The Geological Society
ES3 Earth Science, Systems and Society

ORIGINAL RESEARCH
published: 07 November 2024
doi: 10.3389/esss.2024.10131

Geomorphology and Sedimentology of a Rapidly Retreating Alpine Glacier: Insights From the Taschachferner, Tirol, Austria

D. P. Le Heron[1]*, P. Mejías Osorio[1], M. Heninger[1] and B. J. Davies[2]

[1]Institut für Geologie, Universität Wien, Vienna, Austria, [2]School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, United Kingdom

The rapid retreat and fragmentation of Alpine glaciers is widely reported as humanity faces dramatic climate change in mountainous regions. This rapid change leads to changes in sedimentary processes, which are exposed in recently deglaciated regions. These Alpine glacier forefields offer a wide spectrum of settings through which the ancient sedimentary record can be interpreted. Glacial valley orientation, slope inclination and lithology, and plumbing of subglacial and englacial meltwater drainage all influence the immediate preservation potential of glacial sediments upon deposition. In this contribution, we explore the geomorphology and sedimentology of the Taschachferner (a valley glacier), presenting a new geological-geomorphological map. This small glacier drains an icefield in the Ötztal Alps, and its current ice margin lies at approximately 2550 m a.s.l. Thus far, the glacial sedimentology and its bedrock geology have not been subject to investigation. The bedrock geology is dominated by E-W striking units of paragneiss and amphibolite, and the latter exhibit a series of well-preserved striations together with meltwater-sculpted bedforms (p-forms). The lower region of the glacier can be divided into two parts: (i) a clean-ice part, on the northern valley side with a low, subdued profile and (ii) a debris-covered part at the southern valley side, covered with supraglacial debris. The valley margins are dominated by several generations of lateral moraines, the most prominent of which corresponds to the 1852 Little Ice Age Maximum. A well-developed "hanging sandur" is observed immediately in front of the ice margin. This consists of a series of sand and gravel bars cradled in the lee of an interpreted regional fault cross-cutting the bedrock. Sandur deposition is currently influenced and overprinted by dead ice, influencing the trajectory and location of river channels and gravel bars. This paper provides clear lessons regarding the distribution of ice-margin facies associations, which must be incorporated into models of glacier decay in the context of a rapidly warming climate.

Keywords: glacier, mountain, Alps, sedimentology, climate change, society, geomorphology, mapping

Edited by:
Armand Hernández,
University of A Coruña, Spain

Reviewed by:
Julia Garcia-Oteyza,
University of Barcelona, Spain
Adriano Ribolini,
University of Pisa, Italy

***Correspondence**
D. P. Le Heron,
✉ daniel.le-heron@univie.ac.at

Received: 03 June 2024
Accepted: 13 September 2024
Published: 07 November 2024

Citation:
Le Heron DP, Mejías Osorio P, Heninger M and Davies BJ (2024) Geomorphology and Sedimentology of a Rapidly Retreating Alpine Glacier: Insights From the Taschachferner, Tirol, Austria.
Earth Sci. Syst. Soc. 4:10131.
doi: 10.3389/esss.2024.10131

INTRODUCTION

Up to one-third of present-day ice volume in the European Alps is committed to disappear by 2050 on the basis of deep-learning-aided 3D ice flow models (Cook et al., 2023). In Austria, all glaciers are in negative mass balance and undergoing recession (Fischer et al., 2015), reflecting a global trend in the face of anthropogenic climate warming (Hugonnet et al., 2021). The Ötztal Alps (Tirol, Austria) are host to a number of small ice caps and valley glaciers including the Taschachferner glacier (**Figure 1**) which are severely threatened by climate change and are expected to disappear by 2100. Stocker-Waldhuber et al. (2019) argued that the Taschachferner glacier together with neighbouring glaciers in the Ötztal Alps showed clear indications of recession based on their measurements of decreasing velocities over a decade. At the Taschachferner glacier, ground penetrating radar (GPR) measurements of ice thickness made in 2003 at the then ice margin (Fischer and Kuhn, 2013) indicate a vertical loss of at least 60–70 m in the last 20 years. The rapidity of change has led not only to a negative mass balance for all glaciers in the region but has led to the rapid exposure of sedimentary deposits and geomorphological structures which have never been mapped, and which have a low preservation potential due to their small scale and unconsolidated nature. These sediments and geomorphic features are likely to contrast significantly to those deposited in previous decades, under a more vigorous glacier with more active erosion.

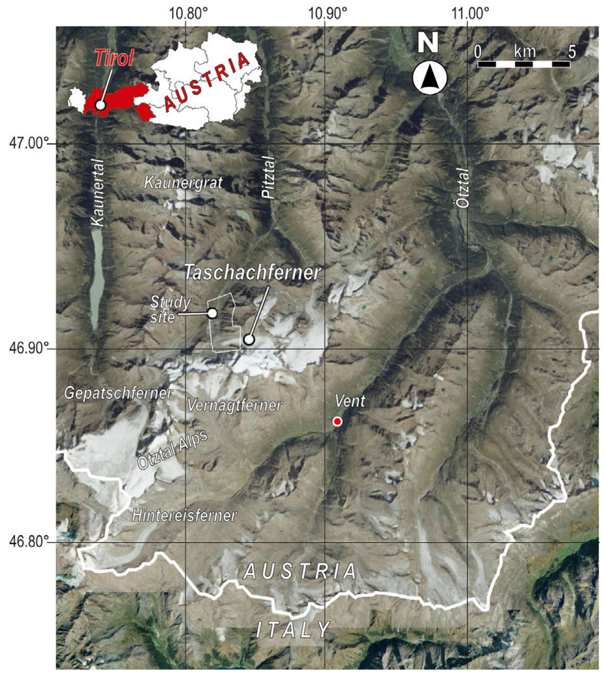

FIGURE 1 | Location map of the Ötztal Alps in Tirol, and the study site of the Tascachferner at the southern fringe of Pitztal.

As part of a long-term University of Vienna research programme on modern Austrian glacial geology, this paper provides detailed descriptions and interpretations of sedimentary deposits and landform associations at the forefield of the Taschachferner glacier (**Figure 1**). Owing to the rapidity of change at modern glacial forefields, the challenge is to describe, map and interpret as much as possible before glaciers and their associated sediments disappear entirely. From a geological and sedimentological perspective, we rely on our observations of modern processes to understand the rock record. Thus, to develop viable models of glacial sedimentation from dying glaciers in the Anthropocene, intense geological study (Le Heron et al., 2022a) is required over the coming years.

STUDY AREA: BACKGROUND AND PREVIOUS RESEARCH

The Ötztal Alps are located in Tirol near the southern Austrian border with Italy (**Figure 1**). They comprise a range populated by several large glaciers, including the Gepatschferner and the Mittelbergferner (Austria's second and third largest glaciers respectively), together with the Taschachferner glacier, the subject of this paper. The study area lies at the southern extremity of the valley of Pitztal, the central of three north-south trending deep valleys in the Ötztal Alps (also including Kaunertal to the west and Ötztal to the east).

Although the glacial geology and geomorphology of the eastern Alps as a whole is well understood (van Husen, 1997), little has been documented in terms of the modern glacial sedimentology and geomorphology of the Ötztal Alps. Concern about shifting and increased bedload in rivers causing potential blockages and downstream flooding in some locations such as Kaunertal have motivated focus of river gravel transport (Baewert and Morche, 2014). The steep terrain, with historical evidence of multiple ice falls in the region (Fisher and Mayer, 2021), makes the existence of large Quaternary paraglacial lakes in lower lying areas of the eastern Alps (e.g., Bernsteiner et al., 2021; Le Heron et al., 2023) unlikely. Nevertheless, the ever present threat of permafrost degradation on slope stability (Buckel et al., 2023), the issue of sustainable water resources in the face of a diminishing source (Weber et al., 2010), and the role that Alpine glaciers play in regional tourism (Salim et al., 2021), underscores the role that they play in society, both in Tirol and globally.

Geological mapping of the Kaunergrat-southern Pitztal area (**Figure 1**) was undertaken almost a century ago (Hammer, 1929). Since then, no further original maps of this area has been published. The Hammer (1929) map recognised three principal basement lithologies in the Taschachferner area, namely a biotite-plagioclase gneiss in the north of the area crosscut by bands of amphibolite and a muscovite granite and granitic orthogneiss in the south. Subsequent research has identified very complex pre-Alpine fold interference patterns in these rocks (Egglseder and Fügenschuh, 2013), but essentially an east-west oriented set of lithological boundaries dominates the basement geology. Hammer (1929) mapped an array of moraines, including the major 1852 lateral moraines, together with other Quaternary features such as landslide deposits and river deposits. To our knowledge, no published sedimentological data has been published specifically from the Tachachferner glacial forefield since this time. Further west, in the Kaunertal, Gerhold (1969) published locality descriptions and interpretations of aspects of the glacial geology with special focus on rock glaciers.

In terms of glaciological research, there has been a long tradition of investigation in Ötztal, starting over 400 years ago with a sketch of the Vernagtferner glacier by Abraham Jäger in 1601 (Fisher and Mayer, 2021). Regular reports measuring the annual retreat of glaciers became established with the "Handbuch der Gletscherkunde und Glazialgeologie" (e.g., Klebelsberg, 1949). Long term mass-balance research initially focussed on the Hintereisferner and the Kesselwandferner glacier from 1952-53 (Fisher and Mayer, 2021). A series of topographic maps were produced by the military which formed the basis of "die Karte des Öztäler Gletschergebietes (von Sonklar, 1860). Remote sensing approaches, using LIDAR or satellite image analysis, focussed on the quantification of changes in volume and area of glaciers over decadal time series (Abermann et al., 2009).

METHODS

Fieldwork was conducted in August 2023 with the main goal being to map the present-day Taschachferner glacier margin and its forefield. This was achieved through combining field surveys with aerial photography acquired from a DJI Mavic 3 uncrewed aerial vehicle (UAV). Such UAV missions of glacial forefields typically promote the use of ground control points should repeated missions be required (for example, for the generation of digital elevation models of difference) (Chandler et al., 2018; James et al., 2019). We deemed this step not necessary in our work as the goal was not to acquire ice loss volume data, rather to map the sedimentary facies and geomorphology. The DJI Mavic 3 is equipped with a 20 megapixel Hasselblad camera; it was flown manually, using a 60° camera angle with double grid configuration to eliminate shadows and overcome distortions. Approximately 800 photographs were then combined in Agisoft Metashape Professional 2.1.0, quality filtered, aligned, and then processed following a standard batch-process workflow (dense point cloud creation, 3D model generation with texture, mesh generation, digital elevation model (DEM) calculation and orthomosaic generation). The 3D model generated complements the field observations by providing oblique and bird eye perspectives of certain features, whilst the orthomosaic and DEM form the basis for mapping. Basic mapping was undertaken in Adobe Illustrator and the final map was georeferenced according to the WGS 84 projection in ArcGIS. In the field, we focussed on differentiating debris covered ice at the ice margin from moraine material, small-scale geomorphological structures (p-forms, striations) and, where possible, differentiating bedrock geological units (paragneiss, granitic orthogneiss, amphibolite) together with lithological boundaries. Owing to the nature of exposure, sedimentary logs of the type produced elsewhere e.g., at the Gepatschferner glacier margin (Le Heron et al., 2022a) or at the margins of the Pasterze glacier (Le Heron et al., 2022b) were not possible.

RESULTS

Geology and Geomorphology

Our main deliverable, namely, an interpretive map of the Taschachferner glacier margin and forefield (**Figure 2**) shows the distribution of the key geomorphological and sedimentological units produced through subglacial, paraglacial, supraglacial and proglacial processes. The 600 m wide valley (as defined by the presence of large 1852 lateral moraines; **Figure 3A**) exposes extensive bare bedrock areas in its upper reaches. These comprise granitic orthogneisses with steeply plunging striations and p-forms in the south of the area (**Figure 3B**), heterolithic paragneiss with complex interference folds (**Figure 3C**) (Egglseder and Fügenschuh, 2013), and roche moutonnées with delicately developed striations on amphibolite bedrock (**Figure 3D**). In some areas, roche moutonnées have a highly disaggregated, disintegrated appearance whereby the surface of the bedrock structures is broken up into large blocks (**Figure 4**). Bedrock areas are draped by sediment closer to the modern ice margin. Our 3D model generated from UAV data allows a perspective on the whole ice margin area to be obtained, in which the spatial relationship between bedrock, a proglacial sandur, a relatively "clean" ice area and a debris-covered part of the glacier can be recognised. The elevation difference between the "clean" ice area and the debris-covered lateral margin of the glacier is up to 40 m (**Figure 3E**), meaning that the elevation profile of the glacier is presently very asymmetrical with respect to the valley margin.

Sedimentary Deposits

In terms of the sedimentology, our map illustrates the existence of 7 main types of deposit in the valley. These are (i) supraglacial sediment, (ii) a fluted till surface with moraine ridges, (iii) delta topsets feeding into small lakes, (iv) lateral moraines, (v) fluvial deposits, (vi) debris cone/gravitational deposits, and (vii) undifferentiated diamict.

The supraglacial debris consists of angular unsorted material where it is exposed at the ice margin. No debris cones such as those well developed on the Pasterze glacier (Le Heron et al., 2022b) were observed or mapped in 2023. On the glacier surface, the thick debris cover at the SW margin (**Figure 5A**) can be clearly mapped but with the UAV approach we have not been able to differentiate the supraglacial material into different categories as has been done elsewhere, such as on the Pasterze glacier (e.g., Kellerer-Pirklbauer and Kulmer, 2019).

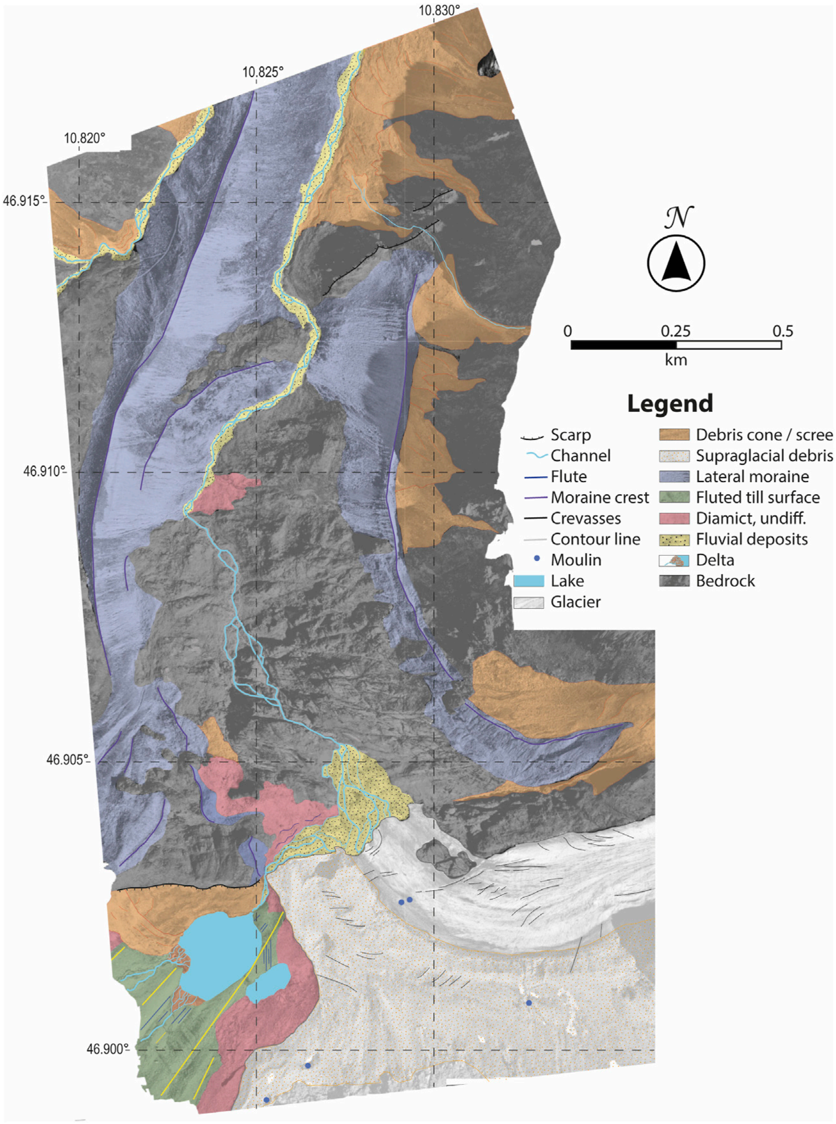

FIGURE 2 | Quaternary geological-geomorphological map of the upper Taschach valley and the Tascachferner glacial margin.

To the southwest corner of the mapped area, an extensive diamict outcrop abuts directly against the debris-covered part of the glacier (**Figure 5B**). This diamict is traversed by 50 m wide, 300 m long moraine ridges and, between them, parallel m-wide, 0.3 m high, 10–20 m long flutes: this is hence mapped as fluted till surface, and both the moraine ridges and interstitial flutes show a predominant SW-NE orientation (**Figure 2**). Superimposed on this surface, we observe small meltwater channels feeding minor deltas which are building into small lakes on the diamict surface (**Figure 5B**). Both a "classical" delta/Δ geometry fanning out into the standing body of water, as well as a somewhat sunken, linear shoreline example can be observed. We also observe m-scale parallel ridges which are oriented almost orthogonally to slightly oblique to the moraine ridges and flutes (**Figures 5B, C**). From a bird's eye view, the differentiation between clean and debris-covered lateral glacier margin is comparatively sharp, with a ca. 10–20 m wide transition zone (**Figure 5D**). The glacier terminates at a sandur fed both by meltwater channels and gravitational deposits (**Figure 5E**). Further downvalley, and high above the ice margins, the valley landscape is dominated by knife-sharp, >100 m high moraine ridges which, in the Ötztal Alps, represent lateral moraines produced at the 1852 Little Ice Age maximum (Hammer, 1929).

The glacier terminus, likewise, shows a relatively clean central portion of the glacier and debris-covered zone: the ice front is characterised by a crescentic, scoop-shaped ice "embayment," swarms of concentric fractures, and scree deposits sourced from supraglacial debris. These deposits

FIGURE 3 | (A): Aerial photograph of the glacier margin showing overall context of the Tascachferner. **(B)**: Striations and p-forms on granitic orthogneiss. **(C)**: Relationship between paragneiss, p-forms and sediment cover. **(D)**: Striated roche moutonnée in amphibolite. **(E)**: Snapshot from UAV data (Agisoft Metashape 3D model) showing lateral partitioning of clean versus debris-covered glacier.

influence the distribution of sand and gravel bars on the sandur which presently measures approximately 100 m wide and 100 m long. The geometry of the sandur, specifically the location of meltwater channels and sand/gravel bars, is closely influenced by the presence of a large dead ice zone at its northern reaches. Throughout the Taschach valley, large debris cones/scree zones are identified (**Figure 2**). Many of these are sourced from bare rock hillslopes on the eastern side of the valley but are buttressed by the lateral moraines. In other cases, such as to the north of the region where lateral moraines are not present, they derive from steep scarps and extend to the river basin, coalescing to produce a bajada-like landform (**Figure 2**).

Finally, we also map areas as undifferentiated diamict where no diagnostic evidence exists to demonstrate the origin of such deposits. It should be noted that the present-day (as of August 2023) margin of the Taschachferner glacier lies stossward of a major bedrock cliff, over which the

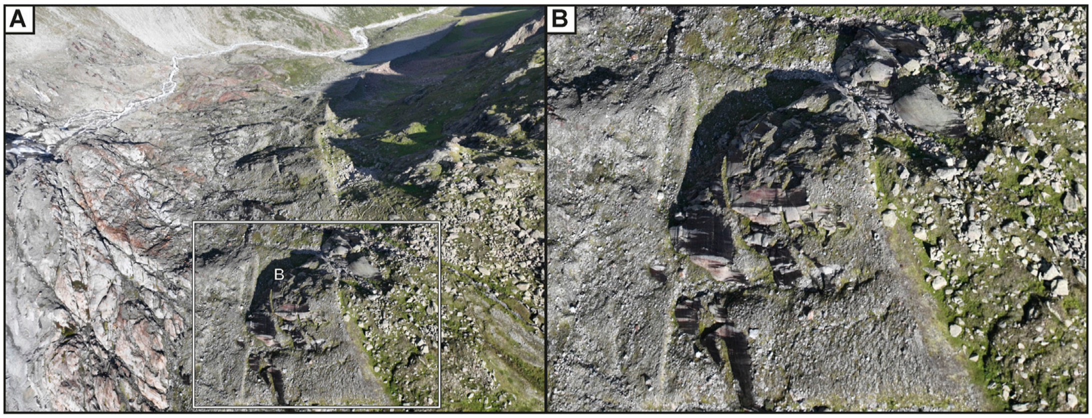

FIGURE 4 | (A): Aerial view looking north over the Taschachferner forefield showing polished bedrock covered with roches moutonées, traversed by bedrock foliation and fractures. Palaeo-ice flow was toward the top of the photo. **(B)**: Zoomed in area shown in A showing highly disaggregated and disintegrated roches moutonées.

meltwater river cascades. This area was ice covered as recently as 2015: historical Google Earth imagery shows evidence that this was an icefall 8 years ago (**Figure 6**).

Interpretation

The heterogeneous crystalline bedrock at the forefield of the Taschachferner glacier testifies to the interplay of subglacial abrasion (striations), with a significant role of meltwater (p-forms: Kor et al., 1991) in the development of larger subglacially-sculpted landforms (roche moutonnées). The apparent concentration of p-forms in the vicinity of the present meltwater rivers is unsurprising and probably records a phase where these subglacial rivers had a strong influence on processes at the ice-bed. The presence of roche moutonées implies the action of "glacial ripping" at the ice-bed interface (Krabbendam et al., 2022). In this process, in eastern Sweden, these workers similarly disaggregated roches moutonnées in similar metamorphic rocks: hydraulic jacking by overpressured water is proposed to have exploited fractures and foliations, causing bedrock fracture which truncated the pre-existing, subglacially smoothed surface. Aerial images reveal a strong foliation trend, striking E-W and thus probably mimick the strike of the main basement trends (Hammer, 1929). Detailed geological mapping of these basement lithologies remains to be done.

The distribution of supraglacial debris deserves consideration. The phenomenon of debris-covered glaciers has attracted much research interest in recent years in terms of their relationship to climate change and the complex feedback mechanisms involved (e.g., Huo et al., 2021; Mayer and Licciulli, 2021; Racoviteanu et al., 2022). In terms of the mechanisms of sediment delivery and concentration on the ice surface, Hambrey et al. (2008) examined a number of glaciers around the Mount Everest region (Nepal). In addition to a debris flux from steep, unvegetated slopes onto the glacier surface, the advection of material from the glacier sole to the glacier surface was also made possible by englacial thrusts, typically in the lee (downslope) of an ice fall. On the Taschachferner glacier, the strong asymmetrical cross sectional profile between debris covered and clean ice segments does not appear to be fully explained by any of these mechanisms, and hence deserves future investigation. Nevertheless, the lateral partition between clean and debris covered glacier shows some similarity with the southern side of the Pasterze Glacier at Großglockner, Austria, where a considerable portion of the debris is derived from slope collapse (Avian et al., 2018; Kellerer-Pirklbauer and Kulmer, 2019).

Comparison between the historical Google Earth imagery and our UAV data (**Figure 6**) show that the sandur system has developed entirely within an 8-year time window. Currently, the network of channels and bars are typical for a steady state meltwater system, rather than an upper flow regime/outburst dominated pattern (Hovikovski et al., 2023). The "scoop-shaped" embayment of ice at the margin with associated fracture swarms are indicative a cauldron structure on the surface of the ice (c.f. Kellerer-Pirklbauer and Kulmer, 2019; Le Heron et al., 2022b), whereby concentric fracture sets evolve in a manner comparable to caldera collapse, with a large moulin at their core. Thus, the fracture style and evolution of a cauldron structure explains the present day geometry of the sandur.

We interpret the fluted till surface with moraine ridges to record a self-similar set of elongate, subglacial landforms. The orientation of these structures is somewhat oblique to the present lateral margin of the glacier, suggesting that they formed beneath an additional ice lobe that converged with the Taschachferner glacier. The crests of the large moraines-representing the apex of structures approximately 50 m wide and at least 500 m long-are intermediate in dimensions between flutes and mega-scale glacial lineations (*sensu* Stokes and Clark, 2001). Flutes represent sliding at the ice-bed interface (Ely et al., 2016) and are recognised to form throughout the year, both in winter and in summer, via

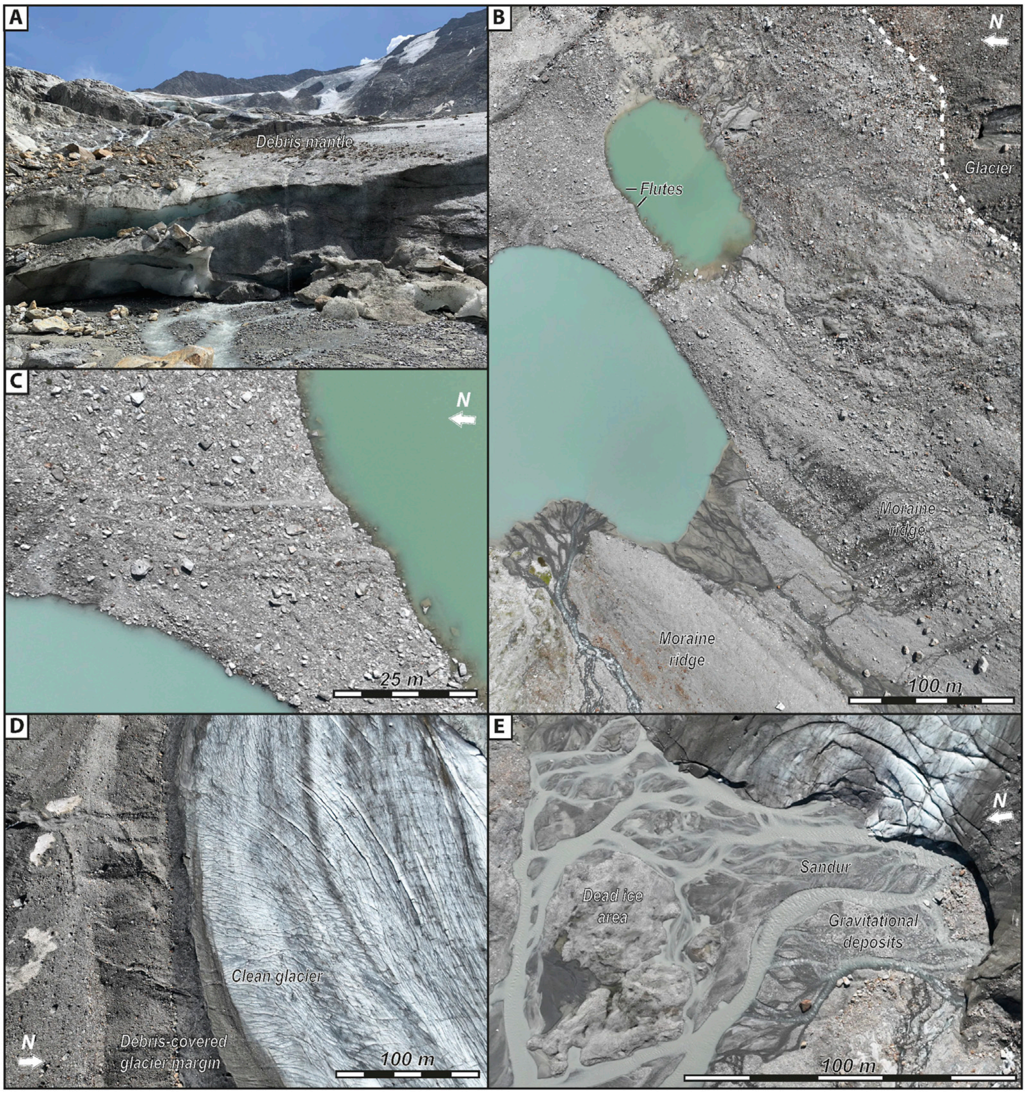

FIGURE 5 | (A): Debris mantle/veneer of supraglacial debris observed at the glacier margin. **(B)**: Linear moraine ridges flanked by flutes to the SW corner of the mapped area. Note also the presence of lakes developed on top of the till sheet, plus evidence for deltas feeding these lakes. Orthogonally oriented ridges (with respect to the linear moraines and flutes) can also be observed, and these are shown in greater detail in **(C)**. **(D)**: Strong lateral partitioning between clean glacier ice and debris-covered glacier margin. **(E)**: Geomorphology and configuration of the sandur which has developed since 2015. The influence of gravitational deposits/reworked supraglacial material and dead ice on the configuration of sand and gravel bars and channels is evident.

deformation of the subglacial bed (Hart et al., 2018). Southwards, at the forefield of the Vernagtferner glacier, swarms of flutes and similar moraine ridges occur (Winkler, 1991): this glacier has a well-documented history of surging, as recorded by artists over 400 years since 1599 (Hoinkes, 1969; Nicolussi, 2013). Thus, the fluted till surface with moraine ridges might also indicate a historical phase of surging at the Vernagtferner glacier (Benn et al., 2019), although it is noted that evidence of rapid flow cessation and subsequent stagnation has not been recorded.

Meanwhile, the m-scale ridges which we observe orthogonal to the moraine ridges and flutes are an increasingly recognised phenomenon at the flanks of modern Alpine valley glaciers, as well as in Iceland (Chandler et al., 2020). We tentatively interpret the structures at the Taschachferner glacier as annual moraines that were superimposed on the subglacial structures. In Austria, they have been described at the margin of the Gepatschferner glacier (Le Heron et al., 2022b), and were investigated in some sedimentological investigation at the Gornergletscher glacier, Switzerland. At this glacier, whose margin lies approximately 250 km SW of the Taschachferner glacier and 8 km south of Zermatt, Rettig et al. (2023) identified four mechanisms of annual moraine

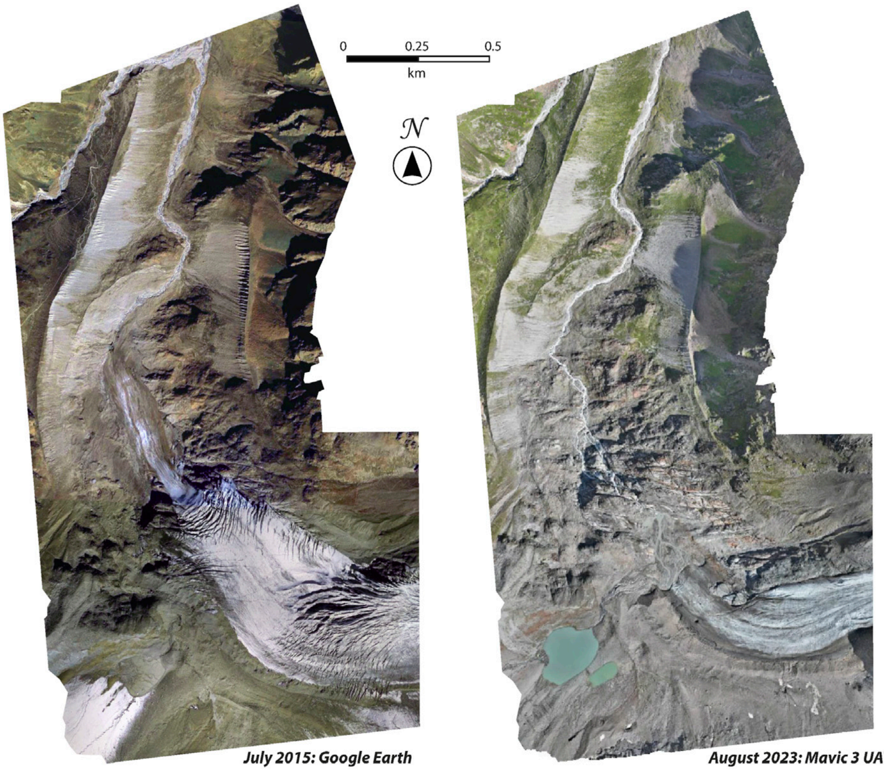

FIGURE 6 | July 2015 satellite imagery compared against August 2023 UAV-acquired imagery of the Taschachferner illustrating dramatic retreat and evolution of proglacial sedimentary systems.

formation that included (i) freeze on of material to the glacier sole, (ii) efficient bulldozing and glaciotectonism, (iii) emergence of ice cored moraines due to melt out of debris bands, (iv) inefficient bulldozing and incorporation of dead ice into moraine deposits. To add to this potential mixture of processes to explain small, flow-orthogonal ridges, Le Heron et al. (2022b) proposed (v) passive infilling of crevasses near the glacier snout.

In terms of present-day processes occurring on the moraine ridges and fluted till, the geometry of the small lakes, which abut against moraine ridges, highlights the role of topography on the soft glacier bed in influencing the lateral extent of lacustrine deposits on the forefield of the Taschachferner glacier. In the ancient sedimentary record, such as in the Late Ordovician rocks of southwestern Libya, lake deposits sandwiched between megascale glacial lineations are recognised as a specific type of small sedimentary basin (Moreau, 2011). At the Taschachferner glacial margin, the presence of "classical" delta geometries as well as the "sunken shoreline" example is suggestive of differential subsidence and compaction on the sediment body, most likely explained by the ablation of dead ice bodies.

The relatively continuous and sharp crestline of the 1852 lateral moraines in the Taschach valley reflects the fact that such features are considered to stabilise in the landscape after about 200 years (Tonkin, 2023). The temporal development of gullies at the flanks of comparable lateral moraines at the flanks of the Bas Glacier d'Arolla in Switzerland has been quantified, with a mean of 0.22 m yr−1 between 1977 and 2009 (Tonkin, 2023).

DISCUSSION

The rapid retreat of the Taschachferner has since 2015 (**Figure 6**) has (i) revealed a bedrock surface covered with striations, p-forms and roches moutonnées, including a large new bedrock outcrop northeast of the glacier margin, (ii) seen the development of a sandur draining the glacier and (iii) witnessed the expansion of small lakes on a subglacial till characterised by mega-scale glacial lineations and flutes (**Figure 2**). Collectively, significant geomorphological and sedimentological changes have therefore occurred in the forefield. The trend toward thinning and degrading ice at the tongue, in 2015 represented by a bedrock area downglacier of an icefall (**Figure 4A**), mirrors in miniature the development of Austria's largest glacier, the Pasterze, whose tongue is fed by only a narrow ice fall (Avian et al., 2018). The appearance of large outcrops of black amphibolite, in particular, is predicted to accelerate the melting process in the immediate future. Not only is albedo locally reduced, but the warmth absorbed by this lithology from sunlight will modify the local microclimate, with heat released at night leading to a series of feedbacks that promote ablation and retreat. The configuration of the glacier tongue between 2015 and 2023, with a former steep ice fall, points to thinning and eventual detachment of the ice margin as demonstrated at the Columbia Glacier in Canada (Rippin et al., 2020) and as a widespread phenomenon in Juneau Icefield, Alaska (Davies et al., 2022). In respect of the bedrock geology, as noted earlier no work has been done specifically on the Taschachferner site since the regional mapping conducted almost a century ago (Hammer, 1929), not least the outcrop freshly exposed during glacial retreat, although attempts to understand the fold geometries in the gneiss elsewhere in the Ötztal Alps (Kalkkoegel area, approximately 40 km NE of the Taschachferner glacier: Egglseder and Fügenschuh, 2013). Remapping of these basement rocks is required to properly understand the character of the crystalline substrate and to better understand ice-bedrock interaction during glacial retreat.

Understanding the rapid development of the sandur is of considerable importance in Pitztal, which has historically been characterised by a number of landslides and debris flows with a number of complex hydro-meteorological triggers (Kaitna et al., 2023). The development of a significant sediment storage zone in a perched basin raises questions about future hazard development downtract in the valley. Glacial cycles are characterized by phases of ice growth, flow and advance of the glacier tongue to a maximum point in a valley, followed by a recession phase until the next cycle begins. The cycles continue until ultimately the glacier enters a dying phase, a concept that is now well established across the Alps and beyond (Cook et al., 2023). However, over such a glacial cycle, there is considerable discussion about when sediment yield should peak, with Antoniazza and Lane (2021) arguing that "glacially-conditioned sediment sources become exhausted" during the latest phases of deglaciation. This statement also appears to account for the dying phase in the glacier life cycle as a debris-mantled glacier evolves to an ice cored moraine. Clearly, owing to the expansion of a sandur system in the last 8 years at the Taschachferner glacier forefield, sediment yield is not yet exhausted.

The lateral partition of debris on the surface of the Taschachferner glacier with so-called debris-covered and clean ice areas is expected to exert a decisive influence on the persistence of dead ice blocks in the future, and thereby to the evolution of elevated, marginal lakes. Although given the geomorphological configuration of the valley future lakes are likely to be small, with examples already developing over presumably impermeable till substrates to the SW of the mapped area, debris-covered glaciers are a significant concern elsewhere, for example, in the Himalayas (Racoviteanu et al., 2022). Ice cored moraines derived from the final phases of glacier melting are known to pose a considerable hazard risk, for example, in the Andes and the Himalayas (e.g., Harrison et al., 2018; Medeu et al., 2022). The thick latero-frontal moraines developed around the fringe of Nepalese debris-covered glaciers also act as a dam whose breaching has initiated glacial lake outburst floods (GLOFs) in the past (Hambrey et al., 2008). In these regions, debris covered glaciers are better researched than in the Austrian Alps, but provide useful lessons both in terms of potential processes and potential hazards. Furthermore, integration of results and interpretations from other glaciated regions of the world is critical to develop a holistic understanding of the challenges of melting valley glaciers to Earth systems and society.

On the Taschachferner glacier, it is notable that the debris covered area is presently restricted to the southern valley margin, which is partly shaded by steep north-facing mountains. With a debris cover of more than a few centimetres, debris plays an insulating role and lowers ablation rates (Nicholson and Benn, 2006). The role debris cover on glaciers will play over coming years and decades in the Ötztal Alps in terms of hazard management deserves intensive investigation. It is too early to speculate whether the Tascachferner glacier will evolve to a completely debris-covered glacier, akin to the current trajectory of the Pasterze glacier (Kellerer-Pirklbauer and Kulmer, 2019). As such, predictions that we will be using a debris-covered landsystem model (Hambrey et al., 2008; Racoviteanu et al., 2022) are premature. New work reveals that recent glacier recession in some parts of Austria has left a comparatively sediment-starved landscape, supported by historical photographs in a time series analysis, and revealing the breakup of rather clean ice bodies (Wytiahlowsky et al., 2024). Thus, it may be that a more hybridized approach to sediment-land system analysis will be required. As a first step, we have presented a snapshot as of 2023, and it is hoped that the mapping efforts form a useful foundation for future analysis.

CONCLUSIONS

- A new Quaternary geology and geomorphological map is presented of the Taschachferner glacier and its forefield. This is the first known mapping attempt of this area at a high resolution, and the most recent map produced for a century (Hammer, 1929);
- Comparison between satellite images from 2015 and UAV-derived aerial photographs from 2023, dovetailed with the mapping efforts, reveal a spectrum of dramatic changes over an 8-year time window. These include (i) development of a new sandur system perched on a bedrock high, and whose geometry is probably controlled by the evolution of cauldron structure. The sandur's geometry is modified by input of supraglacial debris, manifested as rockfall deposits, together with dead ice areas. (ii) a zone of subglacial diamict crosscut by glacial lineations and flutes, testifying to surging behaviour in the past, (iii) expansion of small pro-glacial lakes on the surface of the diamict fed by deltas, and speculated to be influenced by decaying buried ice in the sediment and (iv) the transition of a former ice fall to a bare rock area;
- Mapping of the margins of retreating Alpine glaciers is a vital step in our efforts to understand the accumulation of

perched sedimentary basins (sandurs, debris-covered glaciers). Understanding the processes and nature of sediment storage is important given the susceptibility of high mountainous areas such as Pitztal to slope collapse with accompanying hazards (Kaitna et al., 2023; Tonkin, 2023). Thus, as a high resolution example the results have wide-ranging significance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

DLeH undertook fieldwork, undertook the data analysis, prepared the figures and wrote the draft. PM, MH, and BD undertook fieldwork and helped with the analyses, including editing the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. We wish to thank the International Association of Sedimentologists for funding both the PhD fieldwork of PM via a Postgraduate Research Grant, as well as a Judith McKenzie Field Work Award to support the Masters project of MH.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ACKNOWLEDGMENTS

The authors also benefited from discussion about the Tascachferner with Tom Holt and Marie Busfield.

REFERENCES

Abermann, J., Lambrecht, A., Fischer, A., and Kuhn, M. (2009). Quantifying Changes and Trends in Glacier Area and Volume in the Austrian Ötztal Alps (1969-1997-2006). *Cryosphere* 3, 205–215. doi:10.5194/tc-3-205-2009

Antoniazza, G., and Lane, S. L. (2021). Sediment Yield Over Glacial Cycles: A Conceptual Model. *Prog. Phys. Geogr.* 45, 842–865. doi:10.1177/0309133321997292

Avian, M., Kellerer-Pirklbauer, A., and Lieb, G. K. (2018). Geomorphic Consequences of Rapid Deglaciation at Pasterze Glacier, Hohe Tauern Range, Austria, between 2010 and 2013 Based on Repeated Terrestrial Laser Scanning Data. *Geomorphology* 310, 1–14. doi:10.1016/j.geomorph.2018.02.003

Baewert, H., and Morche, D. (2014). Coarse Sediment Dynamics in a Proglacial Fluvial System (Fagge River, Tyrol). *Geomorphology* 218, 88–97. doi:10.1016/j.geomorph.2013.10.021

Benn, D. I., Fowler, A. C., Hewitt, I., and Sevestre, H. (2019). A General Theory of Glacier Surges. *J. Glaciol.* 65, 701–716. doi:10.1017/jog.2019.62

Bernsteiner, H., Götz, J., Salcher, B. C., and Lang, A. (2021). From Deglaciation to Postglacial Filling: Post-LGM Evolution of an Isolated Glacier System at the Northern Fringe of the Eastern Alps (Austria). *Geogr. Ann. Ser. A, Phys. Geogr.* 103 (4), 305–322. doi:10.1080/04353676.2021.1933958

Buckel, J., Mudler, J., Gardeweg, R., Hauck, C., Hilbich, C., Frauenfelder, R., et al. (2023). Identifying Mountain Permafrost Degradation by Repeating Historical Electrical Resistivity Tomography (ERT) Measurements. *Cryosphere* 17, 2919–2940. doi:10.5194/tc-17-2919-2023

Chandler, B. M. P., Chandler, S. J. P., Evans, D. J. A., Ewertowski, M. W., Lovell, H., Roberts, D. H., et al. (2020). Sub-Annual Moraine Formation at an Active Temperate Icelandic Glacier. *Earth Surf. Process. Landforms* 45, 1622–1643. doi:10.1002/esp.4835

Chandler, B. M. P., Lovell, H., Boston, C. M., Lukas, S., Barr, I. D., Benediktsson, Í. Ö., et al. (2018). Glacial geomorphological mapping: a review of approaches and frameworks for best practice. *Earth-Sci. Rev.* 185, 806–846. doi:10.1016/j.earscirev.2018.07.015

Cook, S., Jouvet, G., Millan, R., Rabatel, A., Zekollari, H., and Dussaillant, I. (2023). Committed Ice Loss in the European Alps Until 2050 Using a Deep-Learning-Aided 3D Ice-Flow Model With Data Assimilation. *Geopysical Res. Lett.* 50. doi:10.1029/2023GL105029

Davies, B., Bendle, J., Carrivick, J., McNabb, R., McNeil, C., Pelto, M., et al. (2022). Topographic Controls on Ice Flow and Recession for Juneau Icefield (Alaska/British Columbia). *Earth Surf. Process. Landforms* 47, 2357–2390. doi:10.1002/esp.5383

Egglseder, M., and Fügenschuh, B. (2013). Pre-Alpine Fold Interference Patterns in the North-Eastern Oetztal-Stubai-Complex (Tyrol, Austria). *Austrian J. Earth Sci.* 106, 63–74.

Ely, J. C., Clark, C. D., Spagnolo, M., Stokes, C. R., Greenwood, S. L., Hughes, A. L. C., et al. (2016). Do Subglacial Bedforms Comprise a Size and Shape Continuum?. *Geomorphology* 257, 108–119. doi:10.1016/j.geomorph.2016.01.001

Fischer, A., and Kuhn, M. (2013). Ground-penetrating Radar Measurements of 64 Austrian Glaciers Between 1995 and 2010. *Ann. Glaciol.* 54, 179–188. doi:10.3189/2013AoG64A108

Fischer, A., Seiser, B., Stocker-Waldhuber, M., Mitterer, C., and Abermann, J. (2015). The Austrian Glacier Inventories GI1 (1969), GI2 (1998), GI3 (2006) and GI LIA in ArcGIS (Shapefile) Format. *PANGAEA*. doi:10.1594/PANGAEA.844988

Fisher, A., and Mayer, C. (2021). “The History of Glaciology in the Inner Ötztal Alps,” in *Glaciers and Ice Sheets in the Climate System: The Karthaus Summer School Lecture Notes*. Editors A. Fowler and F. Ng (Switzerland: Springer), 497–517.

Gerhold, N. (1969). Zur Glacialgeologie der westlichen Ötztaler Alpen unter besonderer Berücksichtigung des Blockgletschproblems. *Veröffentlichungen Des. Tirol. Landesmus. Ferdinandeum* 49, 45–78.

Hambrey, M. J., Quincey, D. J., Glasser, N. F., Reynolds, J. M., Richardson, S. J., and Clemmens, S. (2008). Sedimentological, Geomorphological and Dynamic Context of Debris-Mantled Glaciers, Mount Everest (Sagarmatha) Region, Nepal. *Quat. Sci. Rev.* 27, 2361–2389. doi:10.1016/j.quascirev.2008.08.010

Hammer, W. (1929). *Erläuterungen zur Geologischen Spezialkarte der Republic Österreich- Blatt Ötztal (5146). Geologische Bundesantalt in Wien*. Innsbruck: Österreichischen Staatsdruckerei, 57.

Harrison, S., Kargel, J. S., Huggel, C., Reynolds, J., Shugar, D. H., Betts, R. A., et al. (2018). Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere* 12, 1195–1209. doi:10.5194/tc-12-1195-2018

Hart, J. K., Clayton, A. I., Martinez, K., and Robson, B. A. (2018). Erosional and Depositional Subglacial Streamlining Processes at Skálafellsjökull, Iceland: An Analogue for a New Bedform Continuum Model. *GFF* 140, 153–169. doi:10.1080/11035897.2018.1477830

Hoinkes, H. C. (1969). Surges of the Vernagtferner in the Ötztal Alps since 1599. *Can. J. Earth Sci.* 6, 853–861. doi:10.1139/e69-086

Hovikovski, J., Mäkinen, J., Winsemann, J., Soini, S., Kajuutti, K. K., Hepburn, A., et al. (2023). Upper-flow Regime Bedforms in a Subglacial Triangular-Shaped Landform (Murtoo), Late Pleistocene, SW Finland: Implications for Flow Dynamics and Sediment Transport in Semi-distributed Subglacial Meltwater Drainage Systems. *Sediment. Geol.* 454, 106448. doi:10.1016/j.sedgeo.2023.106448

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., et al. (2021). Accelerated Global Glacier Mass Loss in the Early Twenty-First Century. *Nature* 592, 726–731. doi:10.1038/S41586-021-03436-z

Huo, D., Bishop, M. P., and Bush, A. B. G. (2021). Understanding Complex Debris-Covered Glaciers: Concepts, Issues, and Research Directions. *Front. Earth Sci.* 9. doi:10.3389/feart.2021.652279

James, W. H. M., Carrivick, J. L., Quincey, D. J., and Glasser, N. F. (2019). A geomorphology based reconstruction of ice volume distribution at the last glacial maximum across the Southern Alps of New Zealand. *Quat. Sci. Rev.* 219, 20–35. doi:10.1016/j.quascirev.2019.06.035

Kaitna, R., Prenner, D., Switanek, M., Maraun, D., Stoffel, M., and Hrachowitz, M. (2023). Changes of Hydro-Meteorological Trigger Conditions for Debris Flows in a Future Alpine Climate. *Sci. Total Environ.* 872, 162227. doi:10.1016/j.scitotenv.2023.162227

Kellerer-Pirklbauer, A., and Kulmer, B. (2019). The Evolution of Brittle and Ductile Structures at the Surface of a Partly Debris-Covered, Rapidly Thinning and Slowly Moving Glacier in 1998–2012 (Pasterze Glacier, Austria). *Earth Surf. Process. Landforms* 44, 1034–1049. doi:10.1002/esp.4552

Klebelsberg, R. (1949). "Die Gletscher der österreichischen Alpen 1942 bis 1946," in *Zeitschrift für Gletscherkunde und Glazialgeologie, Band 1, Heft 1* (Innsbruck: Universitäts-Verlag Wagner), 84–97.

Kor, P. S. G., Shaw, J., and Sharpe, D. R. (1991). Erosion of Bedrock by Subglacial Meltwater, Georgian Bay, Ontario: A Regional View. *Can. J. Earth Sci.* 28, 623–642. doi:10.1139/e91-054

Krabbendam, M., Hall, A. M., Palamakumbura, R. M., and Finlayson, A. (2022). Glaciotectonic Disintegration of Roches Moutonnées during Glacial Ripping in East Sweden. *Geogr. Ann. Ser. A, Phys. Geogr.* 104 (1), 35–56. doi:10.1080/04353676.2021.2022356

Le Heron, D. P., Griesmeier, G. E. U., and Reitner, J. M. (2023). A Window into Development of a Complex Ice-Marginal Lake Prior to the Late Glacial Maximum (LGM) in Austria. *Geology* 51, 914–918. doi:10.1130/G51298.1

Le Heron, D. P., Kettler, C., Davies, B., Scharfenberg, L., Eder, L., Ketterman, M., et al. (2022a). Rapid Geomorphological and Sedimentological Changes at a Modern Alpine Ice Margin: Lessons from the Gepatsch Glacier, Tirol, Austria. *J. Geol. Soc.* 179. doi:10.1144/jgs2021-052

Le Heron, D. P., Kettler, C., Grasemann, B., Schöpfer, M., and Wawra, A. (2022b). The Sedimentological Death Mask of a Dying Glacier. *Depositional Rec.* 8, 992–1007. doi:10.1002/dep2.205

Mayer, C., and Licciulli, C. (2021). The Concept of Steady State, Cyclicity and Debris Unloading of Debris-Covered Glaciers. *Front. Earth Sci.* 9. doi:10.3389/feart.2021.710276

Medeu, A. R., Popov, N. V., Blagovechshenskiy, V. P., Askarova, M. A., Medeu, A. A., Ranova, S. U., et al. (2022). Moraine-dammed glacial lakes and threat of glacial debris flows in South-East Kazakhstan. *Earth-Sci. Rev.* 229, 103999. doi:10.1016/j.earscirev.2022.103999

Moreau, J. (2011). The Late Ordovician Deglaciation Sequence of the SW Murzuq Basin (Libya). *Basin Res.* 23, 449–477. doi:10.1111/j.1365-2117.2010.00499.x

Nicholson, L., and Benn, D. I. (2006). Calculating Ice Melt beneath a Debris Layer Using Meteorological Data. *J. Glaciol.* 52, 463–470. doi:10.3189/172756506781828584

Nicolussi, K. (2013). "Kapitel 4: Zur Geschichte des Vernagtferners-Gletschervorstöße und Seeausbrüche im vergangenen Jahrtausend," in *Klima, Wetter, Gletscher im Wandel*. Editors E.-M. Koch and B. Hirschbamer (Innsbruck University Press), 69–94. ISBN 978-3-902811-89-9.

Racoviteanu, A. E., Nicholson, L., Glasser, N. F., Miles, E., Harrison, S., and Reynolds, J. M. (2022). Debris-covered Glacier Systems and Associated Glacial Lake Outburst Flood Hazards: Challenges and Prospects. *J. Geol. Soc.* 179. doi:10.1144/jgs2021-084

Rettig, L., Lukas, S., and Huss, M. (2023). Implications of a Rapidly Thinning Ice Margin for Annual Moraine Formation at Gornergletscher, Switzerland. *Quat. Sci. Rev.* 308, 108085. doi:10.1016/j.quascirev.2023.108085

Rippin, D. M., Sharp, M., Van Wychen, W., and Zubot, D. (2020). 'Detachment' of Icefield Outlet Glaciers: Catastrophic Thinning and Retreat of the Columbia Glacier (Canada). *Earth Surf. Process. Landforms* 45, 459–472. doi:10.1002/esp.4746

Salim, E., Ravanel, L., Bourdeau, P., and Deline, P. (2021). Glacier Tourism and Climate Change: Effects, Adaptations, and Perspectives in the Alps. *Reg. Environ. Change* 21, 120. doi:10.1007/s10113-021-01849-0

Stocker-Waldhuber, M., Fischer, A., Helfricht, K., and Kuhn, M. (2019). Long-term Records of Glacier Surface Velocities in the Ötztal Alps (Austria). *Earth Syst. Sci. Data* 11, 705–715. doi:10.5194/essd-11-705-2019

Stokes, C. R., and Clark, C. D. (2001). Palaeo-ice Streams. *Quat. Sci. Rev.* 20, 1437–1457. doi:10.1016/S0277-3791(01)00003-8

Tonkin, T. (2023). The Paraglacial Adjustment of an Alpine Lateral Moraine, Bas Glacier d'Arolla, Switzerland. *Phys. Geogr.* 44 (5), 643–659. doi:10.1080/02723646.2023.2212989

van Husen, D. (1997). LGM and Late Glacial Fluctuations in the Eastern Alps. *Quat. Int.* 38 (39), 109–118. doi:10.1016/s1040-6182(96)00017-1

von Sonklar, K. (1860). *Die Oetztaler Gebirgsgruppe, mit besonderer Rücksicht auf Orographie und Gletscherkunde*. Gotha: Justus Perthes.

Weber, M., Braun, L., Mauser, W., and Prasch, M. (2010). Contribution of Rain, Snow- and Ice Melt in the Upper Danube Discharge Today and in the Future. *Geogr. Fis. Din. Quaternaria* 33, 221–230.

Winkler, S. (1991). *Glazialmorphologische Untersuchungen am Vernagtferner/Ötztaler Alpen. Diplomarbeit am Geographischen Institut der Universität Würzburg, 372 Seiten, 1 Geomorphologische*

Detailkarte 1:10.000, 1 Geomorphologische Übersichtskarte 1: 25.000.

Wytiahlowsky, H., Busfield, M. E., Hepburn, A. J., and Lukas, S. (2024). Deglaciation Patterns in the Upper Zemmgrund, Austria: An Exploration of Clean-Ice Disintegration Scenarios. *Geomorphology* 452, 109113. doi:10.1016/j.geomorph.2024.109113