Implications of a rapidly thinning ice-margin for annual moraine formation at Gornergletscher, Switzerland

Lukas Rettig

Dissertations in Geology at Lund University,
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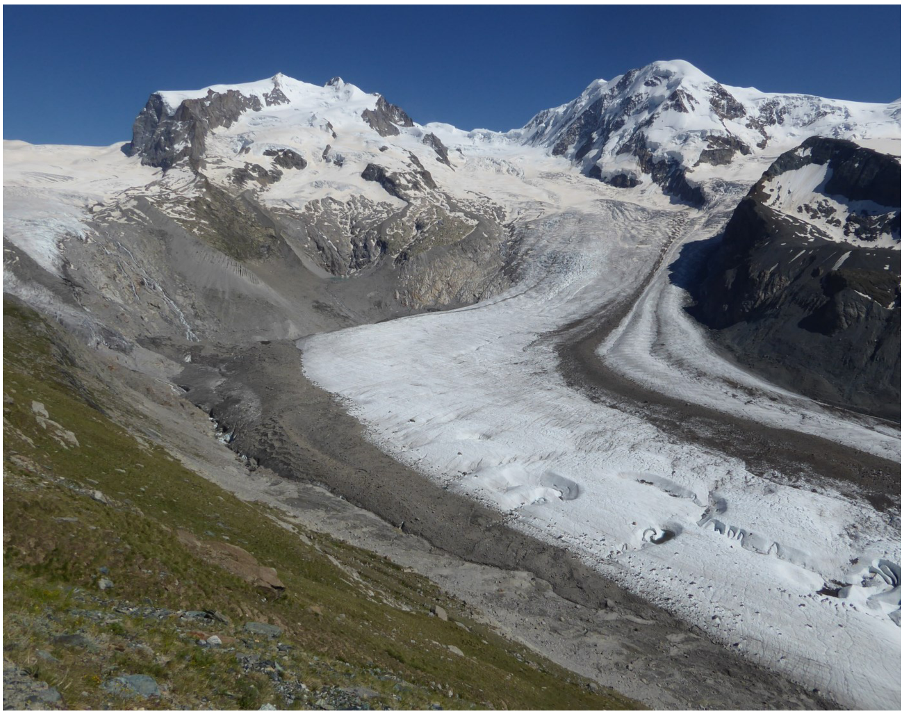

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Contents

Cover Picture: View towards Monte Rosa (left) and Liskamm (right) and the accumulation areas of Gorner– and Grenzgletscher in the southern Valais Alps.

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Abstract: This study examines genetic processes and climatological significance of annual moraine formation in the foreland of Gornergletscher, a large alpine-valley glacier located in the southern Swiss Alps. A particular focus is set on moraine ridges that have been forming between 2007 and 2019, a period when the glacier has been subject to accelerated retreat and pronounced frontal thinning. These moraines exhibit varying geomorphological and sedimentological characteristics, ranging from minor moraines composed primarily of subglacial traction till up to more prominent ridges that comprise deformed glaciofluvial and glaciolacustrine deposits. Based on representative sections through five of these annual moraines, the dominant mechanisms of their formation could be constrained. They include: (1) Freeze-on of submarginal sediments to the advancing glacier front; (2) the formation of ice-cored, controlled moraines from the isolation of ice-marginal debris cones; and (3) bulldozing and deformation of pre-existing proglacial sediments, such as fluvial outwash, by the advancing glacier margin. It is found that the largest and most well-defined moraine ridges are genetically linked to bulldozing processes along a sufficiently steep glacier front. Moraines formed at the present, thin ice-margin are oftentimes affected by post-depositional alteration such as the melt-out of buried ice and hence the preservation potential of these landforms over longer time scales is largely limited. Comparing the spacings between series of annual moraines to climatic records from close-by weather stations reveals that the rates of frontal retreat at Gornergletscher after 2006 are closely correlated to mean annual temperatures. This is in contrast to observations from previous decades, when climatic control on moraine formation was predominantly restricted to temperatures during the accumulation season. This could imply that summer ablation will become increasingly important for governing glacier retreat at a gradually thinning ice-margin. However, as the glacier recedes over a topographically complex foreland, the possibility of non-climatic factors modulating the rates of marginal retreat is high. This study highlights significant challenges that are connected to applying annual moraines as a geomorphological proxy of frontal variations at alpine valley-glaciers over longer timescales.

Keywords: Recessional moraines, Ice-marginal processes, Glacier retreat, Glacial geomorphology, Glacial sedimentology, Alpine glaciers, Swiss Alps

Supervisor: Dr. Sven Lukas

Subject: Quaternary Geology

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Följder av en snabbt uttunnande isfront för bildningen av årsmoräner vid Gornergletscher, Schweiz

LUKAS RETTIG

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Sammanfattning: I denna studie undersöks bildningsprocesser och klimatologisk betydelse av hur av årsmoräner bildas vid Gornergletscher, en stor alpin dalglaciär i de södra schweiziska Alperna. Ett särskilt fokus ligger på moränryggar som har bildats mellan 2007 och 2019, en period då glaciären har retirerat snabbt och det har skett en tydlig förtunning av isfronten. Dessa moräner uppvisar olika geomorfologiska och sedimentologiska egenskaper, allt ifrån mindre moränryggar bestående huvudsakligen av subglaciala sediment till mer framträdande ryggar som innehåller deformerade glaciofluviala och glaciolakustrina avsättningar. Baserat på representativa skärningar genom fem av dessa årsmoräner, kan de dominerande mekanismerna för deras bildning bestämmas. De inkluderar: (1) Tillfrysning av submarginala sediment på den framåtryckande glaciärfronten; (2) bildning av kontrollerade iskärnemoräner från isolering av ismarginala smutskoner; och (3) hoptryckning och deformation av redan existerande proglaciala sediment, t.ex. isälvsmaterial, genom den iskantens framåtrörelse. Det har visat sig att de största och mest väldefinierade moränryggarna är genetiskt kopplade till hoptryckningsprocesser längs en tillräckligt brant glaciärfront. Moräner som bildas vid den nuvarande, tunna iskanten påverkas ofta av förändringar efter avsättning, som utsmältning av begravd is, och följaktligen är bevaringspotentialen för dessa landformer över längre tid till stor del begränsad. En jämförelse av avståndet mellan serier av årsmoräner ochklimatdata från intilliggande väderstationer visar att iskantens reträtthastighet vid Gornergletscher efter år 2006 är nära korrelerad till årsmedeltemperaturen. Detta kontrasterar med iakttagelser från tidigare årtionden, då den klimatiska påverkan på moränbildningen främst var begränsad till temperaturen under ackumulationssäsongen. Detta kan innebära att sommarablationen kommer att få allt större betydelse när det gäller vad som styr glaciärens reträtt med en successivt tunnare isfront. Eftersom glaciären drar sig tillbaka över ett topografiskt komplext landskap är emellertid möjligheten stor för att icke-klimatrelaterade faktorer kommer att påverka hastigheten. Denna studie belyser de betydande utmaningar som är kopplade till att använda årsmoräner som ett geomorfologiskt arkiv för att rekonstruera isfrontens variationer hos alpina dalglaciärer över längre tidsskalor.

Nyckelord: Recessionsmoräner, Ismarginala processer, Glaciärreträtt, Glacial geomorfologi, Glacial sedimentologi, alpina glaciärer, Schweiziska Alperna

Handledare: Dr. Sven Lukas

Ämnesinriktning: Kvartärgeologi

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1 Introduction

Rapid atmospheric warming during the last decades has resulted in the retreat of mountain glaciers on a global scale, emphasising their sensitive response to climatic change (Hock et al. 2019; Zemp et al. 2019). Superimposed on this overall recession, however, some glaciers exhibit seasonal fluctuations of their ice-margins, with minor winter advances resulting in the formation of small recessional moraines each year. The study of these annually formed moraines can provide interesting insights both into the rates and drivers of recent glacier retreat, and into the sedimentary processes that are involved in moraine formation at contemporary ice-margins (Price 1970; Andersen & Sollid 1971; Worsley 1974; Birnie 1977; Sharp 1984; Boulton 1986; Krüger 1995; Bradwell 2004; Beedle et al. 2009; Lukas 2012; Bradwell et al. 2013; Reinardy et al. 2013; Hiemstra et al. 2015; Chandler et al. 2016; Wyshnytzky 2017; Chandler et al. 2020).

Annual moraines are most commonly found in front of glaciers with a high mass-turnover, where their formation is controlled by seasonal variations within the balance between frontal ablation and ice-flow velocities (Boulton 1986; Bradwell et al. 2013). During the winter months, when frontal ablation is extremely limited due to much reduced air temperatures, sustained forward movement of the glacier will lead to a temporal advance of its snout. At the ice-margin, this advance can be reflected in the deposition of a set of minor moraines by the end of the accumulation season (Fig. 1a). Conversely, amplified ablation during the warmer summer months, exceeding frontal flow velocities, will cause the glacier to retreat from its previously deposited moraines (Fig. 1b). If this cyclic pattern of winter advance vs. summer retreat prevails over the course of several years or decades, and the seasonal advances do not exceed the retreat rates of the previous summers (i.e. that the glacier front does not override the previously deposited landforms), longer sequences of moraines can be preserved within the geomorphological record (e.g. Boulton 1986; Beedle et al. 2009; Lukas 2012; Reinardy et al. 2013; Chandler et al. 2016). As such they trace the annual extents of the receding glacier margin back in time and the spacing between two sets of moraines can be used as an equivalent of its ice-marginal retreat rate (IMRR), integrated over the course of the glaciological year (Fig. 1c). The study of annual moraines has been given increased attention during the last decades, because longer records of IMRRs have been successfully correlated to average ablation season temperatures, especially at maritime outlet glaciers in southern Iceland (Boulton 1986; Krüger 1995; Bradwell 2004; Chandler et al. 2016). This apparent link between climatic forcing, glacier response and landform assemblage highlights the potential, annual moraines could yield for paleoclimatic studies - once identified in the geomorphological record, they could be utilised to quantify glacial retreat and ultimately climatic variability over longer timescales (Bradwell 2004; Beedle et al. 2009).

Besides this potential climatic significance, the study of annual moraines in modern glacial forelands can also improve process-based understanding of moraine formation in general (Bennett 2001; Evans 2013) and specifically provide a suitable analogue for recessional moraines from Pleistocene settings (Evans et al. 1999; Ham & Attig 2001). Through the combined use of geomorphological and sedimentological approaches, a variety of different mechanisms of annual moraine formation has been proposed throughout the literature (for a detailed review see Wyshnytzky 2017). Most frequently these include (a) ice-marginal bulldozing of pre-existing proglacial sediments (Birnie 1977; Winkler & Matthews 2010; Lukas 2012), (b) freezing of sediments to the advancing glacier sole and subsequent melt-out of these sediment slabs during summer (Andersen & Sollid 1971; Krüger 1995; Matthews et al. 1995; Reinardy et al. 2013; Hiemstra et al. 2015), and (c) squeezing of submarginal sediments, potentially coupled with successive bulldozing of these deposits into moraine ridges (Price 1970; Chandler et al. 2016; Chandler et al. 2020). The distribution of these mechanisms in any given glacier foreland is controlled by a set of climatological, topographical and glaciological factors (e.g. Sharp 1984; Lukas 2012; Chandler et al. 2016; Wyshnytzky 2017). One of the key factors that has been reported to govern the processes of annual moraine formation in front of several glaciers is the steepness of the ice-margin, along which the moraines are created. Particular mechanisms such as submarginal freeze-on are, for example, are directly coupled to the presence of thin-ice margins (Krüger 1995; Matthews et al. 1995; Reinardy et al. 2013), whereas other processes, especially bulldozing can more effectively operate along a steeper glacier front (Winkler & Matthews 2010; Lukas 2012). As the majority of mountain glaciers worldwide has been subject to pronounced retreat and thinning during the last decades and mass loss is likely to accelerate in a future warming climate (e.g. Paul et al. 2004; Zekollari et al. 2019; Zemp et al. 2019), this might substantially influence the formation of annual moraines at these glaciers as well. In some instances accelerated frontal thinning may even lead to a ceasing of moraine formation once the glacier snout becomes stagnant and is unable to advance during winter anymore (Bradwell et al. 2013). Better understanding the relations between a thinning ice-margin and moraine formation is therefore key to predict how future climatic warming will influence the genesis of annual moraines, their preservation potential over longer time scales and hence also their significance in a paleoclimatic context.

Despite this, process-based understanding of annual moraine formation is still largely derived from studies at temperate maritime glaciers in Norway (Andersen & Sollid 1971; Worsley 1974; Matthews et al. 1995; Reinardy et al. 2013; Hiemstra et al. 2015) and on Iceland (Price 1970; Sharp 1984; Krüger 1995; Chandler et al. 2016; Chandler et al. 2020). Insights into the genesis of these landforms in high mountain ranges, such as the European Alps, remains sparser, partly because comparatively few studies have been carried out in this setting to date (Beedle et al. 2009; Lukas 2012; Wyshnytzky 2017). However, the complex interplay between topography and different sediment sources and transport paths in the glaciated

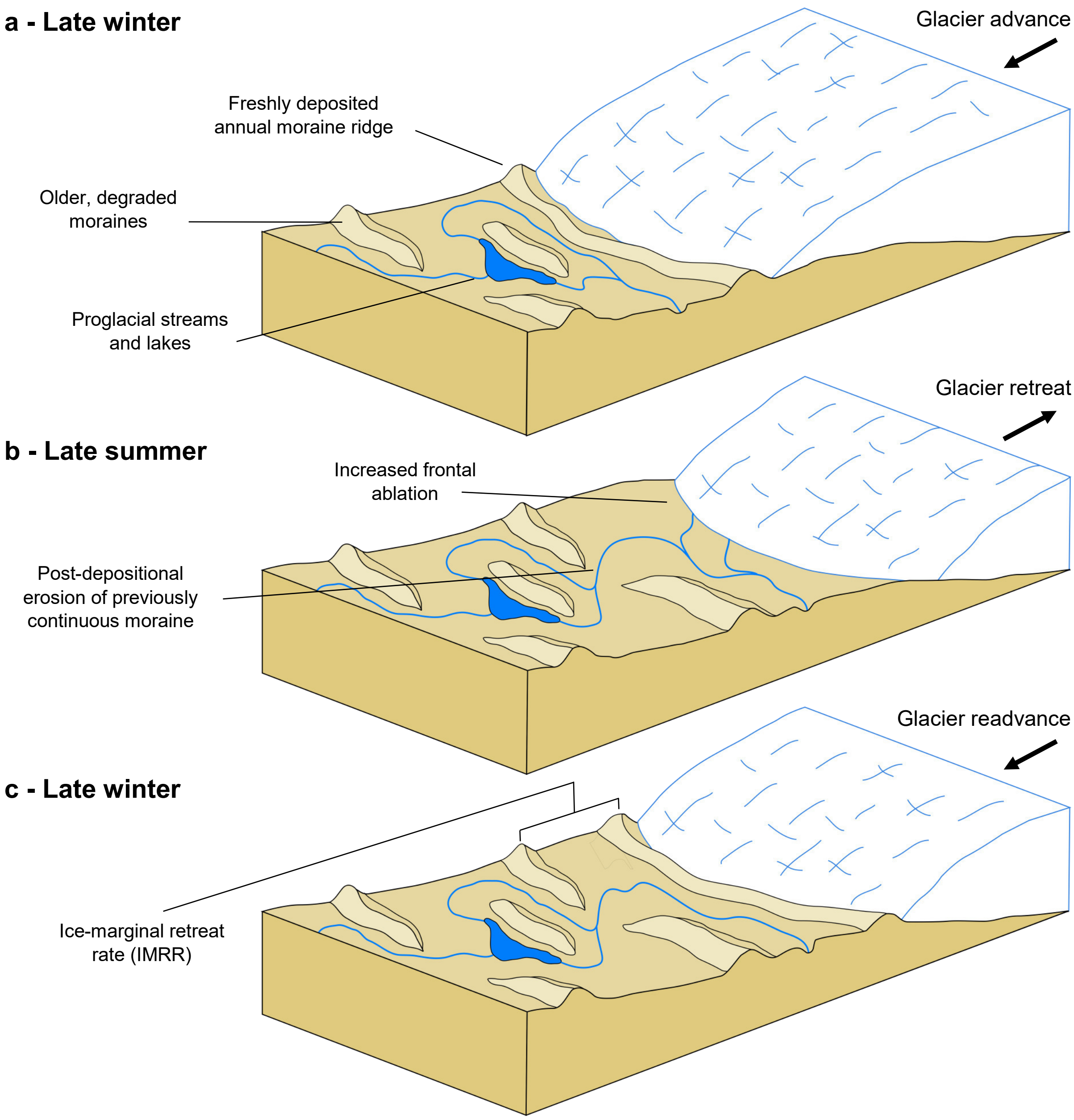

Fig. 1. Conceptual model of annual moraine formation over the course of a glaciological year (starting with the beginning of the accumulation season). a. The advance of the glacier front during winter leads to the deposition of a new annual moraine ridge at the end of the accumulation season. b. Increased frontal ablation in the summer months results in a retreat of the glacier from the previously deposited moraine. c. Readvance of the glacier during the next winter. The spacing between successively deposited moraine ridges is equivalent to the ice-marginal retreat rate, integrated over the previous glaciological year.

valley landsystem makes these environments especially interesting to study a wide range of moraine-forming processes (Boulton & Eyles 1979; Benn et al. 2003). Additionally, the climatic controls on IMRRs appear to be more complex here, potentially including a response of the glacier to winter temperatures or precipitation, and require further validation (Beedle et al. 2009; Lukas 2012). In order to enhance the understanding of both genetic processes and climatic significance of annual moraine formation in an alpine setting, this study examines detailed geomorphological and sedimentological characteristics of annual moraine ridges at Gornergletscher, a large temperate valley-glacier located in the southern Swiss Alps. This glacier is of specific interest, as its ice-margin has been subject to rapid retreat and thinning during the previous decade (Lukas 2012; Wyshnytzky 2017), providing the unique possibility to assess how these changes in glacier geometry have since influenced the formation of annual moraines. Specific objective of this study are to

a) Use high-resolution aerial photographs and digital surface models (DSMs) to construct a geomorphological map of the glacial foreland of Gornergletscher and specifically the distribution of annual moraines therein,

b) Combine process-observations at the contemporary ice-margin and the sedimentology of representative moraine sections to reconstruct the dominant mechanism of moraine formation and

c) Use the moraine record to extend the dataset of IMRRs at Gornergletscher and test for significant correlations between recent glacial retreat and local temperature and precipitation records

This study thereby provides detailed insights into the implications of a rapidly retreating and thinning ice-margin on the genesis and preservation of annual moraines at an alpine valley glacier, and on their application as a potential proxy for climatic reconstructions in these settings.

2 Study area

2.1 Geographical and geological overview

Gornergletscher is an alpine valley glacier, located at the upper end of the Mattertal (Matter Valley) in close proximity to the village of Zermatt, southern Switzerland (Fig. 2a). The Mattertal is framed by high mountain ranges of the Valais Alps with their most prominent peaks, such as Monte Rosa, Matterhorn or Dent Blanche exceeding altitudes of 4000 m. As a result of the high elevations, large parts of these mountain ranges are still extensively covered by glaciers. Indeed, more than a quarter of the glaciated area within Switzerland is located within the Valais Alps surrounding Zermatt (Fischer et al. 2014). The pronounced topography in the area also strongly governs its local climatic conditions. The high mountain ranges shield the central parts of the valley from southerly precipitation, making it one of the driest regions within Switzerland (Denneler & Maisch 1995). Annual mean precipitation around Zermatt during the last 30 years rarely exceeded 800 mm (average of ca. 640 mm), which is considerably less than what is measured for alpine valleys in the central parts of the country (Scherrer et al. 2018). The higher elevated areas situated along the Italian border, however, receive higher amounts of precipitation, creating the main feeding ground for the larger valley glaciers, such as Gornergletscher (Denneler & Maisch 1995).

The bedrock in the upper Mattertal predominantly consists of highly metamorphic units of the Penninic nappes that were stacked during the Alpine orogeny (see Pfiffner 2014 for a detailed overview). In the valley bottom, these mainly include ophiolitic sequences of the former Piedmont-Ligurian Ocean such as serpentinites, meta-gabbros, prasinites or amphibolites (Bearth 1953; Li et al. 2004; Weber & Bucher 2015). In contrast, the upper catchment of Gornergletscher and the Monte Rosa massif consist of metamorphic rocks with a continental origin and paragneisses, mica schists and especially meta-granites are the dominant lithologies (Bearth 1953; Steck et al. 2015). The distribution of these two lithological groups in the catchment of Gornergletscher is of crucial importance to understand the transport of different clasts through the glacial system of Gornergletscher (cf. section 4.3.6). It differs in detail from the neighbouring Findelengletscher, for example, where the ophiolitic lithologies (and especially serpentinite) are also cropping out within its upper accumulation areas (Bearth 1953; Lukas et al. 2012).

2.2 The glacial system of Gornergletscher

The glacial system of Gornergletscher and its tributaries (Fig. 2b) covers a total area of approximately 41 km² and is the largest that is located in the Mattertal and, after Aletschgletscher, the second largest within the Swiss Alps (Fischer et al. 2014). The glacier originates from the north-western flanks of the Monte Rosa massif, where cold firn is accumulating up to altitudes of 4550 m (Suter et al. 2001). From here, two main tributaries are emerging – Grenzgletscher, from the depression between Liskamm (4533 m) and Dofourspitze (4634 m) and Gornergletscher, on the northern side of the Monte Rosa massif (Fig. 3). Until at least 2017, these two tributaries used to merge at an altitude of around 2500 m, forming the trunk part of the glacier that continues to flow westwards, following the course of the glacially carved valley. The confluence of the tributary glaciers at this location created a barrier for meltwaters to form an ice-dammed lake (Gornersee) that drained subglacially each year, sporadically leading to flooding damage within parts of Zermatt (Huss et al. 2007; Sugiyama et al. 2007). Due to ongoing glacial thinning and retreat, however, the tributary Gornergletscher has receded up a steep bedrock slope during the last years and had completely disconnected from the lower parts of the glacial system by 2019 (Fig. 3). This means that, firstly, Grenzgletscher is now the only dominant feeder of the lower lying trunk glacier and, secondly, that the drainage of meltwaters is no longer dammed by the confluent ice-margins. This is in line with field observations in 2019 and aerial photographs from recent years that do not indicate the formation of an ice-marginal lake at this location anymore.

Situated in the lower ablation zone, the trunk glacier itself consists of a relatively gently sloping tongue that extends down to an altitude of ca. 2200 m. Although cold ice from the upper accumulation areas gets partially advected down to these altitudes, the bed of the glacier has been demonstrated to be temperate here (Eisen et al. 2009). Extensive forms of supraglacial melt, such as meltwater ponds or meandering streams can be observed on the surface of the trunk glacier (Fig. 3). Together with the subglacial drainage, these waters eventually feed into the Gornera river flowing down-valley towards Zermatt. As compared to the largely clean accumulation areas, also higher amounts of supraglacial debris can be found on the trunk glacier, largely due to medial moraines that emerge from confluences of different tributaries. Major medial moraines occur on most tributaries and successively become wider towards the glacier tongue. Debris-covered ice is also found in ice-marginal areas,

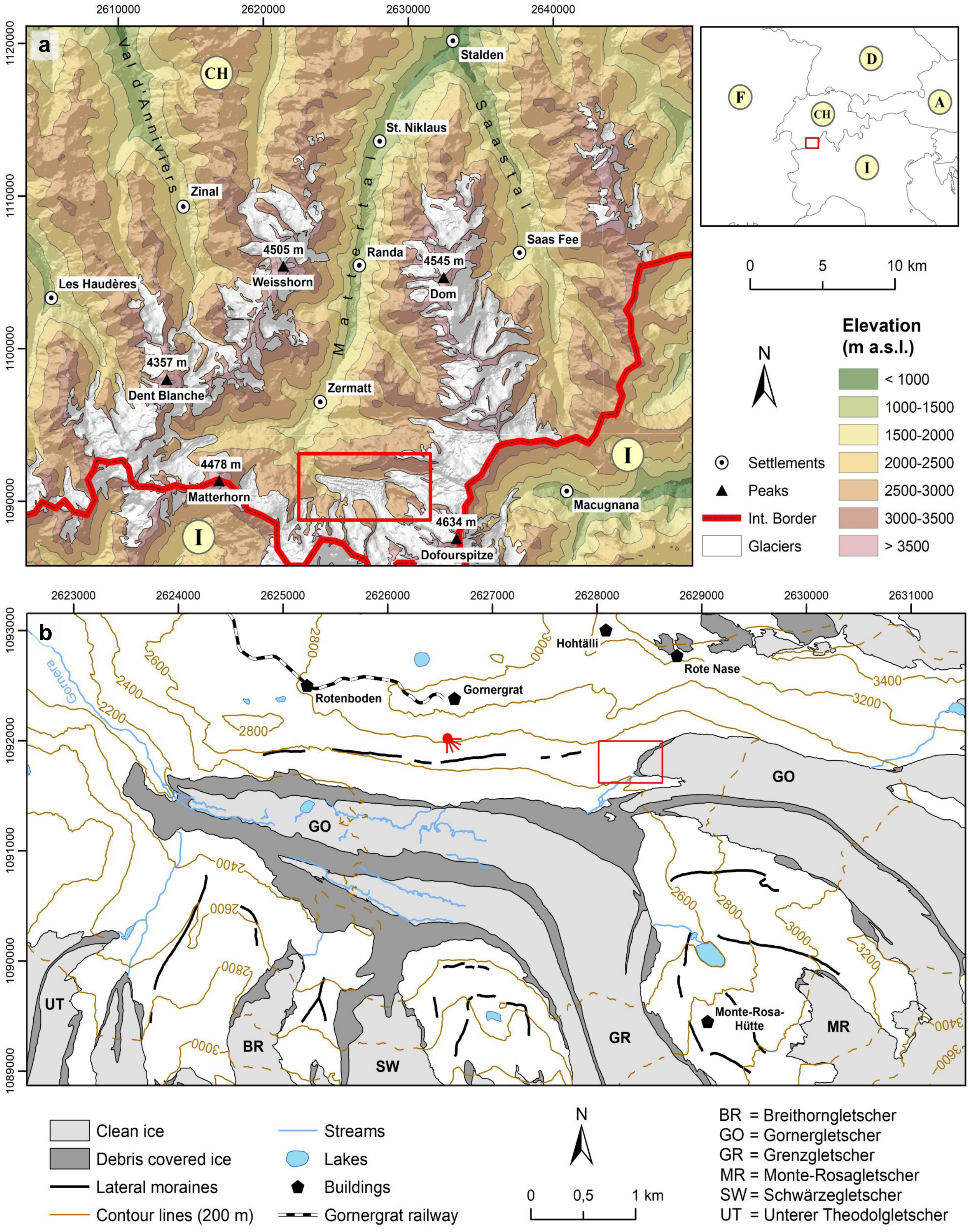

Fig. 2. a. Overview map showing the topography of the upper Matter Valley and the extent of glaciated areas in this part of the Valais Alps. The red frame marks the lower catchment area of Gornergletscher (extent of figure 2b). b. Map of the lower catchment area of Gornergletscher and its main tributaries. The map displays the situation of the year 2017; note that by this time, the two main tributaries (Grenz- and Gornergletscher) were still connected by extensive debris-covered ice. The red frame marks the extent of the immediate study area and the red viewpoint pictogram indicates the location from where and the direction towards which the photograph in Fig. 3 was taken. Both figures are based on regional topographic maps and DSMs, obtained from the Federal Office of Topography, Switzerland (swisstopo.com).

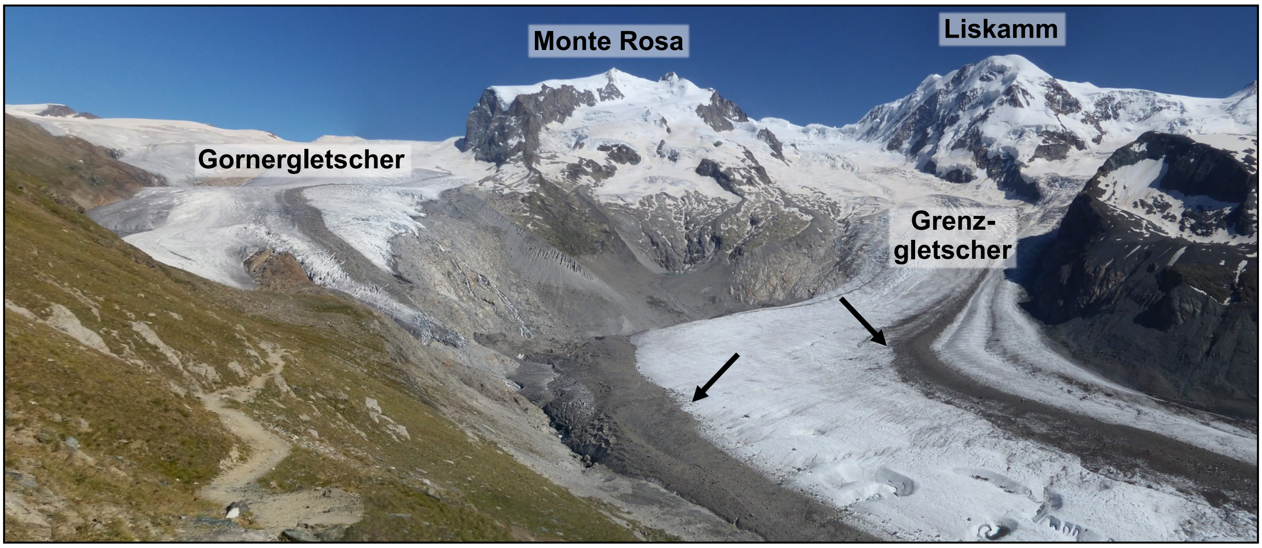

Fig. 3. Panorama photograph of the upper catchment area of Gornergletscher (taken 05.07.2019). Note that Grenz– and Gornergletscher, the two main tributaries, by this time are already disconnected. Note also medial moraines on both tributaries (indicated by small black arrows) and supraglacial meltwater streams on the lower parts of the trunk glacier. View towards SE.

such as at the front of the Gornergletscher tributary, where it seems to be the result of englacial debris bands emerging on the glacier surface (cf. chapter 4.1.3). The distribution of supraglacial debris on the lower parts of the glacial system is visualised in Fig. 2b.

2.3 Retreat history of Gornergletscher

The retreat and advance history of Gornergletscher during the Late Holocene is well documented and dated by both historical archives and paleoclimatic proxies. Glacial maxima were reconstructed for the years 1385, 1670 and 1859 with alternating phases of lower glacier extent (Holzhauser et al. 2005). Especially the mid-19th century was characterised by a rapid advance of the snout of Gornergletscher into the area of Zermatt, partly destroying farms and buildings in the upper Mattertal (Holzhauser 2001). The culmination of 1859 coincides with maxima of other glaciers in Switzerland and the European Alps in general, marking the end of the Little Ice Age (Holzhauser et al. 2005; Ivy-Ochs et al. 2009). It is preserved in the form of large lateral moraines that were formed at the ice-margins of Gornergletscher and its tributaries during this time (Fig. 2b).

Near-surface air temperatures in Switzerland have increased by about 2.0 °C since the mid-19th century, resulting in long-term negative mass balances of most mountain glaciers and pronounced retreats from their Little Ice Age maxima (Huss et al. 2012; Scherrer et al. 2018). Superimposed on this overall retreat, temporary advances of many glaciers in the Swiss Alps, including Gornergletscher, could be observed after successive years of positive mass balances, pronounced especially in the late 1910s and the late 1970s (Huss et al. 2010). After 1980, glacier retreat and mass loss strongly accelerated and the tongue of Gornergletscher has receded by more than 1 km since then. Especially the most recent years are characterised by strongly negative mass balances for Gornergletscher and future mass loss and glacier retreat are likely to continue in the course of ongoing global warming (Huss et al. 2012; Linsbauer et al. 2013; Zekollari et al. 2019).

2.4 Site description and previous research on annual moraines

While the glacial system of Gornergletscher encompasses several different tributaries (cf. chapter 2.2, Fig. 2b), the formation of annual moraines in the study area is restricted to the foreland of a single side lobe of this glacier. This lobe terminates on a plateau situated ca. 150 m above the surface of the trunk glacier, slightly north of the location where Gorner- and Grenzgletscher used to merge previously (Fig. 2b, ca. 45.97°N, 7.80°E, 2650 m). The overall retreat pattern that is recorded in detail for the trunk glacier (cf. chapter 2.3) can be observed equally for the snout of this subsidiary lobe. Three series of prominent lateral moraines mark the extent of the glacier during the advances of the 1850s, the 1920s and early 1980s. The lateral moraine of 1980 is a prominent landform in particular, reaching more than 3 m in height. It has been shown to consist mainly of stacked debris-flows that were deposited along the stationary ice-margin during this advance (Lukas & Sass 2011). Until 2018, the tributary glacier had receded from its 1980 position by around 400 m with around half of the retreat attributed to the period after 2006, highlighting the increased mass loss in recent years (Fig. 4). The retreat of the ice-margin is accompanied by a pronounced thinning of the glacier snout, resulting in a relatively shallow ice-front by 2019 (Fig. 5a, b).

Small recessional moraines have been forming in front of this subsidiary lobe of Gornergletscher since at least 1980 and continuous monitoring of

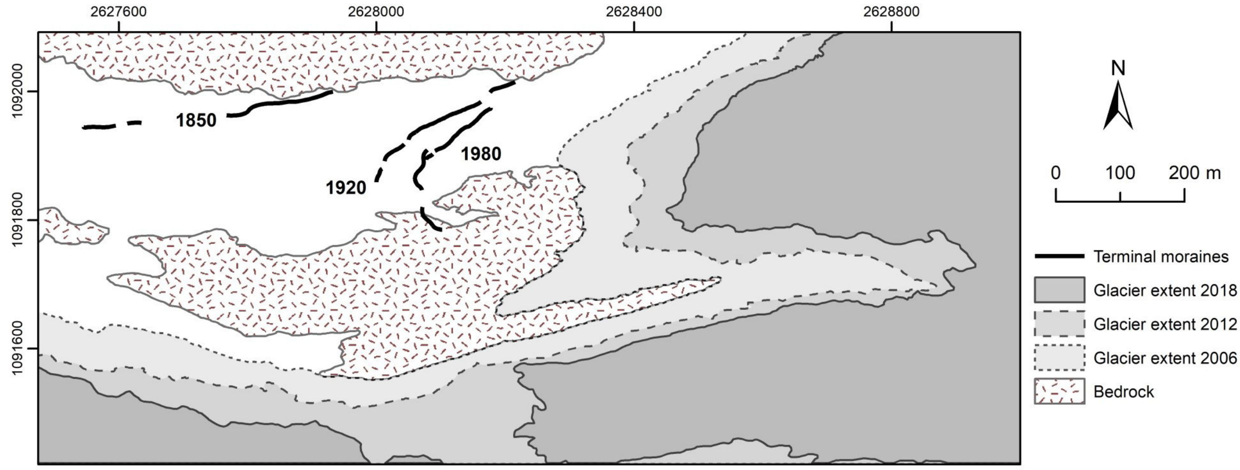

Fig. 4. Comparison of the glacier extent between the years 2006, 2012 and 2018 at the tributary lobe of Gornergletscher, where annual moraine formation takes place. The study site is the foreland between the present ice-margin and the terminal moraine of 1980. This map illustrates the accelerated retreat that is observed during the last decade. The map was created based on a set of aerial photographs, kindly supplied by Matthias Huss (ETH Zürich).

the foreland has confirmed the annual nature of these landforms (Lukas 2012; Wyshnitzky 2017). Detailed geomorphological and sedimentological characteristics of some of these annual moraines that have been deposited prior to 2007 were previously described by Lukas (2012). According to this study, the steepness of the ice-margin seems to exert a key control on the sedimentary processes leading to moraine formation at Gornergletscher. A sufficiently steep ice-margin can efficiently bulldoze proglacial sediments into defined moraine ridges. At thinner parts of the ice-margin, on the other hand, inefficient bulldozing of the proglacial sediments can result in the incorporation of buried ice into the moraine bodies, which upon melt-out can greatly reduce their preservation potential. The recently observed thinning of the glacier and its implications for the moraine ridges that have been deposited after 2007 will therefore be a recurring topic debated throughout this study.

3 Methodology

To investigate the genetic processes and climatological significance of annual moraine formation at Gornergletscher, a combination of geomorphological mapping, moraine sedimentology and climatic data analysis was applied throughout this study. This approach is based on the most recent studies on annual moraines at alpine valley glaciers (Lukas 2012; Wyshnytzky 2017) and elsewhere (Reinardy et al. 2013; Chandler et al. 2016; Chandler et al. 2020). The detailed methodology is described in the following chapters.

3.1 Geomorphological mapping

Geomorphological mapping at Gornergletscher was carried out largely according to the workflow outlined by Chandler et al. (2018), which initially included digital mapping from a variety of remotely sensed datasets. Overview maps of the upper Mattertal and the lower catchment of Gornergletscher were created using regional topographic maps and aerial photographs at a scale of 1:25.000, as well as digital surface models (DSMs) at a ground resolution of 200 m that were derived from the Federal Office of Topography, Switzerland (*swisstopo.com*). Additionally, a detailed glacial geomorphological map was constructed for the study site in the foreland of the side lobe, where annual moraine formation takes place. The creation of this map was aided by high resolution panchromatic aerial photographs (ground resolution of 25 cm) and DSMs (ground resolution of 50 cm) that were obtained from the Glaciology section of ETH Zürich (supplied by Matthias Huss) for selected years between 2006 and 2018. This dataset was used to (a) trace the retreat of the glacier margin during the recent years and (b) to accurately map the distribution of small morphological features in the glacier foreland. These included the extent of ice-moulded bedrock, proglacial streams and lakes, supraglacial debris cover on the glacier front, prominent crevasses within the ice and especially the distribution of annual moraines within the foreland. Construction of hillshade models from the DSMs helped to better emphasize smaller landforms such as partly subdued annual moraine ridges. The initial results of mapping from remotely sensed datasets were later confirmed and where necessary adjusted according to observations made during fieldwork. Minor and degraded annual moraines, for example, could sometimes not be spotted with certainty from aerial photographs and required in field validation, especially in areas where annual moraine spacing was later used to calculate IMRRs. Additionally, to better visualise former ice-flow directions on the map, striae on ice-moulded bedrock were measured at different locations throughout the foreland using a compass-clinometer. The final maps, illustrated in this study, were created within ArcMap 10.5 and are projected to and displayed in the Swiss coordinate system (CH1903+_LV95).

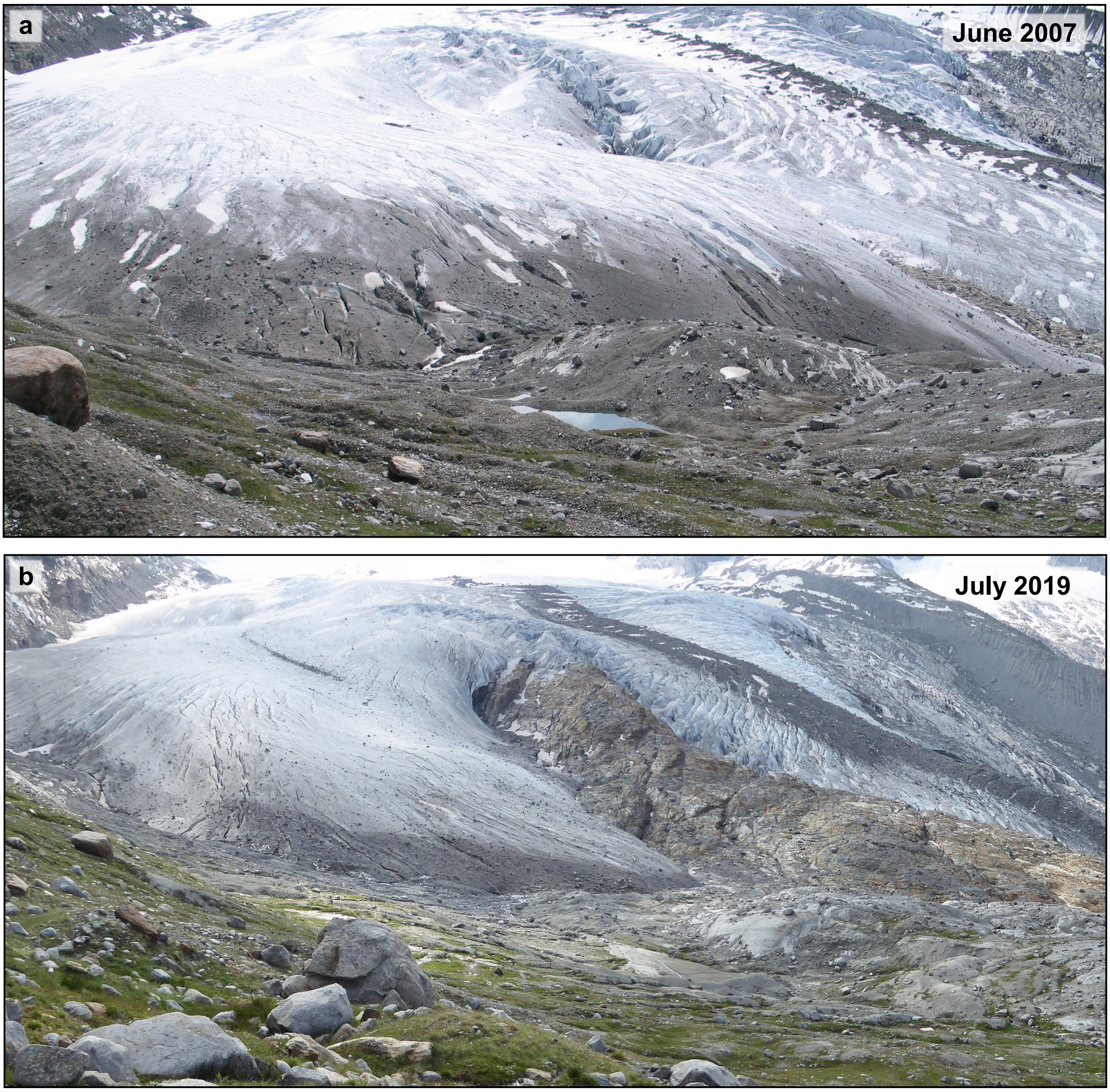

Fig. 5. Two photographs illustrating the pronounced retreat and thinning of Gornergletscher during the last decade. a. Photograph taken by Sven Lukas (13.06.2007). b. Photograph taken during field work by the author (06.07.2019). Note the downwasting of the ice-margin, resulting in a much shallower glacier front by 2019.

3.2 Field work and moraine sedimentology

Field work at Gornergletscher was carried out both in mid-July and in early September of 2019 to compare observations at the glacier margin between the beginning and the end of the ablation season. At first, the field work focussed on a detailed investigation of the glacier foreland inside the terminal moraine of 1980. Observations of characteristics from the ice-marginal, supraglacial and englacial zone were documented photographically to enable a process-based understanding of annual moraine formation. The sedimentological composition of annual moraine ridges was then investigated by creating sections at approximately right angles to their crestlines, using a trenching tool and a trowel. From several test pits, five moraines were selected for a detailed documentation to demonstrate representative sedimentological structures and thereby the range of processes leading to the formation of the moraines. This approach has been widely used in the most recent studies of annual moraines at Gornergletscher and in other settings (Lukas 2012; Chandler et al. 2016; Wyshnytzky 2017). A two-dimensional, sedimentary log was drawn by hand for each of the representative moraine sections in the field. These logs initially included the outline and orientation of the moraine sections plus the locations of prominent clasts and important unit boundaries. Afterwards, more detailed structures such as smaller lenses or bedding structures were added to the drawing. Additionally, a photographic mosaic of each moraine section was taken in the field and later used to enable an accurate digitisation of the hand-drawn log. Sedimentary units within the moraine sections were described with focus on their visual properties including grain size, sorting, deformation structures and in case of diamictic units also matrix composition, clast content and clast lithology. A lithofacies code was applied following the suggestions presented in Evans & Benn (2004) to summarise and effectively present these findings in the sedimentary logs. The logs that are presented throughout this study were created within Adobe Illustrator CC2019 and use a symbology that was modified from logs presented in previous studies of annual moraines (Fig. 6, Lukas 2012; Reinardy et al. 2013; Chandler et al. 2016).

Samples for measurements of clast shape and roundness were collected from diamictic units within the moraine sections to better constrain their genetic origin and transport paths through the glacier (Lukas et al. 2013 and references therein). The sampling was carried out according to the suggestions given by Benn (2004a). This included the collection of 50 clasts from each unit and subsequent measuring of their long- (a-), intermediate- (b) and short-(c)-axes to quantify clast shape. Roundness was determined by attributing each clast to one of the six roundness categories proposed by Powers (1953), ranging from very angular to well-rounded. When present, additional textural features such as striae or bullet-shapes were noted as well. Individual samples comprised only clasts of the same lithology, as it has been shown that clast morphology is largely influenced by lithological properties (Lukas et al. 2013). After field work, data on clast roundness were visualised as bar histograms and the results of clast shape analysis were plotted in ternary shape diagrams, separately for each diamictic lithofacies (Sneed & Folk 1958; Benn & Ballantyne 1993). For the graphical presentation of these diagrams, the Microsoft Excel spreadsheet method described by Graham & Midgley (2000) was used. To compare the individual measurements among each other, C_{40}-indices (ratio of clasts with c/a-axis $\leq$ 0.4) were then calculated for each clast shape sample and plotted against RA-values (ratio of angular and very angular clasts) in covariance diagrams as introduced by Benn & Ballantyne (1994). Additionally, covariance diagrams showing C_{40}-indices against RWR-values (ratio of rounded and well-rounded clasts) were constructed, as this approach can oftentimes more effectively discriminate between different transport paths, especially in high mountain

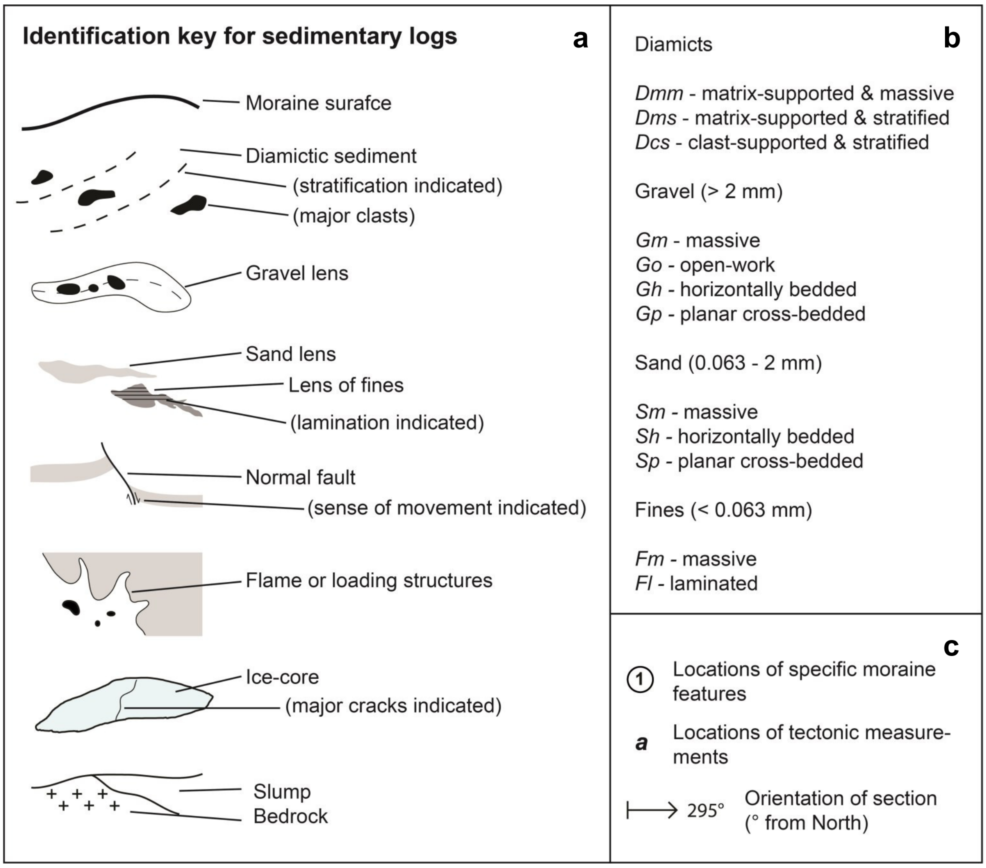

Fig. 6. Identification key for sedimentary logs presented in this study. a. Symbology used for the section logs, modified after Lukas (2012), Reinardy et al. (2013) and Chandler et al. (2016). b. Lithofacies codes applied to describe sediments found in moraine sections (after Evans & Benn 2004). c. Additional signatures used in the section logs.

environments (Lukas et al. 2013). No control samples were collected at Gornergletscher, instead samples of supraglacial, subglacial and glaciofluvial origin from neighbouring Findelengletscher were added to the covariance diagrams for comparison (this data is presented in Lukas et al. 2012). This was possible as the catchments of Gorner- and Findelengletscher largely encompass the same lithological units and clasts therefore were assumed to have experienced similar degrees of modification during their transport.

Structural data from moraine sections were obtained to support the interpretations drawn from sedimentary characteristics and clasts shape. Measurements of fold limb orientations were performed in folded sorted sediment units using a compass clinometer. These data points were afterwards plotted into Stereonet 10.1 (Cardozo & Allmendinger 2013) to reconstruct the direction of the respective fold axis. Analysis of fabric data was performed for one diamict unit where a preferred orientation of elongated clasts was suspected based on its visual appearance. For this method, 50 clasts with a/b-axis ratio > 1.5 were sampled from a restricted outcrop within this unit and the azimuth and dip of their a-axes was measured using a compass clinometer (Benn 2004b). The data points was afterwards transferred into Stereonet 10.1 (Cardozo & Allmendinger 2013) and equally plotted in lower hemisphere equal area Schmidt nets. Eigenvalues (S1, S2 and S3) were calculated to evaluate the strength of the preferred orientation (Woodcock 1977).

3.3 Climatic data analysis

The spacing between annual moraine ridges has been frequently used as a proxy for ice-marginal retreat and correlations between IMRRs and climatic variables have been established successfully in various studies (Krüger 1995; Bradwell 2004; Beedle et al. 2009; Lukas 2012; Chandler et al. 2016). To test if such correlations can also be applied to the most recent retreat of Gornergletscher, individual moraine ridges that were mapped in the glacial foreland had to be first attributed to the respective year of their formation. This correlation was based both on the time series of available aerial photographs and on morphological relations between moraine ridges observed in the field. A moraine that first appeared on a photograph from a certain year was attributed to have been formed during the previous winter advance of the glacier front (Fig. 7). After establishing the chronology, IMRRs were measured from the spacing between moraine crestlines within ArcMap 10.5. To account for localised irregularities within the ice-front, moraine spacing was integrated over a spatially restricted area, as previously suggested by Beedle et al. (2009). To obtain a complete sequence of IMRRs, two transects were selected across the foreland – one at the front of the glacier margin (spanning the season 2005/06 to 2007/08) and one in a more marginal position (2008/09 to 2017/18). The motivation behind the choice of these transects will be discussed in chapter 4.4.

Climatic data, spanning the period from October 1993 until June 2019, were obtained from two MeteoSchweiz automatic weather stations. The first station is located in Zermatt (624350/97560 – 1638 m), ca. 7 km northwest of the study site and the second station at Gornergrat (626900/92512 – 3129 m), ca. 2 km northwest of the study site. From the Zermatt station both daily average temperatures [°C] and daily total precipitation records [mm] were retrieved whereas from the station at Gornergrat only temperature records were available. As several studies have identified seasonal drivers of marginal retreat (e.g. Bradwell 2004; Lukas 2012; Chandler et al. 2016), temperature and precipitation records were split into an average ablation season (summer) and an average accumulation season (winter) signal. In line with the definition used by Lukas (2012), the ablation season was set to last from 01.05. until 30.09. each year and the accumulation season from 01.10. until 30.04. the following year, respectively. Additionally, an annual average of the temperature and precipitation signal was integrated over the whole length of the glaciological year preceding moraine formation (i.e. 01.05. until 30.04.). Ice-marginal retreat rates were then plotted and correlated against the previously calculated annual, summer and winter records. The strength of these correlation was evaluated based on the fit of a linear regression to the dataset, as previously applied in studies of annual moraines (Bradwell 2004; Beedle et al. 2009; Lukas 2012; Chandler et al. 2016). High coefficients of determination (R^2) and low probability-(p)-values are indicative of statistically significant correlations that suggest a link between ice-marginal retreat and climatic variations.

4 Results

In the following chapter, the results of this study will be presented. At first, these include descriptions of characteristic morphological features and sedimentary processes observed in the glacial foreland during field work (chapter 4.1) and the distribution and geomorphology of annual moraines within the study site (chapter 4.2). Afterwards the sedimentology of representative moraine sections is described and moraine genesis interpreted on a section scale (chapter 4.3). Lastly, the correlations between IMRRs and climatic variables will be presented (chapter 4.4). The following descriptions solely focus on the glacial foreland of the subsidiary lobe of Gornergletscher, where annual moraine formation takes place (cf. chapter 2.4). For simplification, this lobe will be referred to as Gornergletscher from hereon.

4.1 Characteristics of the glacial foreland of Gornergletscher

4.1.1 General characteristics

The glacial foreland of Gornergletscher inside its terminal moraine of 1980 can broadly be divided into a southern part, dominated by a prominent bedrock ridge, and a northern part, where the bedrock is covered by sequences of proglacial sediments (Fig. 8). Its overall topography is described by a reverse surface slope that is gently inclined towards the margin of the

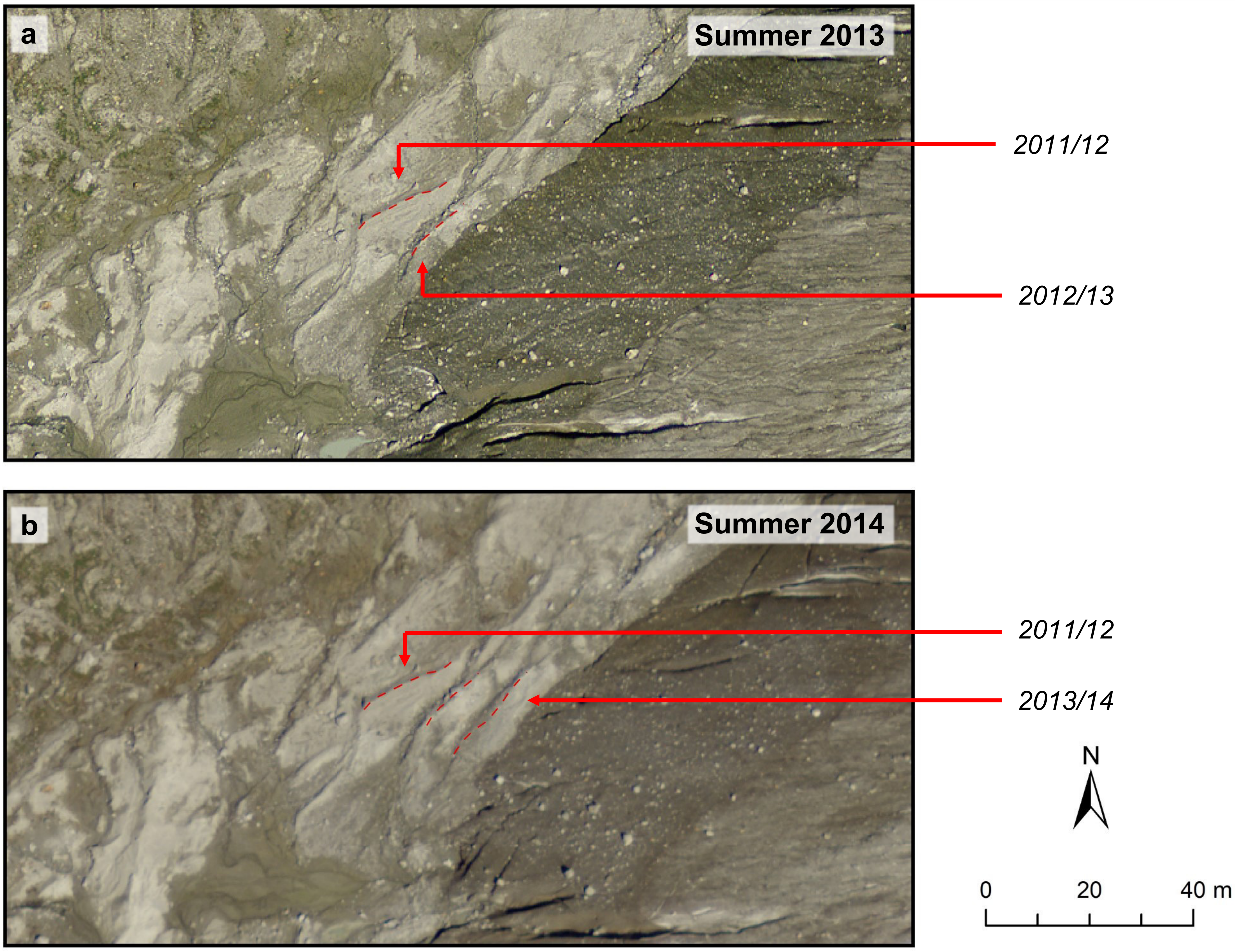

Fig. 7. Example case of how the annual moraine chronology at Gornergletscher was constructed - the two aerial photographs show the same extent of the glacial foreland (a) in the summer of 2013 and (b) in the summer of 2014. The moraines immediately downglacier from the ice-margin in the respective photographs (see red dashed lines) were interpreted to have been formed during the previous winter advance. Note the more prominent annual moraine from 2011/12 in both photographs for orientation. Aerial photographs kindly supplied by Matthias Huss (ETH Zürich).

glacier snout, although localised irregularities such as individual bedrock knobs and smaller basins are common. The bedrock itself consists predominantly of paragneiss and mica schist with a locally restricted lens of serpentinite cropping out at the portal of the glacier, where meltwaters have carved a steep valley into the ridge. As this lens is roughly SW-NE-striking, it is very likely also situated underneath the frontal part of the glacier snout and can be laterally connected to an outcrop of serpentinite that was mapped at the northern margin of Gornergletscher. Signatures of intensive ice-moulding of the bedrock such as roche moutonnées or striae are widespread (Fig. 9a). The orientation of striae indicates the former ice-flow direction of the glacier towards WSW (230-255°). Locally, edge-rounded boulders with a-axes up to ca. 3 m are lodged on top of the bedrock ridge (Fig. 9b) but overall, the sediment cover is either very thin or not present at all. Partly, however, smaller depressions within the bedrock are filled with sandy and gravelly sediments of fluvial or glaciofluvial origin.

Larger amounts of Quaternary sediments are concentrated in the northern parts of the foreland where they are deposited on top of the reverse bedrock slope. Most frequently they consist of material that originates either directly from annual moraine ridges or from gravitational deposits such as angular scree that accumulates underneath steeper bedrock cliffs. Numerous smaller, proglacial streams rework and redistribute these sediments throughout the foreland. The course of these streams and the general hydrology of the foreland is strongly governed by its topography. Proglacial streams largely originate from the steep hillsides to the north of the study site and flow towards the glacier margin as a result of the reverse bedrock slope in the central parts of the foreland. Where slope gradients are relatively high and streams channelised, mostly gravel-sized fluvial sediments are deposited. In smaller depressions situated between bedrock or moraine ridges, where slope gradients are lower also finer grain sizes can be found (Fig. 9c). Occasionally, moraine ridges are building a barrier for the streams, leading to the formation of small intra-moraine lakes (Fig. 9d). The proglacial streams however, rarely

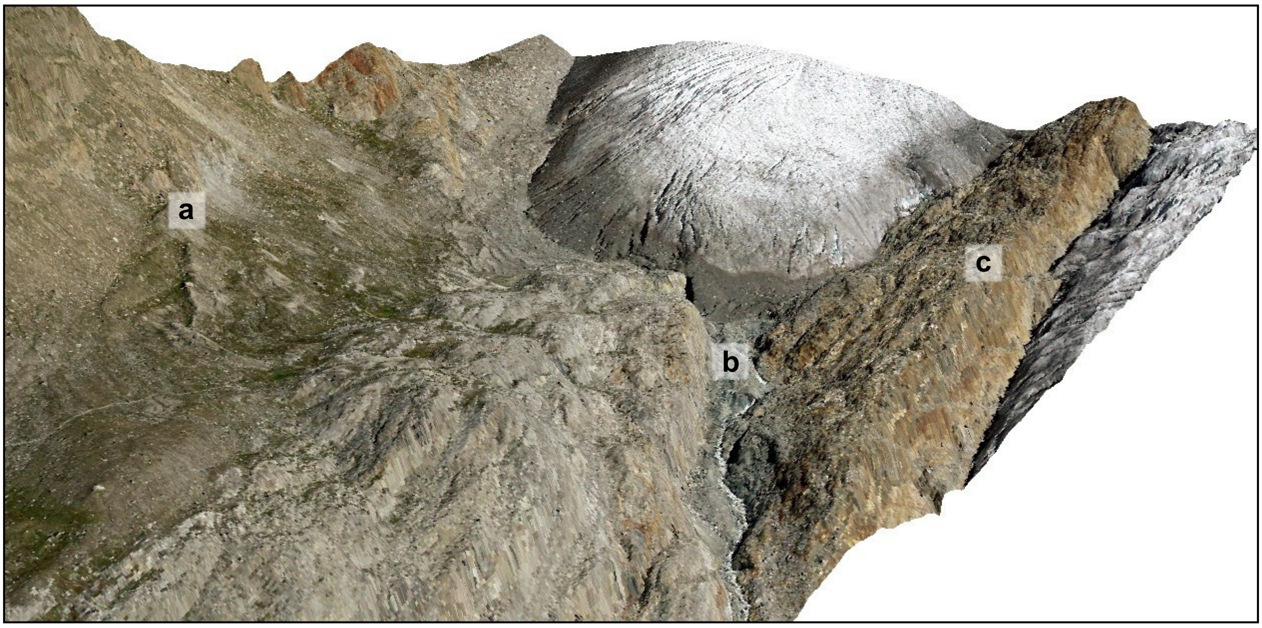

Fig. 8. 3D-Model of the immediate study area in front of the tributary lobe of Gornergletscher, where annual moraine formation takes place. Some characteristic morphological features of the foreland are (a) the prominent lateral moraine of 1980, (b) the main meltwater portal of the glacier snout, and (c) the prominent bedrock ridge dividing the glacier into a northern (left) and a southern (right) branch. View towards NE. The model is based on an aerial photograph (summer 2018) and a DSM which were kindly provided by Matthias Huss (ETH Zürich) and was created within ArcScene 10.5.

exceed a width of 1 m and the water supply during the time of fieldwork was extremely limited. During the summer months, increased frontal ablation leads to the formation of glacial meltwater streams that provide an additional water source to the foreland. These meltwaters either emerge supraglacially or from larger marginal crevasses and are topographically confined to flow south, largely parallel to the glacier margin towards the main meltwater portal.

4.1.2 Characteristics of the supraglacial and englacial zone

Whereas the snout of Gornergletscher is largely clean in its upper parts, the load of supraglacial debris starts to increase at a horizontal distance of between 20-70 m from the ice-margin. This debris cover is composed of a thin layer of silty to sandy sediments that directly covers the ice. Larger gravel-sized clasts, and cobbles and boulders with a-axes up to 2 m, are frequently incorporated into or sitting on top of this layer. These clasts are dominantly angular to very angular and meta-granite and mica-schist are the dominant lithologies. Mica-schist clasts are frequently of oblate or prolate shape while meta-granite clasts are dominantly blocky. Locally, the presence of larger boulders leads to protection of the underlying ice which results in differential melting and a fairly irregular ice surface along the glacier margin (Fig. 10a).

The thickness of the supraglacial debris cover is considerably greater in areas where englacial debris bands are emerging at the glacier surface. These debris bands include both thin coatings of silty sediments but also more prominent layers, composed of sand and gravel with thicknesses of up to 30 cm (Fig. 10b). Partly, also larger individual striated clasts that display distinct edge-rounding are incorporated into shear bands within the ice. It is especially notable that these clasts are sometimes serpentinites, as this lithology was not observed in the primary supraglacial debris cover (Fig. 10c). Lateral views into ice-marginal crevasses show that englacial debris bands occur continuously within the ice (Fig. 10d). However, the thickness of the bands is not uniform and consequently there are areas along the ice-margin where more or less englacial sediments accumulates in a supraglacial position. The distribution of this debris along the ice-margin has a crucial influence on the development of ice-marginal debris cones as will be described in the following section (chapter 4.1.3).

4.1.3 Characteristics of the ice-marginal zone

As annual moraines at Gornergletscher are forming ice-marginally, the observation of sedimentological processes in this setting is most crucial to better understand the genesis of these landforms. A key observation is that the ice-margin has substantially thinned during the last decade (cf. chapter 2.4), which resulted in an extremely shallow surface gradient of the ice-front by 2019 (Fig. 11a). This is especially pronounced in the central parts of the foreland where its surface angle was partly lower than 20°. Additionally, undercutting by small meltwater streams running parallel to the margin, can lead to a further thinning of the immediate ice-front. At parts of the margin it is possible to examine the visual properties of the sediment that is located at the sole of the glacier. This is an extremely firm diamictic sediment with a mostly silty matrix and moderate clast content (Fig. 11b). Its green-greyish

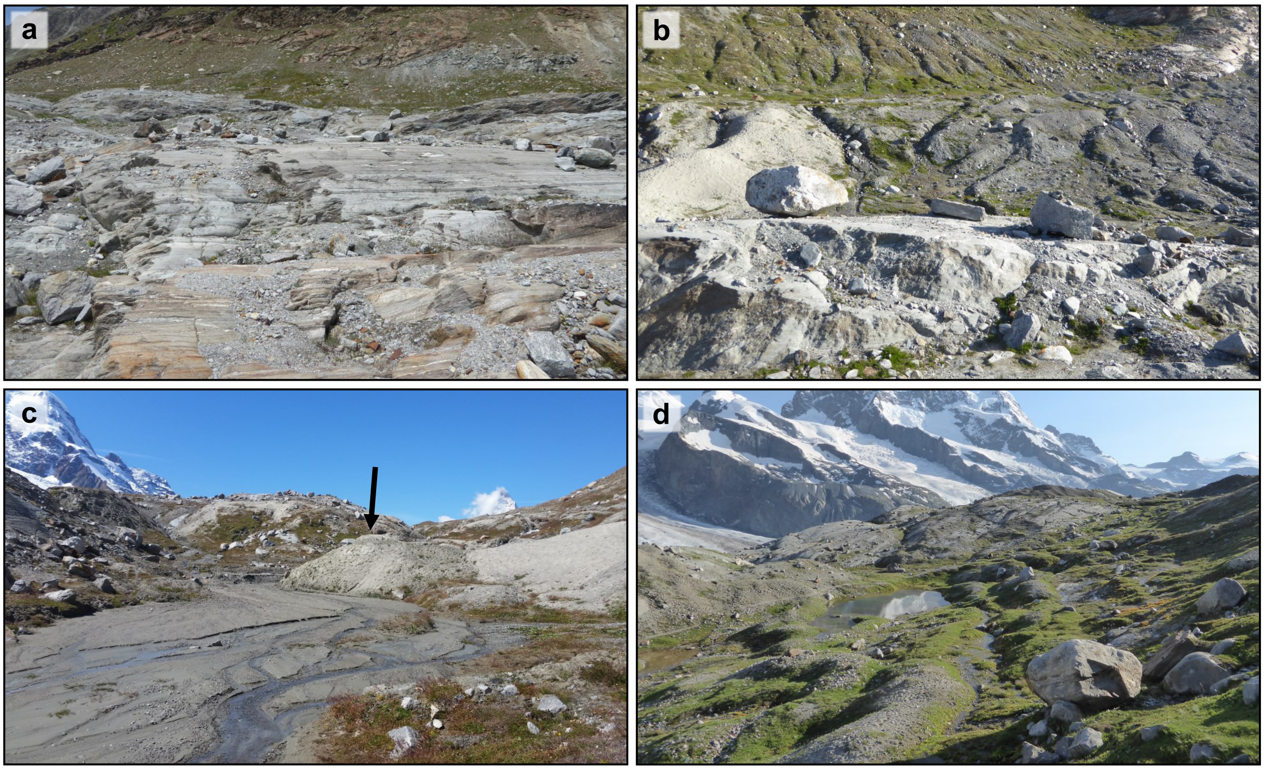

Fig. 9. Photographs showing general characteristics of the foreland of Gornergletscher. a. Ice-moulded bedrock with striations and plucked lee-faces (taken 17.07.2019). b. Ice-moulded bedrock with lodged, edge-rounded boulders (note sequences of annual moraines in the background, taken 19.07.2019). c. Proglacial braided streams depositing glaciofluvial sediments in smaller basins between bedrock and moraine ridges (taken 09.09.2019). In the background, indicated with a black arrow, is the prominent moraine ridge, where section G5 was excavated d. Ponding of proglacial streams in between older, partially vegetated annual moraines (taken 10.07.2019).

colour reflects the high amount of serpentinite clasts within the diamict. Partly, these sediments were still frozen to the basal ice during the ablation season and so the transition from submarginal sediments to basal debris-rich ice was sometimes hard to define. Sediments that are deposited in the immediate front of the ice-margin are visually similar to those observed underneath the ice and probably represent submarginal sediments that were previously exposed by the retreating glacier. However, these ice-marginal sediments are often supersaturated with respect to their water content due to the high amounts of meltwater confined to flow along the ice-margin.

Where thicker englacial debris bands are emerging onto the ice-surface, the ice-margin is characterised by the occurrence of clusters of debris cones (Fig. 11c). These prominent landforms consist of a core of glacier ice draped by a layer of sorted sediments and sometimes exceed heights of 2m (Fig. 11d). However, it is notable that the thickness of the sediment cover of these debris cones is always quite constant in the range of around 10-30 cm and never exceeds the primary thickness of the englacial debris bands. Big debris cones are sometimes undercut by streams running parallel to the margin. Some of these debris cones are still connected to the active margin, but in other cases the ice-bodies have been partially isolated due to ongoing glacial retreat, resulting in the formation of ice-cored moraines. The detailed characteristics and sedimentology of such an ice-cored moraine are described in chapter 4.3.2

4.2 Moraine distribution and geomorphology

Series of minor ridges, most likely ice-marginal moraines, are present in the foreland of Gornergletscher outside the terminal moraine of 1980. However, they are mostly subdued and because of the lack of aerial photographs from this time, no annual formation of these moraines could be confirmed. Consequently, geomorphological mapping in this study focussed on identifying annual moraines that were deposited in the glacier foreland after 1980. The distribution of a total of 432 moraine ridges that are present within this limit is shown within an aerial photograph (Fig. 12a) and within the geomorphological map of the glacier foreland (Fig. 12b).

The majority of annual moraines is deposited on top of pre-existing proglacial sediments in the northern parts of the foreland. Here, individual moraine ridges often form longer, continuous sequences that are only partially interrupted due to erosion by small proglacial streams. These sequences trace the position of the lateral part of the former ice-margin and can most reliably be used to calculate ice-marginal retreat rates (cf. chapter 4.4). In close proximity to the ice-

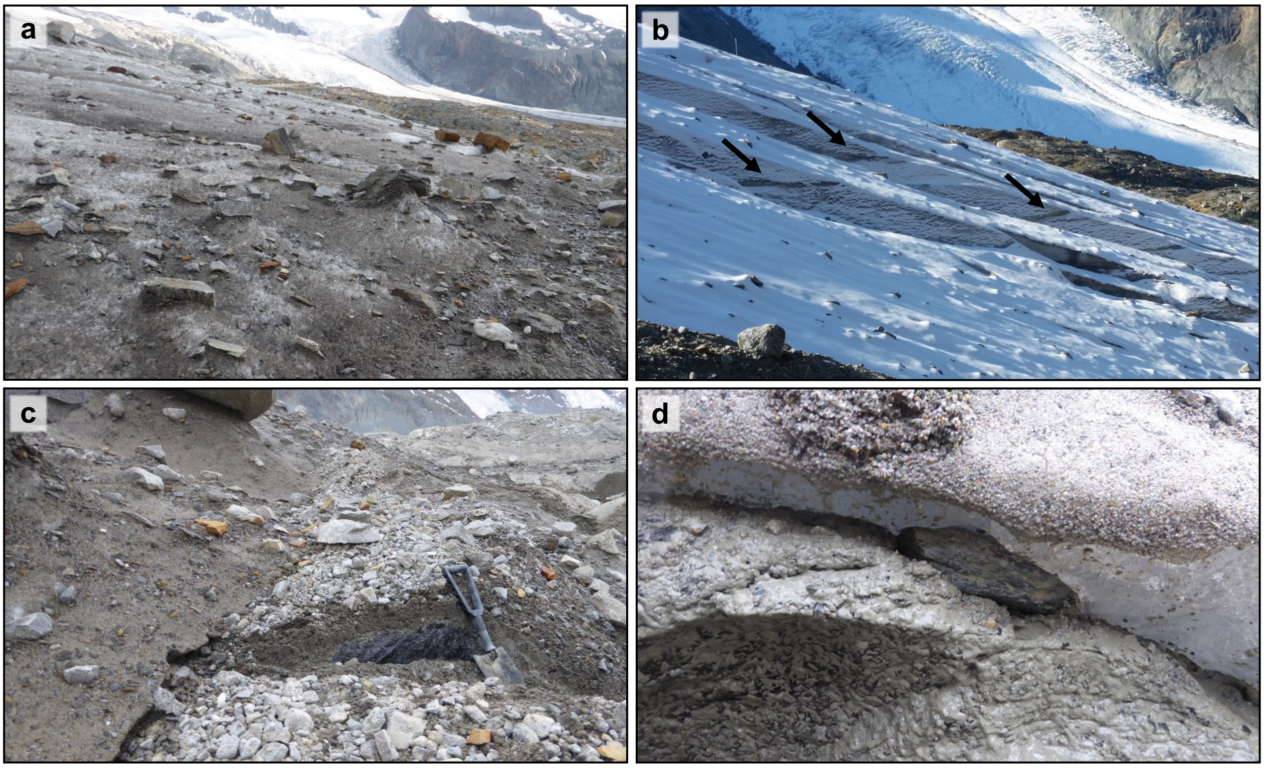

Fig. 10. Photographs showing characteristics of the supraglacial and englacial zone of Gornergletscher. a. Supraglacial debris-cover close to the ice-margin, dominated by angular clasts (taken 17.07.2019). b. Lateral view into ice-marginal crevasses with regularly emerging englacial debris bands visible after a fresh snowfall event (debris bands indicated with black arrows, taken 09.09.2019). c. An englacial debris band emerging on the glacier surface, leading to differential ablation of the underlying ice (note trenching tool, size ca. 50 cm, for scale, taken 11.07.2019). d. An edge-rounded serpentinite clasts incorporated into an englacial shear band in the ice (size of the clast ca. 10 cm, taken 11.07.2019).

margin, where supraglacial debris-cones are widespread, most moraines are rather preserved as individual mounds than continuous ridges, resulting in a hummocky topography of these areas. Moraines situated in the central part of the foreland, at the transition from the proglacial sediment cover towards the outcropping bedrock ridge, are also typically more fragmented in nature and preserved in the form of narrow arcs with ridge limbs pointing up-glacier. These moraines are most heavily affected by post-depositional erosion, due to the course of the largest stream in the foreland running westwards along the margin of the bedrock ridge. On top of the bedrock itself, moraines occur only sporadically and most of them are concentrated in closer proximity to the ice-margin, indicating that older ridges are most likely already degraded. In smaller depressions between bedrock ridges, where larger amounts of fluvial or glaciofluvial sediments have been deposited, moraine ridges are better preserved.

The differences in depositional environment are reflected by variations in moraine sizes and morphologies as well. Whereas some moraines are only hardly standing out from the ground, the most prominent ones exceed heights of 2 m. More commonly, however, are moraines with distal heights between 0.5 and 1.5 m high paired with steeper distal and shallower proximal slopes. This morphology is especially characteristic for those moraines that were deposited against the reverse surface slope in the northern parts of the foreland. A notable exception are moraines located in the hummocky terrain close to the ice-margin, where sometimes steeper proximal slopes could be observed. There is also a clear temporal evolution within moraine morphologies. Most moraines that were deposited before the year 2009/10 (including all moraines described by Lukas 2012) seem to have acquired a stable geometry and are covered by thin layers of soil and vegetation. The younger moraines, in contrast, are characterised by ongoing processes of resedimentation such as slumping of surficial sediment units or alteration by changing proglacial streams. Close to the ice-margin, also the melt-out of ice-cores in individual moraines has a strong influence on changing their morphological characteristics and contributes to the overall hummocky terrain of these areas (this topic will be further elaborated in chapters 4.3.2 and 5.2.2).

4.3 Sedimentology of annual moraine ridges

In this part, the sedimentology of five annual moraine sections will be described and discussed in detail. These moraines are considered to be representative for the varying sedimentary processes and depositional environments that are present throughout the foreland of Gornergletscher. They include:

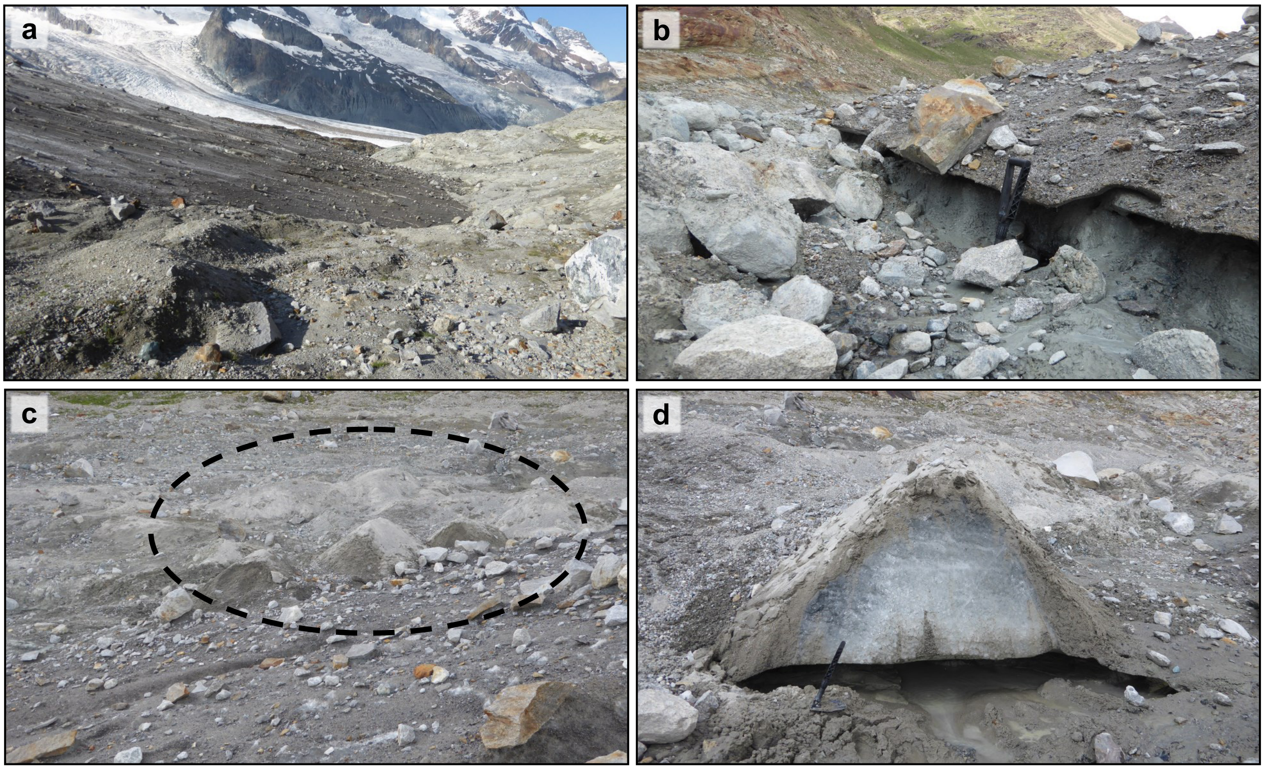

Fig. 11. Photographs showing characteristics of the ice-marginal zone of Gornergletscher. a. The very thin and gently sloping ice-margin of Gornergletscher (taken 06.07.2019). b. Thin glacier margin with underlying basal diamict. Note the greenish colour of the sediment that is a result of its high serpentinite content. Note also larger boulders that get dumped from the glacier front onto the ice-marginal deposits (trenching tool, size ca. 50 cm, for scale, taken 18.07.2019). c. A group of ice-marginal debris-cones (indicated by dashed circle) as seen from the surface of the glacier. Note the high supraglacial sediment load along this part of the glacier margin (taken 17.07.2019). d. Prominent ice-marginal debris-cone with thin surficial sediment cover (trenching tool, size ca. 50 cm, for scale, taken 18.07.2019).

a) a moraine located in close proximity to the thin, central ice-margin (moraine G1),
b) a moraine located within hummocky, ice-marginal terrain (moraine G2),
c) a moraine deposited against the reverse surface slope in the northern part of the foreland (moraine G3),
d) a moraine deposited on top of a bedrock ridge in the southern part of the foreland (moraine G4), and
e) a moraine located in the central part of the foreland at the transition from the bedrock ridge to a shallow sediment basin (moraine G5).

The locations of these moraine sections are visualised in the geomorphological map of the glacier foreland (Fig. 12b) and a legend for the sedimentary logs is presented in Fig. 6. A discussion about the genetic processes that lead to moraine formation and the spatial and temporal distribution of these processes within the foreland of Gornergletscher will follow in chapter 5.1.

4.3.1 Moraine G1 (2018/19)

During the time of field work in July 2019, moraine G1 was part of the innermost series of annual moraines in the foreland of Gornergletscher and located in close proximity (~5 m) to the central part of the ice-margin. This indicates that the moraine was formed during the most recent winter advance of the glacier in 2018/19. The ice-margin at this location is dipping at an extremely shallow angle and exhibits comparatively low amounts of supraglacial debris (cf. Fig. 11a, b). Compared to other annual moraines in the foreland, G1 is relatively minor with a length of ~10 m, a width of ~1.5 m and a maximal height of 0.8 m. Characteristic for the morphology of this moraine ridge are the relatively steep and irregularly shaped proximal and distal slopes (up to 40°) that are frequently littered with large, mostly angular boulders. Groups of these boulders are also accumulating on the foot of both its distal and its proximal slope. A section through the moraine was created at approximately right angle to its crestline (striking 136-152°), where a small meltwater stream had previously dissected the moraine ridge (Fig. 13a).

4.3.1.1 Description of the section

The section reveals that moraine G1 is almost entirely composed of diamictic sediments. In general, two diamictic lithofacies (LFs) can be distinguished based on their differing sedimentary properties – a stratified, matrix-supported diamict (*Dms*, LF1), located in the centre of the moraine body and a stratified, clast-supported diamict (*Dcs*, LF2), draping the former on

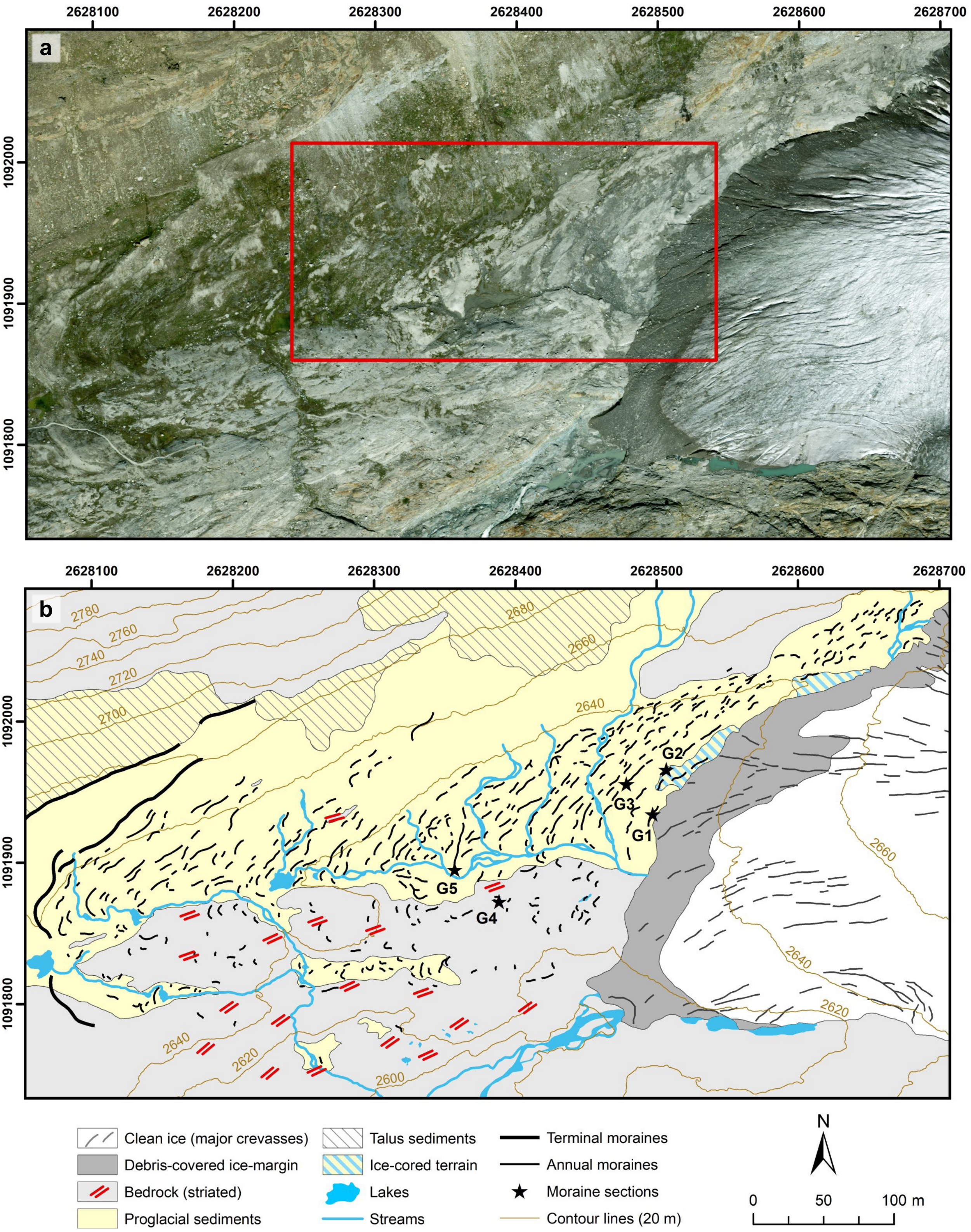

Fig. 12. a. High resolution aerial photograph (taken during summer 2018) of the study site in the foreland of Gornergletscher. The red frame marks the area where spacing between annual moraines ridges was used to calculate IMRRs. b. Glacial geomorphological map showing the distribution of annual moraines within the study site. The moraine sections that are described in detail in this study are marked with black stars. The aerial photograph in (a) plus additional remotely sensed data used for the creation of the geomorphological map (b) was supplied by Matthias Huss (ETH Zürich).

both slopes of the ridge. LF1 is extremely consolidated and hard to excavate. The matrix of this diamict exhibits a greyish colour and is mostly silty to sandy. Larger boulders with a-axes up to 30 cm are incorporated into the matrix framework frequently and those clasts are visually edge-rounded. Clast roundness measurements (Fig. 13c) of a serpentinite sample back up this first impressions with the majority of clasts being subrounded and subangular and only a smaller fraction of angular clasts (RA = 14). Serpentinite is also overall the most dominant lithology within the diamict; these clasts are mostly of prolate or oblate shape (C_{40} = 94) and frequently show striations and facets. The stratification within LF1 is primarily represented by slight variations in matrix-composition and the presence of two thin lenses of sandy to silty sediments (*Sh*) that are gently inclined towards the ice-margin. The orientation of elongated clasts conforms this stratification, as their a-axes are aligned mostly parallel to ice-flow and are equally dipping up-glacier. Measurements of clast fabric show that this preferred orientation towards ENE is significant, with a high principal eigenvalue (Fig. 13b, S1 = 0.67, S2 = 0.18, S3 = 0.15).

LF2 contrasts with most of the properties of LF1 – its appearance is very loose and the diamict was easy to excavate and sample. The matrix is dominantly sandy and finer grain sizes are notably absent. Larger clasts are mostly angular and blocky which is reflected by the results of clast shape and roundness measurements on a meta-granite sample (Fig. 13d, C_{40} = 38, RA = 72). Besides meta-granites, mica-schists are also commonly found in LF2, whereas serpentinite clasts are not present in this diamict. No preferred clast fabric was visible, as elongated clasts are mostly aligned with their a-axes corresponding to the respective surface slope of the moraine ridge.

4.3.1.2 Interpretation of the section

The contrasting sedimentary properties that characterise the two diamicts found in moraine G1 suggest different depositional environments for these lithofacies. In LF1, the dominance of subangular clasts that frequently exhibit striations and facets points to an active transport of these particles along the glacier bed (Boulton 1978; Benn & Ballantyne 1994; Lukas et al. 2013). The abundance of serpentinite clasts in this lithofacies provides further evidence for a subglacial origin, as in the catchment of Gornergletscher bedrock lenses of this lithology are almost exclusively situated

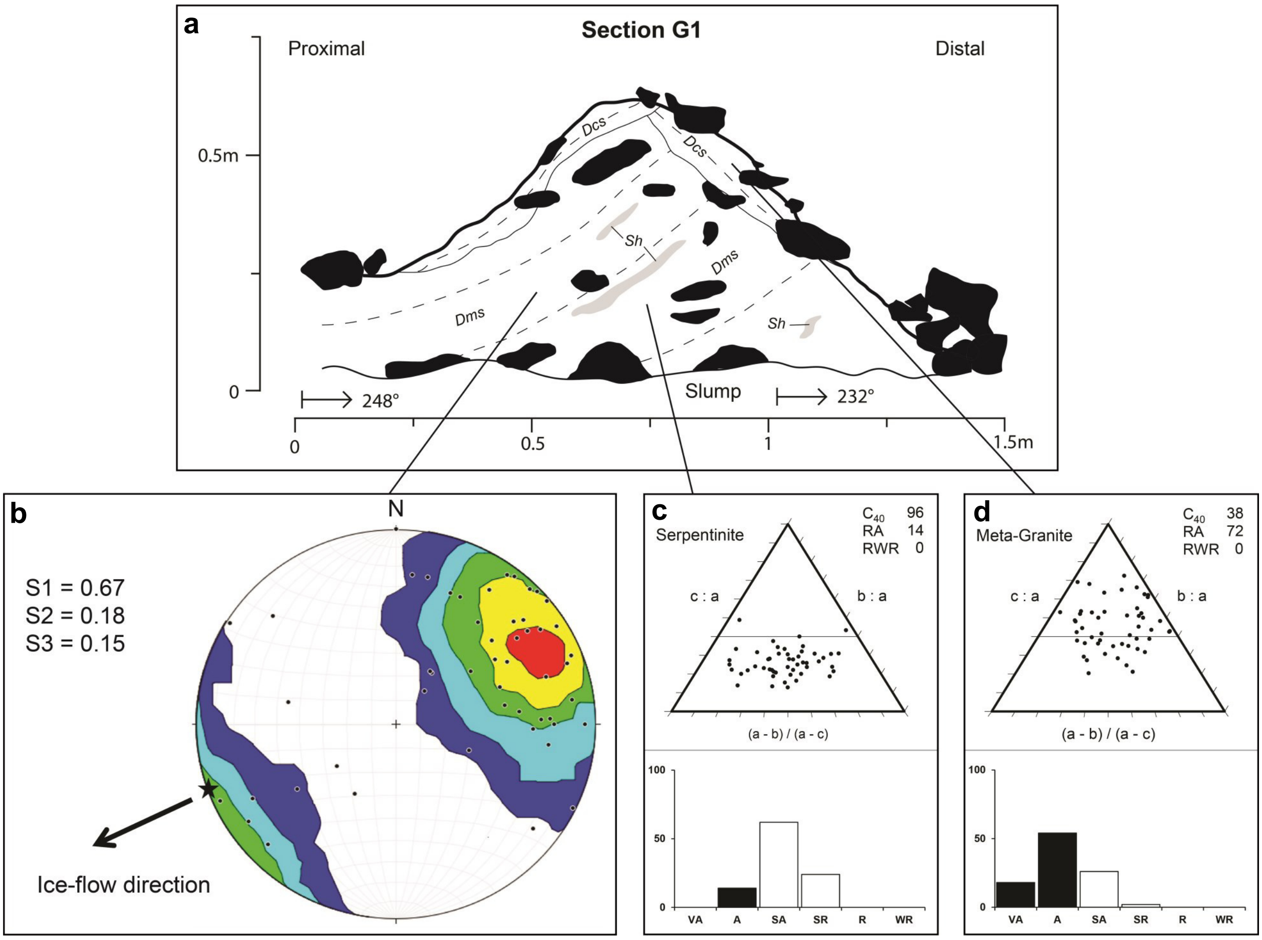

Fig. 13. a. Sedimentary log of section G1. b. Clast fabric measurement for the basal, stratified diamict (LF1). The orientation of a-axes of elongated clasts is plotted in a lower-hemisphere equal area stereonet. Note the preferred alignment of the clasts dipping mostly up-glacier. c. Clast shape and roundness measurements from a serpentinite sample derived from the basal diamict (LF1). d. Clast shape and roundness measurements from a meta-granite sample derived from the surficial diamict (LF2).

underneath the ice (cf. chapter 4.1.1, Bearth 1953). A subglacial source of the clasts in LF1 is in line with the general sedimentary properties of this diamict, e.g. the high degree of consolidation and the dominantly silty matrix that commonly characterise subglacial traction tills (Evans et al. 2006; Hiemstra et al. 2015). Also the strong macrofabric, with a-axes of elongated clasts aligned parallel to ice-flow direction, indicates that these clasts were orienting according to the subglacial stress field (Carr & Rose 2003). The diamict exhibits close similarities to the sediments that were observed to be situated underneath the thin ice-margin at Gornergletscher (Fig. 12b). Most likely these sediments are frozen onto the sole of the glacier during winter and transported forward with the advancing ice-margin before they melt out during summer to form an annual moraine ridge (Krüger 1993; Krüger 1995). Evidence for this mechanism comes from the stratification of the diamict that represents the freezing of the sediment slabs onto an up-arching, advancing glacier snout (Reinardy et al. 2013). The orientation of elongated clasts dipping up-glacier, preserving the dominant fabric of the primary subglacial traction till, is also compatible with the process of submarginal freeze-on to a greater extent than other moraine-forming mechanisms (Evans & Hiemstra 2005; Hiemstra et al. 2015). In concordance, no signs of squeezing of the till or deformational structures such as folded sediment units that relate to ice-marginal push were found in this diamict. The interpretation of LF1 as a subglacial traction till that has been emplaced into the moraine body by submarginal freeze-on is supported by the extremely shallow ice-margin at this location. Such a thin ice-front is necessary to facilitate the penetration of the winter freezing front into the submarginal sediments and is therefore a crucial requirement for the freeze-on process to occur (Krüger 1993; Krüger 1995; Matthews et al. 1995; Reinardy et al. 2013).

In contrast to the subglacial signature of LF1, the dominance of angular, non-striated meta-granite clasts within LF2 points to a supraglacial source of this diamict (Boulton 1978; Benn & Ballantyne 1994; Lukas et al. 2013). This interpretation is corroborated by its extremely loose, unconsolidated nature that is indicative of a subaerial deposition in the absence of the subglacial overburden pressure. The sediments closely resemble material that was observed to be overlying the thin glacier front during the time of field work. They were probably dumped on top of the subglacial traction till (LF1) while the glacier gradually melted back from its previously deposited moraine core during the early summer months. This would also explain the absence of finer grain fractions within LF2, as these were mostly washed away during the melting of the ice-margin (e.g. Lukas et al. 2005).

4.3.2 Moraine G2 (2017/18)

Moraine G2 is located in an area of hummocky, ice-marginal terrain where most annual moraines are preserved rather as individual mounds than continuous ridges and supraglacial debris cones are widespread (cf. Fig. 11c, d). In early July 2019, the distance to the immediate glacier front was measured at approximately 15 m, and a set of moraine mounds was observed closer to the ice-margin. Assuming that these moraines represent the most recent winter advance of Gornergletscher, the formation of moraine G2 can be set at the end of the accumulation season 2017/18. The moraine ridge has a total length of ca. 20 m, an average width of ca. 2 m, a maximum height of ca. 1.5 m and a strongly undulating and rounded crestline. Interestingly, as opposed to the majority of other moraines in the foreland, its proximal slope (30°) is considerably steeper than its distal slope (15-20°). Moraine G2 is deposited against a gently inclined reverse surface slope and on its distal face in contact with the proximal face of another moraine ridge. A section through the moraine was created at approximately right angle to its crestline (striking ca. 200°) at a lateral end of the moraine ridge (Fig. 14a).

4.3.2.1 Description of the section

Visually, the most conspicuous feature of this section is a body of buried ice with a thickness of up to 50 cm that dominates the central part of the moraine (Fig. 14b). The shape of the ice body approximately traces the overall morphology of the moraine and reaches its maximum thickness right underneath the moraine crestline. The base of the ice is gently inclined, dipping up-glacier by around 10°, which reflects the approximate steepness of the reverse surface slope in the area. The ice itself is very clean and no englacial debris bands were observed. However, a major subvertical crack can be traced through the centre of the ice body. On its proximal side, it gradually thins out and is not connected to the active ice-margin of Gornergletscher anymore.

Two distinctly different lithofacies surround the ice-body in this section. Situated underneath the ice is a massive, matrix-supported diamict (*Dmm*, LF1) that is characterised by a green-greyish matrix with mostly silty composition. Larger clasts are frequently incorporated into the matrix framework, with the most prominent boulder reaching an a-axis length of ca. 30 cm. Visually, serpentinite clasts are the most dominant lithology within the diamict. These clasts are frequently broken up into smaller fractions and thereby probably also contribute to the green tone of the matrix colour. During excavation of the section and concurrent partial melting of the ice-body, the initially stiff and consolidated basal diamict started to get supersaturated with water, and the resulting liquefaction obscured any further potential sedimentary structures. Still, clast shape and roundness samples for serpentinite and meta-granite could be retrieved (Fig. 14c, d). They show that serpentinite clasts are frequently of prolate and oblate shape (C_{40} = 86) whereas meta-granite clasts are mostly blocky (C_{40} = 26). Both lithologies are predominately subangular with smaller fractions being subrounded and angular (RA = 16 for serpentinite and RA = 26 for meta-granite). Facets and striations were observed to be widespread, especially on the surfaces of serpentinite clasts.

The ice-body in moraine G2 is draped by a unit of massive gravel (*Gm*, LF2) with a mostly uniform thickness of between 30 and 40 cm. At the proximal and distal margin of the ice-body, this lithofacies is deposited directly on top of the basal diamict. It is relatively poorly sorted and grain sizes range from fine sand up to smaller cobbles. However, the basal parts of this unit, directly overlying the ice, are composed of better sorted, coarse open-work gravel and lack the finer grain sizes. Notable is also the absence of serpentinite gravels within this unit and the dominance of meta-granite and mica-schist. In the distal part of the section a minor lens of silty sand is incorporated into the surficial gravel (*Sh*, LF3). This sand lens exhibits a tight folding structure and is located at a position, where the front of the ice core protrudes into the distally deposited sorted sediments.

4.3.2.2 Interpretation of the section

Based on the dominant body of buried ice, that is not in connection to the active ice anymore, moraine G2 can be referred to as an ice-cored moraine following the terminology of Lukas (2011). The abundance of subangular, striated serpentinite clasts in the basal diamictic lithofacies (LF1) is a sign of active subglacial transport and abrasion (Boulton 1978; Benn & Ballantyne 1994; Lukas et al. 2013). Potentially, this diamict was advected at the base of the ice by a similar freeze-on mechanism as proposed for moraine G1. However, because of the absence of depositional structures in the diamict after liquefaction, it remains unclear if this sediment represents a primary subglacial traction till (*sensu* Evans et al. 2006), or rather a set of pre-existing ice-marginal sediments that were frozen onto the base of the advancing margin (Matthews et al. 1995; Lukas 2012; Reinardy et al. 2013). The massive gravel layer (LF2) that is draping the ice body lacks clear evidence of fluvial deposition (e.g. bedding structures or a high degree of sorting) but rather shares similarities with sediments emerging from englacial debris bands only a few meters up-glacier (Fig. 11c). These sediments are equally massive and characterised by poor sorting and the dominance of meta-granite gravels. Additionally, the maximum thickness measured for these debris bands (ca. 30 cm) corresponds to the uniform thickness of LF2. Process-observations at the ice-margin in July 2019 indicate that, where thicker englacial debris bands are increasing the load of supraglacial debris, differential ablation of the underlying ice leads to the evolution of ice-marginal debris cones (Schlüchter 1983; Goodsell et al. 2005). It is very likely that moraine G2 represents the remnants of such a debris cone that has been disconnected from the active ice-margin after its ongoing retreat (Lukas 2011).

Ice-cored moraines were already present in

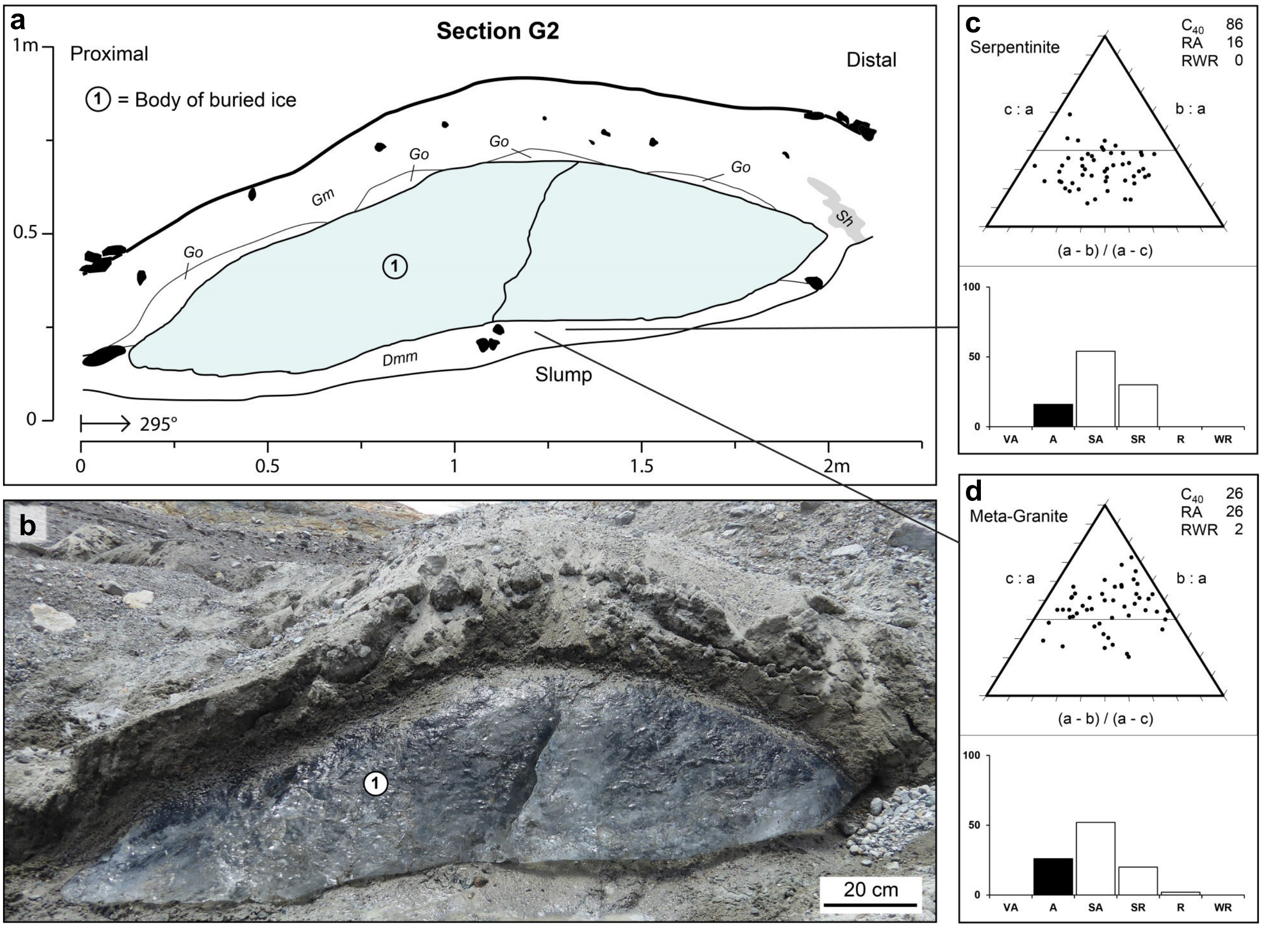

Fig. 14. a. Sedimentary log of section G2. b. Photograph of the dominant ice-core within the moraine (taken 10.07.2019). Note how the shape of the ice-core dictates the overall moraine morphology. c. Clast shape and roundness measurements from a serpentinite sample derived from the basal diamict (LF1). d. Clast shape and roundness measurements from a meta-granite sample derived from the basal diamict (LF1).

close proximity to the margin of Gornergletscher in 2007 (cf. GOR1, Lukas 2012). However, the sedimentary architecture of these previously formed moraines greatly differs from the characteristics of moraine G1. While the moraine described by Lukas (2012) displays a wide set of deformation structures that have been interpreted as the result of ice-marginal push during inefficient bulldozing, sediment deformation in this section is restricted to the folding of a small sand lens at the distal side of the moraine body. The absence of further deformation structures and the massive nature of the overlying gravel suggest that inefficient bulldozing of proglacial sediments *sensu* Lukas (2012) is negligible for the formation of moraine G1. Indeed, the deformation of some distal sediment units in this moraines was only possible, as the ice-core encountered an obstacle, in the form of a moraine ridge on its distal side.

Ice-cored moraines, such as moraine G2, are transitional landforms (Lukas 2011) and their morphology and sedimentary structures are strongly governed by the gradual melt-out of the ice. Initial signatures of a top-down melting of the ice-core already resulted in the removal of fines in open-work gravels of LF2 (e.g. Lukas et al. 2005). Ongoing melt will result in a substantial lowering of the moraine height and probably limit the preservation potential of these landforms (e.g. Kjær & Krüger 2001, cf. chapter 5.3.2).

4.3.3 Moraine G3 (2016/17)

Moraine G3 is located in a lateral to frontal position of the glacier margin and was at a distance of ca. 25 m towards the ice by July 2019. From the analysis of aerial photographs, the formation of this moraine was dated to the end of the accumulation season of 2016/17. The moraine ridge has a total length of ca. 20 m and forms a part of a well-defined longer chain of moraines that were deposited contemporarily along the ice-margin. Notable morphological features are its well-developed, sharp crestline and the asymmetric shape with a steeper distal (35°) and shallower proximal (20-25°) side. The distal slope of the moraine is also considerably shorter, reflecting the deposition of the moraine against the reverse slope at this location. The section that was created through the moraine ridge is at approximately right angle to its crestline (striking at ca. 30°).

4.3.3.1 Description of the section

Moraine G3 is composed of a basal diamictic lithofacies that is covered by a sequence of sorted sediments (Fig. 15a). The diamict (*Dmm*, LF1) is massive, matrix-supported and relatively firm, although it was easier to excavate than the basal diamicts in moraines G1 and G2. The matrix is dominantly silty to sandy and of light brown to greyish colour. Larger clasts that are incorporated into the matrix framework are frequently edge-rounded and sometimes display striations and facets. Serpentinite and mica-schist clasts are dominant and clast shape samples were retrieved for both of these lithologies (Fig. 15d, e). Equally to the diamicts in moraines G1 and G2, serpentinite clasts are mostly prolate and oblate (C_{40} = 94) whereas mica-schist clasts are rather blocky (C_{40} = 32). The majority of clasts is subangular (and for mica-schist also subrounded) and as a result, RA-values are relatively low (RA = 20 for serpentinite and RA = 12 for mica-schist). Visually, some of the largest elongated clasts within LF1 are oriented with their a-axes parallel to the moraine crestline but no fabric measurements were taken to back up this impression quantitatively. Layers of surficial sorted sediments are discordantly overlying the basal diamict. They can be grouped into well-sorted, horizontally bedded gravels (*Gh*, LF2) and a distinct layer of well-sorted, horizontally bedded fine sand that is visible in the centre of the moraine body (*Sh*, LF3). Within the gravel layers, the bedding is visible from vertical variations in grain size. In the proximal part of the section it is subparallel to the moraine surface, although the contact between individual beds is slightly undulated.

A striking characteristic of moraine G3 is that all lithofacies show clear signs of folding at section scale. The folding is present throughout the entire moraine body; only in the very distal part of the section friable gravels have been slumping down the steep distal slope and are therefore absent of any bedding structures. Most evident it is within the surficial sorted sediments and measurements of fold limbs were taken along the contact between horizontally bedded gravels and the distinct central sand layer (Fig. 15b). The results of these measurements are plotted in a southern hemisphere equal area stereonet, which allows the fold axis of this structure to be reconstructed (Fig. 15c). It is found to be gently dipping towards SW, approximately parallel to the moraine crestline and orthogonal to the ice-flow direction in the area.

4.3.3.2 Interpretation of the section

The diamictic lithofacies (LF1) in section G3 exhibits similarities to the basal diamicts found in moraines G1 and G2, with the dominance of subrounded, striated clasts indicating transport within the subglacial traction zone (Boulton 1978; Benn & Ballantyne 1994; Lukas et al. 2013). Yet, the absence of a coherent fabric pattern and the lower degree of consolidation conflicts with the interpretation of the diamict as a primary subglacial traction till (*sensu* Evans et al. 2006). Presumably LF1 therefore represents a sediment that has been initially deposited subglacially but has been subsequently reworked before incorporated into the moraine body. At some parts of the contemporary ice-margin of Gornergletscher, subglacial diamicts are observed to be partly exposed by the retreating ice-margin. Subsequently these sediments get reworked by small meltwater streams running parallel to the ice-margin, leading to widespread liquefaction and alteration of initial depositional structures. It is likely that LF1 represents such an ice-marginal deposit, which would explain both its subglacial clast signature and the absence of primary till characteristics. In turn, the well-sorted, horizontally bedded layers of gravel and sands (LF2 & LF3) are interpreted as deposits of running water, most likely small streams that were running parallel to the ice-margin. Vertical variations in grain size are the result of changing flow velocities in these streams, with gravel layers deposited

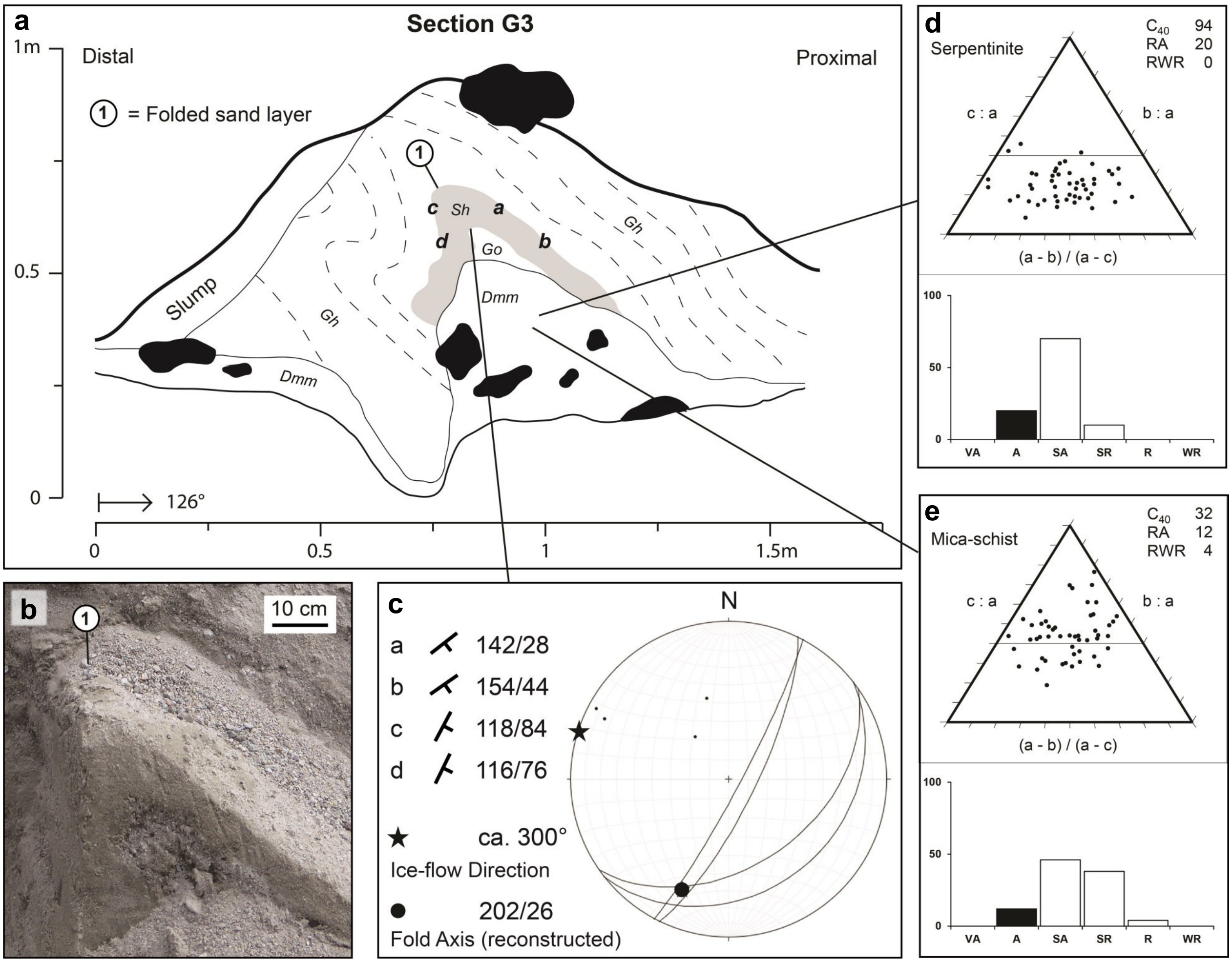

Fig. 15. a. Sedimentary log of section G3. b. Distinct folded sand lens in the central part of the section. c. Plains of fold limbs and poles to these plains plotted in a lower-hemisphere equal area stereonet. The fold axis was reconstructed from the intersection of the fold plains and is dipping at a shallow angle towards SW, roughly at 90° to the local ice-flow direction. d. Clast shape and roundness measurements from a serpentinite sample derived from the basal diamict (LF1). e. Clast shape and roundness measurements from a mica-schist sample derived from the basal diamict (LF1).

by higher-energy events and the finer sand units originating from phases with slower flow (Evans & Benn 2004; Benn 2009). These sediments were probably deposited on top of the ice-marginal diamict during the ablation season, before the following winter advance incorporated the sediments into the moraine body.

All lithofacies in moraine G3 are subject to extensive folding indicating pronounced horizontal shortening of the sediment layers after their deposition. The orientation of the fold-axis, striking approximately NE-SW, corresponds to the orientation of the glacier front in this area. As fold axes are aligned orthogonal to applied stress, it plausible to assume that the source of the compressional deformation in this moraine was the advancing ice-margin (McCarroll & Rijsdijk 2003). Due to the dominance of ductile deformation (i.e. folds) over brittle deformation (i.e. reverse faults), the proglacial sediments are unlikely to have been frozen during this deformation (Bennett et al. 2004). The sedimentological evidence is backed up by the morphological features of moraine 3 with its well-developed crestline and steeper distal side, as it has been reported for moraines created by ice-marginal bulldozing at Gornergletscher and other settings before (Schlüchter et al. 1999; Winkler & Nesje 1999; Winkler & Matthews 2010; Lukas et al. 2012).

4.3.4 Moraine G4 (2011/12)

Moraine G4 is situated in a small depression within a prominent bedrock ridge, at a distance of approximately 100 m to the glacier margin by July 2019. The exact year of formation of this moraine is unclear, as no continuous sequences of annual moraines are present in this part of the glacier foreland. Based on the analysis of aerial photographs, however, a formation at the end of the accumulation season of 2011/12 is favoured. The moraine ridge has a total length of ca. 10 m, a maximum width of up to 3 m and is between 1 and 1.5 m high. It forms a tight arc that traces the approximate shape of the bedrock depression. Distal and proximal slopes of the moraine are generally equally steep (ca. 25°) but frequent slumping of the uppermost friable sediment layers result in a fairly irregular surface of the moraine body. A section through the moraine was created at an approximately right angle to its crestline (striking ca. 295°) in a lateral part of the ridge (Fig. 16a).

4.3.4.1 Description of the section

The section reveals that moraine G4 is entirely composed of sorted sediments units that were deposited directly on top of the inclined bedrock surface. No basal diamict compatible to the previously described sections (G1, G2 and G3) was found. Generally, the sediments can be divided into three different lithofacies – well-sorted, coarse gravel (LF1), well-sorted fine sands (LF2) and bodies of sandy silt (LF3) that can be distinguished from the former lithofacies by their higher consistency and darker colour. In the proximal part of the moraine section, the lithofacies display horizontal bedding and the contacts between individual units are fairly regular. Alternating layers of laminated silts (*Fl*, LF3), horizontally-bedded sands (*Sh*, LF2) and gravels (*Gh*, LF1) are arranged in a well-defined, slightly overturned fold structure (Fig. 16b). Both fold limbs are dipping towards the centre of the bedrock depression (NE), indicating that the fold axis is striking towards SE, subparallel to the moraine crestline. However, due to the friable nature of the sediments no reliable measurements of either fold limbs or axis could be performed. The sediments at the distal end of the fold structure mostly consists of massive fine sands that incorporate thin lenses of horizontally bedded gravels. These gravel lenses are aligned subparallel to the overturned limb of the fold structure but are extremely disrupted and irregular in nature.

In the central and distal parts of the section, the sediment bodies are internally massive and well defined structures are absent. In general, a core of massive, well sorted gravel (*Gm*, LF1) is surrounded by units of massive sand (*Sm*, LF2) and massive silt (*Fm*, LF3). The boundaries between individual units are highly irregular and frequently characterised by structures of soft-sediment deformation such as flame and loading structures. Especially prevalent are upwards intrusions of coarser gravel bodies into the overlying sandy and silty sediments (Fig. 16c).

4.3.4.2 Interpretation of the section

The units of sorted sediments that are present in moraine G4 are interpreted as deposits of running water due to their high degree of sorting and bedding structures that are present in the proximal part of the section (Evans & Benn 2004, Benn 2009). However, proglacial streams in the glacier foreland lie several metres below the bedrock ridge where the moraine is situated. It is therefore unlikely that the sediments in this section were deposited directly by these streams but rather represent deposits of glacial meltwater. The variations in grain sizes from coarse gravel down to fine sand and silt are then probably the result of changing hydrological conditions in the course of the ablation season where coarse gravel units (i.e. LF1) were deposited during times of increased melt and runoff. Specifically, also the presence of a large ice-marginal crevasse, as seen from aerial photographs, could have facilitated higher amounts of meltwater to be released into the bedrock basin, resulting in the deposition of these coarser grain sizes. The finer grain fractions (i.e. silty sands of LF3) were potentially deposited in small ponds when the glacial meltwaters were temporarily pounded against the ice-margin.

The coherent folding in the proximal part of the section with the fold axis aligned parallel to the moraine crestline, is indicative for horizontal shortening of the fluvially deposited sediments. Similarly to the process outlined for moraine G3, this structure most likely results from ice-marginal bulldozing during the winter advance of the glacier (Schlüchter et

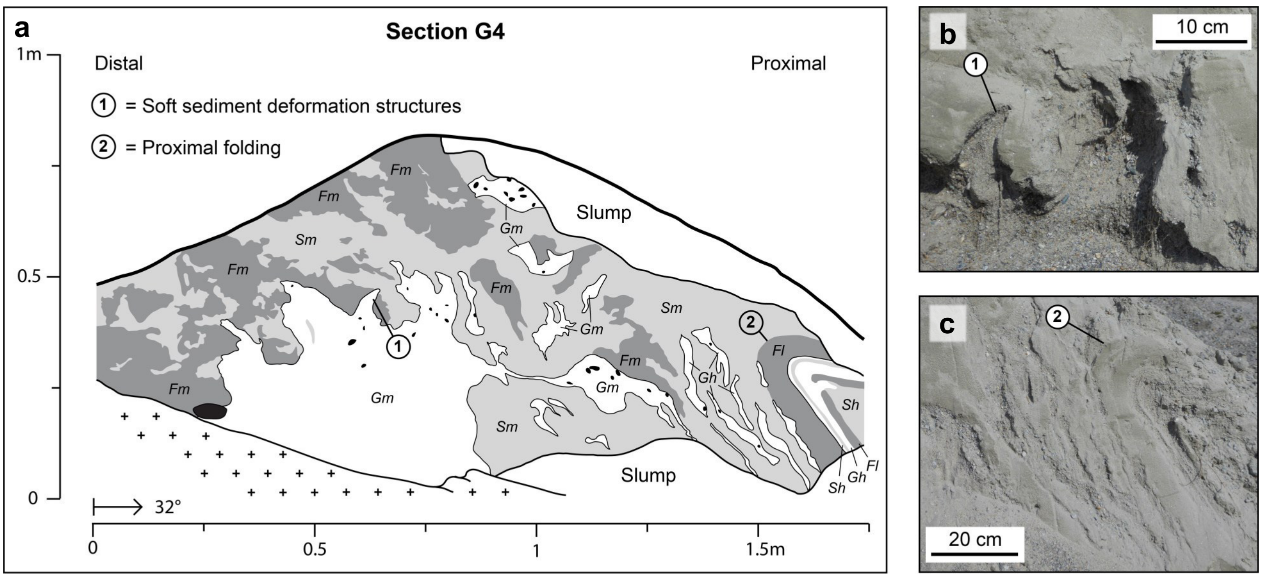

Fig. 16. a. Sedimentary log of section G4. b. Distinct structures of soft-sediment deformation (flames of gravel protruding into overlying sands and silts) in the distal part of the section. C. Folding structure in the proximal part of the section.

al. 1999; Winkler & Nesje 1999; Lukas 2012). However, both the internal architecture and morphology of the moraine seem to have substantially been altered either during or after this deformation. This is evident from the chaotic arrangement of the sedimentary lithofacies in the distal part of the section and especially the widespread presence of flame and loading structures. These structures of soft-sediment deformation can result from the liquefaction and subsequent collapse of water-saturated sediments with density differences between individual units (e.g. Owen 2003; Evans & Benn 2004). The high water content of these sorted sediments could be explained by the low permeability of the underlying metamorphic bedrock which partially impedes drainage of the meltwaters out of the basin. Where moraines are deposited on top of pre-existing proglacial sediments, on the other hand, meltwaters can be evacuated more effectively and therefore, such soft-sediment deformation structures are mostly absent (cf. moraine G3).

4.3.5 Moraine G5 (2009/10)

Moraine G5 is one of the most conspicuous landforms in the foreland of Gornergletscher and the largest annual moraine that is situated within the limit of its 1980 terminal moraine. It is located in the central part of the foreland at a position, where a relatively steep bedrock slope grades over into a shallow basin that is filled with sandy and gravelly deposits, dissected by small braided streams (Fig. 9c). Based on aerial photographs, the formation of moraine G5 can be dated to the end of the accumulation season of 2009/10. The moraine ridge has a total length of ca. 40 m, a maximum width of ca. 12 m, is up to 3.5 m high and characterised by a crestline that is strongly undulated in its vertical extent. The distal slope is marginally steeper (ca. 25°) than the proximal slope (ca. 20°) and equally to moraine G4, slumping and collapse of the friable sediments covering this moraine occurs frequently. This results in a highly irregular moraine morphology and locally steeper slopes both on the distal and the proximal side of the ridge. The sedimentary section through moraine G5 was created at approximately right angle to its crestline (striking 05-25°). However, only the uppermost part of the large moraine body could be exposed due to sediment instability (Fig. 17a).

4.3.5.1 Description of the section

The section created through moraine G5 consists entirely of sorted sediment units but due to the limited extents of the exposure, the presence of a basal diamict

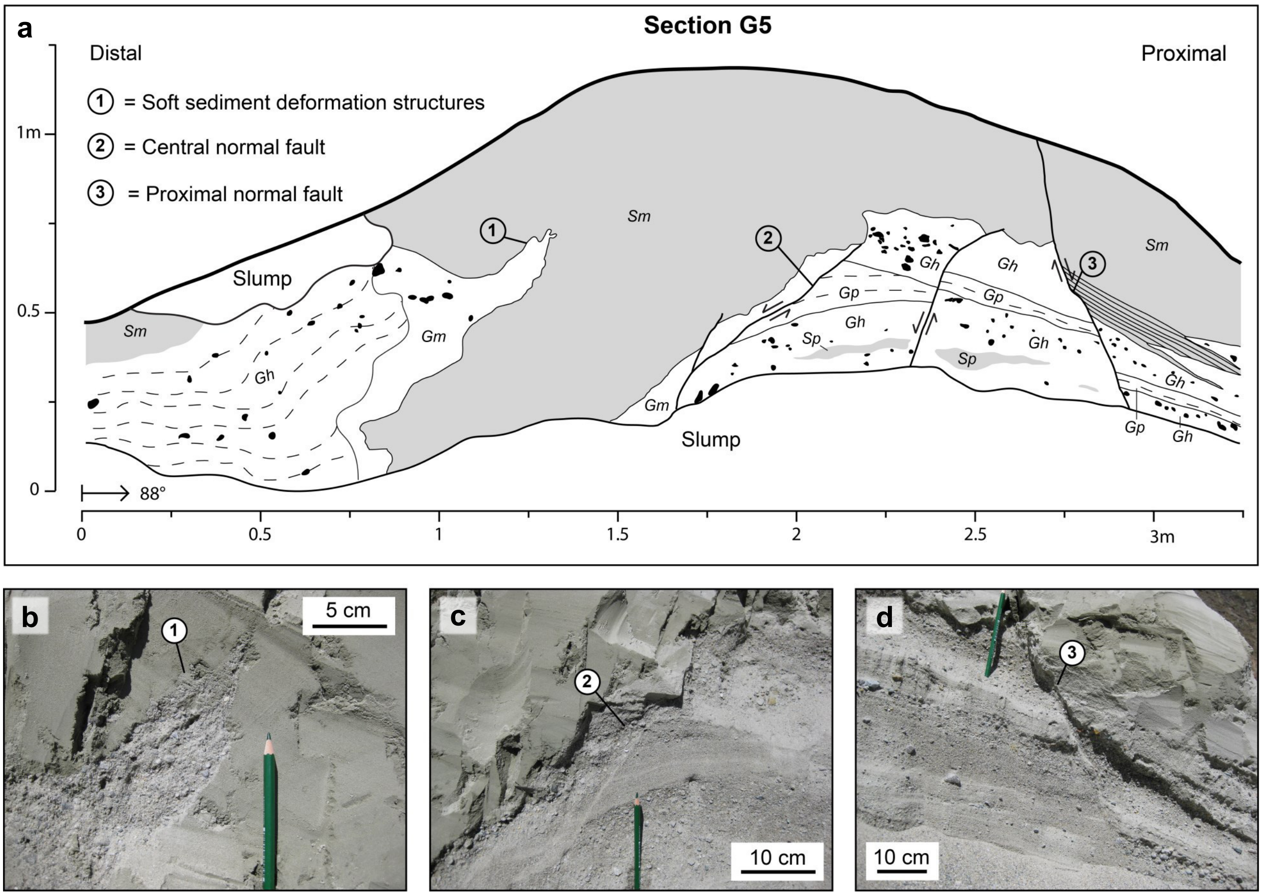

Fig. 17. a. Sedimentary log of section G5. b. Soft sediment deformation structures along the contact of massive sands and gravels in LFA3. c. Normal faulting in the central part of the section. Note to the right on the footwall of the fault stratified gravels of LFA1 and to the left on the hanging wall massive sands of LFA3. d. Prominent normal fault in the proximal part of the section.

in the lower parts of the moraine cannot be ruled out with certainty. It exhibits the most diverse set of sedimentological structures found in any annual moraine within the foreland. For simplification, the units in this moraine will be grouped into three different lithofacies associations (LFAs) based on their sedimentary characteristics. In the following paragraphs, the overall properties of the different LFAs will be described first, before deformation structures and the larger scale architecture of this section will be presented.

LFA1 is present in the proximal part of the section and consists of a sequence of horizontally and planar cross-bedded layers of gravel (*Gh, Gp*) with occasionally incorporated lenses of planar cross-bedded sand (*Sp*). The gravel clasts consist of the regionally present lithologies and are mostly rounded to subrounded although sometimes they also display higher degrees of angularity. Where bedding is horizontal, the beds are gently inclined and approximately follow the slope of the moraine body dipping towards east. Horizontally bedded gravel layers are also present on the distal side of the moraine (*Gh*, LFA2). In comparison to LFA1, these comprise generally coarser grain sizes, fine gravel layers and sand lenses are notably absent throughout this part of the moraine. The bedding of these layers is slightly undulating and beds describe an upwards turn towards the centre of the moraine. In the central and upper parts of the section, a third LFA, consisting mainly of massive, silty sand (*Sm*) is present. Ice-proximally, this unit is directly deposited on top of the horizontally bedded gravels of LFA1 and a subtle lamination of the sand is visible along this contact (*Sh*). In this part, beds of laminated sands and horizontally-bedded gravels are intercalated forming thin wedges. Towards the central parts of the section, lamination structures within the sand are absent and a thin unit of massive gravel (*Gm*) is separating the sand from the underlying sediments. The contact between these units is notably irregular and soft sediment deformation structures, such as flames of gravel protruding into the overlying sand, are frequent (Fig. 17b). A small unit of massive sand is covering the stratified gravels of LFA2 in the distal part of the section. Although it is likely that this sediment body represents a remnant of the massive sand in the centre of the moraine body, a defined contact between these units could not be traced due to the frequent slumping of the sorted sediment bodies along the moraine slope.

The proximal part of section G5 displays a variety of deformation structures, especially normal faulting is common. The trace of the most prominent fault plane dips steeply towards east and offsets the units to its hanging wall by around 20 cm (Fig. 17d). This fault does equally affect the uppermost massive sand and the underlying stratified gravels. A smaller normal fault, with the fault plain dipping steeply towards the centre of the section is visible only within LFA1 and is concordant to an overall stepwise pattern that characterises the contact with the overlying sand of LFA3 (Fig. 17c). A third normal fault dips at a more shallow angle towards the moraine centre and displays the units of LFA3 downwards towards the centre of the moraine. As the units of LFA 3 are heavily affected by soft sediment deformation, no offset could be calculated for this structure.

4.3.5.2 Interpretation of the section

The well-sorted, horizontally bedded gravel layers that dominate LFAs 1 and 2 represent fluvial deposits, where especially cross-bedding structures observed in finer, granulate gravels and lenses of sand incorporated into these successions are strongly indicative for transport by flowing waters (Evans & Benn 2004; Benn 2009). Due to the generally coarser grain sizes in LFA2, it is likely that flow velocities were higher on the distal side of the moraine and decreased towards the proximal side. This can be explained by the setting of the moraine, where on its distal side proglacial streams are rapidly flowing down the steeper bedrock slope and on its proximal side grade over into more slowly flowing braided streams. Yet, the presence of subangular and subrounded gravel clasts excludes an extensive fluvial reworking and indicates that the source of these gravels was very proximal, most likely from previously deposited moraine bodies that were reworked by proglacial streams. Towards the upper part of the section, there is a clear change from the horizontally bedded gravels to the massive body of silty sand that dominates LFA 3. This strongly suggests a switch to a less-energy depositional environment. Most likely, the silty sand can be interpreted as a glaciolacustrine deposit due to the absence of larger grain sizes and the presence of subtle lamination in its proximal parts (Donnelly & Harris 1989). Aerial photographs confirm the presence of a small ice-marginal lake that developed during the ablation season of 2009, changing the sedimentary environment from dominantly fluvial to lacustrine.

A peculiarity of section G5 is that the units in its proximal and distal part display sharp contacts and a set of normal faults, are relatively unaffected by large deformation structures, while the central part of the section is characterised by irregular contacts and pronounced signs of soft sediment deformation. Similar to the interpretation given for moraine G4, the soft-sediment deformation structures indicate the collapse of water-saturated sediments (Owen 2003; Evans & Benn 2004). The fact that these structures are confined to the centre of the moraine indicates the creation of accommodation space in this part of the moraine, resulting in slumping of the water-saturated sediments. The creation of accommodation space is concordant to the orientation of two of the three normal faults in this section. In the setting of Gornergletscher it can most likely be attributed to the melt-out of dead ice that was incorporated into the moraine body during its formation (Kjær & Krüger 2001; Lukas 2012). A dead-ice body confined to the centre of the moraine body would have resulted in the collapse of the overlying, water-saturated sediments, while the successions to its proximal and distal side were only partly affected by brittle deformation. Based on this evidence, moraine G5 was most likely formed through ice-marginal bulldozing with limited incorporation of buried ice, that upon meltout lead to a partial collapse of the overlying sediment units.

4.3.6 Covariance diagrams and transport paths

The use of clast shape and roundness measurements within sediments from glacial environments can provide valuable insights into transport paths and depositional processes (Boulton 1978; Benn & Ballantyne 1993; Benn & Ballantyne 1994; Lukas et al. 2013). In this study, samples were collected from all diamictic units found within the representative annual moraine sections. This includes three consolidated, matrix-supported diamicts within moraines G1 (LF1), G2 (LF1) and G3 (LF1) - in the following referred to as basal diamicts - and one loose, clast-supported diamict within moraine G1 (LF2) - in the following referred to as surficial diamict. While triangular clast shape diagrams and roundness histograms were already presented individual for each moraine section, this part will focus on comparing the measurements among each other and to control samples, previously retrieved from Findelengletscher (Lukas et al. 2012). For this purpose the data are presented as covariance-plots of C_{40}- against RWR- (Fig. 18a, c) and C_{40}- against RA-values (Fig. 18b, d), separately for serpentinite and mica-schist control samples (Benn & Ballantyne 1994; Lukas et al. 2013). Meta-granite samples are plotted within the mica-schist diagram as well, although it has to be noted that the lack of control samples for this lithology makes interpretations of these measurements less robust.

Overall, there is a good agreement between the signatures of serpentinite samples from all three basal diamicts. These are characterised by high C_{40} values (86, 94 and 96), relatively low proportions of angular clasts (RA = 14, 16, 20) and an absence of any rounded or well-rounded clasts (RWR = 0 for all samples). The similarity suggests a common transport history for these diamicts, which is further corroborated by the matching visual properties of these sediments (e.g. matrix composition). When comparing this data to the control samples from Findelengletscher, a dominant subglacial control seems to be the most likely explanation for the clasts that are incorporated into the basal diamicts. Extensive fluvial reworking can be ruled out based on the absence of rounded and well-rounded clasts. Conversely, if the diamict would have a dominant supraglacial source, higher proportions of angular clasts would be expected. The is corroborated by textural characteristics such as striae which are frequently found on the surfaces of serpentinite clasts as well. However, the signatures of the basal diamicts do not exactly match the subglacial control envelopes from Findelengletscher. Notable differences are the extremely high C_{40}-values and the increased ratio of angular clasts. On the one hand, these elevated RA- and C_{40} values could indicate a mixed subglacial and supraglacial source of the clasts at Gornergletscher. This could indeed explain the RA-values measured in the mica-schist sample of the basal diamict in section G3 (and possibly also from meta-granite in section G2), which was previously interpreted to have experienced limited reworking in front of the ice-

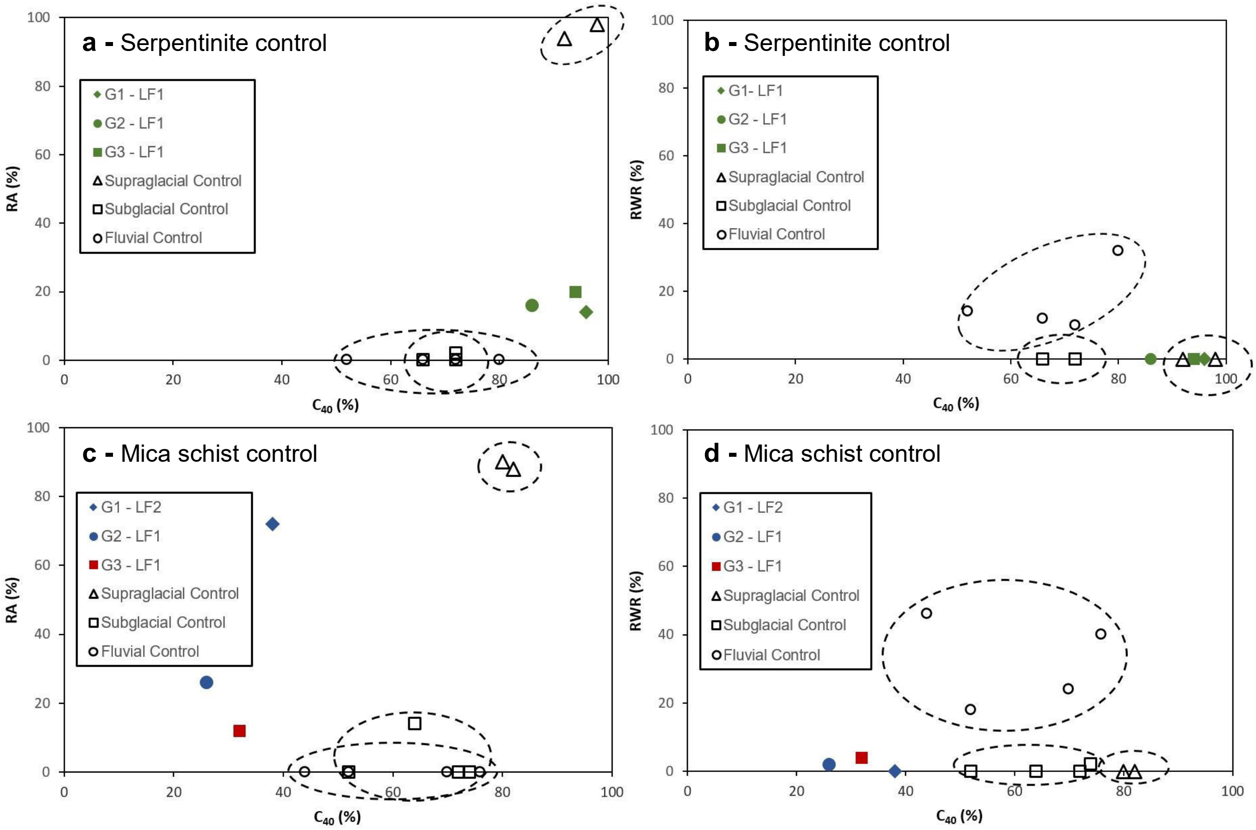

Fig. 18. Covariance diagrams of (a) C_{40} against RA for serpentinite samples, (b) C_{40} against RWR for serpentinite samples, (c) C_{40} against RA for mica-schist (red) and meta-granite (blue) samples and (d) C_{40} against RWR for mica-schist (red) and meta-granite (blue) samples. Data for control samples of serpentinite (a, b) and mica-schist (c, d) control were obtained from Lukas et al. (2012) study from Findelengletscher.

margin. However, regarding serpentinite samples, this interpretation seems unlikely in the present setting of Gornergletscher, where no serpentinite clasts were found in a primary supraglacial position (cf. chapter 4.1.2). In the catchment of Gornergletscher, serpentinite crops out only as a restricted lens, which is for most parts situated beneath the ice-margin. The steeper bedrock cliffs overlooking the snout of Gornergletscher consist mainly of meta-granite and mica-schist and consequently these lithologies dominate the supraglacial debris load (Bearth 1953). The very ice-proximal setting of the serpentinite lens at Gornergletscher could provide another explanation for the different signature compared to the samples from Findelengletscher, where serpentinite mainly is present in its upper catchment area. This prolonged path through the subglacial traction zone, in combination with a relatively large catchment (Lukas et al. 2012) will lead to a more pronounced edge rounding of initially angular clasts and will reduce the amount of prolate and oblate shapes in the clast shape sample (Boulton 1978; Benn & Ballantyne 1994; Lukas et al. 2013).

In contrast to the previously discussed basal diamicts, the meta-granite clast shape sample retrieved from the surficial diamict in moraine G1 exhibits a different signature, most notably from its high RA-values (72). This strongly suggests a supraglacial source of this diamict, where passive transport on top of the glacier has not been able to remove angular and very angular shapes from the clast samples (Boulton 1978; Benn & Ballantyne 1994; Lukas et al. 2013).

Summarising these results, clast shape analysis suggests that basal diamicts found in annual moraines at Gornergletscher predominately display a subglacial signature. Only individual clast-supported, stratified diamicts on top of moraine bodies (i.e. LF2 in moraine G1) can exhibit a strong supraglacial origin. The influence of fluvial reworking on clasts is found to be extremely limited in the present setting of the glacier front. The dominance of subglacial signatures is in concordance with the results by Lukas (2012) but adds a quantitative dimension to these suggestions. Additionally the results presented in this study have shown that the signature of clast shape samples can substantially differ even between neighbouring glaciers that encompass the same lithological units and are characterised by an overall similar setting (i.e. Gornergletscher and Findelengletscher, Lukas et al. 2012). This highlights the importance of collecting separate control samples, whenever possible to enable a more accurate genetic interpretation of clast shape samples of unknown origin. Also, as neither RA- nor RWR-covariance diagrams could individually discriminate between different control samples, using a combination of the two approaches has been demonstrated to be crucial to effectively untangle the variety of transport paths and genetic processes (Lukas et al. 2013).

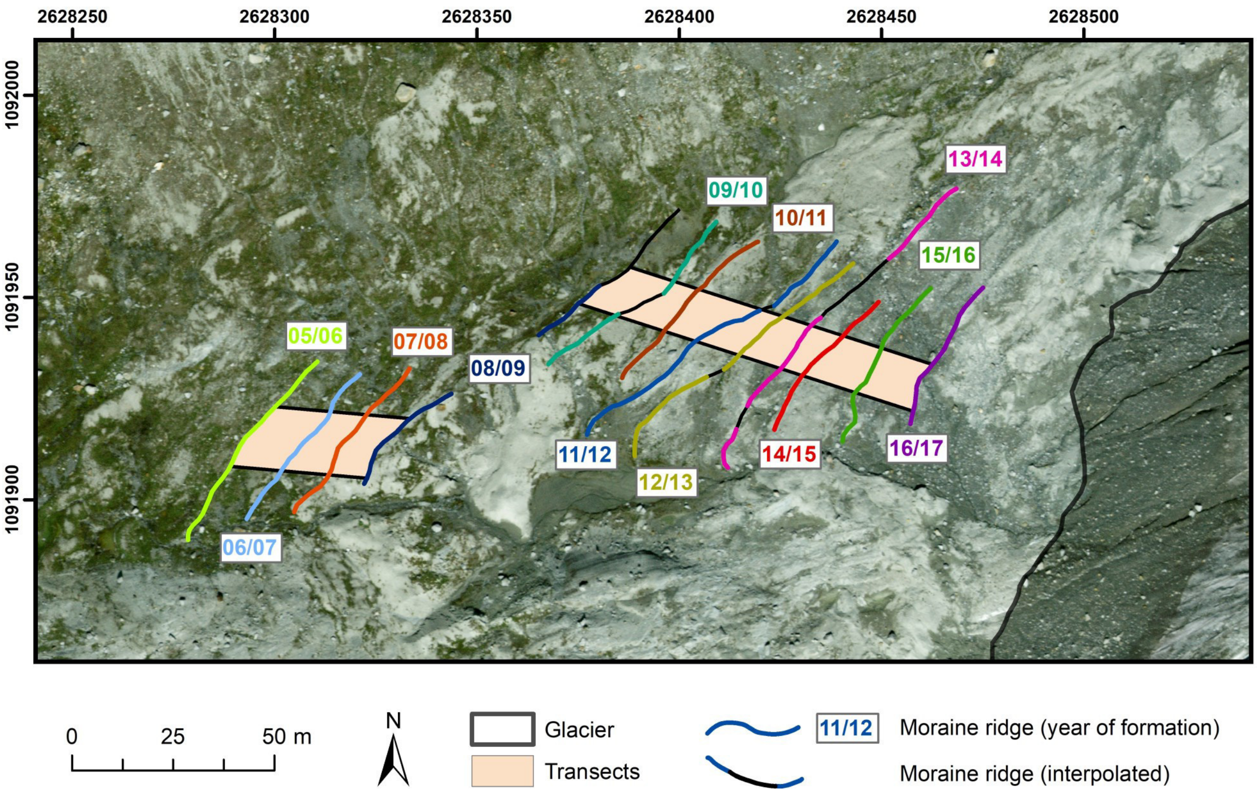

Fig. 19. Location and chronology of annual moraines that were used for climatic correlations in this study. Ice-marginal retreat rates (IMRRs) of the glacier were calculated from the spacing between these moraines along transects in the foreland, where non -climatic factors modulating glacial retreat could be minimised. Average retreat rates were integrated over a defined area (see *transects* in the map layout) to account for the irregularities within the ice-margin. The figure is based on an aerial photograph taken in summer 2018 which was kindly provided by Matthias Huss (ETH Zürich).

4.4 Ice-marginal retreat rates and climatic correlations

4.4.1 Calculations of IMRRs

Ice-marginal retreat rates (IMRRs) at the snout of Gornergletscher were determined from spacing between annual moraine crests for each year from 2007 to 2017 to extend the dataset previously presented by Lukas (2012). When correlating IMRRs to climatic variables, it is crucial to minimise the influence of non-climatic factors on frontal fluctuations. This is especially problematic in an alpine setting, where localised changes of foreland topography or bed composition can substantially modify the rates of glacier retreat (Lukas 2012). Only if these boundary conditions stay constant over a longer time period and moraines are not affected by depositional or erosional censoring processes (Kirkbride & Winkler 2012; Chandler et al. 2016), is it possible to extract a reliable climatic signal from the moraine record.

Through analysis of aerial photographs and field observations, two areas in the foreland of Gornergletscher were identified to be unsuitable for the calculation of IMRRs. The first area is situated in the central part of the foreland where the largest annual moraines are located (cf. moraine G5, chapter 4.3.5). The aerial photograph from 2009 indicates the formation of a small ice-marginal lake at this location during the ablation season. It is possible that the presence of this lake might have changed the very local dynamics of the central part of the ice-front in this period (Tsutaki et al. 2011). Indeed, the N-S orientation of the crestline of moraine G5 is not conform to the overall NE-SW alignment of moraines within the foreland, suggesting a rapid change in the geometry of the ice-margin in this year. The second area that was excluded from the correlation of IMRRs is the cluster of ice-cored moraines that is present in close proximity to the lateral part of the present ice-margin. Because this terrain is notably hummocky and moraine crestlines frequently show bifurcations, reliable measurements of moraine spacing could not be performed within this area. Additionally, the sedimentology of one of these moraines (cf. moraine G1) shows that they most likely originate from ice-marginal debris cones. The crestline of these moraines therefore represents a position on top of the ice-margin, contrary to moraines created by ice-marginal bulldozing, where the crestline is situated in front of it. Because of these uncertainties, the record of moraine spacing was only extended until the year 2017, before ice-cored moraines have been forming during the past two winter advances of Gornergletscher.

The sequence of annual moraine that was considered to be most reliable for climatic correlations is located in the lateral part of the foreland (Fig. 19). This is because (a) these moraines have well-defined crest lines and form parts of longer chains which allows for an integration of ice-marginal retreat over a defined area (Beedle et al. 2009) and (b) because these moraines seem to have predominantly formed by ice-marginal bulldozing and therefore all represent the same position with respect to the glacier front. Additionally, the steepness of the reverse slope is relatively constant throughout the integrated area, which means that topographic effects on glacier retreat can be minimised. The spacing between annual moraines that was calculated along these transects varies between a maximum of 14 m and a minimum of 6.8 m with an average retreat rate of 10.5 m.

4.4.2 Correlations of IMRRs to local climatic records

The IMRRs calculated in this study for the years between 2007 and 2017 were integrated with the previously reported data by Lukas (2012) to obtain a longer record of frontal retreat. Because data from the weather station at Gornergrat were only available from 1994 onwards, the dataset had to be limited to the years between 1994 and 2017, thereby spanning 23 years of frontal retreat at Gornergletscher. For a statistical correlation, annual, summer and winter signals where subtracted from the long term average at the respective stations. These temperature and precipitation anomalies were then compared to the previously calculated IMRRs to evaluate possible climatic drivers for the retreat of Gornergletscher. The strength of these correlations is represented by the coefficients of determination (R^2) and the probability values (p) of a linear regression through these data points (Table 1).

From this data, the following points can be noted: The correlation to IMRRs is strongest for tem-

Table 1. Coefficients of determination (R^2) and probability values (p) for the correlations between IMRRs of Gornergletscher with temperature and precipitation records from MeteoSchweiz weather stations at Gornergrat and in Zermatt. The correlation includes moraines formed between 1995 and 2017 (n = 23) and therefore includes the results of this study and from Lukas (2012). Temperature and precipitation records are split into an ablation season (01.05.-30.09.) and accumulation season (01.10.-30.04.) signal.

	Ablation Season		**Accumulation Season**		**Annual**	
	R^2	p	R^2	p	R^2	p
Temperature (Gornergrat)	0.2983	0.0834	0.2415	0.1248	0.5905	0.0058
Temperature (Zermatt)	0.4280	0.0290	0.1172	0.3028	0.3690	0.0475
Preciptation (Zermatt)	0.1166	0.3040	0.1155	0.3064	0.2318	0.1337

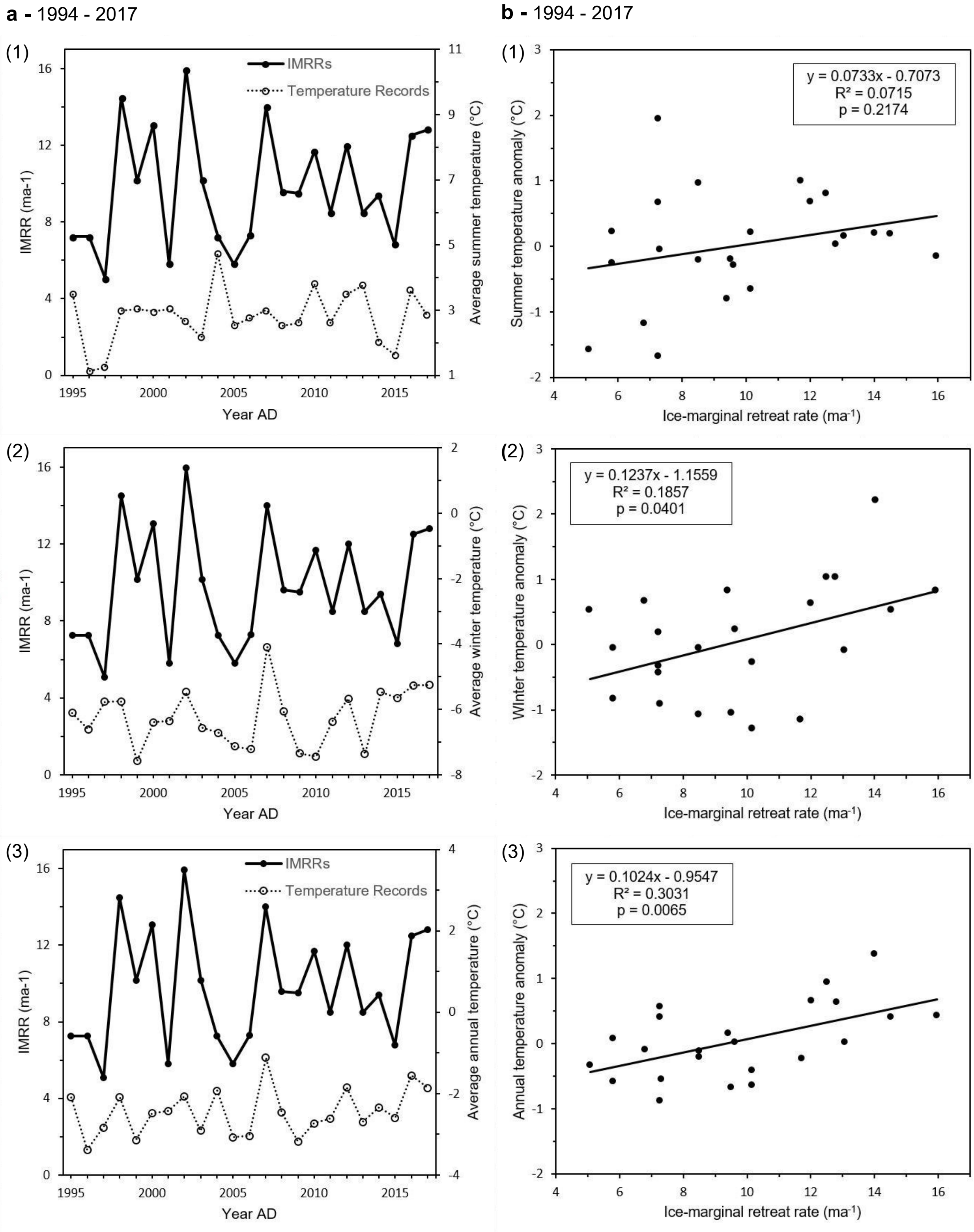

Fig. 20. a. Graphical comparison of annual IMRRs from 1994 to 2017 with (1) average ablation season temperatures, (2) average accumulation season temperatures and (3) average annual temperatures derived from a MeteoSchweiz automatic weather station at Gornergrat. b. Statistical correlation of annual IMRRs from 1994 to 2017 with (1) summer temperature anomalies, (2) winter temperature anomalies and (3) annual temperature anomalies derived from a MeteoSchweiz automatic weather station at Gornergrat. All graphs in this figure integrate data on IMRRs from this study with those previously reported by Lukas (2012).

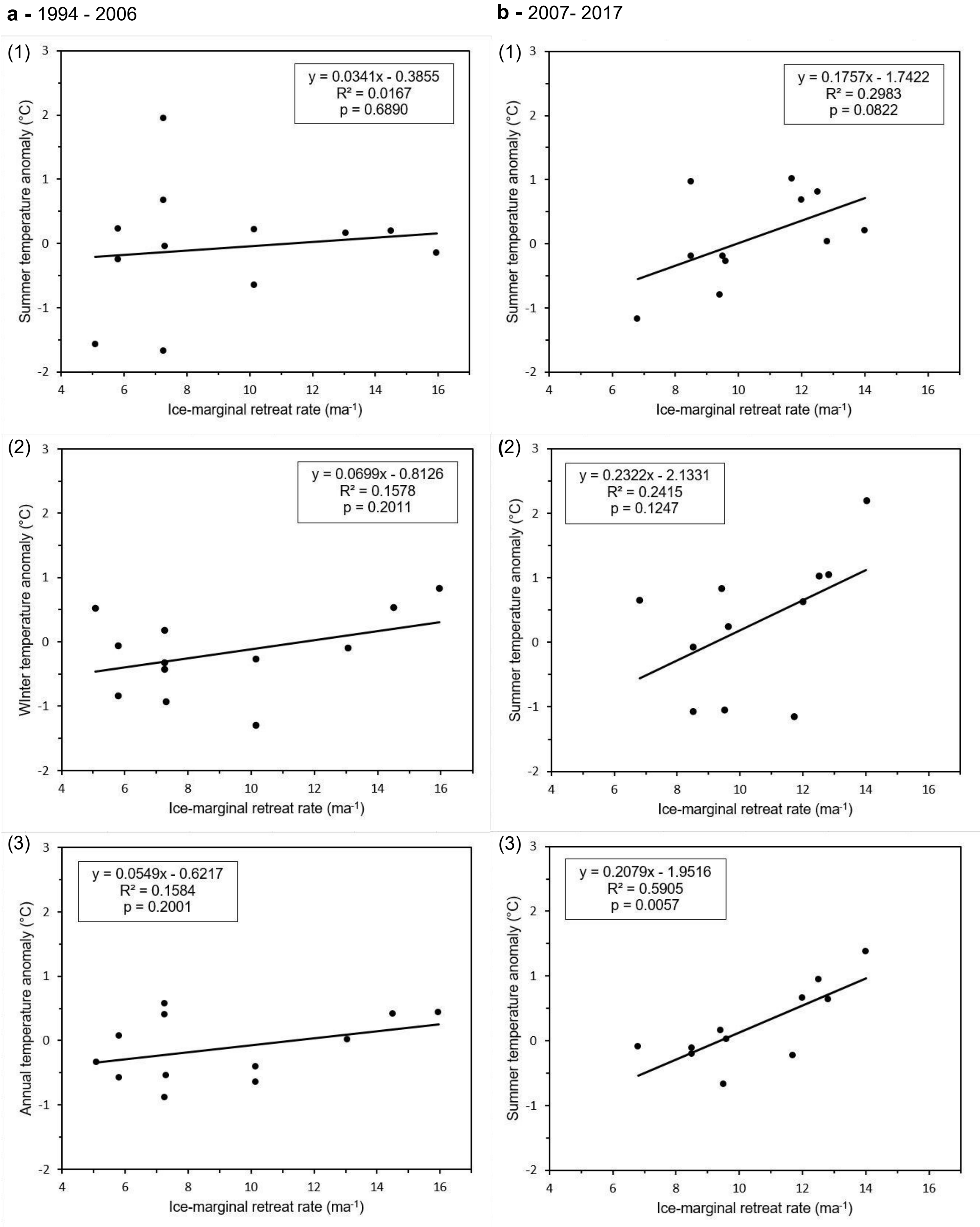

Fig. 21. a. Statistical correlation of annual IMRRs from 1994 to 2006 with (1) summer temperature anomalies, (2) winter temperature anomalies and (3) annual temperature anomalies derived from a MeteoSchweiz automatic weather station at Gornergrat. All graphs in this figure integrate data on IMRRs from this study with those previously reported by Lukas (2012). b. Statistical correlation of annual IMRRs from 2007 to 2017 with (1) summer temperature anomalies, (2) winter temperature anomalies and (3) annual temperature anomalies derived from a MeteoSchweiz automatic weather station at Gornergrat. All graphs in this figure integrate data on IMRRs from this study with those previously reported by Lukas (2012).

perature records derived from the station at Gornergrat. Over the observational period from 1994 to 2017, the correlation is statistically significant ($p < 0.05$) both for winter and annual temperatures, although annual temperatures yield an overall better match ($R^2 = 0.3031$, $p = 0.0065$). The link between IMRRs and summer temperatures on the other hand seems to be less well developed ($R^2 = 0.0715$, $p = 0.0401$). Correlations to the temperature record from Zermatt show a similar pattern, although the strength of the correlation is considerably lower than for the data from Gornergrat. This difference between the temperature records from the two stations is probably owed to very localised climatic conditions and altitudinal differences in the mountain ranges of the upper Mattertal (Denneler & Maisch 1995). Lastly, there was no significant correlation between moraine spacing and precipitation (annual, winter and summer), even when accounting for a delayed reaction (Beedle et al. 2009).

Because of the overall strongest link between IMRRs and temperature records, and the proximity to the study site, it is assumed that the station at Gornergrat is most representative for the local climatic conditions at the study site. To examine more detailed relationship between these variables, the data series is plotted both as graphical correlation (Fig. 20a) and as linear regressions (Fig. 20b) separately. A conspicuous finding that can be seen from the graphical correlation between temperatures and IMRRs is that during recent years the fit between annual temperatures and IMRRs seems to be much stronger than during the previous decades. To test this impression quantitatively, the records of IMRRs and temperature where split into two subsets – moraines formed between 1994 and 2006 and moraines formed between 2007 and 2017. From this, substantial differences between the earlier and later observational period can be seen (Fig. 21a, b). For the years 1994-2006, IMRRs show a somewhat weak correlation to winter and annual temperatures whereas there is no substantial link to the summer record. For the years 2007-2017 on the other hand, all climatic correlations yield stronger correlations and especially the link to annual temperatures is strong. Possible reasons for this observed switch in the link between IMRRs and temperature records will be discussed in chapter 5.3.1.

5 Discussion

In this part, the formation of annual moraines at the contemporary ice-margin of Gornergletscher will be discussed in a wider context. At first, this includes a detailed description of the individual processes that contribute to annual moraine formation and the sequences of events that are typical for these processes in the course of a glaciological year (chapters 5.1.1 to 5.1.3). The suite of processes is then compared to annual moraines in other glacial forelands and controls on the different moraine-forming mechanisms are discussed (chapter 5.1.4). Based on this, the implications of the rapid ice-marginal thinning on annual moraine formation at Gornergletscher are synthesised within a genetic model (5.2). After that, the suitability of using annual moraines as a geomorphological proxy of glacial retreat in high-mountain settings is evaluated (5.3). The thesis concludes with a brief outlook into how annual moraine formation at Gornergletscher might change in the future, coupled with suggestion for further research (5.4).

5.1 Processes of annual moraine formation at Gornergletscher

Based on the sedimentology of representative sections and field-observations during the ablation season of 2019, the processes of annual moraine formation at Gornergletscher during the last decade could be reconstructed. In general, three different mechanisms of moraine formation can be distinguished. In close proximity to the present, thin ice-margin, moraines are created mostly by either freeze-on of submarginal sediments (chapter 5.1.1) or as controlled moraines originating from ice-marginal debris cones (chapter 5.1.2). At further distances to the glacier front, bulldozing of pre-existing proglacial sediments (chapter 5.1.3) is the most common moraine-forming process. Variations of the latter process include post-depositional collapse of water saturated sediment units, or the incorporation of buried ice into moraine bodies through inefficient bulldozing. The individual processes and the controls on the distribution of these processes within the foreland will be explained in stepwise fashion in the following chapters. Conceptual diagrams, visualising the processes of moraine formation are presented in Fig.22. Each process is linked to its sedimentary end-product(s) (i.e. the annual moraine (s) that were created by the respective process) and the part of the glacial foreland, where the process is particularly common.

5.1.1 Freeze-on of submarginal sediments

This process of moraine-formation (Fig. 22a) produces minor moraines that are composed mainly of stratified, subglacial diamicts with a veneer of supraglacially derived debris of limited thickness (cf. moraine G1, chapter 4.3.1). It is restricted to the central part of the glacier foreland, where the ice-front is thinnest and where neither supraglacial debris nor proglacial fluvial or lacustrine sediments are abundant. As a result of the thin ice-margin, the freezing front in early winter can penetrate through the glacier into the submarginal sediments, causing them to freeze onto its sole (Krüger 1993; Krüger 1995; Matthews et al. 1995). Sedimentological evidence from section G1 (i.e. the subglacial signature of clast shape samples and a high degree of consolidation) suggests that the frozen material in this moraine consists of slabs of subglacial traction till (Evans et al. 2006). When the glacier advances in late winter, these till slabs are transported forward at the bottom of the ice over pre-existing ice-marginal material. The coherent transport of the till slabs also ensures that their primary fabric is largely preserved, as compared to other moraine forming processes that would leave their own distinct fabric signature (Evans & Hiemstra 2005; Hiemstra et al. 2015). With subsequent stagnation of the snout and increased temperatures during the following spring and early summer, the basal sediments melt out and are deposited as stratified sediment layers that mimic the wedge shape of the advancing ice-margin (Reinardy et al. 2013). During the thawing of the immediate ice-front, minor amounts of supraglacial material might be dumped onto the moraine body and drape the formerly deposited subglacial sediments.

As outlined above, the freeze-on process at the contemporary ice-margin of Gornergletscher seems to be closely coupled to the emplacement of subglacial traction till into moraine bodies. Such a dominance of till in freeze-on moraines has been frequently reported in the literature before (Krüger 1993; Krüger 1995; Evans & Hiemstra 2005). From other settings, however, the incorporation of pre-existing ice-marginal sediments such as fluvial outwash has also been reported from these moraines (Matthews et al. 1995; Reinardy et al. 2013; Chandler et al. 2016). Additionally, ice-marginal reworking of primary subglacial sediments composing freeze-on moraines has been acknowledged previously (Hiemstra et al. 2015). In fact, at Gornergletscher, the emplacement of pre-existing ice-marginal sediments into moraine bodies via the freeze-on process has also been inferred from the presence of a loose, stratified diamict on the sole of a body of buried ice (Lukas 2012). The incorporation of such sediments into freeze-on moraines might be favoured in areas where proglacial streams are undercutting the thin ice-margin leading both to a liquefaction of the primary subglacial diamicts and the integration of sand and gravel layers into the marginal sediment assemblage.

5.1.2 Formation of controlled moraines

At parts of the present, thin glacier margin, ice-cored moraines with a superficial layer of sorted sediments and potentially the presence of a basal diamict beneath the body of buried ice can be found (cf. moraine G2, section 4.3.2). The formation of this type of moraine can be observed in areas where point sources of debris are accumulating on the glacier surface. As the primary input of supraglacial material from valley sides is found to be limited at Gornergletscher, these debris accumulations are mainly the result of sediments being transported to the glacier surface from an englacial position. The increased thickness of the debris cover will subsequently lead to an insulation of the underlying ice from solar radiation during the ablation season, causing differential melting and the evolution of ice-marginal debris cones. Following ongoing retreat of the glacier, these debris-cones will eventually disconnect from the active ice-margin and become ice-cored moraines *sensu* Lukas (2011). Because the distribution of ice-cored moraines like G2 is governed by the pattern of debris-rich layers within the ice, such moraines can be referred to as controlled moraines (*sensu* Evans 2009). It has to be stressed that the genesis of these landforms is to be clearly distinguished from ice-cored moraines that are formed by the process of inefficient bulldozing (cf. chapter 5.1.3).

Controlled moraine formation is oftentimes reported from arctic, polythermal glaciers (e.g. Evans 2009), however, the presence of englacial debris layers and their genetic relation to ice-marginal debris cones has also been observed from a variety of glaciers within the Swiss Alps (Schlüchter 1983; Goodsell et al. 2005; Lukas et al. 2012; Wyshnytzky 2017). Specifically they are also common at the snout of Findelengletscher, where they provide the main source for the ice-marginal debris load (Lukas et al. 2012). Englacial debris layers at Alpine glaciers might either represent englacial channel fills or consist of subglacial material that gets elevated through thrust faults in the ice (Goodsell et al. 2005). At Gornergletscher, both of these mechanisms probably operate alongside. The presence of edge-rounded, striated serpentinites within englacial shear bands clearly indicates that these clasts originate from a subglacial position (Fig. 11d). Thicker debris accumulations that consist mainly of meta-granitic gravels are more likely to represent the deposits of englacial channels, although clear signatures of fluvial transport are absent within these sediments. Yet, the presence of such conduit fills sediments on the ice surface was already reported previously (Lukas & Sass 2011; Lukas 2012), indicating that they probably represent important point sources that govern the distribution of controlled moraines in the foreland of Gornergletscher.

5.1.3 Bulldozing of pre-existing proglacial sediments

In concordance with the observations made by Lukas (2012), bulldozing of pre-existing proglacial material was found to be the most widespread mechanism of annual moraine formation in the foreland of Gornergletscher. It produces a wide set of different moraines that primarily consist of units of sorted sediments that have experiences varying degrees of syn- and postdepositional deformation (cf. moraines G3, G4 and G5; chapters 4.3.3, 4.3.4 and 4.3.5). As the detailed sequence of processes throughout a glaciological year will largely be influenced by the steepness of the ice-margin, efficient bulldozing (at a steep ice-margin) and inefficient bulldozing (at a shallow ice-margin) will be distinguished from hereon (Lukas 2012).

The process of efficient bulldozing is especially prevalent in areas where the supraglacial debris cover is thin and larger amounts of proglacial sediments are accumulating along the steep ice-margin during the ablation season. These sediments are mostly sands and gravels of fluvial or glaciofluvial origin but in special cases can also comprise more fine-grained material, deposited by seasonally dammed ice-marginal lakes (cf. moraine G5). Locally, the sorted sediments are deposited on top of previously reworked subglacial diamicts that have been exposed by the retreating glacier (cf. moraine G3), but the incorporation of these sediments into moraine bodies is not ubiquitous. During the winter months, this set of pre-existing sediments will be pushed forward by the steep advancing glacier front to form distinct annual moraine ridges. If the proglacial material is evenly spread across a certain part of the foreland, these ridges will create longer series of well-defined, asymmetric moraines in which the internal architecture reflects the horizontal shortening of the sediment layers during ice-marginal bulldozing. Especially ductile deformation structures (i.e. large-scale folding) are widespread alt-

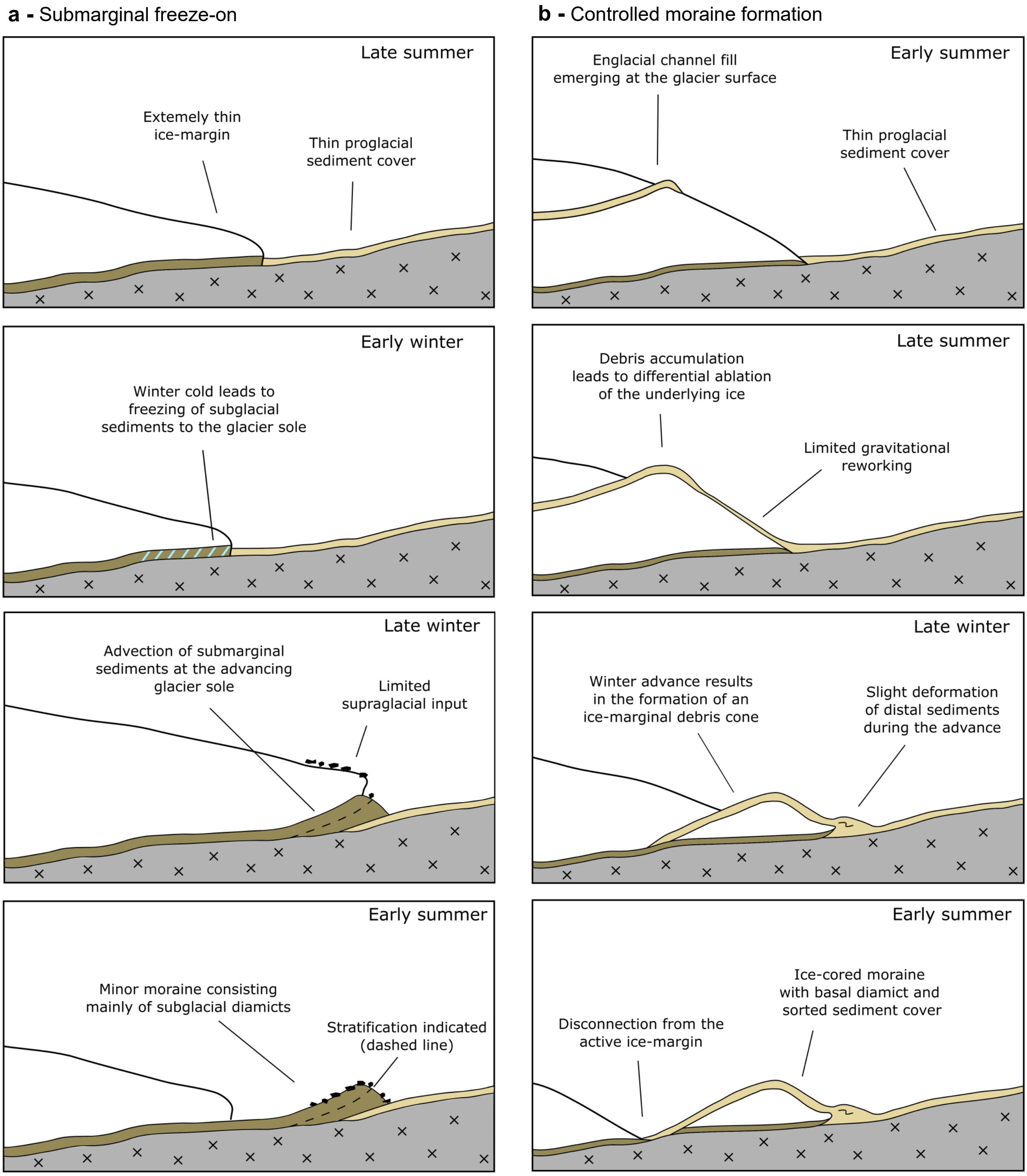

Fig. 22. The mechanisms of (a) submarginal freeze-on and (b) controlled moraine formation, as they operate at the ice-margin of Gornergletscher throughout the course of a glaciological year.

hough Lukas (2012) also reported brittle deformation in the form of reverse faults. During the process of bulldozing, distal sediment units within moraine bodies will tend to become oversteepened and consequently slumping of this material is commonly observed to obscure the primary deformation structures. If the sediments are highly saturated with water, the collapse of these units can lead to the evolution of soft sediment deformation structures (cf. moraine G4). This process is particularly common in areas where moraines are deposited directly onto the gneissic bedrock, which impermeable structure impedes an efficient drainage of glacial meltwaters.

Inefficient bulldozing takes place if the angle of the ice-front is much shallower, such as observed for the recent years at Gornergletscher. In such a setting, fluvial and/or lacustrine sediments can be deposited partly on top of the ice during the course of the

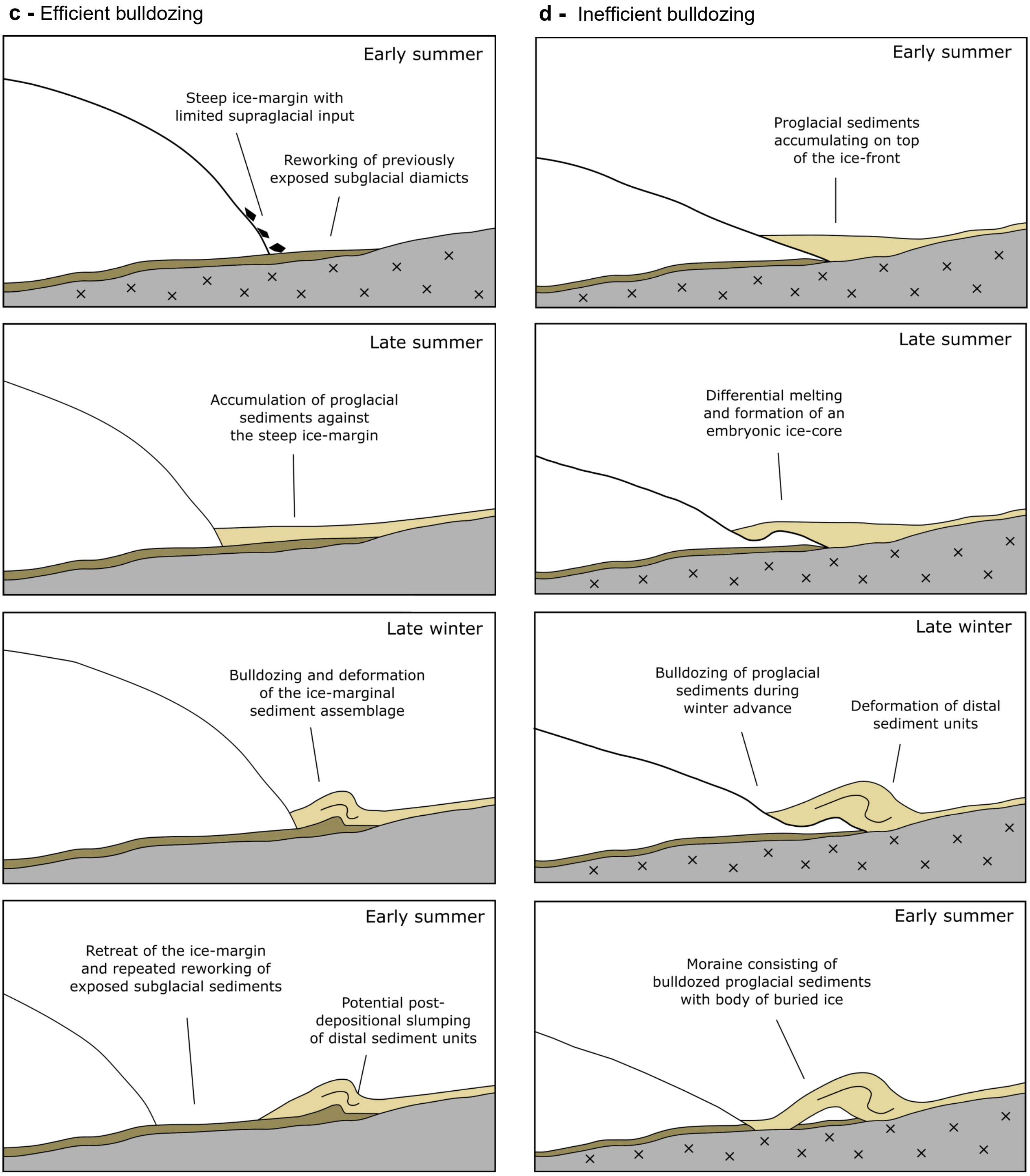

Fig. 22 (cont.). The mechanisms of (c) efficient bulldozing and (d) inefficient bulldozing, as they operate at the ice-margin of Gornergletscher throughout the course of a glaciological year.

ablation season. This is especially the case in areas where the thin glacier snout encounters small deltas that emerge from depressions within bedrock ridges. The thicker sediment cover protects the underlying ice from melting during the summer months, resulting in differential ablation at the ice-front and the formation of an embryonic ice-core underneath the sediments. When the glacier advances in winter, the ice-front will protrude further into the proglacial material. Sediment layers on the distal side of the ice-core will be affected by deformation whereas the sediments that are overlying the ice-core can largely retain their primary depositional structures. Retreat of the ice-margin during the following ablation season results in the disconnection of the ice-core from the active ice-margin and the formation of an ice-marginal moraine that contains a body of buried ice in its centre. Upon melt-out of this ice-core the central parts of this moraine can partially collapse which will be reflected by a wide set of soft sediment deformation structures or reverse faults (Kjær & Krüger 2001; Lukas 2012).

5.1.4 Controls on moraine formation and comparison to other settings

As outlined above, the formation of annual moraines at the contemporary ice-margin of Gornergletscher can be explained by a combination of three different mechanism: (1) freeze-on of submarginal sediments to the advancing glacier sole, (2) the formation of controlled moraines originating from ice-marginal debris cones and (3) bulldozing of pre-existing ice-marginal sediments (which can be efficient or inefficient). This specific set of processes, and especially the presence of freeze-on and controlled moraines is in stark contrast to older moraines in the glacial foreland that are predominately formed by bulldozing processes. Such a temporal development within moraine forming processes was already described by Lukas (2012), who equally observed a general transition from moraines created by efficient to inefficient bulldozing. The controls hereupon therefore merit further discussion. In this context it seems fruitful to evaluate glaciological and climatic boundary conditions that govern moraine formation at other glacier margins and compare them to the present setting at Gornergletscher.

Annual moraines created by a freeze-on mechanism, have been predominantly reported from thin, largely debris-free ice-margins such as Myrdalsjökull, SE-Iceland (Krüger 1995), Styggeldalsbreen, southern Norway (Matthews et al. 1995; Hiemstra et al. 2015) or Midtdalsbreen, southern Norway (Andersen & Sollid 1971; Reinardy et al. 2013). A sufficiently thin glacier front is necessary to allow seasonal surface temperature variations to affect the glacier bed and therefore the snout to become effectively cold-based during winters (Cuffey & Paterson 2010). At the predominantly temperate Midtdalsbreen, for example, pervasive cold-based ice was shown to exist where the ice-margin is thinner than 15 m, enabling the process of refreezing to occur in these areas (Reinardy et al. 2019). At the central part of the present ice-margin of Gornergletscher, this critical ice-thickness is not exceeded for at least 50 m up-glacier and additionally the amount of supraglacial debris is comparatively low. Despite this, freeze-on moraines in the foreland of Gornergletscher are by far not as widespread as in the previously mentioned settings on Iceland and in Norway and seem to be largely restricted to the winter advance of the glacier in 2018/19. The reason for this might also be a climatic one. At Styggeldalsbreen, for example, where freeze-on is the dominant process of moraine formation, average January temperature are around -10°C (Matthews et al. 1995). This is slightly colder than what was measured at the Gornergrat weather station for the previous decade (average of ca. -8.7°C). The weather station is located approximately 500 m above the foreland of Gornergletscher which means that, considering lapse rates of -0.54°C to -0.58°C $(100\ m)^{-1}$, which are typical for the southern part of the European Alps (Rolland 2003), temperatures at the glacier snout are substantially higher (-6 to -5.8°C). Additionally, Lukas (2012) argued that an early snow-cover at the study site might effectively insulate the ground from the cold wave in winter. This is in line with the observation from moraines created by ice-marginal bulldozing, where the dominance of ductile deformation structures suggests that the sediments were unfrozen while they were incorporated into the moraine bodies in late winter (Bennett et al. 2004). In the winter of 2018/19, when moraine G1 was formed, January temperatures at Gornergrat were well below average (ca. -11.9°C). Moreover, in the Valais Alps the majority of snowfall in this season occurred relatively late in winter (Zweifel et al. 2019). The thinner snow cover, coupled with cold air temperatures in December and January, probably created favourable conditions for the freeze-on process to occur in that specific year. Such a sporadic presence of the freeze-on process has been previously reported from the ice-margin of Skálafellsjökull, where the formation of such moraines was equally restricted to years with below average accumulation season temperatures (Chandler et al. 2016).

The formation of controlled moraines at Gornergletscher is closely coupled to the emergence of englacial debris bands and specifically englacial channel fills at the glacier surface. At polythermal glaciers, the upward transport of englacial debris is closely related to the transition from temperate to marginal cold-based ice (e.g. Hambrey et al. 1999; Etzelmüller & Hagen 2005; Evans 2009). Although, as argued above, a thinning of the glacier snout during recent years seems to have resulted in a seasonally cold-based ice-margin, the presence of englacial channel fills at the snout of Gornergletscher had already been recognised earlier when the snout was steeper (Lukas & Sass 2011; Lukas 2012). This indicates that the formation of controlled moraines is not necessarily linked to the basal thermal regime of the snout. Additionally, englacial debris bands have been described from a variety of largely temperate glaciers both in the European Alps (Schlüchter 1983; Goodsell et al. 2005; Lukas et al- 2012) and elsewhere (Spedding & Evans 2002, Swift et al. 2006). From Haut Glacier d´Arolla, Switzerland Goodsell et al. (2005) found that the emergence of debris band was related to the presence of a overdeepening at the base of a steep icefall. Although such a distinct glacial overdeepening is not present within the ice-marginal area of Gornergletscher, the transition from a steep bedrock cliff up-glacier to the reverse slope of the glacier foreland could have resulted in an overall compressional flow pattern in the ice-marginal area. Even if this means that the decreased steepness of the ice-margin is most likely not the primary factor that governs the distribution of controlled moraines at Gornergletscher, it could yet have played a secondary influence. At a steeper ice -front, inputs of supraglacial material are more likely to be redistributed over the glacier surface and slumping down the ice-margin can lead to the formation of ice-contact fans (Lukas 2012). With a more gentle surface slope in recent years, this material is more likely to remain on the ice where differential ablation leads to the formation of ice-marginal debris-cones and eventually the formation of ice-cored, controlled moraines.

To summarise, the occurrence of freeze-on processes and controlled moraines at the present ice-margin of Gornergletscher can most likely directly or indirectly be attributed to a thinning of the glacier front during the recent years. This is in line with frequent evidence for dead-ice incorporation via inefficient bulldozing throughout the foreland (Lukas 2012). This general trend from moraines created mainly by efficient bulldozing to a more complex set of processes is, however, modulated by local factors regarding sediment availability, topography or proglacial hydrology. The local steepness of the ice-front, for example, varies between different parts of the glacier foreland. At the lateral parts of the ice-margin, moraines created by efficient bulldozing were still observed in 2017 (cf. moraine G3), whereas in the central part inefficient bulldozing was observed already several years earlier (cf. moraine G5).

5.2 Synthesis: annual moraine formation at a rapidly thinning alpine valley-glacier

In the previous chapter it was shown that the rapid thinning of Gornergletscher during the last decade has largely influenced the style of how annual moraines are formed within the glacier foreland. Based on this premise, and by integrating the sedimentological observations presented in this study and previously (Lukas 2012), an exemplary genetic model of annual moraine formation at a rapidly thinning alpine valley-glacier is developed in this part. Two general stages within the evolution of the glacier front are distinguished – a steep, convex ice-margin (such as Gornergletscher in the 1980s and 1990s) and a thin ice-margin, dipping at a shallow surface angle (such as Gornergletscher since at least the 2010s).

At a sufficiently steep ice-margin, annual moraine formation will be dominated by the process of efficient bulldozing. The size of these moraines is largely dependent on the availability of proglacial material to be pushed into moraine ridges. Where the glacier encounters larger amounts of fluvial sediments or in special cases also the deposits of ice-marginal lakes, the most prominent annual moraines are formed. Where the proglacial sediment cover is thinner, bulldozing might be restricted to the deformation of pre-existing ice-marginal diamicts with a thinner surficial cover of sorted sediments. If there is a substantial input of supraglacial debris to the glacial system, such as through the emergence of englacial debris bands or englacial channel fills at the glacier surface, this material will to the most extent be redistributed over the steep ice-front to form small ice-contact fans at the glacier margin. These contact fans might subsequently also be affected by bulldozing processes during the winter advance of the glacier. A thinner ice-margin, in contrast, will have less capacities to efficiently bulldoze proglacial material and as a consequence, the set of processes of annual moraine formation is more complex here. If proglacial material is widespread, the deposition of this material on the shallow ice-front can lead to inefficient bulldozing and the incorporation of dead-ice into moraine bodies. If proglacial sediments are not as abundant, moraines can be solely formed through freeze-on of submarginal sediments, assuming winter temperatures are low enough. Lastly, where supraglacial debris accumulations are thick, they can lead to differential melting of the underlying ice and the formation of ice-marginal debris cones and ultimately controlled, ice-cored moraines.

This model primarily reflects the observation gained from continuous observations at a single glacier. However, it may similarly be representative for annual moraine formation at any clean ice alpine valley-glacier that is undergoing enhanced frontal thinning. At the thin ice-margin of Silvrettagletscher, for example, annual moraine formation is equally controlled by a combination of freeze-on, controlled moraines and bulldozing of pre-existing sediments (Wyshnytzky 2017). Yet, for any given glacier foreland, it is important to consider the influence of local effects such as topography, climatic conditions or bed composition and therefore an enhanced understanding of the formation of annual moraines would greatly merit from further research into these landforms at other ice-margins.

5.3 Annual moraines as climate proxy at mountain glaciers

The potential significance of annual moraines in a paleoclimatic context is based on strong correlations between moraine spacings and ablation season temperatures that were established mainly from studies at outlet glaciers of Icelandic ice-caps (Boulton 1986; Krüger 1995; Bradwell 2004; Chandler et al. 2016). The idea is that once longer sequences of annual moraines are identified within the geomorphological record, they can be used to reconstruct short-term glacier fluctuations and ultimately climatic variations over longer time scales (Bradwell 2004; Beedle et al. 2009). More recently, however, the practical applicability of this approach has been questioned, mainly owing to difficulties in establishing reliable moraine chronologies and potential post-depositional erosion of the landforms (Chandler et al. 2016; Chandler et al. 2020). Throughout this chapter, the applicability of using annual moraines as a paleoclimatic proxy at an alpine valley-glacier, such as Gornergletscher, will be discussed and evaluated. This is based mainly on the climatic significance of IMRRs (5.3.2) but also considers the preservation potential of the moraines in the geomorphological record, specifically in the face of recent frontal thinning and its influence on the mechanisms of their formation (5.3.1).

5.3.1 Preservation potential of annual moraine ridges

Annual moraines, as the majority of landforms in modern glacial environments, are subject to varying degrees of post-depositional alteration that may greatly reduce their preservation potential over longer time scales (Kjær & Krüger 2001; Putkonen & O'Neal 2006; Kirkbride & Winkler 2012; Barr & Lovell 2014). Yet, for using annual moraines as a geomorphological proxy of glacial retreat (Bradwell 2004;

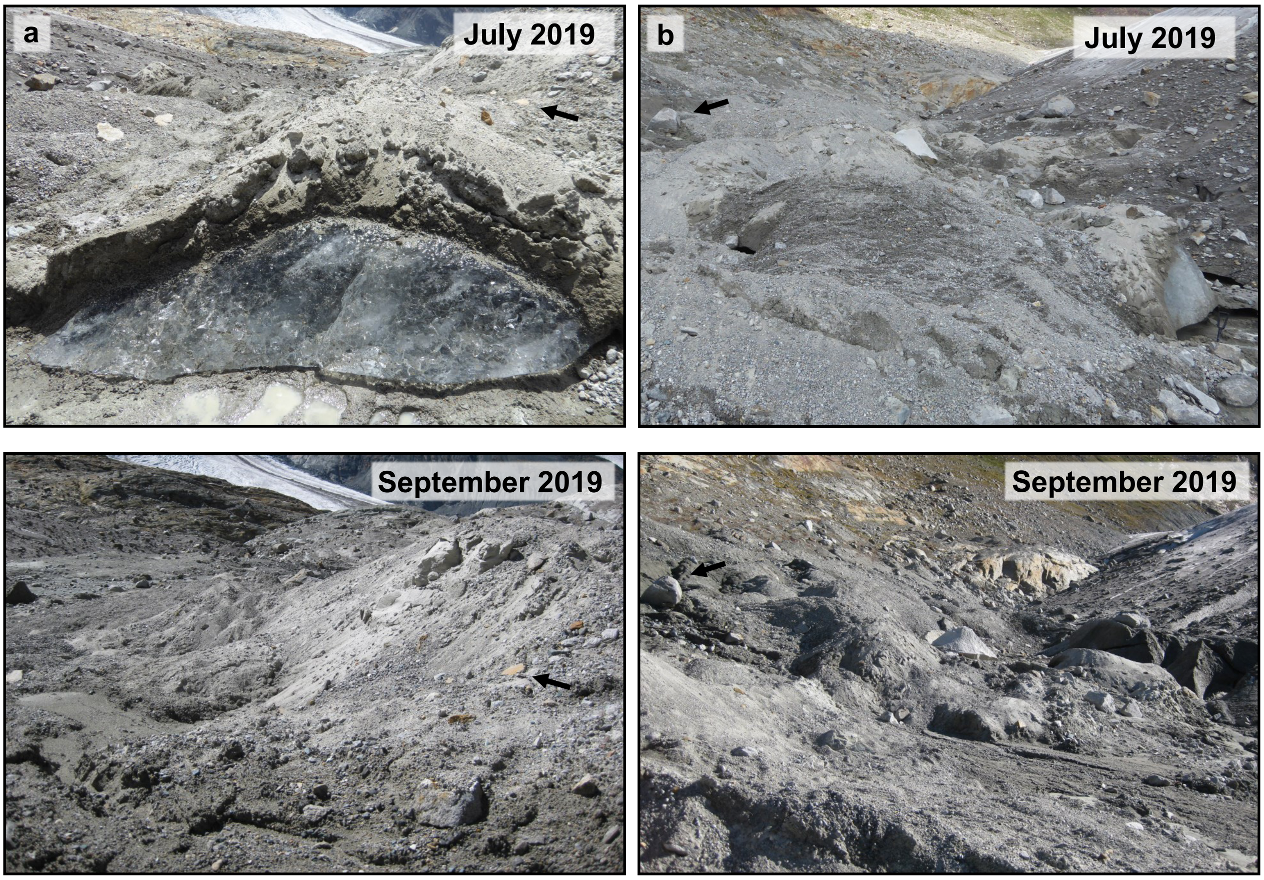

Fig. 23. Degradation of ice-cored features in the foreland of Gornergletscher during the ablation season of 2019. a. The comparison of the two photographs shows the collapse of moraine G1 during the summer months and the subsequent redeposition of the overlying sediments (upper photograph taken 10.07.2019 and lower photograph taken 04.09.2019). b. The comparison of the two photographs shows the general downwasting of hummocky, ice-cored terrain (upper photograph taken 18.07.2019 and lower photograph taken 04.09.2019). Conspicuous rocks or clasts are marked in both comparisons with small black arrows to visualise that the respective photographs encompass the same extent.

Beedle et al. 2009), it is necessary to assure that these landforms will be preserved over the course of at least several decades or centuries so they can be identified within the landscape record. In the present foreland of Gornergletscher the preservation potential of annual moraine ridges seems to be closely coupled to the respective processes of their formation.

Annual moraines with the lowest preservation potential are ice-cored moraines that originate as controlled moraines from ice-marginal debris cones. As evident from section G2, the morphology of these landforms is strongly dictated by the shape of their ice-cores. Therefore it has to be expected that after melting of the ice-core and subsequent resedimentation of the overlying deposits, any surface expression of this type of moraine body will be lost (Kjær & Krüger 2001; Lukas 2011). Indeed, a revisit of the glacial foreland in September 2019 revealed that moraine G2 had completely degraded in the course of the ablation season (Fig. 23a). This was also partly the case for larger ice-marginal debris cones, especially if they were undercut by ice-marginal streams that enhanced bottom-top melting of the ice (Fig. 23b). Only individual controlled moraines in close proximity to the ice-margin were still present by September. This shows that some of these landforms may be stable throughout the full course of an ablation season before the ice-core completely melts out in the following summer. The extremely low preservation potential of controlled moraines at Gornergletscher is probably caused both by relatively warm summer temperatures and the limited thickness of the supraglacial debris cover. This is in contrast to arctic or subarctic environments where such ice-cored moraines can be preserved over the course of multiple decades or more (e.g. Everest & Bradwell 2003). Annual moraines created by freeze-on of submarginal sediments appear to have a slightly higher preservation potential. This is both because they do not incorporate any dead-ice that will lead to a postdepositional alteration of the moraine morphology and because they mainly consist of extremely consolidated subglacial traction till that has a high resistance against erosional processes. From Midtdalsbreen, freeze-on moraines with similar dimensions have been reported to be preserved for at least 40 years in the glacial foreland (Reinardy et al. 2013). It is difficult to assess if this is an accurate estimate for the preservation potential of freeze-on moraines at Gornergletscher as well. This is mainly because no moraines of this type have been forming in previous years when the ice-margin was steeper. Additionally, the formation of freeze-on moraines is at the moment confined to the central part of the ice-margin, where they are subject to extensive alteration and dissection by the largest proglacial streams.

In contrast to the relatively limited preservation potential of freeze-on and controlled moraines in close proximity to the ice-margin, well-defined moraine ridges from the 1980s and 1990s are still visible in the geomorphological record of Gornergletscher. More subtle moraines are also present outside the limit of its 1980 terminal moraine, indicating that the preservation potential of some of these landforms can partly be higher than decadal. Most of these older moraines have been forming by the process of efficient bulldozing or through ice-contact fan formation along a relatively steep ice margin (Lukas 2012). Moraines created by such bulldozing processes therefore seem to be the ones that are best preserved on longer time scales. This is not only caused by the abundance of proglacial material in the foreland of Gornergletscher that allows the formation of relatively prominent moraines ridges, but also because these moraines often form parts of longer, continuous chains. Therefore, even if individual moraines might be partly subject to post-depositional erosion (e.g. by proglacial streams), it is still possible to reconstruct the position of the former ice-margin by interpolating between the neighbouring landforms. The incorporation of dead-ice into these types of moraines via inefficient bulldozing at a thinner ice-margin, however, may lead to significant post-depositional alteration of the moraine body (Lukas 2012). The question if this also reduces the preservation potential of those moraines largely depends on the relative dimensions of the ice-core vs. the moraine body itself. Minor moraines created by inefficient bulldozing (cf. moraine GOR1 in Lukas 2012) that are to the largest extent dominated by their ice-cores will most likely completely be degraded upon meltout in a similar way as it was observed for ice-cored, controlled moraines. At more prominent moraine ridges (cf. moraine G5 in this study) on the other hand, the effect of ice-melting might be restricted to internal changes in sediment structure, while its overall prominent morphology can still remain once de-iced. Yet, even if individual, larger moraine ridges, created by inefficient bulldozing, might be stable over longer periods, the resulting moraine record will be much more patchy and strongly governed by the distribution of proglacial sediment sources. Therefore it is here concluded that the preservation of a continuous sequences of annual moraines that could be exploited for the reconstruction of IMRRs requires a sufficiently steep ice-margin where efficient bulldozing is the dominant process of moraine formation.

5.3.1 Climatic significance of ice-marginal retreat

As opposed to lowland, maritime glaciers, where ice-marginal retreat is closely coupled to average ablation season temperatures (Boulton 1986; Krüger 1995; Bradwell 2004; Bradwell et al. 2013; Chandler et al. 2016), the linkage between climatic forcing, glacier response and moraine formation seems to be more complicated in high-mountain environments. From analysing series of annual moraines at a mountain glacier in the Canadian Rocky Mountains, Beedle et al. (2009) found that, next to ablation season temperatures, glacial retreat is also characterised by a delayed response to accumulation season precipitation. Contrary to this, Lukas' (2012) study from Gornergletscher was the first to report a link between moraine spacing and accumulation season temperatures. A similar correlation was later again established for annual moraines in the foreland of Silvrettagletscher (Wyshnytzky 2017). The data on ice-marginal retreat rates (IMRRs) at Gornergletscher, presented in this study, underline the complex response of this alpine-valley glacier to climatic forcing. Averaged over a longer observational period (1994-2017), IMRRs show a somewhat weak correlation to accumulation season temperatures but the strength of this correlation is relatively low ($R^2 = 0.1857$, $p = 0.0401$). These results are in good concordance with the data previously presented by (Lukas 2012) over the time period 1982-2006 ($R^2 = 0.2026$, $p = 0.0240$). However, the more recent data show a closer match between IMRRs and annual temperatures ($R^2 = 0.3031$, $p = 0.0065$), whereas from the earlier observational period this link is not as strong ($R^2 = 0.1925$, $p = 0.0282$; Lukas 2012). This becomes especially evident when limiting the data to the most recent years between 2007 and 2017. For this period the correlation between moraine spacing and annual temperatures is especially significant ($R^2 = 0.5905$, $p = 0.0057$), which indicates that frontal retreat is governed by both winter and summer temperatures (cf. chapter 4.4.2).

This apparent disagreement between the climatic significance of younger and older moraine records at Gornergletscher merits further discussion. On the one hand, the modified response of the glacier to climatic forcing could be a glaciological phenomenon, related to the pronounced thinning that the ice-front underwent during the last decade. From Virkisjökull–Falljökull, SE-Iceland it was shown that enhanced frontal thinning can substantially lower the forward driving stress of the glacier snout (Bradwell et al. 2013). This in turn will limit the potential of the glacier snout to advance during winter and make frontal retreat mainly a function of summer ablation. At Virkisjökull- Falljökull, this process eventually lead to a stagnation of the glacier snout and ceasing of moraine formation (Bradwell et al. 2013). At Gornergletscher, moraines are still being formed on an annual basis, indicating that winter advances are still happening and partly controlling the magnitude of net annual retreat. However, the enhanced frontal thinning could explain why winter temperatures are nowadays not the only factor governing glacial retreat.

Alternatively, however, the modified response of the glacier could also be inherited from variations within the topographical settings of the foreland. It was previously highlighted that extracting a reliable climatic signal from moraine records at high-mountain glaciers might be hindered by complexities in foreland topography or bed composition (Lukas 2012; Wyshnytzky 2017). Acknowledging that these non-climatic factors can play a significant role in governing frontal retreat, it is of crucial importance to measure moraine spacing along transects in the foreland where these influences can be minimised. For the period between 2007 and 2017, IMRRs were calculated from the spacing between annual moraines that were deposited in areas where the surface slope of the foreland is largely continuous and non-climatic drivers of ice-marginal retreat could be mostly ruled out (cf. chapter 4.4.1). If IMRRs are calculated over a longer observational period, when changes in foreland topography are inevitable and backup from aerial photographs is not as available, it becomes more likely that non-climatic factors are obscuring a potential climatic signal. This perspective might also partially explain why strong correlations between IMRRs and temperature records are dominantly reported from outlet lobes of Icelandic glaciers. These glaciers are mostly terminating on low-topography sandur plains where topographic controls on glacier retreat are negligible as compared to the more complex alpine forelands (e.g. Krüger 1995; Bradwell 2004; Chandler et al. 2016). It is difficult to assess if the changes in climatic representativeness of annual moraine ridges are rather a topographical or a glaciological phenomenon and possibly both factors are contributing. Yet, these considerations highlight the complexity of coupling frontal retreat unequivocally to climatic factors in high-mountain settings (Lukas 2012; Wyshnytzky 2017).

5.3.3 Summary: reliability of annual moraines as a paleoclimatic proxy in high-mountain settings

The previous chapters have highlighted the difficulties that can be connected to a potential use of annual moraines as a paleoclimatic proxy at alpine valley-glaciers, like Gornergletscher. This is especially the case if the glacier is undergoing rapid thinning which might (a) limit the preservation potential of the moraines formed along the thin ice-margin (cf. chapter 5.3.1), and (b) lead to a modified response of frontal retreat to climatic forcing (cf. chapter 5.3.2). As longer sequences of annual moraines can only form during sustained net glacier recession, the presence of these landforms is nearly always coupled to periods with above average temperatures (Boulton 1986; Krüger 1995; Bradwell 2004; Beedle et al. 2009; Bradwell et al. 2013; Chandler et al. 2016). During such climatic conditions therefore any glacier might be subject to enhanced frontal thinning at some point, which in turn will affect the drivers and mechanisms of moraine formation. Therefore great care has to be taken when analysing annual moraines in a paleoclimatic context (Chandler et al. 2016; Wyshnytzky 2017). Ideally, any study will profit from combining geomorphological observations of these landforms with detailed sedimentological data. By doing so, the mechanisms of moraine formation can be better constrained and potential limitations on their climatic representativeness considered.

Even if a longer sequence of well-defined push moraines is preserved in the geomorphological record over the course of several decades or longer, problems might still arise from establishing a reliable chronology of the formation of these landforms (Chandler et al. 2016). At Gornergletscher, an accurate dating of individual moraine ridges was only possible through the use of annual high-resolution aerial photographs. Especially in close proximity to the ice-margin a simple counting back of moraine ridges was hardly possible due to frequent post-depositional alteration of the landforms. In more sparsely researched mountain chains such an availability of remote sensing datasets might be more limited and therefore chronological control less robust. In other settings, lichenometry has been occasionally applied as an additional chronological control for the formation of annual moraines (e.g. Bradwell 2004; Chandler et al. 2016). Although this technique can help to assign sets of moraines to specific periods of glacier recession, it cannot provide an annual resolution which hinders a comparison with detailed climatic data. More recently also the possibility of moraine formation on a subannual basis has been highlighted (Chandler et al. 2016; Chandler et al. 2020). Although this process seems to be closely related to squeezing which has not been observed to operate at high-mountain glaciers yet, it highlights the complexities if moraine formation cannot be described by one and the same mechanism over longer periods.

5.4 Future outlook and suggestions for further research

During the recent decades, the majority of Alpine glaciers has been subject to pronounced thinning and mass loss will likely accelerate in a future warming climate (e.g. Paul et al. 2004; Zekollari et al. 2019). Despite the fact that such thinning has been demonstrated to eventually lead to a stagnation of the ice front and ceasing of moraine formation in other settings (Bradwell et al. 2013), at Gornergletscher moraines are still being formed in its foreland on an annual basis. This means that the retreat of the glacier remains to be dynamic, which is probably caused by its extremely high elevation that ensures sufficient amounts of snow being deposited in its accumulation areas, exerting enough driving stress on the glacier snout to cause temporal advances. However, this study has also demonstrated that the formation of stable annual moraines at Gornergletscher largely depends on the availability of proglacial material to be bulldozed by the advancing ice-margin. In the present glacial foreland this is ensured by the presence of a reverse bedrock slope, where fluvial material gets washed towards the glacier front constantly. Extrapolating the rates of current recession into the future, Gornergletscher will soon retreat from this reverse slope and up a steeper bedrock cliff. It is unlikely that in this future setting, sufficient proglacial material for moraine formation will be available, leading to the assumption that annual moraines will probably cease to be formed in the future, even if the glaciological boundary conditions for their presence (i.e. a seasonally oscillating ice-margin) might still remain fulfilled. This perspective demonstrates that annual moraine formation at any alpine valley glacier is only a temporal phenomenon that can occur if certain glaciological, topographical and sedimentological criteria are favourable. This might also be a part of the reason why comparatively few of these glaciers exhibit longer sets of annual moraines in general.

This study has examined the complexities that are connected to annual moraine formation in high mountain settings both regarding their genetic processes and climatic significance. Further research is therefore needed to better unravel these complexities specifically if annual moraines are used as modern analogues for larger terminal moraines or recessional moraines from Pleistocene settings (e.g. Evans et al. 1999; Ham & Attig 2001). In a recent study, the potential of using uncrewed aerial vehicle (UAV) imagery for untangling the processes of annual moraine formation has been described (Chandler et al. 2020). Using such techniques more widely would provide a valuable tool to obtain a subannual resolution of aerial imagery and therefore to better constrain the sequence of moraine-forming processes over the length of a glaciological year. Additionally such an approach could also help to quantify the relations between ablations season glacier retreat and accumulation season glacier advance. This could present valuable data for understanding climatic influences on glacier retreat and moraine formation in further detail.

6 Conclusions

This study has presented detailed geomorphological and sedimentological characteristics of annual moraine ridges in the foreland of Gornergletscher, a temperate alpine valley-glacier located in the Valais Alps, southern Switzerland. The focus was set on moraines that have been forming between 2007 and 2019, in order to assess the implications of recently observed rapid ice-marginal thinning on the genetic processes and climatological significance of moraine formation. The key findings of this work are listed in the following.

- Annual moraines in the foreland of Gornergletscher exhibit varying geomorphological characteristics, ranging from minor moraines up to larger landforms that can reach heights up to more than 2 m. Their geomorphology seems to be closely coupled to the different depositional environments throughout the foreland, with the most well-defined sequences of annual moraines being deposited on top of pre-existing proglacial sediments along the lateral part of the ice-margin.
- The majority of moraines consist of a set of proglacial sorted sediments of either fluvial or lacustrine origin that display varying degrees of deformation structures. Where diamictic sediments are incorporated into moraine bodies, the dominance of subangular, striated clasts indicate a subglacial transport of these sediments through the glacial system. The diamicts include both primary subglacial traction till that has been incorporated into individual moraine bodies, as well as deposits that have been reworked in an ice-marginal setting.
- Based on representative sedimentary sections through five annual moraine ridges, the dominant mechanisms of their formation could be constrained. They include: (1) Freeze-on of submarginal sediments to the advancing glacier front; (2) the formation of ice-cored, controlled moraines from the isolation of ice-marginal debris cones; and (3) bulldozing and deformation of pre-existing proglacial sediments, such as fluvial outwash, by the advancing glacier margin. The latter process can in instances be complicated if dead-ice is incorporated into moraine bodies during the advance, leading to post-depositional changes in moraine sedimentology upon its meltout.
- From comparing the suite of moraine forming processes to process-observations at the ice-margin and the characteristics of annual moraines in other glacial forelands, it is found that recent frontal thinning has exerted a major control on moraine forming processes at Gornergletscher. An important implication of this is that moraines that are deposited along the present, thin ice-margin are oftentimes affected by post-depositional alteration such as the meltout of buried ice and hence the preservation potential of these landforms over longer time scales is largely limited.
- Calculating ice-marginal retreat rates (IMRRs) from spacing between moraine crests revealed that frontal retreat at Gornergletscher after 2006 is closely governed by mean annual temperatures. This is in contrast to observations from previous decades, when climatic control on moraine formation was predominantly correlated to temperatures during the accumulation season. This could imply that summer ablation will become increasingly important for governing glacier retreat at a gradually thinning ice-margin. However, the possibility of non-climatic factors modulating the rates of frontal retreat in a topographical complex alpine glacier foreland is high.
- It is concluded in this study that using annual moraines as a potential paleoclimatic proxy of glacier retreat at alpine valley glaciers is connected to considerable challenges, especially if the ice-margin is thin. However, better understanding the processes that lead to moraine formation and the factors that govern these still can provide suitable analogues to understand the genesis of ice-marginal landforms in general.

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