Tirol: www.tirol.gv.at).

slope from the Debant valley to the Drau valley. Thus, a sediment transport from the tributary valley towards a still existing ice body in the broad Drau valley is evident. On top of this kame terrace a prominent, 200 m-long ridge, interpreted as a moraine and running from NW to SE with a height of 15 m, is evident (A-01, Obergöriach; Figs. 2 & 4). It consists of sandy gravels with subangular to rounded clasts and angular boulders with a diameter of up to 2 m. These morphological and sedimentary characteristics, together with the clast lithology (mica schists and gneiss), indicate a formation of this moraine remnant by a glacier descending from the Debant Valley.

The type locality of Debant stadial (= Gschnitz) as defined by Buchenauer (1990) is located on the true left flank in 1185 m a.sl. at the limit between the gorge like lower valley and the middle part (site A-02; Figs. 2 & 4). It is interpreted as a partly eroded alluvial fan with a polymictic clast spectrum typical of the hinterland ranging from angular mica-schist which makes up the bedrock on this flank to (sub-)rounded gneiss, eclogite and amphibolite. According to Buchenauer (1990), this fan-like feature resembles an accumulation at the margin of a stabilised glacier tongue over a considerable time. However, compared to neighbouring slopes, the till cover which is extensive elsewhere along the surrounding valley flank, has been eroded down to the bedrock in the catchment area of the creek linked to the apex of the alluvial fan. Hence, this deposit is composed of reworked glacial material from the higher ground and has no implications for the reconstruction of a former glacier extent (Reitner 2003a).

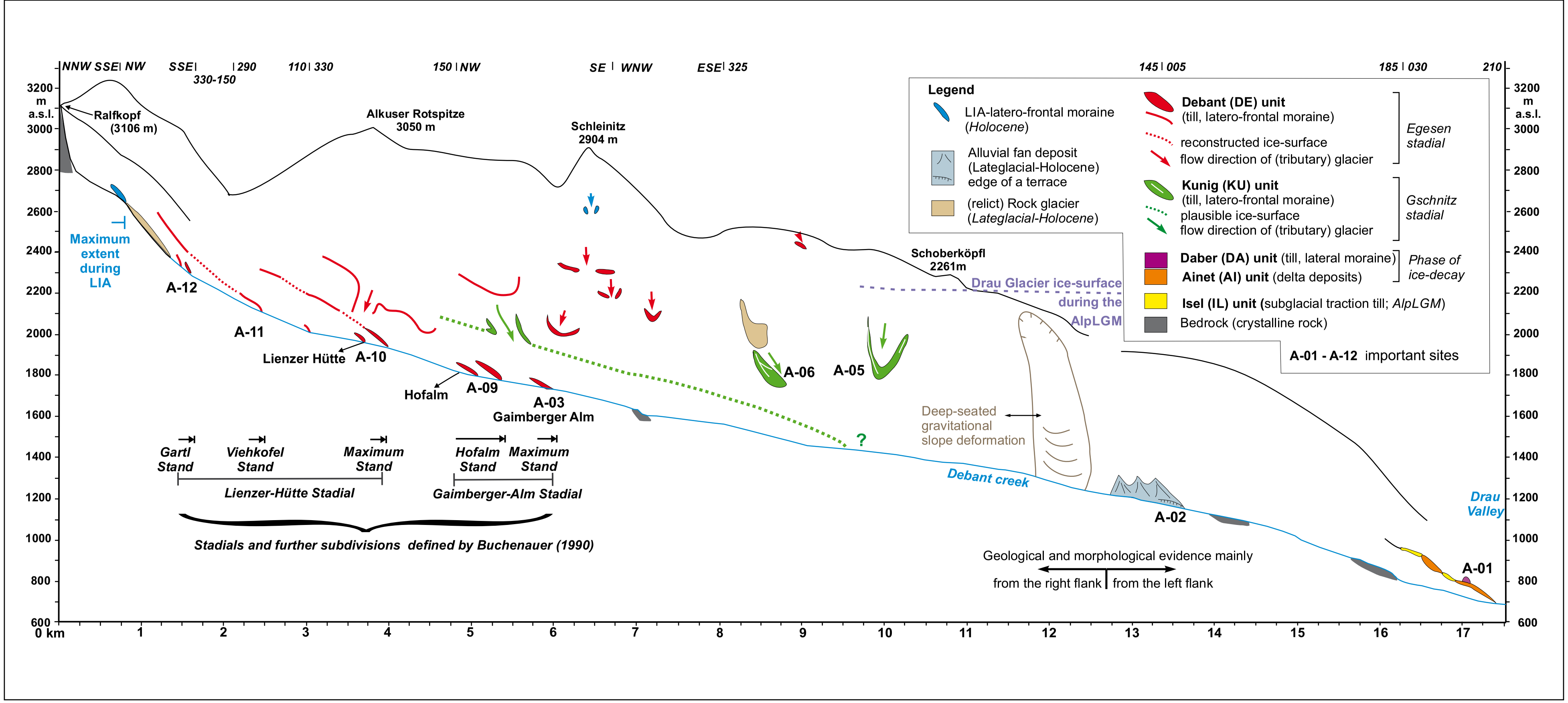

Fig. 4: Section along the Debant Valley with the sites A-01 – A-12.

Abb. 4: Geologischer Schnitt entlang des Debanttales mit den Lokalitäten A-01 bis A-12.

The middle part of the Debant Valley from location A-02 to up to an altitude of c. 1400 m shows a narrow V-shaped cross section due to the pushing toes of DSGSDs (Fig. 4). This is followed upstream for 1.3 km by a broad valley floor where the creek shows isolated signs of braiding in this part of the valley.

Between location A-02 and location A-03 no glacial sediments can be found on the valley floor. However, on the valley flanks, around 250 m above the valley floor WNW of location A-03, ridge-like landforms, which are interpreted as lateral moraines of a valley glacier, are evident (Figs 3, 4 & 5a). In one case (A-04) the geometry of these moraines allows the reconstruction of a confluence with a tributary glacier deriving from a small cirque on the southwestern valley flank. These moraines were attributed by Buchenauer (1990) to his Kunig stadial (Table 1), whose type locality will be described in Section "6. Daber Valley". On the true right flank downvalley of A-04 no indication of a cirque glacier joining the valley glacier is present. In contrast those glaciers formed prominent latero-frontal moraines (location A-05 = Wellalm & A-06 = Nussdorfer Alm). On the opposite, south-west facing valley flank pal-

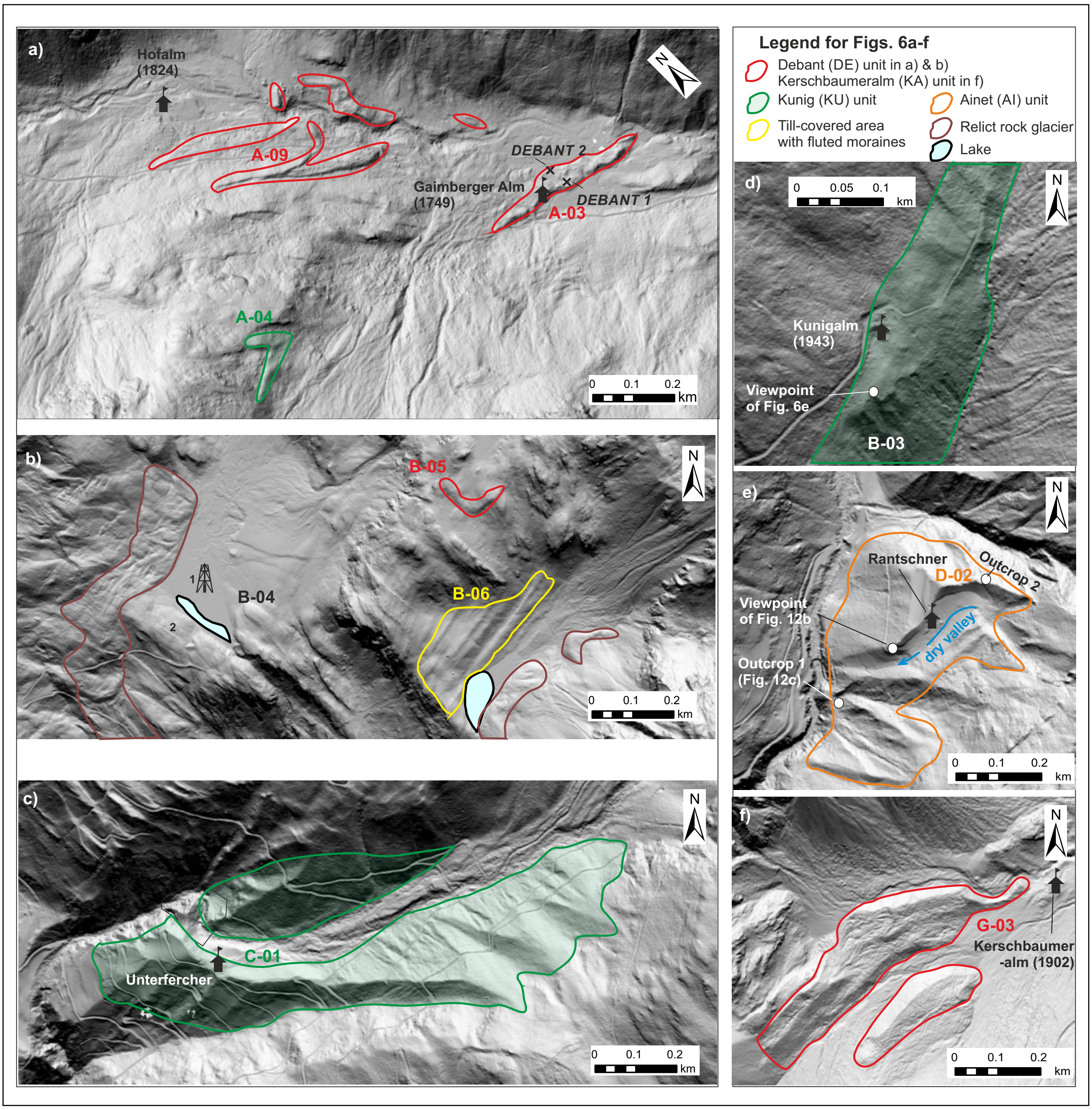

Fig. 5: Comparison of DEM images of different stratigraphic units (s. legend) and sites. a) Site A-03, A-04 and A-09 in the Debant Valley. b) Site B-04 (with 1 – drilling site for the peat core, 2 – bedrock riegel), B-05 and B-06 in the Daber Valley. c) Site C-01 in the Leibnitz Valley. d) Site B-03 in the Daber Valley. e) Site D-02 in the Kals Valley. f) Site G-03 in the Galitzen Valley. (shaded relief image from TIRIS online map of the Province of Tyrol: www.tirol.gv.at).

Abb. 5: Vergleich der verschiedenen stratigrafischen Einheiten als Bilder im digitalen Höhenmodell. a) Lokalitäten A-03, A-04 und A-09 im Debanttal. b) Lokalitäten B-04 (mit 1 – Bohrplatz für den Torfkern, 2 – Karschwelle), B-05 und B-06 im Daber-Tal. c) Lokalität C-01 im Leibnitz-Tal. d) Lokalität B-03 im Daber Tal. e) Lokalität D-02 im Kalser-Tal. f) Lokalität G-03 im Galitzen-Tal (Hillshade von der TIRIS online Karte des Bundeslandes Tirol: www.tirol.gv.at).

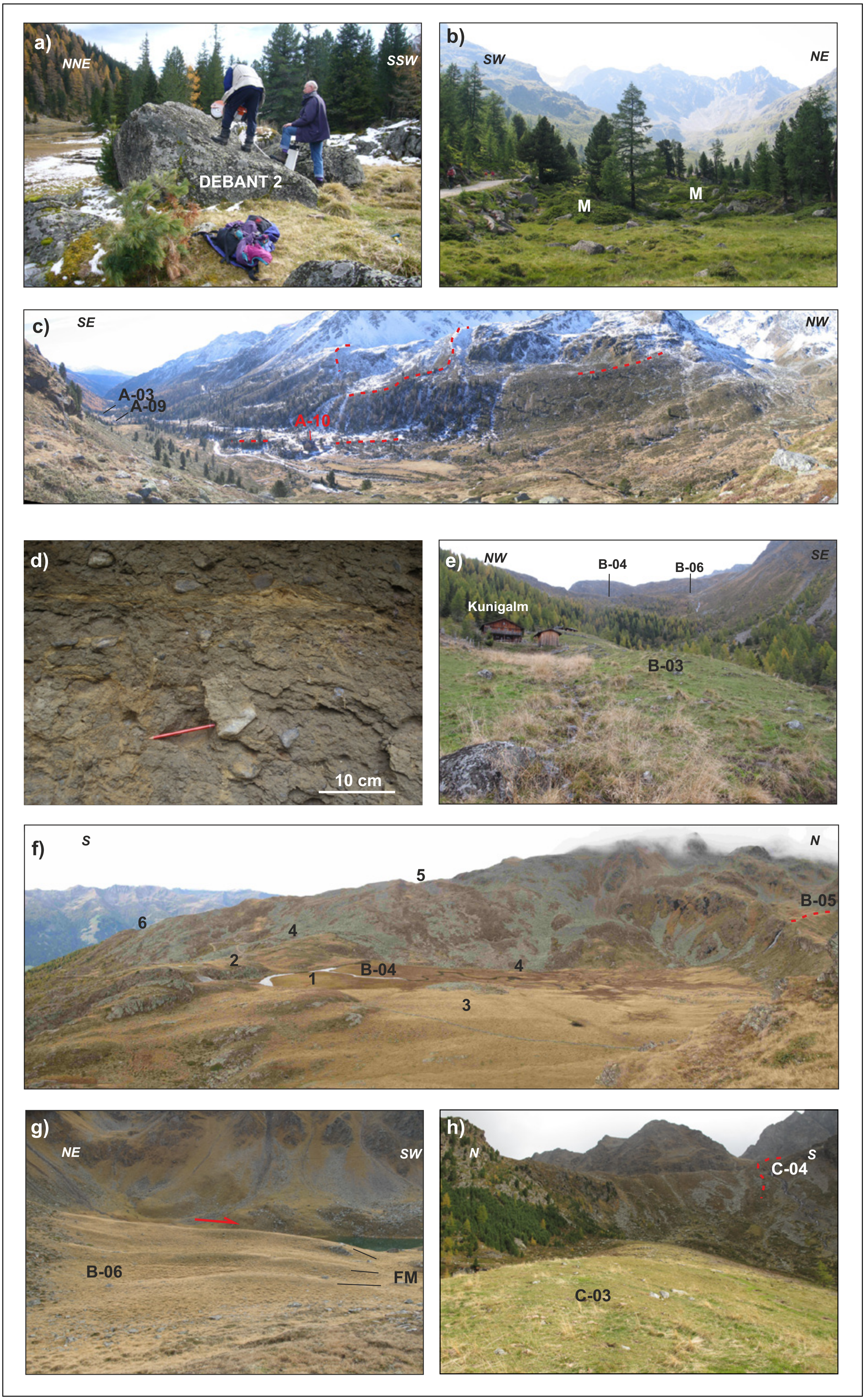
a)
NNE
SSW
DEBANT 2
b)
SW
NE
M
M
c)
SE
NW
A-03
A-09
A-10
d)
10 cm
e)
NW
B-04
B-06
SE
Kunigalm
B-03
f)
S
N
5
B-05
6
4
2
B-04
4
1
3
g)
NE
SW
B-06
FM
h)
N
S
C-04
C-03

Fig. 6: a) Gneiss boulder of sample DEBANT 2 on top of the moraine of the DE unit during sampling (view towards ESE). b) Multiple small boulder-rich moraines (M) in the vicinity of site A-09. c) Latero-frontal moraines of the DE unit around site A-09 (Lienzer Hütte) at the true right side of the Debant Valley. Red dotted lines indicate the crest of some prominent moraines. The sites A-03 (Gaimberger-Alm) and A-09 (Hofalm) are located downstream. d) Dark-grey basal till of the DA unit with shear planes and with deformed sand layers at location B-01 in 1150 m a.s.l. (see also Fig. 10). e) Location B-03 in the Daber Valley with the lateral moraine of the Kunig (KU) unit right of the Kunigalm hut (viewpoint shown in Fig. 5d). Sites B-04 and B-06 are indicated. View upvalley towards NNE. f) Site B-04 (Pitschedboden) with a mire (1 -drill location), (2) a bedrock riegel, (3) areas of subglacial till cover, (4) relict rock glaciers, (5) graben structure and (6) antislope scarps of the deep-seated toppling deformation (Reitner & Linner, 2009). Location B-05 with latero-frontal moraines of the DE unit (crest indicated by red dotted line). g) Location B-06 (Gutenbrunn) in the Daber Valley with three fluted moraines (FM). Red arrow indicates former ice-flow direction. h) Site C-03 in the Leibnitz Valley with a broad subglacial ridge in the foreground. The onset of a lateral moraine of the DE unit (red dotted line indicates the crest) on site C-04 (in the upvalley direction) is evident.

Abb. 6: a) Gneisblock der Probe DEBANT 2 auf der Moräne der DE-Einheit während der Beprobung (Blick gegen ESE). b) Multiple kleine blockreiche Moränen (M) in der Nähe von Lokalität A-09. c) End- bis Seitenmoränen der Debant (DE)-Einheit nahe der Lokalität A-09 (Lienzer Hütte) an der orographisch rechten Flanke des Debanttales. Rot strichlierte Linien dokumentieren den Kammverlauf einiger prominenter Moränenzüge. Die Lokalitäten A-03 (Gaimberger-Alm) und A-09 (Hofalm) liegen flussabwärts. d) Dunkelgraue Grundmoräne der DA-Einheit mit Scherflächen und mit deformierten Sandlagen bei Lokalität B-01 in 1150 m Höhe (Lage siehe auch Abb. 10). e) Lokalität B-03 im Daber-Tal mit der Seitenmoräne der Kunig (KU)-Einheit rechts von der Kunigalm (Blickpunkt in Abb. 5d markiert). Lokalitäten B-04 und B-06 sind angezeigt (Blickrichtung talaufwärts gegen NNE). f) Lokalität B-04 (Pitschedboden) mit einem Moor (1 -Bohrplatz), (2) mit einer Karschwelle, (3) mit Gebieten aus Grundmoräne, (4) reliktischen Blockgletschern, (5) Grabenstruktur und (6) antithetischen Brüchen der tiefgreifenden Kippung (Reitner & Linner, 2009). Lokalität B-05 mit End-bis Seitenmoräne der DE-Einheit (Kammlinie rot-strichliert dargestellt). g) Lokalität B-06 (Gutenbrunn) im Daber-Tal mit drei „fluted moraines" (FM). Der rote Pfeil zeigt die ehemalige Eisflussrichtung an. h) Lokalität C-03 im Leibnitz-Tal mit einem breiten, subglazial-geformten Rücken im Vordergrund. Der Ansatz der Seitenmoräne der DE-Einheit (rot-strichlierte Linie markiert die Kammlinie) bei Lokalität C-04 ist ersichtlich (Blickrichtung talaufwärts).

aeoglacier reconstruction is hampered by the combined action of fluvial, gravitational processes. Thus, landforms previously interpreted by Buchenauer (1990) as lateral moraines at locations A-07 (Obere Göriacher Alm; Fig. 3) are here interpreted either as ridges within the AlpLGM till cover due to dissection by DSGSDs or remnants resulting from linear erosion or as rock glacier deposits. Only in areas with no or less severe impact of mass movements corresponding latero-frontal moraines allow to constrain the geometry of small cirque glaciers (location A-08 in Fig. 3; Gaimberger Feld). The uppermost onset of those lateral moraines in 2300 to 2250 m might serve as a robust proxy for ELA-reconstruction in the sense of the maximum elevation of lateral moraines (MELM) approach (Lichtenecker 1938, Benn & Lehmkuhl 2000).

On the valley floor at location A-03 (Gaimberger-Alm at 17409 m a.s.l.) a prominent frontal boulder-rich moraine with a height of up to 12 m crosses the valley (Fig. 3, 5a, 6a). The lithology of the subangular to subrounded clasts reflects the geology of the hinterland. Buchenauer (1990) defined this ridge as the type-locality of his Gaimberger-Alm stadial (correlated by him with the Daun stadial; Table 1).

From site A-03 upvalley, isolated moraine ridges occur at location A-09 (Hofalm; Fig. 4 & 5a), the type locality of the Hofalm stand as defined by Buchenauer (1990), two closely-spaced boulder-rich end moraines document stillstands. However, beside these two prominent moraines with a height of up to 10 m many small, 1–2 m-high ridges are present (Fig. 6b).

At site A-10 (Lienzer Hütte; Figs. 3, 5a & 6c) a well-preserved boulder-rich end moraine crosses the valley, which represents the maximum extent of the Lienzer-Hütte stadial (Buchenauer 1990). The good preservation of the latero-frontal moraine and of a set similar minor features upvalley enables a reconstruction of the glacier tongue, its confluences with the tributary glaciers and, lastly, their separation during retreat. Buchenauer (1990) describes differences in the morphological appearance of the moraines of Gaimberger-Alm stadial, Hofalm halt and Lienzer Hütte stadial (Table 1), with the last one appearing as the freshest landform with sharp crestlines. However, only the difference between the moraines of the aforementioned stadials and the more subdued ones of his Kunig stadial is undoubtedly recogniseable in the field and in the DEM-images (Fig. 5a).

The final breakup of the Debant Glacier into separated glaciers after the Lienzer-Hütte stadial interrupted by considerably smaller glacier halts at location A-11 (Viehkofel halt) and A-12 (Gartl halt) is documented by a series of moraines (Fig. 4) which can be traced close to the LIA-moraines (*cf.* Buchenauer for details; Table 1).

Fluted moraines with a trend parallel to former ice-flow and a height of up to 2 m are evident on the till-covered cirque floor at location A-13 (south of A-04) which was covered by a small cirque glacier for the last time during the Lienzer-Hütte stadial (Buchenauer 1990: 108).

5.2 Results of the ^{10}Be surface exposure dating

In order to cross-check Buchnauer's attribution based on ELA-depressions of the Gaimberger-Alm end moraine as a regional document of the Daun stadial two gneiss boulders were sampled at site A-03. DEBANT 1 and DEBANT 2 (Figs. 5a & 6a) provided consistent ^{10}Be ages of 13.3–12.1 ka and 13.5–12.1 ka (Table 2) which document a glacier stabilisation most likely at the onset of the Younger Dryas.

5.3 Discussion

According to findings of the fieldwork together with the results of the ^{10}Be-exposure dating, the Lateglacial deposits of the Debant Valley can be subdivided into four mappable geological units (Figs. 2, 3, 4 & 7).

The **Daber (DA) unit** (named after the type locality described in Section 6) consisting of a remnant of a lateral moraine (location A-01 at Obergöriach) deposited by a Debant Glacier on top of a kame terrace, which belongs to the **Ainet (AI) unit** (named after the type locality described in Section 6). The latter feature documents deltaic accumulation at the margin of a decaying Drau Glacier after a loss of 1400 m ice-thickness compared to AlpLGM conditions.

Tab. 2: Sample information, AMS concentrations, and calculated surface exposure ages for the samples DEBANT 1 and DEBANT 2 from the latero-frontal moraine at site A-03 in the Debant Valley.

Tab. 2: Probeninformationen, AMS-Konzentrationen errechnete Oberflächenalter für die Proben DEBANT 1 und DEBANT 2 von der Endmoräne bei Lokalität A-03 im Debanttal.

Sample name	Latitude (DD)	Longitude (DD)	Elevation (m)	Thickness (cm)	Shielding factor	^{10}Be (at/g)	Error (at/g)	Exposure age (yr)	Error (yr)
DEBANT 1	46,9218	12,7667	1737	2,5	0,9637	202420	8690	12740	550
DEBANT 2	46,9223	12,7665	1735	2,5	0,9335	197410	9970	12840	650

AMS concentrations blank corrected ^{10}Be (long time laboratory blank of ^{10}Be/^{9}Be = 3.7±2.4 e-15). Given errors are at the 1σ level based on the analytical uncertainties. No correction was made for erosion or snow cover.

Furthermore, any indication of a stabilised glacier halt is missing. In total, such a finding is typical for an active local glacier (scene IV in Fig. 7), which got separated from the downwasting transection glacier complex in the large valleys, advancing to its Lateglacial maximum position (LMP) during the phase of ice-decay (Reitner, 2007).

The **Debant (DE) unit**, named after the valley containing the clearest and most complete record, consists of a set of moraine clusters that had previously been defined by Buchenauer (1990) as Gaimberger-Alm stadial, Ho-

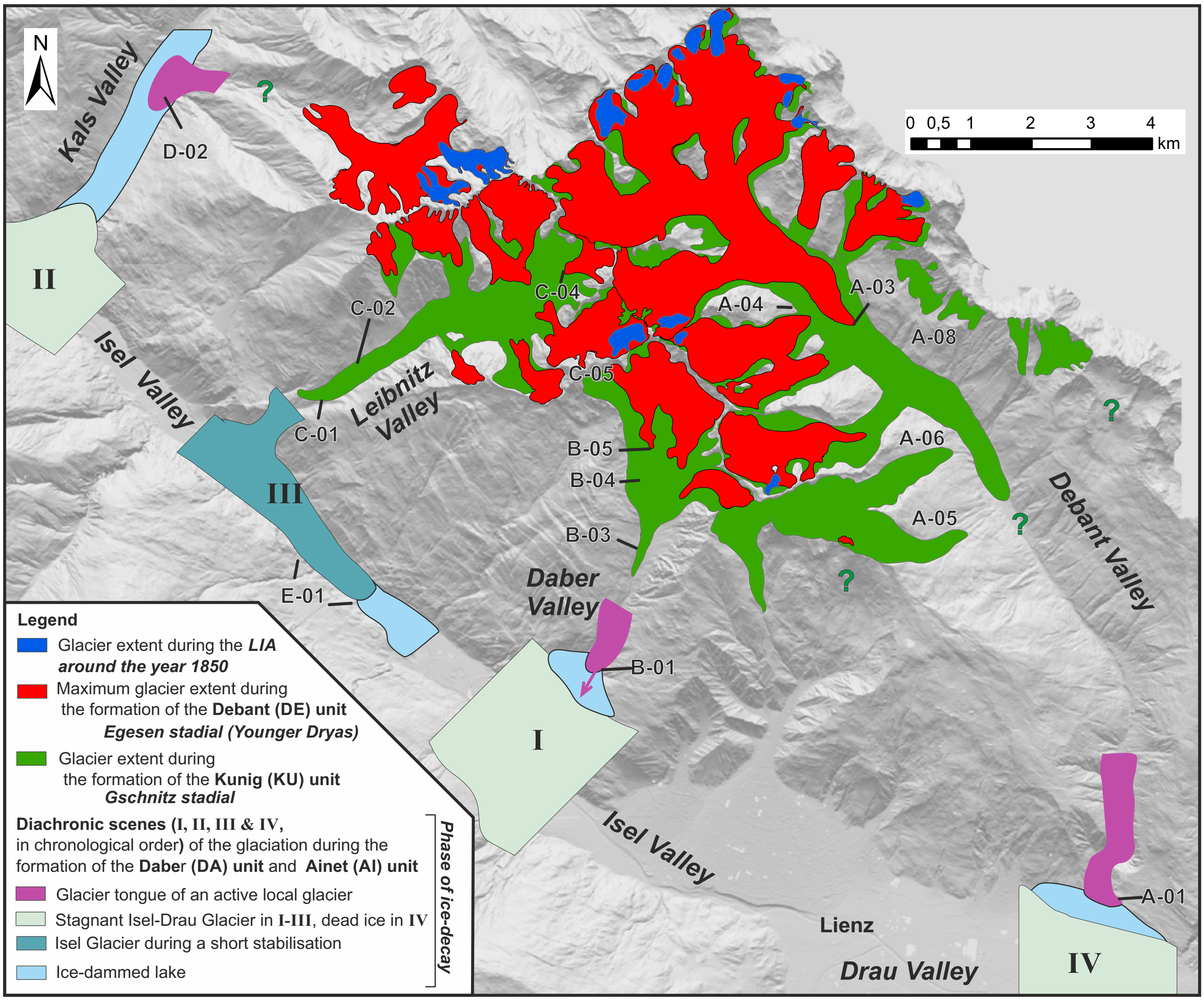

Fig. 7: Palaeogeographic sketch showing the ice extent in parts of the Schobergruppe mountains during the formation of the Ainet (AI) unit and Daber (DA) unit in the Phase of ice-decay, of the Kunig (KU) unit in the Gschnitz stadial and of the Debant (DE) unit in the Egesen stadial (Younger Dryas) in comparison to the glaciation during the LIA$_{1850}$. Important sites (e.g. A-01, B-01, C-01 etc.) of Figs. 2, 3 and 9 are indicated (shaded relief image from TIRIS online map of the Province of Tyrol: www.tirol.gv.at).

Abb. 7: Paläogeografische Skizze mit der Vergletscherung in Teilen der Schobergruppe während der Bildung der Ainet (AI)- und Daber (DA)-Einheit in der Eiszerfallsphase, der Kunig (KU)-Einheit im Gschnitz-Stadial und der Debant (DE)-Einheit in the Egesen-Stadial (Jüngere Dryas) im Vergleich zur Vergletscherung um das Jahr 1850 (LIA$_{1850}$). Wichtige Lokalitäten (z.B. A-01, B-01, C-01 etc.) der Abb. 2, 3 und 9 sind angezeigt (Hillshade von der TIRIS online Karte des Bundeslandes Tirol: www.tirol.gv.at).

falm halt, Lienzer Hütte stadial, Viehkofel halt and Gartl halt, respectively (Table 1). According to the two ^{10}Be-ages (12.7 ±0.6 ka and 12.8 ±0.7 ka) of the outermost moraine at Gaimberger-Alm (A-03) the formation of this unit most likely began most on in the Younger Dryas at the margin of a valley glacier that retreated from the dated maximum extent, interrupted by a number of stillstands (possibly after minor readvances). The succession of DE moraines up to the foreland of the LIA end moraines without an evident break might imply a continuous deposition exclusively during the Younger Dryas. With the geochronologically-backed definition of the DE unit including the moraines of the former Gaimberger-Alm stadial, the previous differentiation between a Daun and a Egesen stadial glacial deposit based on ΔELA correlation has to be rejected for the study area. In addition, the same is true in this case for a general rule based on the morphology of moraine ridges as a criterion for classification.

For the isolated lateral moraines on the valley flanks indicating a valley glacier extent between the units of DA and DE the term **Kunig (KU) unit** in the sense of the original stage defined by Buchenauer (1990) is used (Table 1). Unfortunately, the geometry of the palaeoglacier tongue is not well constrained. In considering the gradient of the glacier surface, a terminal position of the glacier around 4 km downvalley of location A-03 seems to be plausible.

The latero-frontal moraines of the cirque glaciers described at location A-04 – A-08 indicate a larger glacier extent (compare Buchenauer 1990), in balance with climate for a considerable timespan, in the cirques where the DE unit is present (e.g. location A-05). Furthermore, as the Debant stadial defined by Buchenauer (1990) was proven to be non-existent at its type locality, those latero-frontal moraines which were previously attributed to this obsolete stadial are also included in the KU unit.

6 Daber Valley

The Daber Valley is a tributary valley of Isel Valley with the characteristics of a hanging valley (Figs. 7, 8 & 9). Accordingly, the lower part of this 7 km-long valley between 800 m and 1250 m a.s.l. is the steepest part where Daber creek is incised into bedrock followed by a moderately-sloping middle part up to 2100 m. The uppermost part of the drainage area is characterised by a series of terrain steps, where partly lakes (e.g. Lake Alkus; site B-07 in Fig. 8) or mires (Pitschedboden; site B-04) are present behind bedrock thresholds (Riegel). The highest peaks surrounding the catchment area, which were free of glaciers during the LIA, are in the range 3050 m a.s.l.

6.1 Field evidence

Between the lower part of the Daber Valley (above the village of Ainet) and parallel minor valley to the east a prominent broad ridge is evident between 800 m and 1300 made up of glacial and fluvioglacial sediments (location B-01). The stratigraphically-lowest deposit is a grey, highly-compacted massive and matrix-supported diamicton with fissility and striated clasts lying unconformably on bedrock (Fig. 10). The clasts consist of lithologies which are present on the true left flank of the Isel Valley including the prominent Tonalite which appears to have quarried from 10 km upvalley. This deposit is interpreted as a characteristic sub-

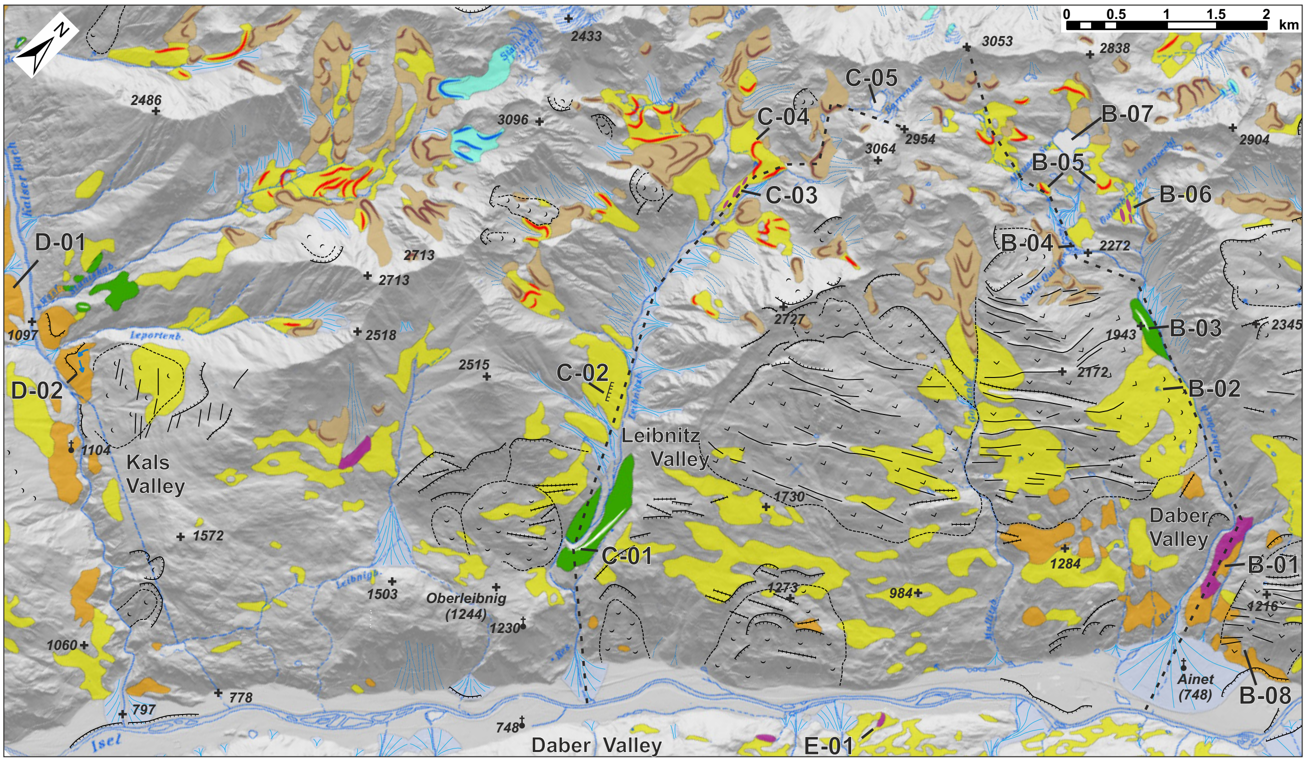

Fig. 8: Map showing the Quaternary sediments of the Daber Valley (with sites B-01 to B-08), of the Leibnitz Valley (with sites C-01 to C-05), of the Kals Valley (with sites D-01 & D-02) and of the Isel Valley (site E-01) (shaded relief image from TIRIS online map of the Province of Tyrol: www.tirol.gv.at).

Abb. 8: Quartärgeologische Karte des Daber-Tales (mit den Lokalitäten B-01 bis B-08), des Leibnitz-Tales (mit den Lokalitäten C-01 bis C-05), des Kalser-Tales (mit den Lokalitäten D-01 & D-02) und des Isel-Tales (Lokalität E-01) (Hillshade von der TIRIS online Karte des Bundeslandes Tirol: www.tirol.gv.at).

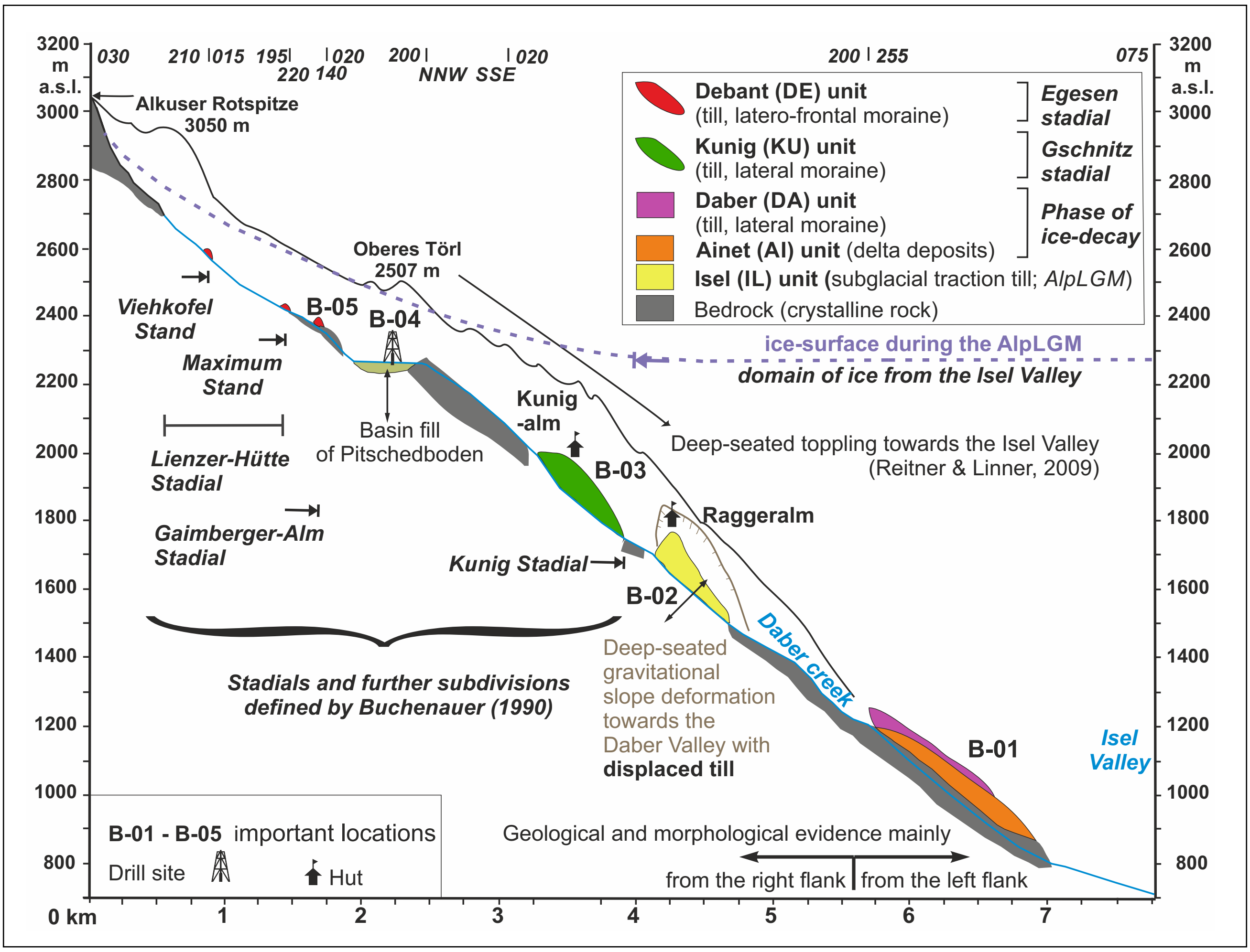

Fig. 9: Section along the Daber Valley with sites B-01 – B-05.

Abb. 9: Geologischer Schnitt entlang des Daber-Tales mit den Lokalitäten B-01 bis B-05.

glacial traction till which was deposited by the Isel Glacier and is unconformably overlain by a sediment package dominated by sandy gravels partly with boulders. In small outcrops clinoforms made up of planar-bedded sediment with a dip around 10° towards the SW are evident. In the lower part a transition to sandy and and silty layers with isolated glacially-shaped clasts, interpreted as dropstones, is present. This deposit is interpreted as a suite of deltaic sediments, topped by a grey, again highly-compacted, fissile massive and matrix-supported diamicton which makes up the surface of the ridge. Some of the outcrops show deformed sand-stingers within the diamicton (Fig. 6a). In contrast to the lower diamicton, striated clasts made up of marble and a remarkably-higher proportion of eclogite are evident. Hence, this deposit is best explained as a subglacial traction till of a local glacier sourced in the Daber Valley catchment. The upper till cover overlying the deltaic sediments reaches from around 1300 m down to ca. 1000 m a.s.l. The uppermost part in 1240–1300 m of the ridge has a curved crest like a typical latero-frontal moraine. The sediment matrix on the southern flank appears slightly sandier and thus less fine-grained than on the opposite side. In absence of good outcrops the morphology in this position could either be the product of a glacier stillstand or of fluvial erosion of the Daber creek.

In the middle part of the Daber Valley both flanks show the signs of different apparent processes which have a severe impact on the distribution and interpretation of glacial deposits. On the left side only talus fans below steep rock walls are present. In contrast the rock of the right flank was firstly loosened by deep-seated toppling towards the Isel Valley (towards SW) and was subsequently affected by mass movements towards the Daber Valley (towards SE) (Reitner & Linner 2009; Figs. 8 & 9). Accordingly, in this area many ridges with a (thin) cover of diamicton or gravel-sand-mixtures i.e. till or ice-marginal sediments, are due to the deformation of the underlying rock by various, partly overlapping types of DSGSDs rather than being purely attributable to glacial processes (Reitner & Linner 2009). Thus, Buchenauer's lateral moraines attributed to his Großbohn stadial (correlated to Steinach stadial; s. Table1) and to his Debant stadial (=correlated to Gschnitz; at location B-02) could not be verified as proofs for a glacier stillstand, but are just as likely candidates for being products of mass movement processes.

The only undoubtable lateral moraine in this part of the valley is at location B-03 (Kunigalm), the type locality of the Kunig stadial (Buchenauer 1990). It consists of a ca. 200 m long broadly developed ridge with a smoothed crest at an altitude of between 1975 and 1930 m running parallel to the Daber Valley (Figs. 5e & 6d). With glacially-rounded boulders on top and it standing above the adjoining flank

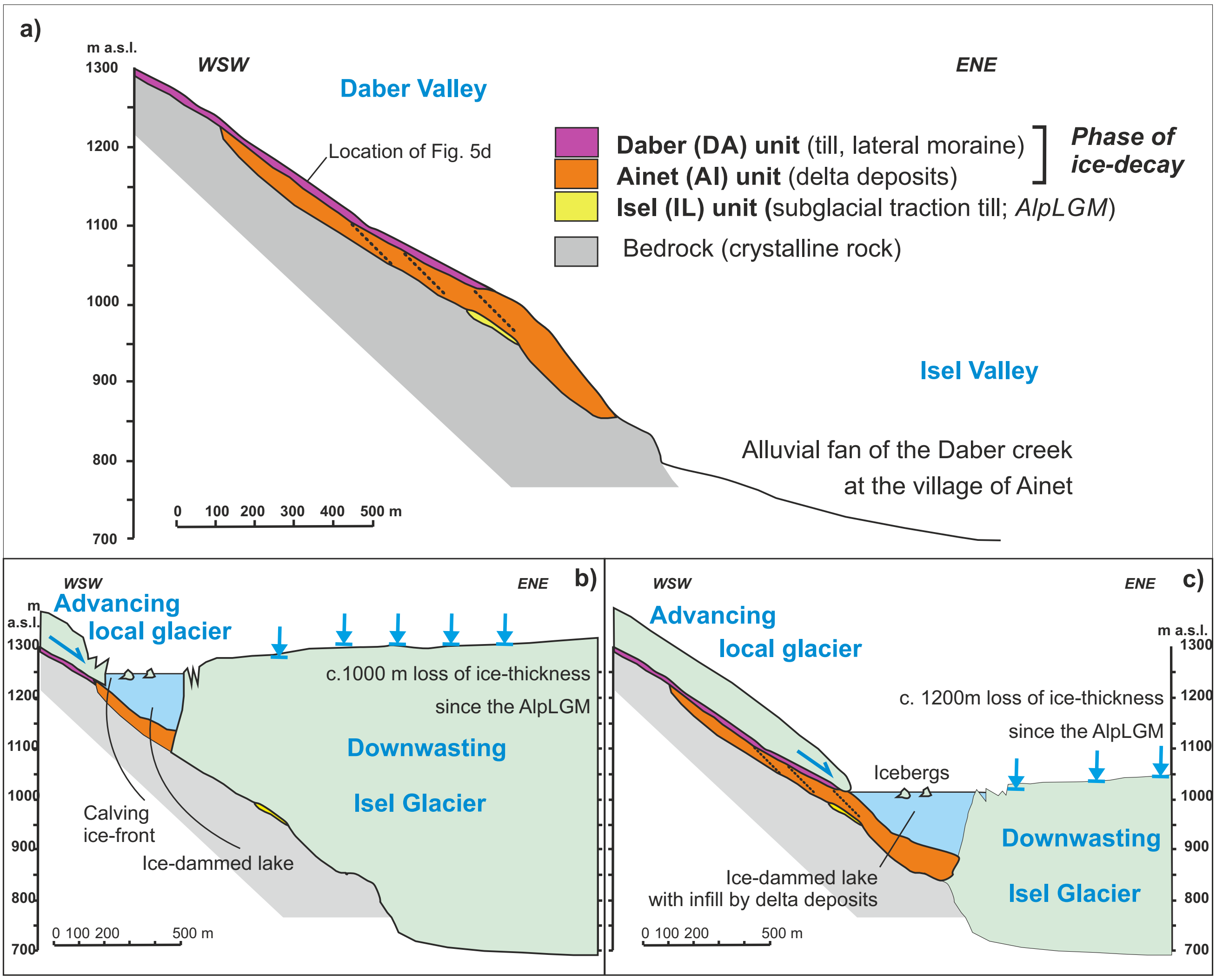

Fig. 10: a) Section east of the lower Daber Valley at B-01 b) and c) Palaeogeographic scenarios explaining the formation of the Daber unit and the Ainet unit.

Abb. 10: a) Geologischer Schnitt unmittelbar östlich des unteren Daber-Tales bei Lokalität B-01 b) und c) Paläogeografische Szenarios zur Erklärung wie die Daber (DA)- und die Ainet (AI)-Einheit gebildet wurden.

by up to 6 m, it marks a sharp contrast to the angular slope deposits in the surroundings.

One of the most remarkable features in the upper part of the valley is a small basin with a mire in its centre (s. Section 6.2) at around 2270 m at location B-04 (Pitschedboden), which is closed by a bedrock riegel (Figs. 5b, 6f & 9). The latter marks the limit to a steep bedrock slope extending down to 2000 m. The shape of the riegel and the surface of the neighbouring till cover show glacial moulding as a result of glacier flow in the direction of location B-03 (towards S to SE).

Typical latero-frontal moraines with sharp crestlines compared to those of the Kunig stadial type locality occur on top of the next terrain step in the main valley (up the valley of B-04) in 2370 m a.s.l. at site B-05 (Figs. 5e, 6d & 9). According to these characteristics, as well as ΔELA correlations with the findings in Debant Valley, Buchenauer (1990) argued for a local equivalent of the Gaimberger-Alm stadial. Considering the sedimentary evidence of multiple further glacier stillstands upvalley such a parallelisation seems to be plausible for this part of the upper catchment including the adjoining area of Alkus Lake (B-07).

A completely different situation is given at location B-06 (Gutenbrunn), where a set of up to five parallel ridges made up of till show a subdued crest running NW-SE. In the longitudinal direction some of these up to 300 m long features resemble a whale back (Figs. 5b & 6g). As the surrounding bedrock shows lineations with the same trend on its glacially-smoothed surface, these ridges are interpreted as subglacial landforms in the sense of fluted moraines showing local ice-flow direction. This is in contradiction to a previous interpretation by Buchenauer (1990: 122) who regarded these ridges as lateral moraines of the Gaimberger-Alm stadial and of the Lienzer-Hütte stadial.

6.2 Palynological and geochronological analysis of the drill core at location B-03 (Pitschedboden)

In order to get a minimum age of the last glacial event at location B-03 (Figs. 5b, 6f, 8 & 9), a core was taken from the mire Pitschedboden (Fig. 11). This shows that a 1.5 m-thick sedge peat overlies 5 m of gyttja. At a depth 6.5 m the drilling terminated in sandy deposits as further penetration was not possible.

A radiocarbon analysis of a sample taken in 6.45-6.50 m depth consisting of selected seeds and fruits of *Potentilla*

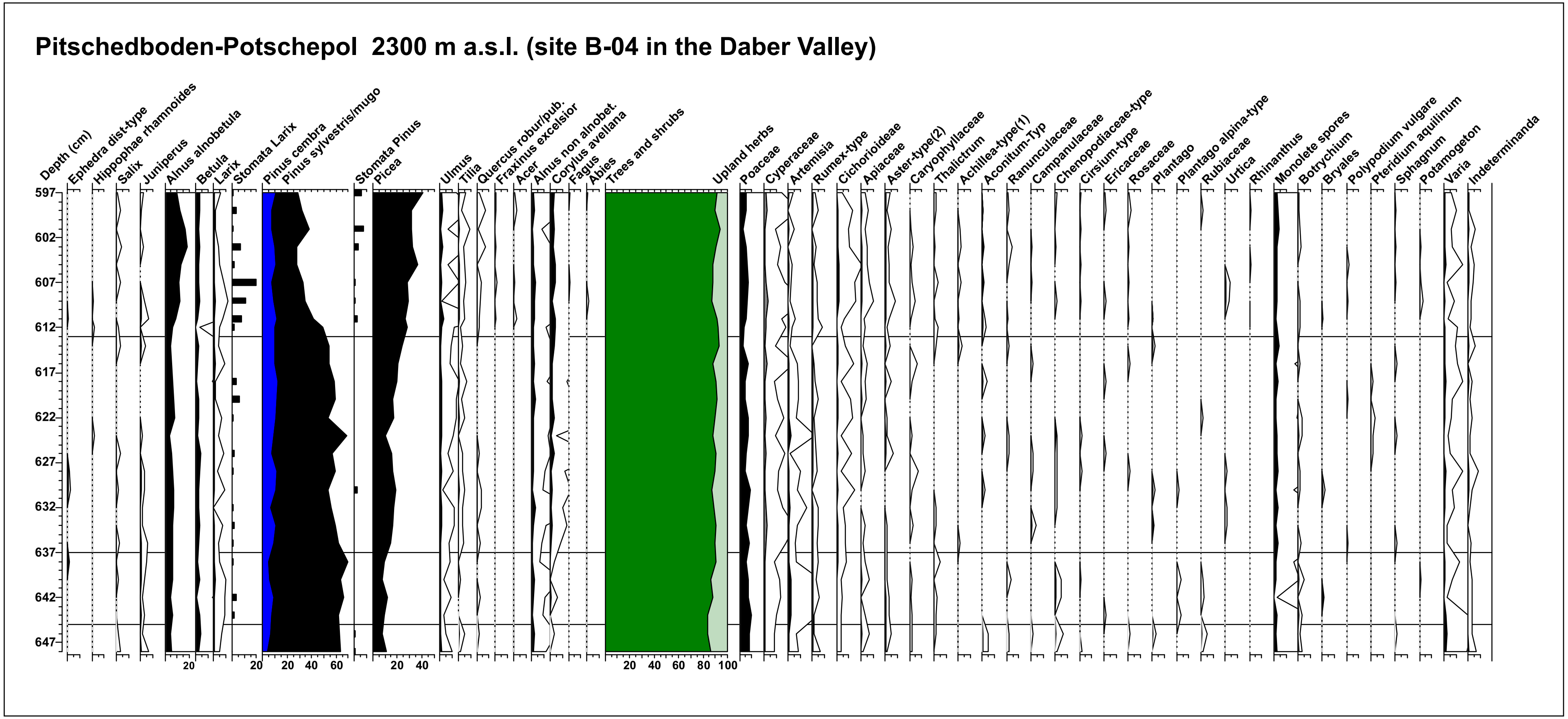

Fig. 11: Percentage pollen diagram of the lower part of the Pitschedboden drill core from site B-04 showing the most important taxa. The black line indicates the percentages blanked 10 x. The stomata are presented as number of findings per horizon.

Abb. 11: Pollendiagramm (in Prozent) des unteren Teiles des Pitschedboden-Bohrkerns von Lokalität B-04 mit den wichtigsten Typen. Die schwarzen Linien zeigen die Prozente in zehnfacher Überhöhung. Die Stomata sind als Anzahl der Funde pro Horizont dokumentiert.

and *Carex* as well as some pieces of bark provides a ^{14}C-age of 11.525 ±36 (ETH-48227) (13.470–13.260 cal BP (95%)). Thus, a minimum age for the start of sedimentation during Allerød interstadial (broadly equivalent to Greenland Interstadial (GI) 1a-c; WALKER et al. 2001) seems to be plausible.

However, the pollen analysis reveals a different picture. Pollen-assemblage zone (PAZ) 1 (648–637 cm) shows high contents of AP (85–90%) dominated by *Pinus* (Pine 65–70 %) with 5–7 % *Pinus cembra* (Arolla Pine) and the rest made up of the indistinguishable pollen types of *Pinus sylvestris* (Scots Pine, most likely from the lower valley) and *Pinus mugo* (Dwarf Mountain-pine, probably from the higher areas). Other trees typical for the timber line are *Larix* (Larch, 0.5-1 %; also proven by stomata) and *Alnus alnobetula* (Green Alder, 5–7%). In addition, *Betula* (2–5%), *Juniperus* (<1%), *Picea* (Spruce, 5–10%), *Alnus incana/glutinosa* (Alder, 0.5–2%) and *Ulmus* (Elm, <1%) occur regularly within PAZ 1. PAZ 2 (637–613 cm), also characterised by a dominance of AP (85 %), shows a continuous increase in *Picea*, a decrease of *Pinus sylvestris/mugo* and the onset of a continuous presence of *Corylus* (Hazel, >1%) and *Tilia* (Lime, <1%). The content of *Pinus cembra* reveals a slightly positive trend whereas that of *Larix* is oscillating, but corresponding stomata are constantly present.

A further increase of *Picea* towards 40 % and considerable decrease of *Pinus sylvestris/mugo* are evident in PAZ 3 (613–597 cm) together with a strong development of *Alnus alnobetula. Larix is* constantly present at a low level but with more findings of stomata. A minor increase o*f Ulmus* and as well of *Corylus* is evident together with a regular presence of *Quercus* (Oak) and first findings of *Acer* (Maple) and *Fraxinus* (Ash).

In summary, the pollen curves of the lowermost part of the core show a continuous development from initially pine–dominated to spruce forests in the middle range of the valley flanks and the expansion of mixed oak forest on the valley floor. Based on the increased occurrence of stomata of *Pinus* and *Larix* a rise of the timberline up to at least 2300 m a.s.l. during PAZ 1 and PAZ 2 is indicated which resulted in a sparse Larix wood with first stocks of *Pinus cembra* together with *Pinus mugo* and *Alnus alnobetula.* This assemblage corresponds very well to the basal part (PAZ 2–4) of the profile of Hirschbichl in St. Jakob in Defereggen (35 km W of Pitschedboden) at 2140 m a.s.l. (OEGGL & WAHLMÜLLER 1994), where the bottom of PAZ 2 yielded an age of 9370±170 ^{14}C BP (10.238–11.131 cal BP (95%)) as a clear evidence of a Preboreal stage. Thus, there is an apparent discrepancy between the lowermost ^{14}C age as an indication for the Lateglacial Allerød interstadial and the pollen content documenting the Holocene Preboreal stage, which cannot be explained at the moment. The higher content of organic matter compared to younger parts (above 579 cm of core depth) may be due to erosion of soil- and peat layers, followed by deposition in small pockets of the uneven basin floor. Despite this problem with the consistency of the core, the ^{14}C- date is a strong indication of ice-free conditions during and since the Allerød interstadial, strongly implying that the small Pitschedboden basin was last occupied by glaciers prior to that time.

6.3 Discussion

According to findings of the fieldwork, together with the results of the drilling core investigation, the Late Pleistocene deposits of the Daber Valley can be subdivided into five mappable geological units (Figs. 8 & 9).

The sediment sequence at the lowermost part of the Daber Valley, just above the village of Ainet shows at its base a subglacial traction till on top of bedrock which was deposited by the Isel Glacier and is called **Isel (IL) unit**. As glacier flow along the Isel Valley was a prerequisite for the deposition of such a subglacial sediment, its formation most likely took place during the AlpLGM. The overlying deltaic sediments of the **Ainet (AI) unit** (named after the village) indicate the infill of an ice-dammed lake formed at the margin of the decaying Isel glacier (Fig. 10). Using the highest occurrence of these sediments at 1240 m a.s.l. as a crude marker for the highest lake level at this phase, the damming Isel Glacier may have suffered a loss in ice-thickness since the AlpLGM in the range of 1000 m. Preserved foreset-beds indicate an infill of the lake by sediment sourced from the Daber Valley. The subglacial traction till of the **Daber (DA) unit** at the top of this succession clearly documents a local glacier advance to its Lateglacial maximum position (LMP), which is typical for the phase of ice-decay where local glaciers responded to decoupling from a decaying transection glacier complex by temporary readvances (REITNER 2007). The sand layers within the till are regarded as indications of ice-bed-decoupling, most probably due to a high (ground-)water table during advance (*cf.* LESEMANN et al. 2010), which corresponds to the ice advancing into a lake. The deformation structures are further evidence of deformable bed conditions and, thus, the presence of a temperate glacier. The geometry of the quite steeply-sloping till cover on top of the deltaic deposits may best be explained by a drop in lake level which would have further facilitated the advance. Otherwise, the thickness of the tongue would have had to increase significantly during the advance to overcome the floatation threshold and to remain grounded in a proglacial lake (e.g. BENN & EVANS 2010), whose depth increased in a downvalley direction due to the topography of the niche. The latter case seems to be very unlikely during deglaciation, therefore making a lake-level lowering the more likely explanation.

The depositional setting of the ensemble of local subglacial till (DA unit) with underlying delta deposits (AI unit) shows striking similarities with that of the lower Debant Valley. The oldest U/Th dated calcit cement from sediments of the Ainet unit at site B-08 (travertine of Ainet) with an age of 13.96 ± 0.11 ka (BOCH et al. 2005) provides a minimum age of the Ainet unit at a local scale.

The **Kunig (KU) unit** consists of the lateral moraine at location B-03 (Kunigalm) which is the type locality of the Kunig stadial as defined by BUCHENAUER (1990). Despite its limited preservation some constraints for the corresponding ice-cover and glacier dynamics at the time of its formation are available which allow some conclusions to be drawn. Firstly, it has to be emphasised that the bed of the Daber creek is not incised in bedrock but in talus for most of its middle part. Thus, ice-thickness was most probably greater than BUCHENAUER assumed in his reconstruction.

Fig. 12: a) Site D-01 (at Arnig) in the Kals Valley. Boulder-rich alluvial fan deposits unconformably overlying (red dotted line) delta deposits of the AI unit which show flexures due to post-sedimentary subsidence most probably as a result of dead-ice melting. b) (1) Sharp-crested crescentic ridge (red dotted line) in the deposits of the AI unit at site D-02 in the Kals Valley due to meltwater erosion in the nowadays (2) dry valley (viewpoint indicated in Fig. 5e). c) Outcrop in 1120 m a.s.l. (outcrop 1 in Fig. 5e) in the southern part of the D-02 site with (1) massive and matrix-supported diamicton overlying (2) stratified gravel and ripple sand of the AI unit. d) Lower part of the outcrop in Fig. 12c with small post-depositional faults. e) Small moraine of the DA unit at location E-01. f) Outcrop at the moraine of location E-01 with till. g) Delta foresets at site F-01 (image provided by S. Lukas). h) Detail of delta-forests in Fig. 12f showing mostly angular to subangular clasts beside some rare subrounded species.

Abb. 12: a) Lokalität D-01 (bei Arnig) im Kalser-Tal. Block-reiche Schwemmfächerablagerung überlagert diskordant (rot-strichlierte Linie) Deltaablagerungen der AI-Einheit. Diese zeigen postsedimentäre Flexuren als Folge von Setzungen, die wahrscheinlich im Kontakt mit abschmelzenden Toteiskörpern gebildet wurden. b) (1) Der Sedimentkörper der AI-Einheit bei Lokalität D-02 im Kalser-Tal weist einen scharf-ausgebildeten Kamm (rot-strichlierte Linie) auf. Diese Oberflächenform ist das Produkt von Schmelzwassererosion im heutigen (2) Trockental (der Blickpunkt ist Abb. 5e angezeigt). c) Aufschluss 1 (in Abb. 5e) in 1120 m Seehöhe im südlichen Teil der Lokalität D-02 mit (1) massiven und matrixgestützten Diamikten die (2) geschichtete Kiese und rippelgeschichtete Sande der AI-Einheit überlagern. d) Unter Teil im Aufschluss 1 von Abb. 12c mit kleinen postsedimentären Versetzen. e) Kleine Moränenkörper der DA-Einheit bei Lokalität E-01. f) Aufschluss der Moräne bei E-01 mit glazigenem Sediment. g) Delta-Foresets bei Lokalität F-01 (Bild: S. Lukas). h) Detail der Delta-Foresetlagen in Abb. 12f mit zumeist angularen bis subangularen Geröllen neben wenigen angerundeten Exemplaren.

Hence, the terminus of the tongue may have been located close to B-02. Secondly, the geometry of the features documenting glacial moulding at location B-04 and B-06, as documented by fluted moraines and ice-moulded bedrock (Figs. 5b & 6f), reveals for the last time an active, temperate glacier (with deformable bed conditions), which had its last stillstand when the KU unit was formed. Thirdly, the geometry of the small basin with the bedrock riegel in the downflow direction resembles a small overdeepening. More importantly, the results of ^{14}C dating of the basin infill provide a minimum age for the KU unit (see Section 6.2). As the infill already occurred in the Allerød interstadial, the basin would have last been occupied before the Bølling/Allerød (B/A) interstadial when the glacier reached the type locality of the KU unit.

The **Debant (DE) unit** comprises a set of moraines previously attributed to the Gaimberger-Alm and Lienzer Hütte stadial by Buchenauer (1990). However, there are fewer moraines here compared to the Debant Valley. This difference could be explained by the rugged bed topography in the upper reaches of the Daber catchment, which may have more constrained the glacier geometry compared to the wide proglacial foreland consisting of loose sediment in the Debant Valley. Alternatively, such a difference may be due to other external factors influencing glacier response to climate change during retreat like aspect, snow-bearing wind and glacier-size (*cf.* Benn et al. 2003, Lukas 2006). However, comparing the reconstructed palaeogeographic positions (Buchenauer 1990) based on the occurrence of latero-frontal moraines with the occurrence of lakes (e.g. Lake Alkus; site B-07) the latter again appear as small-scale overdeepened basins.

7 Leibnitz Valley

The Leibnitz(-bach) Valley is a valley that is up to 7.7 km long, with the Hochschober (3242 m a.sl) forming the highest peak of the catchment (Figs. 8 & 13). The glaciation during LIA was quite limited to a glacier at location C-05 where only a lake remains at present. With respect to the Isel Valley, this area represents a hanging valley with a steep gorge-like lower part cut into bedrock from 840 to 1220 m and with an upper end at the flat Oberleibnig. This is followed by a moderately-sloping middle part up to ca. 2200 m a.sl. A major terrain step of up to 100 m in height marks the onset of the upper part where the cirques drained by the Leibnitz creek and its tributaries are located.

7.1 Field evidence

In the lower part glacial sediments, i.e. AlpLGM till cover, are only found at the glacially-moulded bedrock flat of Oberleibnig.

The onset of the middle part of valley is characterised by the largest end moraine of the Lienz area and, hence, a real landmark high above its foreland (location C-01 Unterfercher; Fig. 5c). On the true left flank, this ridge can be traced from 1350 m a.s.l up to nearly 1600 m a.s.l. It appears mostly sharp-crested, as the result of lateral erosion by the Leibnitz creek on its inner flank, whereas only the uppermost original part shows a smoothed morphology. The formation of this moraine resulted in the filling of the original valley, which is now an abandoned furrow east of the Leibnitz creek (Klebelsberg 1931), whereas in this segment the modern valley is incised into bedrock. Outcrops on the crest expose a massive diamicton with sandy matrix and subangular to subrounded clasts ranging from gravel to boulder size is evident, whereas on the outer flank the sediment occasionally shows stratification. Upstream of location C-01, there is an absence of unambiguous constraints for the corresponding palaeoglacier geometry. A terrace-like feature at location C-02 might indicate the former surface (Buchenauer 1990), but an estimation of ice thickness still seems to be problematic as the bed of the creek in the middle part of the valley has developed overwhelmingly in alluvial sediments.

The lowest latero-frontal moraines with comparatively sharp crests are found at the break of slope between the middle and the upper Leibnitz Valley just below a major terrain step at site C-04 (Figs. 6h & 13). Furthermore, in a flat area just above, a set of multiple ridges (Fig. 8) shows striking similarities with the DE unit in the Debant Valley. This correlation is in general agreement with the ΔELA-backed correlation by Buchenauer (1990), who regarded a 500 m long, 100 m broad 20 m high smoothed ridge (at location C-03; Fig. 6h) consisting of glacial sediment on the top as well as a lateral moraine specifically that of his Gaimberger-Alm stadial. In contradiction to this interpretation, the morphological characteristics including a rather symmetric cross-profile of this feature are seen as an indication for a subglacial and not for an ice-marginal landform.

Between the aforementioned latero-frontal moraines at und just above C-03 and the former LIA–maximum ice extent at C-05, (relict) rock glaciers dominate the scene. Thus, periglacial reworking seems a plausible cause for the complete absence of DE moraines at higher ground despite good topographic conditions for preservation.

7.2 Discussion

Based on the results of the fieldwork, two Lateglacial units are documented in the Leibnitz Valley (Figs. 7, 8 & 13).

The clear end moraine at location B-01 is regarded as the local expression of the **KU unit**, which appears to have only been well preserved in this position due to fluvial incision of this epigenetic valley. However, the sheer size and the

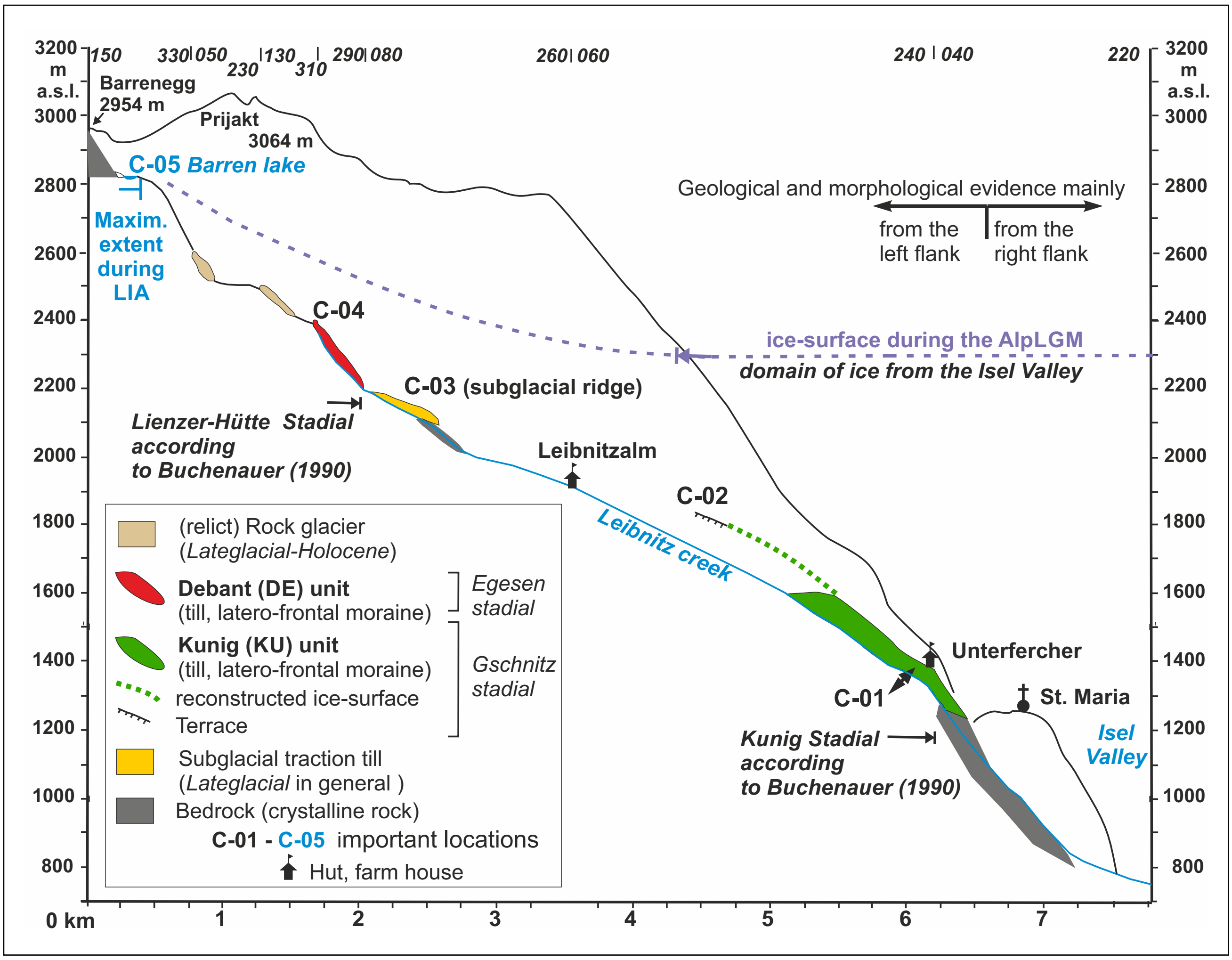

Fig. 13: Section along the Leibnitz Valley with sites C-01 – C-05.

Abb. 13: Geologischer Schnitt entlang dem Leibnitz-Tal mit den Lokalitäten C-01 bis C-05.

absence of a prominent contribution of supraglacially transported debris to the composition of the moraine documents a considerable time of formation without any signs of contact to ice-dammed lakes or impeded drainage in the foreland. Hence, Lucerna (1928) and Klebelsberg (1931) classified this moraine as Gschnitz stadial. In contrast, Buchenauer (1990) argued that its formation should have happened later, during his Kunig stadial (equivalent to Senders/Clavadell; Table 1) because of the ΔELA-value of 450 m which was considered to be too low for his local equivalent of the Gschnitz stadial, the Debant stadial (s. Section 6).

Like in the Debant Valley, the **Debant (DE) unit** is characterised by multiple fairly sharp-crested latero-frontal moraines which mark the maximum postion of the Egesen/Younger Dryas glaciation at the slope break between the middle and upper part of the valley. Moraines of the DE unit documenting smaller ice-extents are mostly missing due to reworking of glacial material by periglacial processes, i.e. rock glaciers.

8 Additional evidence for pre-Younger Dryas ice-extent in the catchment of the River Drau

Based on the findings of the Debant Valley the definition of the DE unit (Younger Dryas) summarising the sediments attributed by Buchenauer (1990) to the Gaimberger-Alm stadial and younger Lateglacial stillstands or minor readvances could be applied in the geological map sheet Lienz (Linner et al. 2013) for the other cirques and valleys of the Schobergruppe mountains. In contrast, the results of fieldwork revealed major changes in the classification of deposits attributed to the pre-Younger Dryas glacier stages and corresponding palaeogeography. The analyses of two examples are briefly presented for further context and to demonstrate that the issues identified above exist elsewhere and are thus consistent across the whole area.

8.1 Kals Valley

This valley is a tributary valley of the Isel Valley and shows the typical features of a hanging valley i.e. a gorge in its lower part (Fig. 8).

From the outlet of the Kals valley up to location D-01, remnants of kame deposits (AI unit), consisting mostly of stratified gravel-sand mixtures partly with boulders, sandy gravels and sands which partly contain ice-contact structures (s. Fig. 12a Arnig in location D-01), occur at different levels ranging from 800 m at the flank to the Isel Valley up to 1200 m on the bedrock step above the gorge. The dip direction of clinoforms as well as characteristic clast-lithologies, e.g. Manganese-bearing ore from the Penninic super unit, show that these deltaic deposits descend from the Kals Valley. According to these features together with the altitudinal distribution such deposits of the **AI unit** (s. Section 7) document formation during the phase of ice-decay when a downwasting Isel Glacier was blocking the ice-free Kals Valley (see also Veit 1988).

At site D-02 (Rantschner; Fig. 5e) a more than 100 m thick depositional unit with a peculiar morphology in its lower part at 1090 m is present on the true left flank of the Kals Valley. There, a prominent very sharp-crested up to 20 m-high ridge shows a crescentic planform with a lower part parallel to the Kals Valley, while in the upper part a turn towards a tributary is evident (Fig. 12b). A dry valley is obvious between this ridge and a ridge-like feature on the valley flank. An up to 40 m high outcrop on the southern flank (outcrop 1 in Fig 5e) reveals a sequence of stratified mostly sand and gravels with boulders with a dip of up to 25° towards SW (see also Veit 1988). The clast lithology consists of subrounded to rounded prasinite from the Pennininic Superunit and of mostly mica-schist and gneiss as well as tonalite from the Austroalpine Superunit. In the upper part of this outcrop, stratified and massive diamicton-units are overlying ripple-bedded sand (Figs. 12c, 12d). The grey massive and matrix-supported diamicton with a sandy to coarse silty matrix with only subangular to rounded gneiss and mica-schist clasts, and with a moderate compaction, is in turn overlain by sand gravel-sand deposits.

An outcrop (outcrop 2 in Fig. 5e) on the northern flank of aforementioned prominent ridge just below the crest exposes clinoforms consisting of planar-bedded sand and clast-supported gravel with dips of between 35 to 45° towards W to NW.

In total the entire **AI unit** is more than 100 m thick and consists of deltaic deposits as documented by the foreset beds with occasional oversteepened dips (45°). Together with the findings along the Kals Valley down to the outlet, this evidence denotes a depositional setting in an ice-dammed lake during the phase of ice-decay. Accordingly, the prominent ridge is an erosional landform, which was formed during the further down-wasting of the ice accompanied by a lowering of the local base-level as also evident in the neighbouring dry valley. The previous interpretations of the ridge as a latero-frontal moraine deposited by a glacier descending from a northward located tributary valley (Staniska Valley) during the Gschnitz stadial by Veit (1988; with a ΔELA of 640 m) and by Buchenauer (1990; with a ΔELA of 550 m) have therefore to be discarded as the sedimentary evidence contradicts these geomorphological interpretations strongly. Furthermore, the weakly-developed soil layer (Leptosol) as well as a reworked soil described by Veit (1988) below the diamicton appears to be more likely hydromorphically-altered material without any indication of a former stable surface before the deposition of the diamicton according to the relationships between these units during the logging summarised here. Veit (1988) correlated this presumed palaeosol with the that of Roppen (Heuberger 1966) which was believed to be a formation of the Steinach/Gschnitz – interstadial and has now been shown to be of late Holocene age (Patzelt 2012). However, the massive diamicton with the local clast spectrum within the ice-marginal deposited can be interpreted as a subglacial traction till of a local glacier advancing into an ice-dammed lake which overrides not only typical delta deposits but also subaquatic debris-flow deposits descending from the ice front (scene II in Fig 7). Such an oscillation of a local glacier during the phase of ice decay is quite common at the type locality (Reitner 2007) and also known from the study area (DA units in the Debant and Daber Valley; Sections 5 & 6) as from elsewhere in similar depositional settings (e.g. Fyfe 1990, Benn 1996).

8.2 Valley flanks of the Drau and Isel Valley

The valley flanks of the Isel Valley and those of the Drau Valley at Lienz usually show a patchy cover of stratified sandy and gravelly fluvioglacial sediments of the type described in the Kals Valley (Figs. 2, 8 & 14). The thickness of this **AI unit** on the flanks is mostly limited to some meters and increases only at junctions with tributary valleys, indicating preferential locations of temporary lakes at the margin of the downwasting ice masses in both valleys during ice decay. In the best case, outcrops with delta foresets, containing partly angular clasts (Figs. 12g, 12h) as an indicator of short-distance transport, document the infill of theses ice-dammed lakes by the tributary rivers, high above modern valley floors (e.g. at location F-01 in Fig.14). Considering the altitudinal distribution of such sediments it is evident that the most extensive deposits of this kind occur on south-facing slopes below 1760 m a.s.l., especially in areas where no or only local glaciers of limited size were present at that time.

In the upper Drau Valley (also called Puster Valley) the nearly continuous occurrence of these delta deposits (AI unit) indicate an ice-decay of the Drau Glacier without any stillstand. However, on the right flank of the Isel Valley two up to 10 m-high ridges are present at the rim of a bedrock plateau (location E-01; Schlaiten; Fig 12e) at an altitude between 800 and 880 m a.s.l.. Small outcrops reveal diamicton with a sandy matrix and a polymictic spectrum (including prasinite from the Penninic Superunit) of subangular to rounded clasts (Linner 2003). This evidence is interpreted as lateral moraines (attributed to the **DA unit**) of an already less-extensive Isel Glacier and, thus, as the only sign of an active glacier tongue of the Isel Glacier during the Phase of ice-decay, which may have stabilised for a very short phase. According to the topographic constraints with a broadening of the valley towards Lienz a calving terminus just downvalley of the moraines seems to be a possibility at this time (III in Fig. 7). The occurrence of well traceable remnants of a kame terrace in the Drau Valley west of Lienz (site F-02 in Fig. 14), consisting in the upper part of horizontally-bedded sandy gravels with crystalline and carbonatic clasts (Hoffert 1975: 82f, Reitner 2003b) with a surface trend showing a lowering towards north from 860 to 740 m, support this scenario. Thus, an unimpeded drainage was already possible in the Drau Valley upstream of Lienz, and the palaeo-Drau had, at least within a short time span, a delta front into a lake with a level of around 740 m (VI in Fig. 17). The latter was most probably caused by the last dead ice remnants in the broad Drau Valley blocking the drainage east of Lienz.

9 Lienz Dolomites

The largest valley on the northern flank of the Lienz Dolomites with a length of 8 km is drained by the Galitzen creek and its tributaries (Figs. 14 & 15). The lower part of the Galitzen Valley between 700 and 1100 m a.s.l. is characterised by a gorge, typical of a hanging valley. From the middle part, which is characterised by confluences with the source creeks above, the lithology of the river bed changes from bedrock to debris. This is due to the dominance of talus fans derived from the steep valley flanks made up of dolostone (Fig. 15, 16b & 16c). The upper part is characterised by elevated cirque floors above 2100–2200 m a.s.l. with backwalls including peaks with altitudes around 2700 m.

9.1 Field evidence

In the lower part at two different levels delta deposits, typical for the **AI unit**, with crystalline clasts are overlain by matrix-supported massive diamicton with only striated carbonate clasts, a typical till of a local glacier from the Lienz Dolomites (Reitner 2003b). These two situations of superposition at location G-01 are contiguous, with the lower one as the relatively younger above Galitzen gorge. According to this occurrence the till unit is called **Galitzen (GA) unit**).

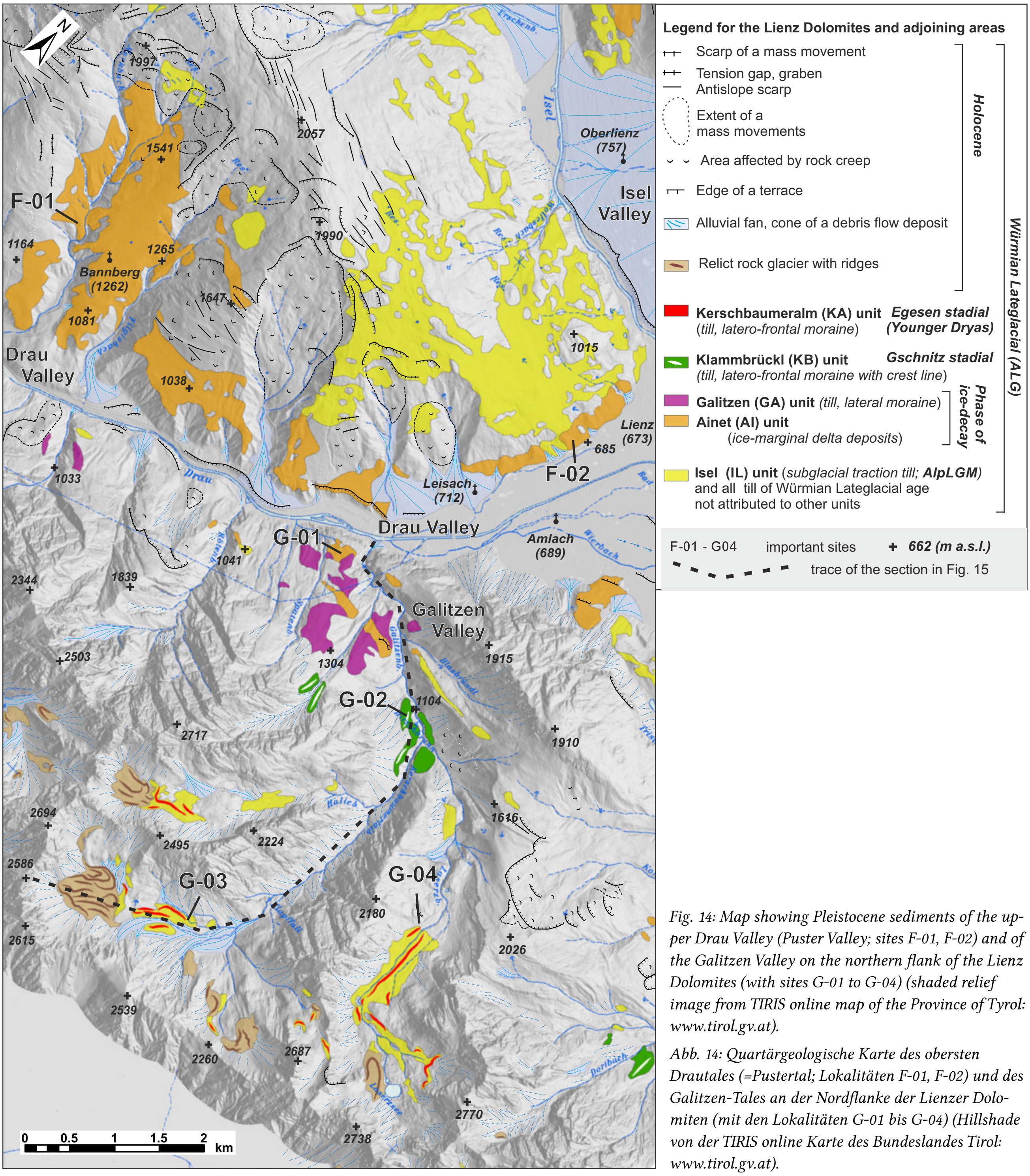

Fig. 14: Map showing Pleistocene sediments of the upper Drau Valley (Puster Valley; sites F-01, F-02) and of the Galitzen Valley on the northern flank of the Lienz Dolomites (with sites G-01 to G-04) (shaded relief image from TIRIS online map of the Province of Tyrol: www.tirol.gv.at).

Abb. 14: Quartärgeologische Karte des obersten Drautales (=Pustertal; Lokalitäten F-01, F-02) und des Galitzen-Tales an der Nordflanke der Lienzer Dolomiten (mit den Lokalitäten G-01 bis G-04) (Hillshade von der TIRIS online Karte des Bundeslandes Tirol: www.tirol.gv.at).

From the break between the middle and the upper valley upward, a prominent, up to 30 m-high, latero-frontal moraine, the **Klammbrückl (KB) unit**, can be traced to the left flank of the major creek. A big outcrop at location G-02 (Klammbückl; Fig. 16a) reveals stratified and massive diamictons with glacially-shaped clasts consisting solely of dolostone. Remnants of this KB unit on the true right flank towards the junction of the Laserz creek allow the reconstruction of a glacier tongue, which at that time was sourced from all three cirques (Fig. 17). Based on the occurrence of till west of the Klammbrückl gorge incised in bedrock at location G-02, the favourable conditions for palaeoglacier reconstruction are again due to an epigenetic valley.

In the valley of the major creek above the KB unit, talus fans from both flanks dominate the area. At G-03 at Kerschbaumeralm hut in 1902 m a.s.l. a prominent latero-frontal moraine (**Kerschbaumeralm (KA) unit**) with a height of up to 10 to 40 m is evident (Figs. 5f & 16b). Its surface consists of diamictic material, composed mostly of angular dolostones clasts that range from gravel- to large boulder size, partly clast supported or within a sandy matrix (like in Fig. 16d). From this location upwards, a set of similar features is present until the uppermost cirque floor, which in turn contains evidence of at least three glacial stillstands or potentially (minor) readvances, documented by moraines. Typical relict rock glaciers (Reitner 2003b) and linear structures developed in debris, which were interpreted by Stingl (1969) as being of periglacial origin, are the dominant features below the steep backwalls (Fig. 16c). The other cirques show a similar set of landforms with well-traceable ridges of the KA unit beside rock glacier deposits. A major deviation is present in a part of the Laserz Valley where a ramp-like structure (location G-04) is linked to the KA unit indicating a rock avalanche interacting with a glacier (Reitner et al. 2014), which will be described in detail in a separate contribution.

9.2 Discussion

In the catchment of the Galitzen creek three units document glacial activity (Figs. 14, 15 & 17).

The lowermost **GA unit** consists of till units resting on top of sandy gravels typical of the **AI unit**. As the latter dominantly consists of crystalline clasts in contrast to the local till, an advance of a glacier sourced from the Lienz Dolomites is evident. According to the distribution of crystalline clasts within AlpLGM subglacial traction tills on the adjoining valley flanks, this local glacier reached its LMP while pushing into an area that was covered by the Drau Glacier during the AlpLGM. Hence, a situation during the phase of ice-decay is documented with a similar palaeogeographic setting as described for the southern flank of the Wilder Kaiser mountains (Reitner 2007).

In contrast, the **KB unit** documents a glacier tongue of a Gailitzen Valley glacier, fed by all three cirques, which might have stabilised for some time without any contact to dead ice, a situation which resembles that of the KU unit in the Leibnitz Valley.

Multiple lateral moraines of the **KA unit** show striking similarities with the characteristics of the DE unit in the Schobergruppe mountains. However, the geometries are partly not as well constrained, and in the uppermost cirques a considerable reworking of glacial material by

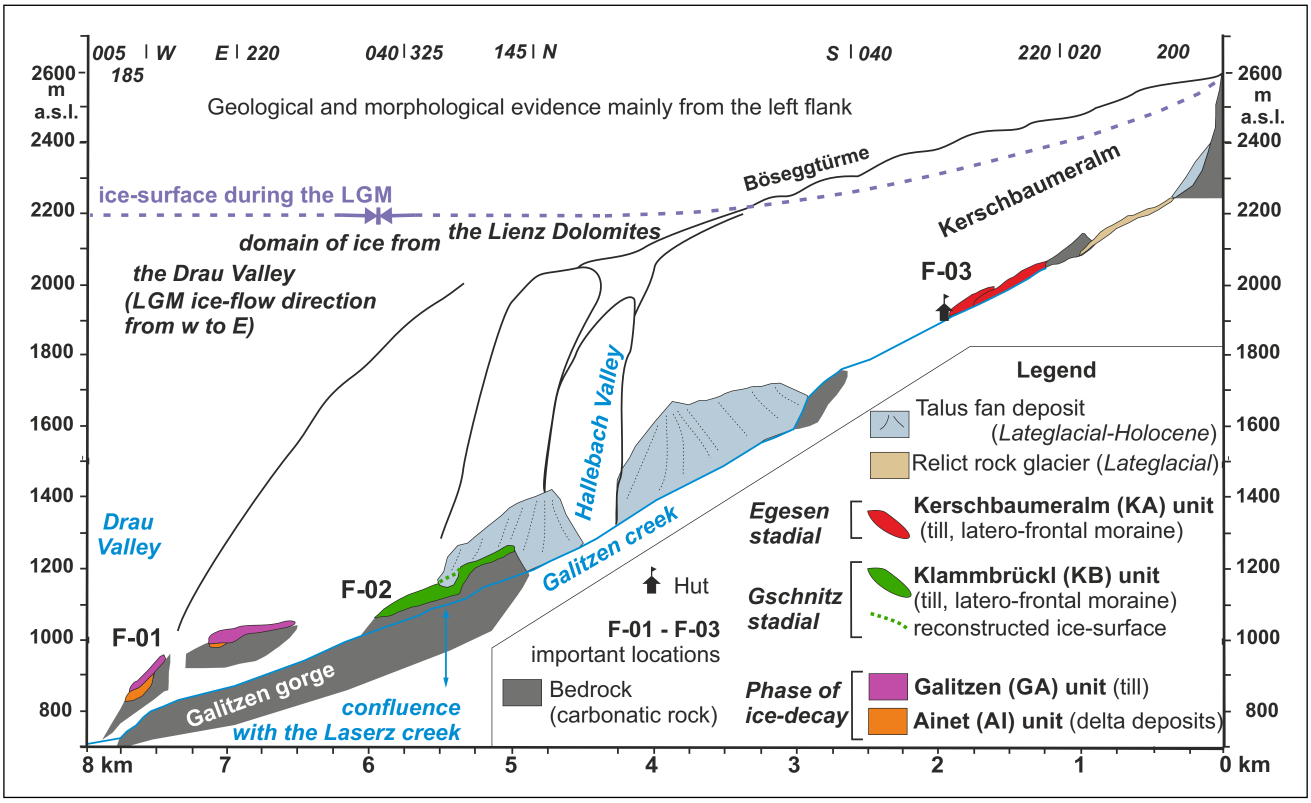

Fig. 15: Section along the Galitzen Valley with sites G-01 – G-03.

Abb. 15: Geologischer Schnitt entlang dem Galitzen-Tal mit Lokalitäten G-01 bis G-03.

rock glaciers is evident. According to the topographic and depositional setting, with its concurrent debris accumulation below steep flanks, palaeoglaciers during the formation of the KA unit as well as before were most likely debris mantled; the most extreme case is documented by a rock avalanche deposit in the area of location (F-04, Laserz creek; *cf.* Reitner et al. 2014). Hence, it was refrained from calculating any ELA-values independently of a missing $\mathrm{ELA}_{\mathrm{LIA}}$ reference. A possible approximation for the corresponding ELA is given with the maximum elevation of lateral moraines (MELM-method; Lichtenecker 1938, Benn & Lehmkuhl 2000) which in the cirque at location F-03 is in the range of 2250 m a.s.l.

In total, the catchment of the Gailitzenbach creek shows a similar tripartite succession of glaciogenic deposits as the Schobergruppe mountains indicating a contemporaneous formation of GA and DA unit, KL and KU unit as well as KA and DE unit. Interestingly, previous work by Srbik (1930) and Klebelsberg (1950) describes evidence of three glacier stillstands or minor readvances, but with different geometries compared to this study, which both authors attributed to the stadials of Schlern, Gschnitz and Daun (compare Mayr & Heuberger 1968 for terminology).

10 Synthesis

The sedimentary and morphological documents of the ALG indicating glacial activity in the area of Lienz show a sequence that can be subdivided into four unconformity-bounded units (at least in the rank of informally defined allobeds) with specific characteristics with respect to formation and depositional setting (Fig. 18; Table 1). Furthermore, geochronological and biostratigraphical evidence in the Schobergruppe mountains, specifically in the Debant Valley (Section 5) and in the Daber Valley (Section 6), reveal that three of these units are older than the Bølling/Allerød interstadial whereas the youngest one is of Younger Dryas age. Hence, additional constraints for correlations with typical succession elsewhere in the Eastern Alps are

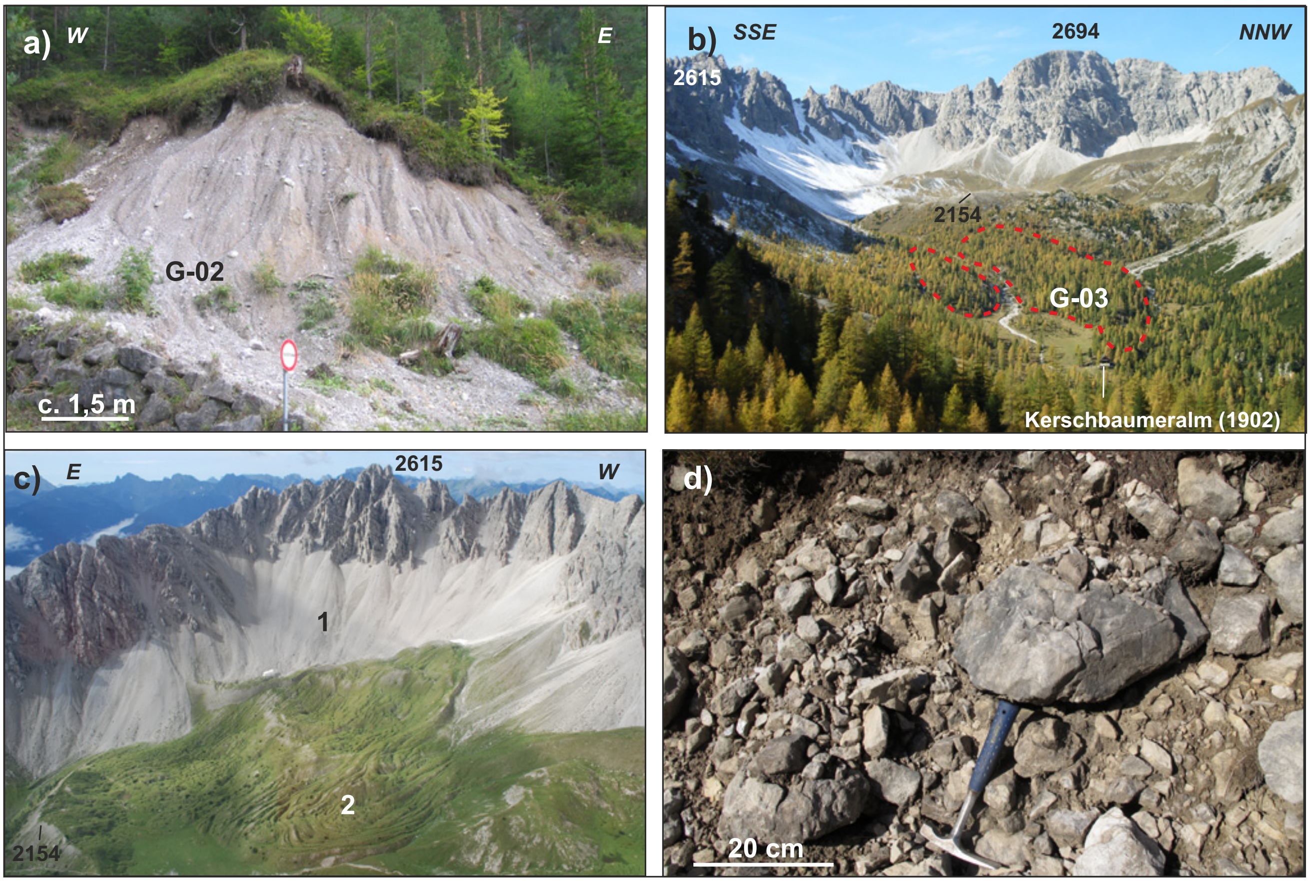

Fig. 16: a) Latero-frontal moraine of the KB unit with a till outcrop on its inner flank at site at site G-02 in the Galitzen Valley. b). Site G-03 with the moraines of the KA unit (extent shown by red dotted lines) and its upper hinterland with cirque wall made up of dolostone. The location of Kerschbaumeralm hut is indicated. Numbers indicate altitude in m a.s.l. (image provided by G. Ortner). c) The uppermost cirque floor, upvalley of site G-03, indicated in the section along the Galitzen Valley in Fig. 15. The scene is dominated by (1) talus fan below the dolostone flanks and by (2) relict rock glaciers with multiple ridges on the cirque floor (aerial image provided by S. Melzner). Numbers indicate altitude in m a.s.l. d) Outrop of one of the latero-frontal moraines of the KA unit upvalley of location G-04. The till consists of a dominantly clast-supported diamicton with angular to subangular dolostone clasts.

Abb. 16: a) Seiten- bis Endmoräne der KB-Einheit mit Aufschluss von glazigenem Material auf der inneren Flanke bei Lokalität G-02 im Galitzen-Tal. b) Lokalität G-03 mit den Moränenkörpern der KA-Einheit (rot-strichlierte Linien markieren den Umriss) und deren Hinterland mit aus Dolomit aufgebauten Karwänden. Die Lage der Kerschbaumeralm ist angezeigt. Die Zahlen sind Höhenangaben in Meter (Bild: G. Ortner). c) Der in Abb. 15 dargestellte oberste Karboden, talaufwärts von Lokalität G-03. Die Szene wird von (1) Schuttfächern unter den Dolomitwänden und von (2) reliktischen Blockgletschern mit multiplen Wällen dominiert (Luftaufnahme: S. Melzner). Die Zahlen sind Höhenangaben in Meter. d) Aufschluss am Rand einer Seitenmoräne der KA-Einheit talaufwärts von Lokalität G-04. Die glazigene Ablagerung besteht aus einem dominant korngestützen Diamikt mit angularen bis subangularen Dolomitgeschieben.

given. In the following a short synopsis of the findings begins with the oldest units.

The **DA unit** at the outlet of the Debant Valley and Daber Valley document advancing local glaciers that reached their LMP by overriding deposits of kame terraces (**AI unit**) (Fig. 7). The latter were formed at the margin of a decaying glacier still filling parts of the main valleys i.e. Drau and Isel Valley after a loss of ice-thickness in the range of 1400 m and 1000 to 1200 m compared to AlpLGM conditions (Fig. 10). A similar setting is very likely for location D-02 in the Kals Valley with a till layer sandwiched between delta deposits of the AI unit (Figs. 7 & 12c). In the Lienz Dolomites the location of the **GA unit** at the outlet of the Galitzen gorge (Figs. 14 & 15) exposes a prominent advance of a local glacier, which was separated after the AlpLGM into an area covered by the main valley glacier during the AlpLGM (V in Fig. 17). In contrast to the aforementioned local glacier activity, elevated delta deposits below c. 1800 m a.s.l. (e.g. Figs. 12g & 12h) are evidence of the former existence of ephemeral ice-dammed lakes with changing geometries at the margin of down-wasting ice of the Drau Glacier system without any evidence of a stillstand or minor readvance with the exception of the lateral moraines at location E-01 (Figs. 8, 12e & 12f). Based on the small size of the moraines compared to the assumed size of the Isel Glacier during formation, the termino-glacial deposits indicate only a very short stabilisation of its tongue (III in Fig. 7). After that a minimum of 1400 m of ice thickness was lost in this valley segment since the AlpLGM. During this final phase of ice-decay an unimpeded fluvial drainage was already established in the upper Drau valley W of Lienz as documented by delta deposits with topsets at around 740 m a.s.l.; these relate to a lake that filled up due to damming by dead ice in the Drau Valley downstream of Lienz (VI in Fig. 17). According to the geometry of the overdeepening W of Lienz (Wallach 1993), a thickness of the damming ice body in the range of 500 or more metres seems to be likely.

The sediment-landform associations of the DA and AI units, together with the plausible palaeogeographic scenarios during their formation, show a striking similarity with those of the basin of Hopfgarten and the Wilder Kaiser mountains, the type localities of the phase of ice-decay (Reitner 2007). Hence, these units are regarded as the local expression of this glacial phase in the Lienz area. As in the aforementioned type localities, the local glaciers did not reach their LMPs synchronously *sensu stricto* as indicated by the different amounts of ice-loss necessary for a consistent reconstruction of the palaeogegraphic setting (Figs. 7 & 17). Accordingly, a top-down-chronology of the relevant processes can be applied as the decaying ice mass in the large valley acted as the local pacemaker of glacier evolution, where local glaciers first separated from the stagnant main trunk glaciers and, then, responded to this decoupling by a reconfiguration of hypsometry that resulted first in a restabilisation of ice margins and then triggered an advance (Reitner, 2007). According to the best reference site at B-01 (in the Daber Valley close to the village of Ainet; Figs. 9 & 10) with a delta deposit – local till sequence on top of a AlpLGM till (Isel unit), DA unit and AI unit are the names chosen for this stratigraphic sequence in the Lienz area. In addition, the deformation structures within the local till (DA unit; Fig. 6d) provide evidence for deformable bed conditions and thus temperate glaciers during this phase, in agreement with the results of micromorphological investigations in the type region (Menzies & Reitner 2016).

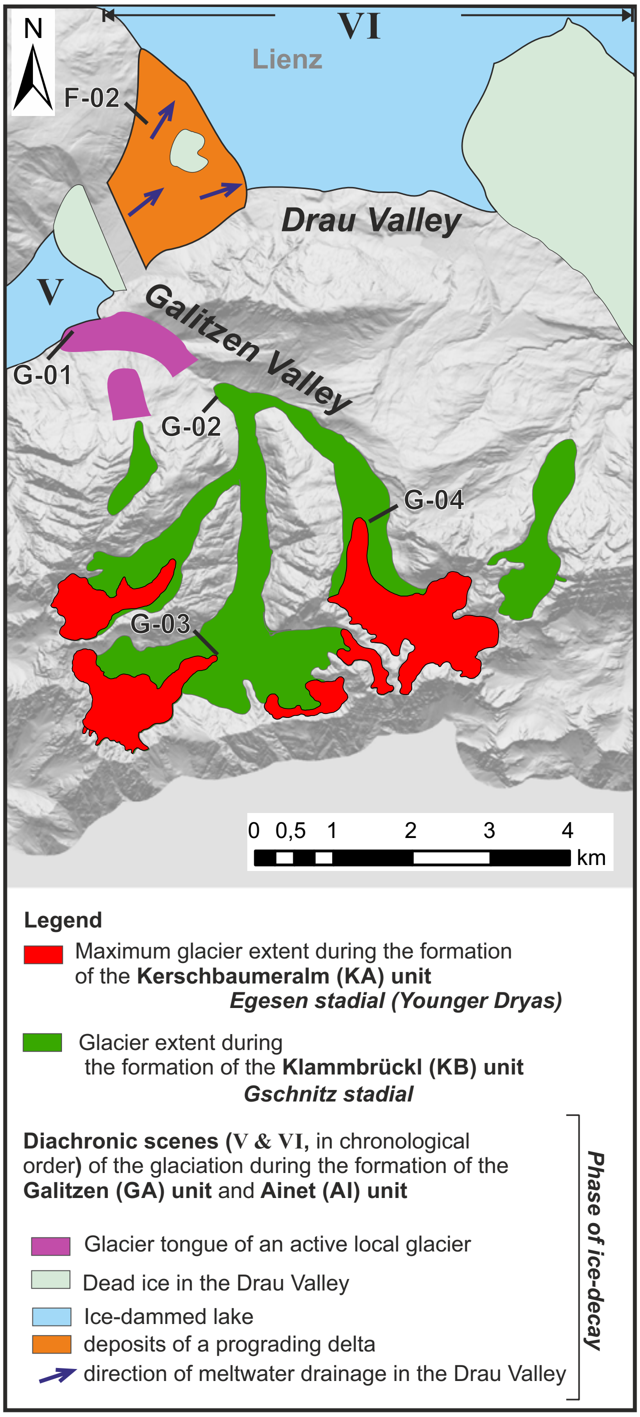

Fig. 17: Palaeogeographic sketch showing the ice extents in parts of the Lienz Dolomites during the formation of the Galitzen (GA) unit and of the Ainet (AI) unit in the Phase of ice-decay, of the Klammbrückl (KB) unit in the Gschnitz stadial and of the Kerschbaumeralm (KA) unit in the Egesen stadial (Younger Dryas). Important sites (e.g. F-01, G-01) of Fig. 14 are indicated.

Fig. 17: Paläogeografische Skizze mit der Vergletscherung in Teilen der Lienzer Dolomiten während der Bildung der Galitzen (GA)- und der Ainet (AI)-Einheit in der Eiszerfallsphase, der Klammbrückl (KB)-Einheit im Gschnitz-Stadial und der Kerschbaumeralm (KA)-Einheit im Egesen-Stadial (Jüngere Dryas). Wichtige Lokalitäten (z.B. F-01, G-01) der Abb. 14 sind angezeigt.

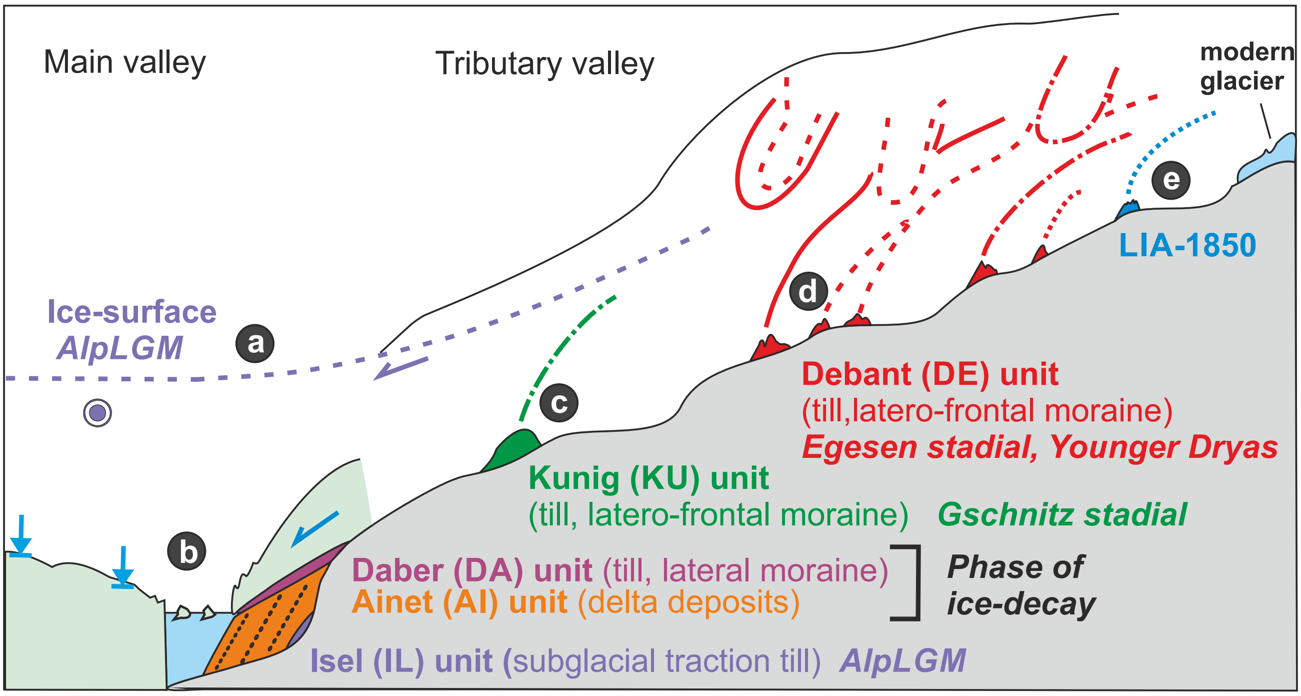

Fig. 18: Schematic sketch of the characteristic glacial development during the Alpine Lateglacial in an Alpine tributary valley from the AlpLGM (Würmian Pleniglacial) to the Holocene in different scenes (a-e). The stratigraphic units of the Schobergruppe mountains are used as an example. a) AlpLGM: Ice surface during the climax of the AlpLGM (c. 27–20ka). The ice flow of the tributary valley was perpendicular to that of the main valley. Deposition of basal till (Isel unit) on bedrock occurred. b) Phase of Ice-decay (c. 19–20 ka): The glacier in the main valley got stagnant and eventually transformed to dead ice resulting in massive downwasting. Short-lived ice-dammed lakes developed which were filled by delta deposits (Ainet unit) from tributary valley. The still active tributary glacier advanced over the delta sediments towards the lake and deposited its basal till (Daber unit) while it reached its Lateglacial Maximum Position (LMP). c) Gschnitz stadial (c. 16–17 ka): After a major readvance the glacier of the tributary valley could stabilise for a considerable time forming large latero-frontal moraines (Kunig unit). d) Egesen stadial (Younger Dryas; 12.8–11.7 ka): The glacier of the tributary valley reached its maximum extent documented by latero-frontal moraines (Debant unit). Multiple moraines document various halts during recession. e) Holocene (11.7 ka until now): The LIA-1850 moraines exemplify one of similar maximum extents of glaciers during the Holocene compared to modern conditions.

Fig. 18: Schematische Skizze zur Charakteristik der glazialen Entwicklung im Alpinen Spätglazial in einem Seitental vom AlpLGM (Würm-Hochglazial) bis zum Holozän in verschiedenen Szenen (a-e). Die stratigrafischen Einheiten der Schobergruppe sind beispielhaft angeführt. a) AlpLGM: Die Eisoberfläche während des Höhepunktes des AlpLGM (ca. 27–19ka). Der Eisfluss aus dem Seitental verlief senkrecht zu jenem des Haupttales. Die Ablagerung der Grundmoräne (Isel unit) erfolgte auf Festgestein. b) Eiszerfallsphase (ca. 19 ka): Der Gletscher im Haupttal stagnierte und verwandelte sich schließlich in einen Toteiskörper begleitet von massivem Einsinken. Kurzlebige Eisstauseen entwickelten sich, die mit aus den Seitentälern geschütteten Deltablagerungen (Ainet-Einheit) verfüllt wurden. Der noch aktive Lokalgletscher aus dem Seitental stieß über die Deltasedimente in den Eisstausee vor und lagerte die Grundmoräne (Daber-Einheit) ab während er seine Spätglaziale Maximalposition (LMP) erreichte. c) Gschnitz-Stadial (ca. 16–17 ka): Nach einem bedeutenden Wiedervorstoß konnte sich die Lokalgletscherzunge aus dem Seitental über einen längeren Zeitraum stabilisieren und lagerte so mächtige End-und Seitenmoränenkörper (Kunig-Einheit) ab. d) Egesen-Stadial (Jüngere Dryas; 12,8–11,7 ka): Der Gletscher aus dem Seitental erreichte seine durch Endmoränen (Debant-Einheit) belegte Maximalausdehnung. Multiple Moränenwälle dokumentieren verschiedene Haltestände während des Zurückweichens. e) Holozän (11,7 ka bis Heute): Die LIA-1850 Moränen veranschaulichen ähnliche Maximalausdehnungen von Gletschern während des Holozäns im Vergleich zu heutigen Bedingungen.

In the middle part of the Schobergruppe mountain valleys the **KU unit** with lateral moraines such as those found at location B-03 in the Daber Valley (Figs. 5d, 6e & 9) or, more impressively, end moraines, such as those in the Leibnitz Valley at location C-01, are present (Fig. 5c & 13). Crucially, these are not linked to any dead-ice feature like a kame terrace (Fig. 7). The latter landmark in particular marks a considerable stillstand of the glacier after a presumed major readvance. Such a major glacier stabilisation is also indicated by the much smaller, but in relation to the source areas of the glaciers, large latero-frontal moraines in the Debant Valley at location A-04 and A05 (Figs. 3 & 4). According to the basal ^{14}C-date of the peat at location B-04 (Section 6.2), which was last ice covered during the formation of the KU unit in the Daber Valley, this stillstand occurred before the Bølling/Allerød interstadial (14.7–12.8 ka) and thus in the Oldest Dryas. Ridges with smoothed crests compared to those of Younger Dryas-age are characteristic of those early Lateglacial features in areas that were not affected by postdepositional fluvial erosion (Figs. 5a, 5s, 5d & 6e).

Similar characteristics of the **KB unit** in the Lienz Dolomites (Figs. 14, 15 & 16a) regarding the palaeographic setting (Fig. 17) and the position within the valley with respect to older and younger units, are seen as a strong evidence for a synchronous formation with that of the KU unit.

Location B-01 in the Daber Valley (Figs. 5d, 6e, 8 & 9) is the local type localitiy of the KU unit, which is identical to that of the Kunig stadial by Buchenauer (1990). Despite the limited extent of the moraines there, compared to location C-01, the immediate link to the older DA-AI units and to the younger DE unit in the same valley as well as to the geochronological constraints at B-04 provide good reasons for choosing this location. Furthermore, the corresponding subglacial landforms at B-06 (Figs. 5b & 6g), which once more document deformable bed conditions and the presence of a temperate glacier, are linked to the same palaeoglacier extent (Fig. 7).

The **DE unit** as the youngest Lateglacial one is present in the upper valleys of the Schobergruppe mountains close to or within the cirques (Figs. 3, 4, 7, 9 & 13). In the type-area in the upper Debant Valley from the location A-03 up to the last moraines in the foreland of the LIA moraines, it consist of a set of latero-frontal moraines which were previously attributed by Buchenauer (1990) to his stadials and substadials (halts) of Gaimberger-Alm, Hofalm, Lienzer Hütte, Viehkogel and Gartl, respectively (Fig. 4; Table 1). The geometry of these deposits reveals a very active snout of the Debant glacier and corresponding tributary glaciers with many phases of stabilisation from its maximum extent at location A-03 to the last recessional phase. Such glacier behaviour was most likely facilitated by temperate subglacial conditions with at least occasionally the presence of deformable bed conditions (e.g. fluted moraines in Section 5). As already highlighted by Buchenauer (1990), the relatively older moraines of the DE unit were more affected by concurrent periglacial processes (including rock glaciers) depending on the altitude. Thus, in some cirques like in the Leibnitz Valley, the occurrence of multiple moraine ridges is limited where rock glaciers or their deposits dominate (Figs. 8 & 13). However, there is no general rule evident that the oldest set of moraines, correlated by Buchenauer (1990) to his Gaimberger-Alm stadial, are generally smoother due to geli-solifludial processes than the younger ones (Fig. 5).

According to the results of ^{10}Be surface exposure dating (Table 2) with a consistent age of 13.4–12.2 ka at location A-03 in the Debant Valley (Figs. 3, 4 & 5a) the formation of the DE unit began in the Younger Dryas. Based on correlations of the last recessional moraines (of the Gartl halt) by Buchenauer (1990) with the Kromer stadial, the last part of the DE unit could be of early Holocene age according to recent dating results at the Kromer type-locality (Moran et al. 2016). However, corresponding to Buchenauer (1990: 232), no field evidence justifies a separation of the Gartl halt from the Younger Dryas (see also discussion below).

In total, the characteristic set of multiple moraine ridges appears to be a diagnostic feature which is also present with the **KA unit** in the cirques of the Galitzen creek (Figs. 14, 15 & 16b), therefore, indicating the former presence of Younger Dryas glaciers in the Lienz Dolomites as well (Fig. 17; Table 1).

By comparing this sequences of three units showing glacial activity (DA unit, KU unit & DE unit) with that of the frequently published subdivision of the ALG (e.g. Maisch 1982, Ivy-Ochs et al. 2006b, Kerschner 2009, Heiri et al. 2014, Ivy-Ochs 2015) with – from old to young – phase of ice-decay, Gschnitz, Senders/Clavadell and Daun as the stadials older than the Bølling-Allerød (B/A) interstadial and the Egesen Stadial as the equivalent of the Younger Dryas. Hence, the question may arise if the documents in the Lienz area are incomplete and/or major indications have been overlooked.

It has been argued before that the AI, DA and GA units (Table 1) can be correlated with the phase of ice-decay according to the similarities in the sequence and the deduced palaeography with that of the type-area in Northern Tyrol (Reitner 2007). Based on available data, the formation of these units is likely to have taken place after the climax of the AlpLGM (c. 26–19 ka; Monegato et al. 2007) and was finished before the large Alpine valleys became ice free. For the Drau Glacier system, the latter is indicated by lake sediments from Lake Längsee (Schmidt et al. 2002; location see Fig. 1) and Lake Jeserzersee (Schultze 1984, Schmidt et al. 2012), which provide minimum ages of c. 18–19 ka in agreement with comparable data from Rödschitz in the Traun Glacier area (van Husen 1977, 1997). The results from luminescence dating of kame terrace deposits at Hopfgarten (Fig. 1) with a date of 19 ±2 ka (Klasen et al. 2007) in general support these time constraints that show that rapid down-wasting of the former network of thick trunk glaciers happened within a short timespan around 19 ka in accordance with further geochronological evidence from the Eastern Alps (Wirsig et al. 2016) and the Friulian plain (Fontana et al. 2014).

Concerning the DE unit, the ^{10}Be dates show that the maximum glacier extent was reached around 12.8 ka during the first half of the YD correlated to Greenland stadial (GS) 1 lasting from 12.9 to 11.7 ka (Rasmussen et al. 2008), which is in general accordance to other dated regions in the Alps (see Ivy Ochs et al. 2006, 2008, 2009, Ivy-Ochs 2015). Thus, no traces of a Daun stadial in the sense of a pre-Bølling/Allerød interstadial glacier advance or stillstand with an ice extent slightly larger than that of the Younger Dryas is evident anywhere in the study area. Especially the recently published data from Kolm-Saigurn (Bichler et al. 2016), a site in the Hohen Tauern (Fig. 1) only c. 25 km NE of Debant Valley, just north of the main divide, show striking similarities with those of the Debant Valley. The maximum extent was reached there at least around 12.6 ka with a size of the reconstructed palaeoglacier of similar configuration and dimension. The following retreat phase, documented by at least eight stillstands or minor readvances according to the number of arcuate moraine ridges, shows comparable ice-marginal dynamics, with two constituting glaciers in this case operating progressively more independently. Based on the dating results of Bichler et al. (2016) and the continuous moraine sequences in an area with good preservation conditions, crucial to the correct interpretation of moraine sequences (Lukas & Benn 2006, Kirkbride & Winkler 2012), the last glacier stabilisation occurred at the end of the Younger Dryas without any trace of a separated early Holocene stadial. However, the recalculation of ages pertaining to the Kartell stadial (Ivy-Ochs et al. 2006b), which Buchenauer (1990) correlated with the second youngest part of the DE unit (Viehkofel stadial), gives ages of 11.9±0.9 ka at its type locality indicating a last phase of the Egesen stadial (*cf.* Bichler et al. 2016). The uppermost latero-frontal moraines of the DE unit in the foreland of the LIA moraine defining Buchenauer's Gartl halt were correlated by him with the Kromer stadial, based on ΔELA values, but this has recently been re-dated at the type locality by Moran et al. (2016) to c. 10 ka. In the absence of dating of this youngest part of the DE unit, it is inferred here that the results of the nearby Kolm-Saigurn area (Bichler et al. 2016), with the last glacier extent significantly larger than LIA, occurred during the Younger Dryas, and that this correlation is also applicable to the present study area.

Such a view is also supported by a review of available ^{14}C-dated archives from other forelands of LIA moraines in the Eastern Alps, which shows that a formation of the Kromer moraines before c. 10.9 ka is very unlikely (Patzelt 2016).

So, in summary, the DE unit at its type-valley, with its 8–9 multiple ridges, not counting the smaller ones of the size of annual LIA moraines, was deposited by a very active glacier tongue which is also known for the Younger Dryas in Scotland, for example (e.g. Benn & Ballentyne 2005, Lukas 2006). Even looking at the major groups as defined by Buchenauer (1990) i.e. Gaimberger-Alm, Hofalm, Lienzer Hütte, Viehalm and Gartl (Table 1), shows that the Younger Dryas – moraines can be subdivided in more than three phases as previously published (*cf.* Kerschner 2009). Comparing the Debant Valley with other locations of Younger Dryas-glaciation in the study area this high number of documented stillstands (after presumed small advances) may be the result of the number confluences and thus that of the contributing cirques as the accumulation areas, in addition to the good potential for moraine preservation. Thus, internal ice dynamics besides the overall climatic control may have played an underrated role in moraine formation (see also Lukas et al. 2012, Barr & Lovell 2014).

Any correlation of the remaining KU unit, younger than the phase of ice-decay and older than the Bølling- Allerød (B/A) interstadial, with the known Lateglacial stratigraphy has to take into account that the KU unit is the product of a major stabilisation of the snout, indicating a considerable time of formation. Buchenauer (1990) argued for a corresponding glacier stillstand after the Gschnitz stadial, during the Senders stadial, based on ΔELA values. But his presumed equivalent of the Gschnitz stadial, the so-called Debant stadial, could not be verified either at the type-location in the Debant Valley (A-02; Figs. 1 & 4) nor in the Daber Valley (B-02; Fig.8) nor in the Kals Valley (D-02; Fig. 8). In all three cases, the ridges interpreted as moraines by Buchenauer, are the result of mass movements (Fig. 9) or (glacio-)fluvial activity (Figs 5e & 12c). Based on the remaining classification of Buchenauer (1990), the most well-known Lateglacial phase, the Gschnitz stadial, characterised by large valley glaciers having an unimpeded drainage in their forelands while producing prominent moraines is seemingly missing in the study area. This appears to be very unlikely when comparing this to the evidence of the areas of formerly covered by the Inn, Traun, Salzach and Drau Glaciers (e.g. Mayr & Heuberger 1968, Gross et al. 1978, van Husen 1977 und 1997, Schuster et al. 2006, Reitner 2013, Zasadni 2014). Moreover, in the Gschnitz Valley (location in Fig. 1), where the type locality of the Gschnitz stadial is located, only three Lateglacial stadials are documented between the LIA moraines and the valley mouths, despite good conditions for moraine preservation. The oldest one at the mouth is the previously called Steinach stadial with a local basal till resting on delta deposits of a kame terrace (Mayr & Heuberger, 1968), which is now seen as a typical glacier advance of the phase of ice-decay (*cf.* Reitner 2007). The moraines of the Gschnitz type locality in the middle part of the valley at the village of Trins (Penck & Brückner 1909, Mayr & Heuberger 1968, Rockenschaub & Novottny 2009) were dated to 16.8±1.7 ka (Ivy-Ochs et al. 2006a; recalculated with the NENA production rate of Balco et al. 2009). They are clearly separated from the Younger Dryas moraines in the upper valley close to the still glaciated cirques (*cf.* Kerschner et al. 1999). Furthermore, a reinvestigation of the Senders stadial type locality (Kerschner & Berktold 1982) casts doubts on the nature and relative chronology of glacial deposits there and, consequently, challenges the relevance of this stadial (Reitner, Bichler & Gruber, unpublished data). Thus, the KU unit is best explained as the product of the long-lasting glacier stillstand of the Gschnitz stadial.

The strength of this tripartite succession is that it is based on a comprehensive re-assessment of both geomorphological and sedimentological evidence and incorporates independent age control; in contrast to the older approach based on ΔELAs, the present approach demonstrates that these multiple lines of evidence converge in the present study area and correspond very closely to findings from other regions in the Eastern Alps. Therefore, the new classification, with its three remaining stages, is considered more robust than the preceding classification that was based entirely on geomorphological evidence and ΔELA values, as for example carried out by Buchenauer (1990) for the Schobergruppe mountains. In our study, successions of units along neighbouring valleys have been used to establish a foundation for correlation with the climatostratigraphy of the ALG. Despite the high-mountain topography showing obvious fluvial erosion, dissection by mass movements and reworking by rock glaciers, it has been possible to extract more than just a synthetic master succession (summarised in e.g. Ivy-Ochs et al. 2008, Kerschner 2009, Heiri et al. 2014) that is documented by highly similar evidence in the valley of the Daber creek (Schobergruppe mountains; Fig. 9) and in the valley of the Galitzen creek (Lienz Dolomites; Fig. 15). Together with the geochronological evidence, this bears a remarkable resemblance to the master sequence of the Gschnitz Valley, and this challenges the standard chronology that had hitherto been regarded as valid. The main argument for the weakness of this previous standard model is that this was strongly based on ΔELA values. In addition to a mismatch with the detailed and converging multiple lines of evidence presented here and elsewhere, correlations based solely on ΔELA over different regions run into the very real danger of ending up in a circular argument. This is because regional differences in palaeoclimatic conditions of any given phase are on the one hand proposed to be defined by ΔELA ranges, but on the other hand, changes in the ELA are already the product of precipitation and temperature, among many other factors that can confound extraction of any meaningful stratigraphic assignment. These confounding factors have been noted prominently elsewhere (e.g. Benn & Ballantyne 2005, Benn & Evans 2010, Lukas & Bradwell 2010, Boston et al. 2015), but these problems have not been taken into account, with rare exceptions (e.g. Federici et al. 2016), when reconstructing glaciers and palaeoclimate in the Alps. With ΔELAs as a base for Lateglacial stratigraphy the palaeoclimatic reconstructions for a time period are already biased. Hence, major climatic shifts since e.g. the Gschnitz stadial between the northern and the southern flank of the Alpine main divide cannot be detected anymore. As no documents of the stadials Senders and Daun as proposed by Kerschner & Bektold (1983), Kerschner (1986) and Kerschner (2009) could be detected, the ΔELA calculations by Buchenauer (1990) for his Kunig stadial with a mean ΔELA of 422 m (405–450 m) are taken as palaeoclimate information for the Gschnitz stadial in the Schobergruppe mountains in good faith, i.e. without any independent means of checking. The same is true for his Gaimberger-Alm stadial with a mean ΔELA of 281 m (265–300 m), which has been taken to represent a firm base for the Egesen maximum extent in the same region.

The situation in the Lienz Dolomites is more complicated as no LIA reference exists and even simple ELA calculations have to take into account a thick debris cover due to talus sedimentation on the surface and in the most extreme case due to rock fall or rock avalanches, like in the Laserz creek area (Reitner et al. 2014). Thus, any treatment of ablation at the tongue is far beyond the standard AAR procedure (with a ratio of 0.67) applied in the Schobergruppe mountains, but also elsewhere. Alternatively, the highest onset of the lateral moraine (MELM) is regarded as a possible proxy for the ELA estimation. However, until now there is only one situation where the MELM method could be employed due to good conditions for moraine preservation of the supposed Younger Dryas.

Thus, it is understandable that the ΔELA approach has been prevalent for so long, but the evidence presented here and elsewhere strongly suggests that it is preferable if this approach be retired and a more robust approach, based on local palaeoclimatic proxies (e.g. treeline, chironomids), an integration of geomorphology, sedimentology and independent geochronological methods take its place. Nevertheless, ΔELAs are still considered as a useful tool for correlation on the local scale e.g. in one mountain group (like the Schobergruppe mountains) with a quite comparable topography and lithology and taking into account the limitations, especially the impact of debris cover.

11 Conclusions

The results of a geological mapping campaign supported by geochronological analyses showed that the ALG sedimentary record of the Schobergruppe mountains and the Lienz Dolomites can be respectively subdivided into four (informally defined allostratgraphic) unconformity-bounded units i.e. Ainet (AI), Daber (DA), Kunig (KU), Debant (DE), respectively, Ainet (AI), Galitzen (GA) Klammbrückl (KB), Kerschbaumeralm (KA), which are linked to three phases of glacier activity (Fig. 18; Table 1). The latter are correlated to the already defined climatostratratigraphic subdivisions phase of ice decay (c. 20–19 ka), Gschnitz stadial (c. 17–16 ka) and Egesen stadial (c. 13–12 ka).

Our approach of establishing a stratigraphic framework relies on the allostratigraphic subdivision of glacial sediments in valleys with defined local type localities of (unconformity-bounded) units, which show the sedimentary and the geomorphological characteristics within a sequence deposited after the AlpLGM and before the Holocene. Thus, successions of glacial sediments within neighbouring valleys, which also show an imprint of post-depositional periglacial and gravitational processes, are regarded as the key for deciphering the glacial chronology and, eventually, the landscape evolution of a mountain chain. ΔELAs are still considered as a useful tool for correlation on the local scale e.g. in one mountain group (like the Schobergruppe mountains) with a quite comparable topography and lithology and taking into account the limitations, especially the impact of debris cover. However, our results show that a stratigraphic correlation across the whole Alpine chain via ΔELAs is not a successful approach and can potentially lead to bias. There is a problem of circular arguments in previous work as the palaeoclimatic development to be reconstructed was already encompassed in the ΔELA criterion for stratigraphic subdivision. Such an approach runs into the real danger of disabling the detection of any major regional changes in climatic patterns in the Alps since the AlpLGM. To overcome this problem, identification of sequences and the definition of geochronologically constrained type localities seem to be inevitable for further progress. Furthermore, our results show the problem of the up-to-now used stratigraphic terminology with respect to Daun and Egesen stadial which is used irrespective of the original meaning. There is an evident need for defining the Egesen stadial in the sense of the Younger Dryas glaciation based on a new type locality in the sense of a “lectostratotype” as the term Egesen is now used in this sense whereas the original type locality (“holostratotype”), as defined by Kienzel (1929), documents only a younger and minor part of the Younger Dryas (*cf.* Kerschner 2009). The sequence consisting of multiple moraines in the upper Debant Valley – from the moraines of Gaimberg-Alm to the foreland of the LIA-moraines – is a strong candidate for at least a local type locality (in the sense of a “parastratotype”) after additional geochronological analyses. Moreover, the evidence of the Schobergruppe mountains, the Lienz Dolomites together with combined evidence of the Gschnitz Valley, make a strong case for reconsidering the status of the Daun stadial. The morphological criterion for subdividing Egesen from Daun moraines based on Heuberger (1966) is challenged with the dating results in the Debant Valley. It seems to be that local differences within moraines series of Younger Dryas age deriving from geologically the same catchment might be the result of periglacial reworking (gelifluction) during the long Younger Dryas stadial. In addition, the previous approach since Heuberger (1966) of extending the Egesen stadial beyond its original meaning resulted in a glacial stadial which has now the same meaning as the Daun stadial as originally defined by Penck & Brückner (*cf.* Kerschner 1978, 2009) leading to an evident redundancy as Egesen is already the widely used name for the Younger Dryas glaciation in total. To overcome this confusion, we propose to withdraw the term Daun until a re-investigation of the type locality. If there is the case of a reconstructed glacier halt between the Younger Dryas and the Gschnitz moraines, it is recommended to define a new stadial with a new name based on a well-constrained type locality. Reconstructing a glacial history while retaining abandoned stratigraphic terms (e.g. Bühl) will in our view hamper future efforts for Alpine-wide stratigraphic and eventually palaeoclimatic correlations.

Finally, the findings of fluted moraines and also deformed layers within basal till revealed that the glaciers during the phase of ice decay, Gschnitz stadial and Egesen stadial were temperate and had at least partially deformable beds.

In conclusion, we emphasise the power of, and advocate, a holistic approach involving geomorphological and sedimentary features, including not only those of glacial but also of periglacial and especially of gravitational origin, in order to decipher as well as possible the glacial record in the context of Lateglacial landscape development. This may serve as a useful template for applying dating methods.

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