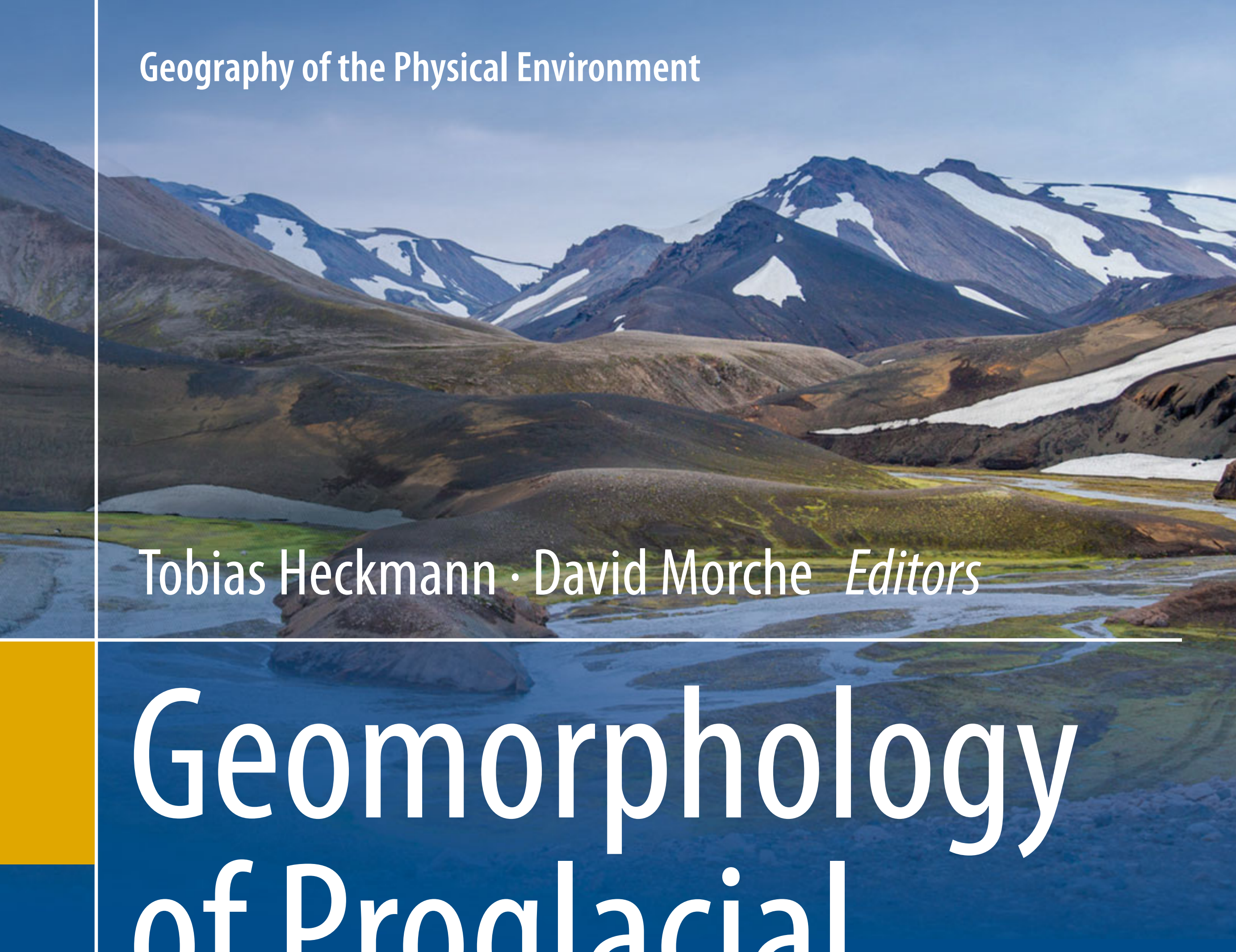

Geography of the Physical Environment

Tobias Heckmann · David Morche *Editors*

Geomorphology of Proglacial Systems

Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes

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Introduction

1

Tobias Heckmann, David Morche and Michael Becht

Abstract

Mountain regions are both sensitive to and disproportionally affected by recent climate change. Among the most important and most visible changes is glacier retreat. The latter entails the exposure of formerly glaciated terrain to subaerial conditions, with implications for hydrological, geomorphic and ecological processes. The geomorphic response to deglaciation has been conceptualised in paraglacial geomorphology, encompassing spatial and temporal changes in the activity of geomorphic processes, slope instability, and the build-up and depletion of sediment storage landforms. The transitional character of these adjustments to deglacial condition has been highlighted in recent research. In this chapter, we propose and discuss the definition of proglacial areas as the area that has been deglaciated since the glacial highstands at the end of the Little Ice Age. We then summarise the geomorphic response to deglaciation and recent geomorphological research in proglacial areas; based on this literature review, we identify avenues of future research. These include (i) investigations extending further into the past based on historical imagery; (ii) the assessment of the relative importance of glacial vs. non-glacial processes; (iii) the role of direct, local climate change impacts vs. the transient response to deglaciation; and (iv) the potential propagation of local geomorphic changes (with connectivity being an important system property moderating this propagation) with potential downstream effects on hydropower generation, freshwater ecosystems and natural hazards. Observing and understanding past- and present-day changes may provide templates for likely responses to future changes. The PROSA project conducted from 2012–2017 in the proglacial area of the Gepatsch glacier, Central Austrian Alps, forms the framework of several case studies presented in the present volume; therefore, we briefly outline the joint project, its study area, research problems and methods.

Keywords

Climate change · Glacier retreat · Little ice age · Paraglacial · PROSA project

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1.1 Motivation

Mountain regions worldwide host complex and fragile ecosystems, provide water and other resources and have always been important for mankind in terms of settlement, traffic and trade, culture and religion (Körner and Ohsawa 2005; FAO 2011). They have been shown to be disproportionally affected by recent climate change (Rangwala and Miller 2012; Beniston 2005). Together with the sensitivity of mountain ecosystems, their topographic and climatic conditions entailing intensive morphodynamics make mountains "sentinels of change" that allow us to observe the consequences of climatic and environmental changes more readily than elsewhere (Beniston and Stoffel 2014). Shrinking glaciers are one of the most emblematic manifestations of climate change today (Orlove et al. 2008; Smith and Joffe 2009), raising public attention for scientific work on glacier fluctuations. The latter have been observed on a global scale; the corresponding records of glacier length and mass balances are interpreted as consequences of measured climate change (Barry 2006; Zemp et al. 2008, 2009, 2015; Leclercq et al. 2014; Chap. 2). Dated evidence of past glacier extents and dynamics (trimlines, moraine landforms and sediments, varved lake sediments, soils and vegetation remains, etc.) has been used to infer climate changes of the past (Klok and Oerlemans 2004; Oerlemans 2005; Joerin et al. 2006). Hewitt (2002) emphasises the significance of mountain glaciers for water and sediment fluxes that is "out of all proportion to their share of the global ice cover. That applies to both landscape development and human affairs" (see also Milner et al. 2017 on the effects of glacier shrinkage on ecosystem services).

Many mountain ranges were shaped by Pleistocene glaciations. Their "glacial legacy" includes a characteristic topography (Sternai et al. 2011), including glacial cirques, U-shaped valleys with steep sidewalls and a wide valley bottom and large sediment stores (e.g. moraines, valley infill); it is, however, not limited to large-scale and long-term effects of multiple "Ice Ages" on the appearance of the present-day landscape. Deglaciation, both on the long and short temporal scale, exposes formerly glaciated terrain to subaerial conditions. In terms of landform and material properties, deglaciated terrain is not at equilibrium with non-glacial conditions and therefore prone to changes. Glacier retreat that started in the second half of the nineteenth century, after the end of a cold phase called the "Little Ice Age" (LIA; Mann 2002; Grove 2004; Matthews and Briffa 2005), has been accelerating (e.g. Zemp et al. 2008, 2009, 2015). Since only few decades ago, scientists have become increasingly aware of the consequences of global warming and deglaciation for "cold regions" at high latitudes and high elevation. These include changes of permafrost properties and distribution (e.g. Kneisel and Kääb 2007), river runoff (e.g. Moore et al. 2009), development of soil (e.g. Egli et al. 2006a, b) and vegetation (e.g. Moreau et al. 2008; Klaar et al. 2015) and the activity of a wide range of geomorphic processes (e.g. Ballantyne 2002b; Laute and Beylich 2014a; Beylich et al. 2016; Carrivick and Heckmann 2017).

Knight and Harrison (2014a) argue that observing and understanding past and present-day changes may provide templates for likely responses to future changes; although there are also differences between recent changes and those that occurred during the Holocene, they highlight the importance of the post-LIA transition for geomorphological research. As we outline in Sect. 1.2, the forefields of receding glaciers are hotspots with respect to the consequences of climate change since the end of the LIA. If these changes were to effectively propagate in the downstream direction, they would not remain restricted to the comparatively small proglacial areas but add to the geoecological, hydrological and geomorphic consequences of climate change on a more regional scale, affecting densely populated mountain ranges and entailing challenges for risk management in these regions (Keiler et al. 2010; Milner et al. 2017). Knight and Harrison (2014a) state that the geomorphic consequences of deglaciation "will become the most significant process controlling sediment supply and landscape change in the mid- to high latitudes over the next few hundred years".

1.2 Proglacial Areas and Paraglacial Dynamics

In alpine terrain, most glaciers are either cirque or valley glaciers, some of them emanating from larger plateaus. For a typical valley glacial landsystem, Benn et al. (2003) identify as most important controls (i) topography, (ii) debris supply to glacier surfaces and (iii) the efficiency of sediment transport from the glacier to the proglacial environment by the glacifluvial system. The elements of a (pro-)glacial landsystem can be categorised according to their geomorphic function as sediment sources, stores and sinks (c.f. Ballantyne 2002a). These functions are associated with geomorphic processes that transfer glacigenic (and other) sediments towards the outlet of the channel network.

Rockwalls, and glacigenic deposits on hillslopes and the valley floor, represent sediment sources. Deglaciated rockwalls are subject to different types of gravitational mass movements, ranging from small-scale rockfall to deep-seated gravitational deformations and rock avalanches (e.g. Cossart et al. 2008; Kellerer-Pirklbauer et al. 2010; McColl 2012; Chap. 8); evidence for destabilisation after deglaciation has been collected by studies that link measured rates of rockfall, rock mass strength and time since deglaciation (Vehling et al. 2016; Chap. 9). Mass movements also occur in surficial materials, both on massive moraine landforms (e.g. Hugenholtz et al. 2008; Klimeš et al. 2016) and comparatively shallow drift-mantled hillslopes (e.g. Holm et al. 2004). Especially steep lateral moraines are reworked by slope wash, fluvial erosion and debris flows (Palacios et al. 1999; Curry et al. 2006; Hürlimann et al. 2012; Haas et al. 2012; Chaps. 10 and 11); debris flows also initiate in steep proglacial gullies (Legg et al. 2014). "Dirty" snow avalanches transferring sediment to and within the proglacial area are another relevant process (Cossart 2008; Laute and Beylich 2014b). These processes supply sediment to storage landforms such as talus cones, debris flow or alluvial fans, and valley fluvial deposits. Sediment storage can be intermediate/short term, and the corresponding landform can function as sediment source for other processes—we may refer to these as sediment stores, while long-term storage landforms (e.g. a lake basin) are termed sinks. Ballantyne (2002a) further distinguishes primary and secondary sediment stores, with primary stores being derived directly from sediment sources and secondary stores being produced by the reworking of primary sediment stores.

The processes listed in the previous paragraph are non-glacial; i.e., they are gravitational, slope-aquatic, fluvial, periglacial, etc. In deglaciated terrain, however, the spatial domains and dynamics of many of them are directly conditioned by (de-)glaciation (Church and Ryder 1972; Ballantyne 2002a), that is, they "would operate at different rates (or not at all) had glaciation not occurred" (Ballantyne 2002a). Several authors have explained the response of geomorphic processes and sediment fluxes to deglaciation in a similar fashion as the reaction to a disturbance such as wildfires, developing a family of conceptual models of "paraglacial geomorphology" (Church and Ryder 1972; Church and Slaymaker 1989; Ballantyne 2002a, b; see also Church 2002). These models describe how morphodynamics and sediment transfer change over time: They highlight the transitional character of the response to deglaciation as topography adjusts, sediment stores are depleted, and/or sediment waves propagate from deglaciated areas through the downstream catchment. The response to deglaciation takes place on different temporal and spatial scales, reaching from decades (at the hillslope scale; Curry et al. 2006; Delaney et al. 2018) to millennia (at the catchment scale; Church and Slaymaker 1989; Buechi et al. 2014), and differs between deglaciated environments (Ballantyne 2002a, b).

Here, we adopt the clarifications made by Slaymaker (2009, 2011) in reaction to ongoing confusion in terminology (proglacial vs. paraglacial vs. periglacial): "Proglacial" refers to an area, "periglacial" is a processual term like fluvial or gravitational, defining geomorphic processes driven by frost. Finally, "paraglacial" addresses the specific morphodynamics (including their development over time) within a deglaciated landscape that were briefly summarised in the previous paragraphs. However, the area “close to the ice front” of a glacier, i.e. the proglacial area as defined by Penck and Brueckner (1909 *fide* Slaymaker 2011), is difficult to delineate in the field today. At present-day rates of glacier melting, the glacier snout in one year may be located tens of metres away from its position in the previous year (see Chap. 2). Moreover, under these conditions, the proglacial area is no longer a system at equilibrium between sediment delivery from the glacier and fluvial reworking (Slaymaker 2011). Where it does exist, this equilibrium is highly dynamic and prone to fundamental changes in system configuration, for example in the glacifluvial domain (c.f. Marren and Toomath 2014; Baewert and Morche 2014; Curran et al. 2017; Shugar et al. 2017). Proglacial systems have therefore been conceptualised as systems in transition from glacial to non-glacial conditions (Johnson 2002), or from an un- or metastable state (a state reached with deglaciation) towards a new equilibrium (periglacial or non-glacial conditions; Slaymaker 2011).

Regarding the delimitation of a present-day proglacial landsystem, we argue that the conspicuous termino-lateral moraines formed by many glaciers during the LIA serve as a reasonable distal boundary. Curry et al. (2006) observed that gullies on lateral moraines of a Swiss valley glacier reached their maximum level of incision approximately 50 years after deglaciation, stabilising within the following 30–90 years. Delaney et al. (2018) report a stabilisation of the Griesgletscher forefield (Switzerland) that has been ice-free since 1986 towards the end of their study period (2014), thus supporting a faster transition; however, the distal boundary of their study area is a reservoir lake, not the LIA maximum extent, which makes a direct comparison difficult. Using the results of Curry et al. (2006), the total of 80–140 years required for this transition is roughly consistent with the period after the end of the LIA (~1850; although other dates have been suggested for the LIA termination, see Matthews and Briffa 2005). Hence, today, the area that has become ice-free since the end of the LIA is characterised by paraglacial dynamics, the most distal parts approaching stability (Carrivick and Heckmann 2017). Under this assumption, the corresponding termino-lateral moraines may be taken as the boundary of a proglacial system, as implemented by Schiefer and Gilbert (2007), Heckmann et al. (2012a, b), Geilhausen et al. (2013), and Bosson et al. (2015). Zasadni (2007) cite Kinzl (1932) and Holzhauser (1982) to justify this definition of proglacial areas (“glacier forefields”) by stating that they are “clearly different from the surrounding area in respect to geomorphic setting, pedological characteristics, floristic succession and the degree of weathering”. In the definition adopted in this book, the ice-marginal criterion still applies, but the transient character of paraglacial adjustment in a deglaciating environment is given more importance (c.f. the “paraglacial landscape”; Slaymaker 2011). It has to be noted though that paraglacial dynamics are not strictly limited to the proglacial area; Church and Ryder (1972) state that paraglacial dynamics occur “around and within the margins of a former glacier”.

The use of LIA glacier extent as a frequently conspicuous boundary of proglacial landsystems facilitates their delineation (Fig. 1.1), quantitative analysis and comparison (Chap. 3). Glacier inventories containing the LIA extents of glaciers have been compiled on the basis of geomorphological evidence, for example in several parts of the Alps (Austria: Fischer et al. 2015; Groß and Patzelt 2015; Piedmont: Lucchesi et al. 2014; South Tyrol: Knoll et al. 2009; Trentino: Zanoner et al. 2017) and the Pyrenees (reviewed by Oliva et al. 2018).

Comparisons with present-day glacier extents show that the distance by which many glaciers have retreated since the end of the LIA is in the order of 10^2 to 10^3 m, and the area deglaciated is in the order of 10^3 to 10^6 m^2 (Chaps. 2 and 3). It should be noted, however, that moraine ridges may be ambiguous or obliterated, making their relation to former glacier dimensions difficult (see Table 1 of Kirkbride and Winkler 2012; Barr and Lovell 2014); moreover, the maximum extent may be of different age in different regions

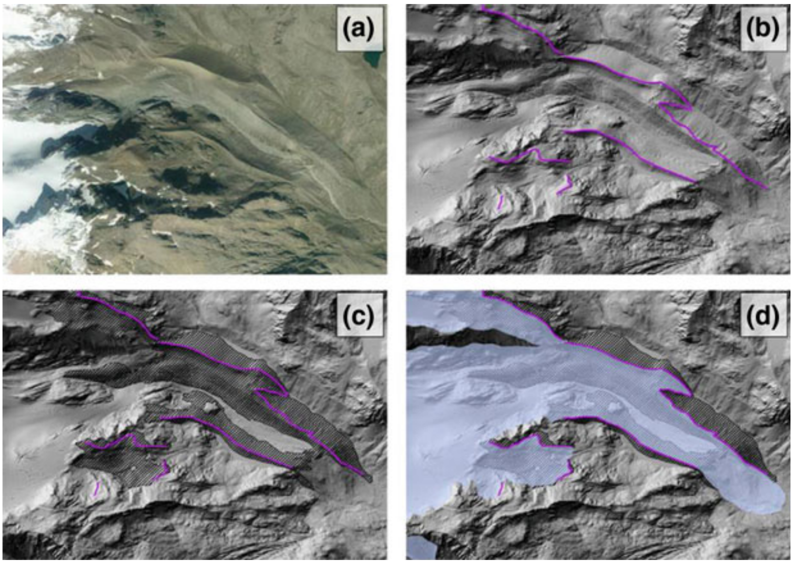


Fig. 1.1 Reconstruction of the LIA maximum glacier extent and LIA and post-LIA glacial deposits (La Mare glacier, Ortles-Cevedale group). **a** Analysis of archival data and visual interpretation of the 2006 orthophoto; **b** identification of the LIA moraine ridges (purple lines) and trimlines on the hillshade relief map derived from a LiDAR digital elevation model (DEM); **c** drawing of the complete area occupied by LIA and post-LIA glacial deposits (polygon areas with black fill symbol); and **d** final reconstruction of the LIA maximum extent of La Mare glacier (light-blue polygon area). *Source* Zanoner et al. (2017), with permission from Elsevier

of the world (Luckman 2000; Mann 2002; Matthews and Briffa 2005). Another problem of our delineation that is focused on post-LIA deglaciation and recent paraglacial dynamics is the neglect of the potentially very large area between the limits of last glacial maximum (LGM) glaciation and the LIA maxima that are characterised by multiple Holocene glacial advances and recessions (e.g. Zumbühl 1980; Nicolussi and Patzelt 2001). This area used to be close to the ice margin as well, experienced associated paraglacial dynamics during and after deglaciation, and may contain sediment sources that affect the present-day proglacial area. Glacier variations before and within the LIA (e.g. Le Roy et al. 2015, 2017) also may have induced multiple phases of paraglacial activity. However, we expect hillslopes adjacent to the LIA glacier forefields to be comparatively stable, given the long period of adjustment since the previous phase of deglaciation; in fact, historical paintings and photographs of nineteenth-century glaciers depict vegetated, even forested hillslopes in their immediate vicinity (e.g. pictures collected by Zumbühl 1980).

1.3 Recent Geomorphological Research in Proglacial Areas

Research in proglacial areas has long been focused on ecology (Matthews 1992). More recently, there has been an increase in geomorphological interest, reflected for example in a series of sessions at the EGU general assembly (2013–2016), a special issue of Earth Surface Processes and Landforms (Heckmann et al. 2016b), and last but not least in the publication of the present volume. In this section, we provide an overview of recent research in proglacial areas and outline avenues of future research.

Proglacial areas are natural laboratories where the initial development of soils and vegetation can be observed (Matthews 1992). This has mostly been based on the investigation of chronosequences (e.g. Egli et al. 2006a for soil;

Moreau et al. 2008 for vegetation). In this “ergodic reasoning” approach, space (=distance from present-day ice front) is substituting time since deglaciation, and sequences of soil and vegetation types and properties with increasing distance from the ice front are interpreted as representing temporal developments. More recent research has identified factors other than “just” time, and increasingly recognises the complex interplay of morphodynamics and soil formation (Temme and Lange 2014; Temme et al. 2015; Chap. 18), and the mutual interactions of vegetation development and geomorphic processes (Eichel et al. 2013, 2015; Chap. 17) that complicate chronosequence studies, particularly on smaller spatial scales (Burga et al. 2010). These disturbances to soil and vegetation development can be caused by glacial and glacifluvial dynamics, and non-glacial processes initiating both within and outside of the proglacial area. Where disturbances are not linked to glacial activity or deglaciation, they are consequently not controlled by terrain age (Matthews 1999 *fide* Eichel, Chap. 19). In geomorphology, chronosequences of landform morphological properties have been investigated to infer the development of morphodynamics (e.g. Curry et al. 2006). However, the interaction of different geomorphic processes, human impact and (dis-) connectivity of sediment transfer lead to site-specific and path-dependent behaviour that may strongly affect the applicability of the exhaustion model at the scale of specific locations or (sub-)catchments (Knight and Harrison 2014a). For example, repeated undercutting and sediment removal from secondary paraglacial storage landforms by the proglacial channel network may lead to sustained incision of lateral moraines because the accumulation of storage landforms is impeded and slope gradients are being kept high (c.f. Chap. 11). Cossart and Fort (2008, Fig. 1.2) use chronosequences and historical aerial photography to explain the geomorphic evolution of an alpine proglacial area; they illustrate how moraines that acted as a barrier to sediment flux at an earlier stage are breached, overspilled, or even act as sediment sources at a later stage. Thus, landforms can both store and release sediment (at different spatial and temporal scales), which adds complexity to the deglaciation response (Chap. 10). The influence of topographic factors on channel patterns in proglacial rivers through the modification of discharge and sediment supply is highlighted by Marren and Toomath (2014). Research projects should aim at monitoring these systems with a focus on the interaction of processes.

Changes in sediment fluxes occur on multiple temporal scales, from sub-daily to decadal (Hetherington et al. 2005; Milan et al. 2007; Mao et al. 2014; Bechet et al. 2016; Guillon et al. 2018; Geilhausen et al. 2012; Micheletti et al. 2015; Chap. 11). This has implications for the temporal scale, that is resolution and extent, of measurements. Investigations in highly dynamic proglacial areas have been facilitated by the advent and increased availability of high-resolution and high-accuracy surveying data. Terrestrial and airborne LiDAR and structure-from-motion (Westoby et al. 2012) enable the detection and quantification of surface changes and the computation of morphological sediment budgets (see recent review by Carrivick and Heckmann 2017; Chaps. 11 and 17). Terrestrial radar interferometry has proven capable of detecting subtle changes of surface elevation (Caduff et al. 2015 and references therein, Rouyet et al. 2016). With expected high rates of surface changes in proglacial areas, these measurement techniques allow for the detection of changes within comparatively short periods of time. A high temporal resolution supports the distinction of surface changes caused by different geomorphic processes, especially where they occur in response to events, or due to specific hydrometeorological conditions. Longer inter-survey periods are more likely to reflect the combined activity of multiple processes. The temporal extent of investigations has been expanded considerably by using historical imagery as a basis for multitemporal mapping (e.g. Ravanel and Deline 2011). Photogrammetric methods such as structure-from-motion are increasingly used to construct digital elevation models from these sources, providing new opportunities for quantitative appraisal of morphodynamics on decadal timescales

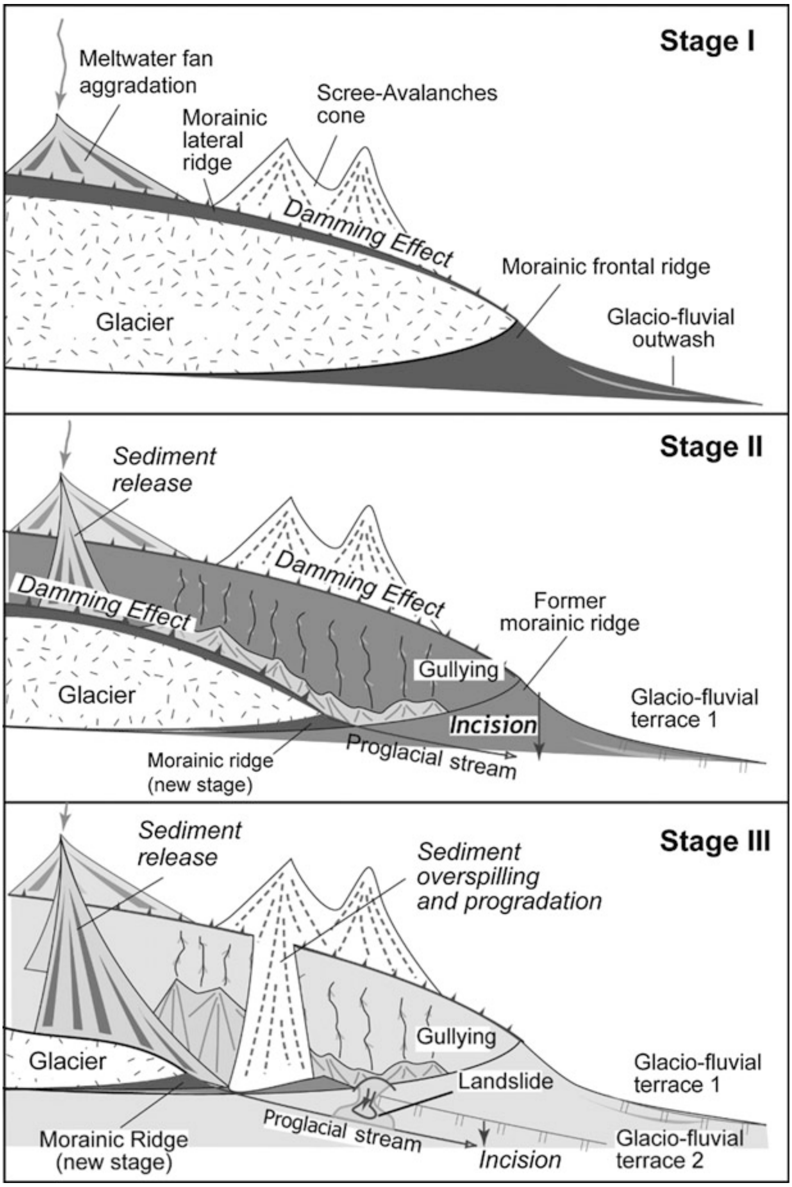


Fig. 1.2 Conceptual model of the geomorphic evolution of a recently deglaciated proglacial landsystem. The presence of moraines creates a damming effect, hence a fragmentation of the cascade sedimentary system, as shown by local aggradation of sediments usptream of both lateral and frontal moraines. The duration of such damming effects depends on (i) the number, volume and cohesion of moraines and (ii) the erosion processes at work on the moraine (note the difference between dammed meltwater cones and undammed scree cones). *Source* Cossart and Fort (2008: 128), with permission from Taylor and Francis

(Schiefer and Gilbert 2007; Micheletti et al. 2015) and model testing (Staines and Carrivick 2015). Future studies should use historical aerial photos and DEMs derived from them to provide present-day measurements with a context of longer-term evolution, e.g. in order to explore path-dependence. Present-day and historical observations and measurements of geomorphic processes and landforms can be complemented by absolute and relative dating of deglaciated surfaces or sediments. However, the short timescale and comparatively high temporal resolution needed to date post-LIA landforms and deposits determine the range of suitable dating techniques. Schimmelpfennig et al. (2014), for example, use cosmogenic nuclides exposure dating (see also Balco 2011) to distinguish pre-, within- and post-LIA surfaces. Sediments in proglacial lakes have been dated using annual varve counts [varves additionally yield sediment accumulation rates and palaeoenvironmental and palaeoclimatological proxies; e.g. Guyard et al. (2007), see also review by Zolitschka et al. (2015)] and radionuclides such as ^{137}Cs. Lichenometry has been frequently used to date moraines or the deposits of mass movements within proglacial areas (e.g. Thompson and Jones 1986; Winkler 2004; Loso et al. 2016). Dendrogeomorphological studies have been conducted to reconstruct glacier advances (by establishing the time when a tree was killed by the advancing glacier), but also, more indirectly, to date paraglacial responses further downstream (e.g. Hart et al. 2010).

Geomorphic change in proglacial areas is also related to the subsurface, specifically the changing distribution of ground ice (e.g. Bosson et al. 2015; Ribolini et al. 2010; Chaps. 6 and 7). This is typically investigated using geophysical methods such as electrical resistivity tomography (e.g. Kneisel and Kääb 2007) or ground-penetrating radar (e.g. Schwamborn et al. 2008). Ground ice dynamics have implications on measurements of changes in surface elevation as they cause changes that may compensate or add to changes that are due to erosion and deposition, providing big challenges for the interpretation of DEMs of difference and the quantification of erosion or deposition (e.g. Sailer et al. 2012; Micheletti and Lane 2016; Avian et al. 2018). The presence of snowcover in DEMs is another reason for the need to conduct such analyses with care (e.g. Carrivick et al. 2013).

The relative importance of different non-glacial processes occurring within proglacial areas needs further investigation, especially in order to compare them to glacial erosion (Harbor and Warburton 1993; O'Farrell et al. (2009) and references therein, Laute and Beylich 2014a, Chaps. 15 and 17). Delaney et al. (2018) conclude that denudation rates in the proglacial area of Griesgletscher, Switzerland, are almost 40 times the rates in the remaining catchment; they also highlight the importance of subglacial erosion for sediment export from the proglacial area. Using a cosmogenic nuclides and geomorphological mapping approach, Delunel et al. (2014) found that more than 75% of fluvial sediments in the glaciated Etages catchment, French Alps, were derived from glaciers (see also Guillon et al. (2015) with a 50–90% proportion derived from subglacial erosion). Other studies found a dominance of non-glacial processes (e.g. O'Farrell et al. 2009), highlighting persistent research needs regarding factors that control the relative importance (e.g. lithology, glacier dynamics, catchment area, glaciated area, relief, connectivity; see Guillon et al. 2018). Proglacial areas with glaciers remaining are judiciously the main focus of present-day research, because the glacial component of the runoff regime maintains high transport capacities and thus enhances the (potential) transfer of sediment beyond the proglacial area. In contrast, former proglacial areas whose glaciers have already disappeared (Chaps. 2 and 3), allow to study the assumed stabilisation of surface sediments and its implications for downstream fluvial systems where this component has already ceased to exist, which is arguably the fate of most catchments in the Alps that are still glaciated today (Haeberli et al. 2013). As the influence of glacial meltwater (see Chap. 3 for an assessment of spatial patterns) declines, the relative influence of snow melt and precipitation is bound to increase. Direct, local impacts of climatic change (e.g. changing intensity and/or frequency of forcing events such as heavy rain) may enhance or attenuate the effects of transient changes such as paraglacial dynamics—the onset and evolution of these does not require climate change except as the reason for deglaciation. Knight and Harrison (2014a) point out that, in case of deglaciation after the LIA, climate change and consequences of deglaciation are coeval rather than subsequent.

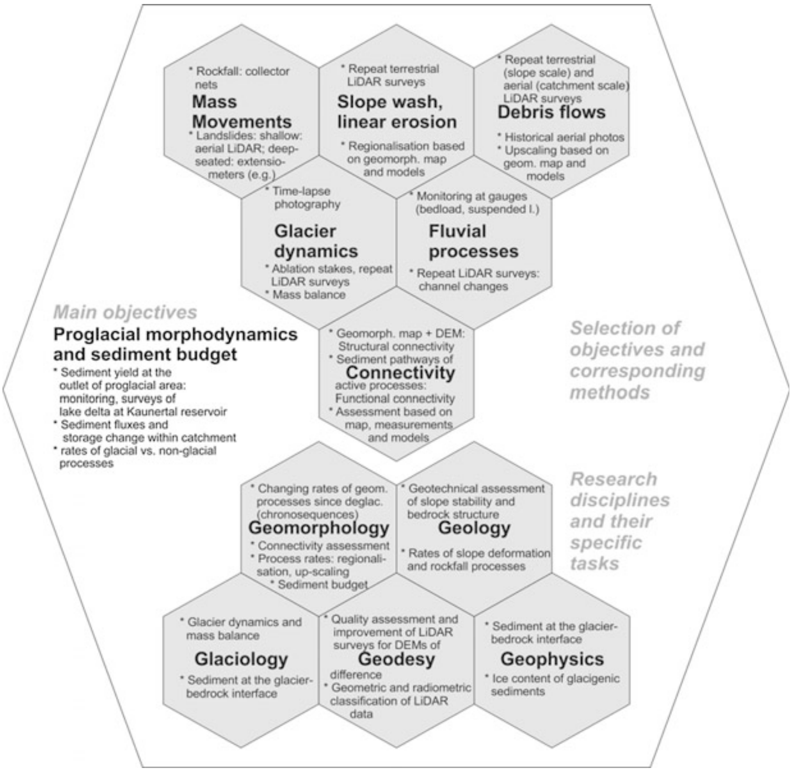
Proglacial areas are part of larger systems that have been described as cascading systems (Burt and Allison 2010; Chap. 15). Consequently, enhanced morphodynamics in proglacial areas may lead to increased sediment loads downstream (Knight and Harrison 2014a), representing a sedimentary disturbance that is being propagated through the system (Church 2002; Milner et al. 2017). These "off-site" effects include issues associated with reservoir sedimentation (Einsele and Hinderer 1997; Geilhausen et al. 2012) and natural hazards (O'Connor and Costa 1993; Richardson and Reynolds 2000; Moore et al. 2009). The propagation of geomorphic changes through mountain catchments, however, may be buffered by poor connectivity (Beylich et al. 2009; Lane et al. 2017; Chap. 16): Specific landforms and their topographic and material properties impede sediment transfer and consequently moderate the (transmission) sensitivity of catchments (Fryirs 2017) to climate and geomorphic change. Cossart et al. (2013) review the effects of landslides on sediment fluxes in deglaciated mountain slopes, stating that their importance as sediment source may be counteracted by disconnectivity: Landslides may not be coupled to other processes, sediments being stored in storage landforms; moreover, landslide deposits frequently construct barriers to sediment flux. At a large spatial and temporal scale, Bernhardt et al. (2017) investigated the propagation of sedimentary signals from the (deglaciating) Andes to marine sediment sinks on the Southern American continental shelf and in the deep ocean. While they inferred a maintained high connectivity in the north-central part of Chile that facilitated the propagation of decreasing sediment flux, the formation of piedmont lakes following deglaciation abruptly led to a decrease of sedimentation in the ocean. Connectivity, however, is not a time-invariant system property. Structural changes such as the re-direction of drainage, lake formation and drainage (Geilhausen et al. 2013; Bogen et al. 2015; Chap. 14), de- or recoupling of system components with the catchment outlet, and those affecting the interaction of processes are found more frequently within a limited area than in other geomorphic systems (c.f. Fig. 1.2). Such system-internal changes are likely to affect sediment yield as well, independent of, or in addition to, climate change. Shugar et al. (2017) describe how the retreat of Kaskawulsh glacier (Alaska) triggered a complete reorganization of the drainage network, which affects, among others, river discharge and sediment transport, water level and sediment influx of a lake. Lane et al. (2017) highlight that connectivity is not only influenced by topography and topographic change but also by the evolution of grain sizes and their implications for sediment transfer (see also Cossart 2008). They also recommend the investigation of the historical evolution of connectivity using historical data (e.g. DEMs reconstructed from historical aerial photos).

To conclude, more data from multiple proglacial areas across different mountain ranges and alpine regions are needed to explore the influence of local/regional (climate, lithology, etc.) versus contingent factors on the evolution of proglacial areas and off-site effects of proglacial morphodynamics. Datasets may include "documentary, geologic, sedimentary, radiocarbon and cosmogenic dating, dendrochronometric, instrumental climate and ecological data types" (Knight and Harrison 2014a: 1). Standardised sampling schemes and techniques should warrant comparability (Milner et al. 2017; see e.g. Beylich et al. 2007). Based on improving understanding of proglacial dynamics, knowledge gained from present-day and historical studies should be combined with the results of regional climate models in order to assess future trajectories of sediment fluxes (Micheletti and Lane 2016). In some study areas, long-standing records of glaciological, hydrological and geomorphological data exist that need to be organised and published (see Strasser et al. 2018 for an excellent example) in order to be leveraged for such endeavours.

1.4 The PROSA Project

The PROSA project (high-resolution measurements of morphodynamics in rapidly changing *PRO*glacial *S*ystems of the *A*lps) was designed to employ state-of-the-art techniques to quantify and analyse morphodynamics and sediment budgets in proglacial areas. It was run during the years 2012–2017 by five working groups at the universities of Eichstätt-Ingolstadt, Erlangen, Halle (Germany) and Vienna (Austria) and jointly funded by the German Research Foundation (DFG) and the Austrian Science Fund (FWF) (Fig. 1.3).

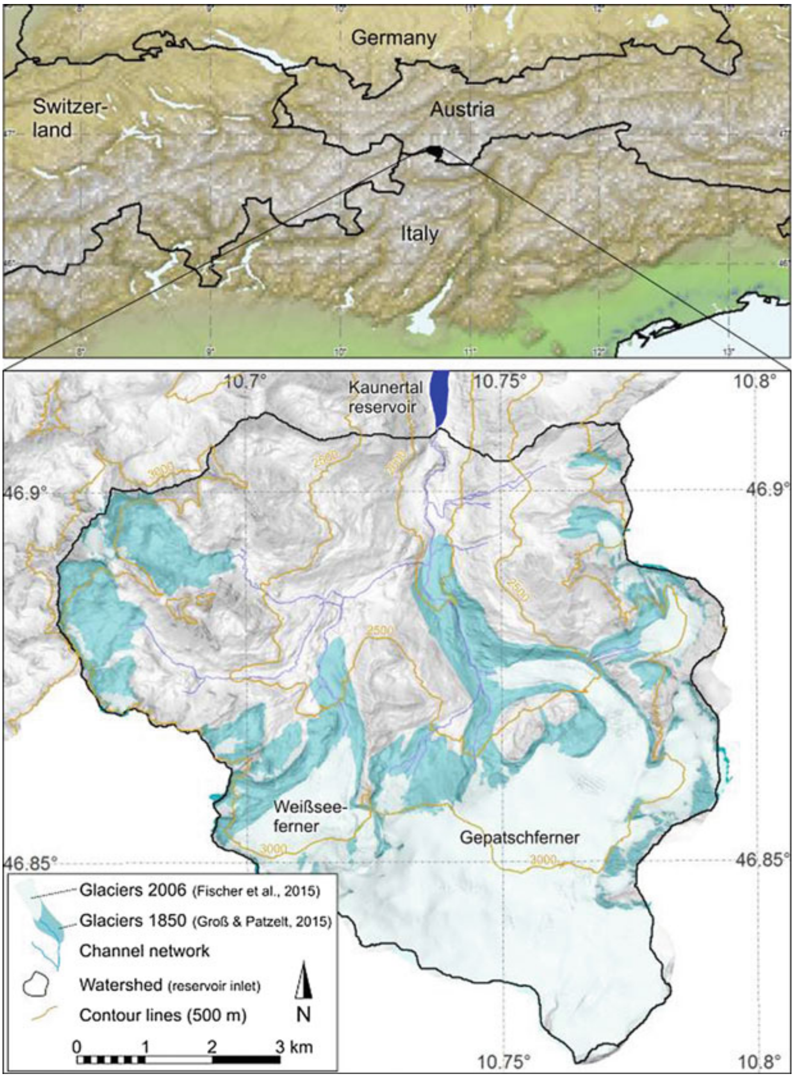
Fig. 1.3 Structure of the PROSA project. The main objectives are addressed from the perspectives of (i) partial objectives referring to processes in proglacial systems (top) and (ii) research disciplines taking part in the joint project, with their specific tasks (bottom)



The overarching research objective of the PROSA project was to set up a holistic sediment budget of the proglacial area of an Alpine glacier (see Heckmann et al. (2012a, b) for a project description). Sediment budgets are “quantitative statement[s] of the rates of production, transport, and discharge of detritus” (Dietrich et al. 1982: 6), and establishing a budget requires “(1) recognition and quantification of transport processes, (2) recognition and quantification of storage elements and (3) identification of linkages among transport processes and storage elements” (ibidem). In rough high-mountain terrain, the measurement of sediment fluxes is still a challenge and requests coordinated interdisciplinary research efforts. Hence, the PROSA team members worked in five research groups from different disciplines, including geomorphology, glaciology, geophysics, applied geology and geodesy. Although proglacial landsystems are regarded as highly dynamic, the short time scale of a publicly funded research project, and the low rate of surface change induced by the majority of geomorphic processes on a monthly scale require the reliable detection of subtle surface changes. The PROSA project aimed to take advantage of the advent of high-resolution, highly accurate and precise surveying techniques that have made such measurements possible since c. 15 years ago. The contribution of geodesy was to harness these techniques for geomorphological, geological and glaciological investigations, including accurate registration of both area-wide airborne and local terrestrial surveys and rigorous error assessment to distinguish significant changes from noise.

The upper Kaunertal (Kauner valley), defined as the catchment area of the river Fagge where it enters the Kaunertal reservoir (c. 62 km^2; Fig. 1.4), was selected as study area. The Kaunertal is a tributary valley of the river Inn, located in the Ötztal Alps, Tyrol, Austria, just north of the Italian border. It has experienced extensive glacier recession and features large, morphologically different proglacial areas (Fig. 1.5). Ample information is available

Fig. 1.4 Map of the study area showing the glacier extent at the end of the LIA (1850; Groß and Patzelt 2015) and 2006 (Fischer et al. 2015)



regarding historical glacier extent (e.g. Hartl 2010, and the Austrian Glacier Inventories, e.g. Groß and Patzelt 2015; Fischer et al. 2015). In the upper Kaunertal, glaciers covered 20.55 km^2 in 2006; the proglacial area, i.e. the area that has become ice-free after the end of the Little Ice Age, amounts to 13.3 km^2. The proportion of glaciated area decreased from c. 55% in 1850 to 34% in 2006. The tongue of the Gepatschferner retreated by c. 2.2 km, with only two short periods of stability or re-advance in the 1920s and 1980s (Nicolussi and Patzelt 2001). The large LIA lateral moraines deposited by the Gepatschferner reach over 200 m of height above the valley floor; they are characterised by intense geomorphodynamics that can be quantified using repeat surveys. The climate of Kaunertal is characteristic of the dry Central Alpine region; mean annual precipitation is between 920 and 1100 mm (at Weißsee and Gepatschalm gauges, respectively, data courtesy of TIWAG, Innsbruck), with a pronounced summer maximum and winter minimum. The mean annual temperature is between 2.8 °C (Gepatschalm, 1941 m elevation) and −0.9 °C (Weißsee, 2516 m).

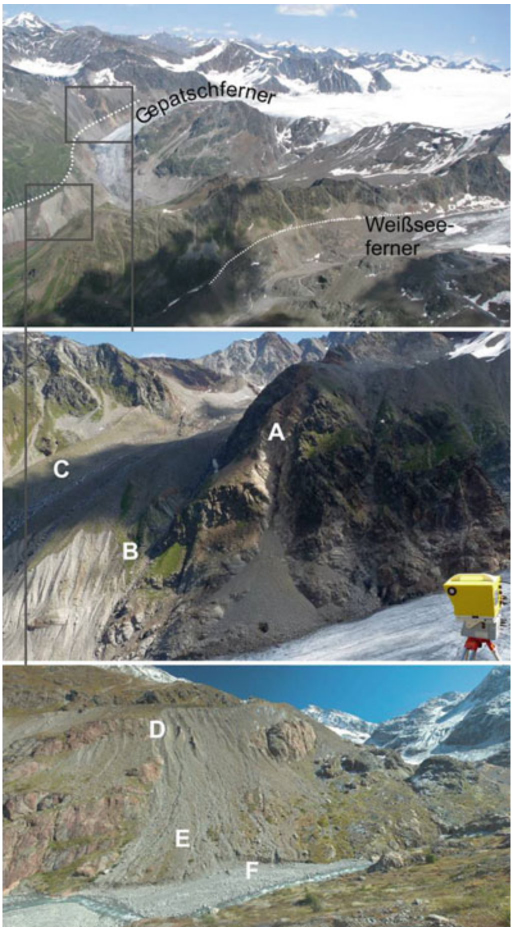


Fig. 1.5 Photographs from the Kaunertal study area. Top: Aerial photograph taken during the airborne LiDAR acquisition campaign on 18 July 2012. The dotted white lines show LIA lateral moraines of Gepatschferner and Weißseeferner glaciers. Contrary to the Gepatschferner, the proglacial area of Weißseeferner shows strong human impact (buildings, roads and construction works associated with ski runs). Photograph: TU Vienna. Middle: A terrestrial laserscanner surveys the unstable rock slope of "Schwarze Wand" on 12 August 2012 including the fresh scar (**a**) and deposits of a major rockfall (see Chap. 9). **b** and **c** denote LIA lateral moraines of Gepatschferner and a tributary glacier, respectively. Photograph: Morche. Bottom: **c** 200 m high section of the LIA right-hand lateral moraine of Gepatschferner with bedrock outcrops. The very steep slope is heavily dissected (**d**) by fluvial erosion and debris flows, the eroded sediment being partially deposited on alluvial/debris cones (**e**). The latter are being undercut by the proglacial river Fagge (**f**). Data from this section are also published in Chap. 10, Haas et al. (2012), Heckmann and Vericat (2018). Photo: Dusik

In addition to the case studies collated in this book, PROSA members have published papers in following fields of research:

- Quantification of rates of geomorphic processes, for example debris flows (Haas et al. 2012), rockfall (Vehling et al. 2016; Heckmann et al. 2016a; Vehling et al. 2017) and fluvial sediment dynamics (Morche et al. 2012; Baewert and Morche 2014; Morche et al. 2015).
- Rapid disintegration of glaciers (Stocker-Waldhuber et al. 2017).
- Genesis and dynamics of rock glaciers and their interaction with glaciers (Dusik et al. 2015).
- Radiometric calibration (Briese et al. 2012) and strip adjustment (Glira et al. 2015) of airborne LiDAR data. The modules "ICP" and "StripAdjust" of the airborne laserscanning processing software OPALS (http://geo.tuwien.ac.at/opals) were developed within the PROSA project.
- Use of DEMs of difference from airborne LiDAR to investigate snow cover on glaciers (Helfricht et al. 2014) and sediment delivery on hillslopes (Heckmann and Vericat 2018).
- Soil development and its interplay with geomorphodynamics (Temme et al. 2016).

1.5 Scope and Structure of This Book

This book focuses on the forefields of alpine glaciers as showcases of both climate-driven glacier retreat and the subsequent reaction of affected geomorphic and geoecological systems, at the small spatial and short temporal scale. The collection contains papers that deal with different aspects of geomorphic change and dynamics in high-mountain proglacial areas, specifically targeting areas that have become ice-free since the end of the LIA. It is intended as an "update" and complement of existing literature on proglacial areas (and paraglacial dynamics), namely Matthews (1992), Hewitt et al. (2002), Ballantyne

(2002b), Knight and Harrison (2009, 2014b). Furthermore, it contributes to the science of glaciers and environmental change (Knight 2006; Martini et al. 2011).

The book is structured by five parts, namely

1. Glaciers and ground ice in the proglacial zone (Chaps. 2–7).
2. Hillslope processes (Chaps. 8–11).
3. Proglacial rivers and lakes (Chaps. 12–14).
4. Proglacial sediment cascades and budgets (Chaps. 15–17), and
5. The role of time and morphodynamics in soil and vegetation development (Chaps. 18 and 19).

The parts and chapters are ordered along virtual sediment cascades (or more generally, cascades of processes), starting from glaciers and adjacent hillslopes (Chaps. 2–11), continuing along the glacifluvial system or ending on temporary or long-term sinks (Chaps. 12–14). The rates of geomorphic processes, and the way they interact spatially and functionally (that is, connectivity) determine the sediment budget of the proglacial area and sediment yield at its outlet (Chaps. 15–17). Soil formation and vegetation development (Chaps. 18 and 19) interact with morphodynamics and may exert considerable influence on these cascades.

Several chapters review the state of science in the respective field of research (Chaps. 2, 4, 6, 8, 10, 12, 14, 15, 16, 18 and 19), while others represent case studies (Chaps. 3, 5, 7, 9, 11, 13 and 17), most of which are derived from the PROSA joint research project (Sect. 1.4).

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Part I

Proglacial Areas, Glaciers and Ground Ice

2

Glacier Changes Since the Little Ice Age

Frank Paul and Tobias Bolch

Abstract

The majority of glaciers are currently retreating globally but had been in an advanced position for several hundred years during the so-called Little Ice Age (LIA). During this period, the lateral accumulation of rock and debris created impressive moraine walls. Between these LIA moraines and the actual terminus position is the glacier forefield, which is growing as glaciers retreat. Whereas the forefields are constantly changing (e.g. due to the transport of sediment and rock, lake formation and growth, plant colonization), the outer boundary marked by the moraines changed little and has widely been used to reconstruct maximum LIA extents and volume for numerous glaciers around the world. Together with field and satellite measurements, a detailed time series of glacier fluctuations since the LIA has been obtained for hundreds of glaciers that indicate some regional and glacier-specific variability, but also robust global trends of shrinkage and volume loss. Overall, the kilometre-scale retreat and upward shift of glacier termini by several 100 m since the end of the LIA confirm a global temperature increase by about one degree. As most glaciers have not yet adjusted their geometry to current climatic conditions, they will further shrink while forefields will continue to grow.

Keywords

Climate change · Little Ice Age · Glacier fluctuations · Glacier mass balance
Glacier inventory

2.1 Introduction

In most regions of the world, glaciers reached a Holocene maximum extent at the end of the so-called Little Ice Age (LIA) and decreased in size more or less continuously afterwards (Grove 2004). This maximum extent was not reached everywhere at the same point in time. For example, in the Alps this was during the seventeenth to nineteenth century (often around 1820 or 1850), in Scandinavia in the mid-eighteenth century and in New Zealand or parts of Alaska in the early eighteenth century (Rabatel et al. 2008). The LIA is understood as a slightly cooler period in the Holocene, lasting from about 1300 to 1850 that is often explained by a reduced solar activity

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(e.g. the Maunder Minimum) along with increased volcanism and internal climatic variability over this period (Grove 2004; Wanner et al. 2008). However, the period was neither geographically nor temporarily homogenous at a global scale and details of the precise timing are still a matter of research (Matthews and Briffa 2005). Dating of moraines and reconstructions from a variety of sources such as pictorial and written documents revealed a detailed chronology of glacier fluctuations over the LIA period for selected glaciers in the Alps (e.g. Zumbühl and Holzhauser 1988; Nussbaumer et al. 2007), Norway (Nussbaumer et al. 2011a) or Patagonia and South America (Masiokas et al. 2009a, b). In general, terminus fluctuations during the period of maximum extent were within a few hundred metres. The exact timing and amplitude of these fluctuations are glacier-specific, e.g. a function of glacier size and slope as well as topographic conditions (e.g. hypsometry and shading) and mass balance sensitivity.

After 1850 however, glaciers globally decreased in size and volume and their fronts retreated by up to a few kilometres for the largest (land-terminating) glaciers (Oerlemans 2005; Vaughan et al. 2013) in response to a general increase in temperature. For smaller and more quickly adjusting glaciers, intermittent phases of re-advance were observed in several regions in the 1920s and 1980s (e.g. Alps, Alaska, Tropics) and 1990s (e.g. Norway, New Zealand, Caucasus), but the specific reasons for these fluctuations might have been different (Chinn et al. 2005; UNEP 2007; Zemp et al. 2015). In the Alps, some glaciers advanced several hundred metres during these periods, but none reached again the LIA maximum extent. Moreover, the 1970s advances did by far not reach the one from the 1920s advance so that glacier forefields (i.e. the ice-free terrain between the current glacier terminus and the 1850s maximum extent) show two further terminal moraine walls within the 1850s extent, a bigger one from the 1920s and a smaller one from the 1970s to 1980s (Fig. 2.1). Outside but very close to the extent from around 1850, glaciers in the Alps and elsewhere have further lateral or terminal moraines from the LIA period. They reveal larger glacier extents before 1850 as they were not buried by the latest advance. In the Alps, these are seldom well preserved and are only slightly larger than the 1850 extent (Fig. 2.2) so that the latter is often taken as a synonym for the maximum extent of the entire LIA. In other regions, however, this is wrong, as former extents (e.g. mid-eighteenth century in Scandinavia or mid-seventeenth century in Patagonia) were much larger than the mid-nineteenth-century extents (Nussbaumer et al. 2011a; Masiokas et al. 2009a). Hence, the '1850s maximum extent' mentioned above and in the following is only the *latest* LIA maximum extent, but often not the largest one in absolute terms. As the lateral LIA moraines from the latest advance are still comparably well preserved and often have vegetation-free inner sides, they can be identified on medium resolution (Landsat-type) optical satellite imagery and related extents can be mapped (Paul and Kääb 2005; Wolken 2006).

In response to a strong increase in global temperature around 1985 (Beniston 2006; Wild et al. 2007; Reid et al. 2016), glacier mass loss increased in many regions of the world (Zemp et al. 2009). As an immediate reaction, glaciers lost mass by surface lowering in the ablation area (Paul and Haeberli 2008). Additionally, several glaciers also started thinning in their upper parts, indicating a disequilibrium response where glaciers will ultimately melt away completely (Pelto 2010). For the time being, the accumulation area of glaciers is too small to sustain their current size and they will thus continue shrinking (Carturan et al. 2013b). This so-called committed area and volume loss will reduce the size of current glaciers by a further 30–60% within the next few decades, even without a further increase in temperature (Dyurgerov et al. 2009; Zemp et al. 2015).

With constantly shrinking glaciers, their forefields constantly grow (Heckmann et al. 2016). If not taken over by lakes that form between the glacier terminus and the LIA moraine or in local overdeepenings of the bedrock (e.g. Haeberli et al. 2016b; Loriaux and Casassa 2013; Chap. 14), the forefields provide new land where soil can develop (Egli et al. 2006; Chap. 18) and vegetation can grow (Chap. 19).

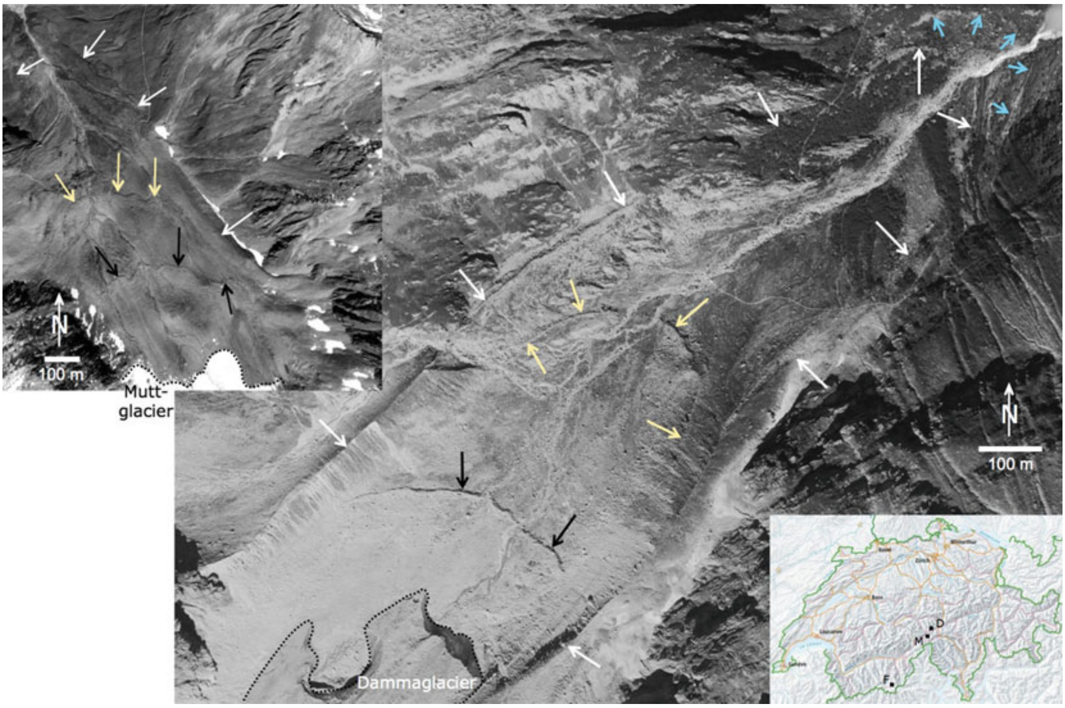

Fig. 2.1 Glacier forefields of Mutt (inset left) and Damma Glacier with moraines from the latest LIA maximum extent around 1850 (solid white arrows), the 1920s (light yellow) and the 1980s (black). Dotted black lines indicate current glacier extents. Short arrows in light blue for Damma Glacier (upper right corner) indicate a possible larger extent before 1850. The inset map in the lower right shows the location of Mutt (M), Damma (D) and Findelen Glacier (F), and the latter being displayed in Fig. 2.2. The image of Mutt Glacier is a satellite image (screenshot from Google Earth), and the Damma Glacier image is based on aerial photography (screenshot from map.geo.admin.ch)

Despite a large amount of studies that have reconstructed LIA glacier extents, little is known about the geomorphological and geomorphometric characteristics of the glacier forefields and their genesis over the past century, maybe apart from a few well-studied cases (see Chap. 3).

As a more glaciological background to glacier forefields, this study provides an overview on the response of glaciers to climate change with a focus on the centennial timescale (Sect. 2.2), observation of glacier fluctuations from the ground and from space (Sect. 2.3), the observed glacier changes since the LIA on a global scale and for the Alps (Sect. 2.4), and a discussion on potential future changes and related developments of glacier forefields (Sect. 2.5).

2.2 Glacier Response to Climate Change

2.2.1 Glacier Formation and Climate

As glaciers originate from compressed snow, they can be found where climatic conditions allow snow to survive summer melting and later accumulation over several decades. This results in three main factors required to build a glacier: temperatures must be sufficiently low so that precipitation falls in solid form and accumulates, precipitation must be sufficiently high that snow survives the summer melting (higher amounts can compensate higher temperatures), and there must