8.9 Erosional Landscapes

AP Stroeven, Stockholm University, Stockholm, Sweden
J Harbor and J Heyman, Purdue University, West Lafayette, IN, USA

Glossary

Areal scouring Glacial erosion over extensive areas resulting in a stripping of regolith and loose sediments and scouring of the underlying bedrock.
Equilibrium line The concept of a line on the surface of a glacier along which accumulation and ablation are equal.
Palimpsest landscape A landscape where traces of several landform generations can be recognized. Palimpsest landscapes in glacial settings are commonly characterized by landforms having cross-cutting relationships formed by ice flow of varying directions. The word palimpsest comes from Greek *pálin* (again) and *psēstós* (scraped) and was originally used for manuscripts where a text written on top of an incompletely removed original text created multiple layers with fragments of text from different times.
Relict landscape A landscape surface that has survived underneath an ice cover without modification.
Selective linear erosion A process of topographically controlled elongated zones of glacial erosion (normally restricted to valleys) and zones of subglacial preservation in between (normally over uplands).

Abstract

Glacial erosion has created distinctive types of landscapes reflecting the extent, duration, and processes of the parent glaciers. Alpine landscapes are representative of pervasive erosion at the local scale. Landscapes formerly covered by larger scale glaciations display a wide range of appearances, from intensively eroded to preserved. Landscapes of selective linear erosion were formed, where subglacial melting occurred along certain corridors that were flanking regions of subglacial freezing. Landscapes of areal scouring were formed where subglacial melting on low-relief surfaces allowed spatially extensive subglacial stripping to dominate. Landscapes of little or no erosion indicate a dominance of subglacial freezing conditions.

8.9.1 Introduction

A recognizable landscape is produced when a set of processes and their patterns, driven by a specific range of environmental conditions, operate with sufficient intensity or time to produce a distinctive assemblage and pattern of landforms. Landscapes of glacial erosion are generally divided into four distinctive types that relate to the scale and type of glaciations (**Table 1**; cf. Sugden and John, 1976).

This landscape classification structure is logical from a historical perspective, given the way in which landscapes are used in glaciology to infer the former impact of ice caps and ice sheets to aid our understanding of glacier dynamics and processes. It also fits well with a perspective of Quaternary landscape evolution (Kleman and Stroeven, 1997; Kleman et al., 2008; Porter, 1989), based on an early Quaternary

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dominance of cirque and valley glaciers, followed by the growth of ice caps and small ice sheets, and ultimately over the past 700 000 years, continental ice sheets. Finally, it links to a general model for ice sheet evolution over a single glacial cycle, starting with the formation of cirque glaciers, expansion out of the cirques forming valley glaciers and ice fields, and finally coalescence of different ice fields into ice sheets (Flint, 1943; Ljungner, 1949). Landscapes of regional and continental glaciation are subdivided by a geomorphological appearance, which in turn reflects the integrated effect of variations in the subglacial process system.

The current landscape represents a snapshot image of an integrated history of the impacts of glaciations; it is often dominated by the last glacial imprint but may contain remnants and influences from prior glaciations and earlier stages of the most recent glaciation. Hence, the landscape we observe may be: (1) a landscape where glacial erosion is simply the last imprint of glaciation; (2) a landscape of extensive and sustained glacial erosion over multiple glacial cycles; (3) a landscape where glacial deposition is the last imprint of glaciation; (4) a landscape of extensive and sustained glacial deposition; or (5) a landscape of little or no glacial erosion. The picture is further complicated by the fact that a particular location may have had a complex history of changing glacial regimes. Hence, understanding the glacial landscape requires visualizing the entire spectrum of ice configurations and their subglacial impact over the integrated time period for which glacial conditions have been effective.

In understanding such complex landscapes, it is good to start by considering landscapes of straightforward origin, where one glacial setting has left a characteristic imprint on the landscape, and this motivates the structure for this chapter. Because several texts have previously explored this (Sugden and John, 1976) or similar structures (Benn and Evans, 2010; Bennett and Glasser, 2009; Embleton and King, 1975), we encourage the reader to refer to one of these for an introduction and overview.

Since the seminal publication of Sugden and John (1976), significant progress has been made in understanding complex landscapes, primarily as a result of an increased awareness that ice sheets can be highly protective at times rather than simply erosive or depositional in nature. We therefore review in much more detail than previous works various perspectives on 'Landscapes of little or no erosion,' and end with a discussion of complex landscapes.

Table 1 A classification of landscape types associated with glacial erosion

	Glacier type	*Glacier system*
Alpine landscape	Cirque and valley glaciers	Local glaciation, glaciers constrained by topography
Landscape of areal scouring	Ice caps and sheets	Regional and continental glaciation, glaciers largely unconstrained by topography
Landscape with little/no erosion	Ice caps and sheets	
Landscape of selective linear erosion	Outlet glaciers and ice streams	

Source: Modified with permission from Sugden, D.E., John, B.S., 1976. Glaciers and Landscape: A Geomorphological Approach. Edward Arnold, London, 376 pp.

8.9.2 Landscapes of Local Glaciation

8.9.2.1 Alpine Landscapes

Alpine landscapes are typically dominated by two dominant form elements: glacial cirques and glacial valleys (**Figure 1(a)**).

8.9.2.1.1 Glacial cirques

Cirques are conspicuous forms of alpine glacial landscapes and in their most typical form exhibit a semicircular amphitheater shape, have steep (vertical) backwalls, and gentle floors commonly with a reversed gradient toward a lip, resulting in a lake-filled depression (tarn) (**Figure 2(a)**). They can be singular features or occur as compound forms. As cirques become enlarged and intersect, they remove the original interfluve topography and create alpine-style sharp-crested topography including arêtes and horns. Most commonly, they form the uppermost and highest portions of glacial valleys, and sometimes of fluvial valleys, and may be isolated features or part of a larger alpine landscape where cirque glaciers advanced beyond their cirque constrictions to form more extensive valley glaciers.

Cirques dominantly occur high in mountainous areas, which were the first areas to become glaciated in the Quaternary and were the seeding areas of glaciation during glacial cycles (e.g., Flint, 1943). Geographically, cirque floor elevations vary as a function of precipitation and temperature – which combine to define the erosional potential of the former cirque glacier. Elevation of cirque floors, therefore, is lower in more maritime areas such as Norway and British Columbia, Canada (Trenhaile, 1975; Vilborg, 1977), and higher in more continental areas. The importance of precipitation in controlling cirque formation is apparent from cirque aspect (direction); cirques occur preferentially on the lee-sides of mountain ranges with respect to predominant wind directions (Vilborg, 1977). Cirques are common features world-wide in formerly glaciated high-mountain areas. They are in part such recognizable features because they experienced the longest time of glaciation, in many places including ice occupation during interglacial periods. Hence, once formed, cirques remain a stable feature of alpine landscapes, even when subsequently overridden by ice sheets (Kleman and Stroeven, 1997).

8.9.2.1.2 Glacial valleys

Glacial valleys occur both as single entities, usually with one or more (compound) cirques forming glacial valley heads, and as compound structures where two or more valleys join to form larger structures. Glacial valley components of alpine landscapes are numerous in formerly glaciated upland areas and can be interpreted as such because of typical suites of erosional landforms associated with this landscape type: such

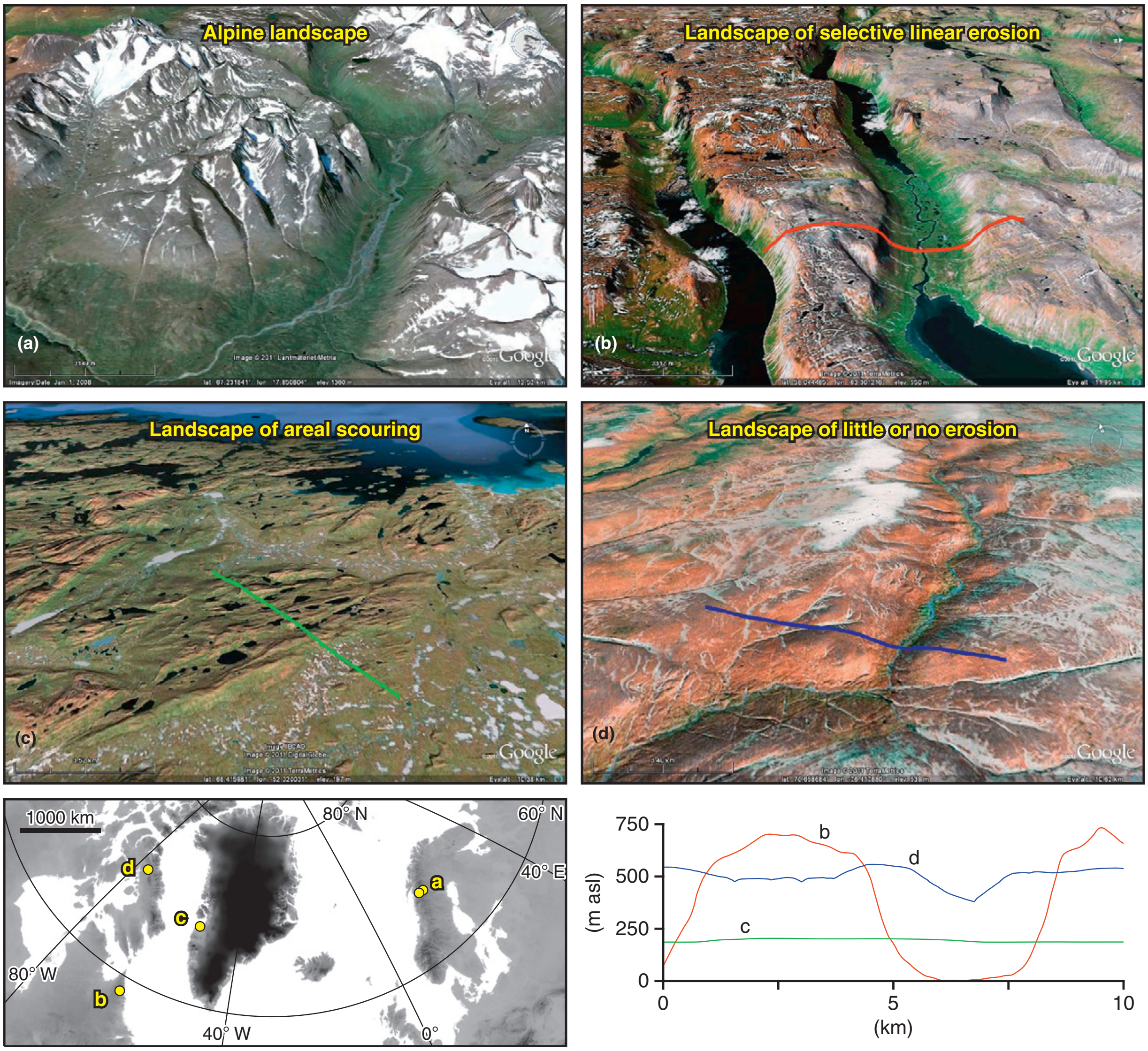

Figure 1 Examples of different landscapes in formerly glaciated regions. (a) Alpine landscape in the northern Scandinavian mountains with cirques and glacial valleys (67.24° N, 17.86° E) (Image © 2011 Google, Image © 2011 Lantmäteriet/Metria). (b) Landscape of selective linear erosion in the Torngat Mountains, Canada, with U-shaped glacial valleys and intervening interfluves showing little signs of glacial erosion (58.31° N, 63.64° W) (Image © 2011 Google, Image © 2011 TerraMetrics). (c) Landscape of areal scouring in eastern Greenland (68.40° N, 51.92° W) (Image © 2011 Google, Image © 2011 DigitalGlobe). (d) Landscape of little or no erosion on Baffin Island, northern Canada (70.66° N, 76.42° W). Topographic profiles in the lower right panel show (b) a U-shaped valley and intervening areas lacking marks of glacial erosion from a landscape of selective linear erosion, (c) an almost flat landscape of areal scouring, and (d) a low-relief landscape of little or no erosion including a V-shaped valley cross-section.

valleys typically exhibit characteristic U-shaped transverse profiles (Figure 2(b)), longitudinal profile overdeepenings (with lakes), and hanging valleys. The margins of glacial valleys also display landscape characteristics associated with cirques, including horns and arêtes, and marked breaks-in-slope between the glacial valley and uplands. The term 'alpine' was coined by Linton (1963) for valleys of this type. Linton (1963) further distinguished composite, Icelandic, and intrusive types of glacial valleys.

Where valley glaciers thicken considerably, they may overflow lower points on interfluve areas (passes or cols) and invade adjacent valleys. Amalgamation of accumulation areas may eventually lead to the formation of ice fields (where a large upland central accumulation area feeds a number of outlet glaciers). Patterns of glacial valleys that are composed of sections consisting of preglacial precursors and valley sections that were cut through the original valley divides were therefore termed 'composite.' Ice caps may also form on top of higher plateau-type surfaces and feed ice in to outlet glaciers in valleys cut into the plateau (Figure 3). The typical characteristic of such glacial valleys is the absence of cirques and higher terrain where ice would have first formed. Although they occur in most formerly glaciated regions, they are particularly typical in Iceland, which motivated the introduction of the term 'Icelandic' for these valleys. Glacial valleys were termed 'intrusive,' where valley cutting was accomplished

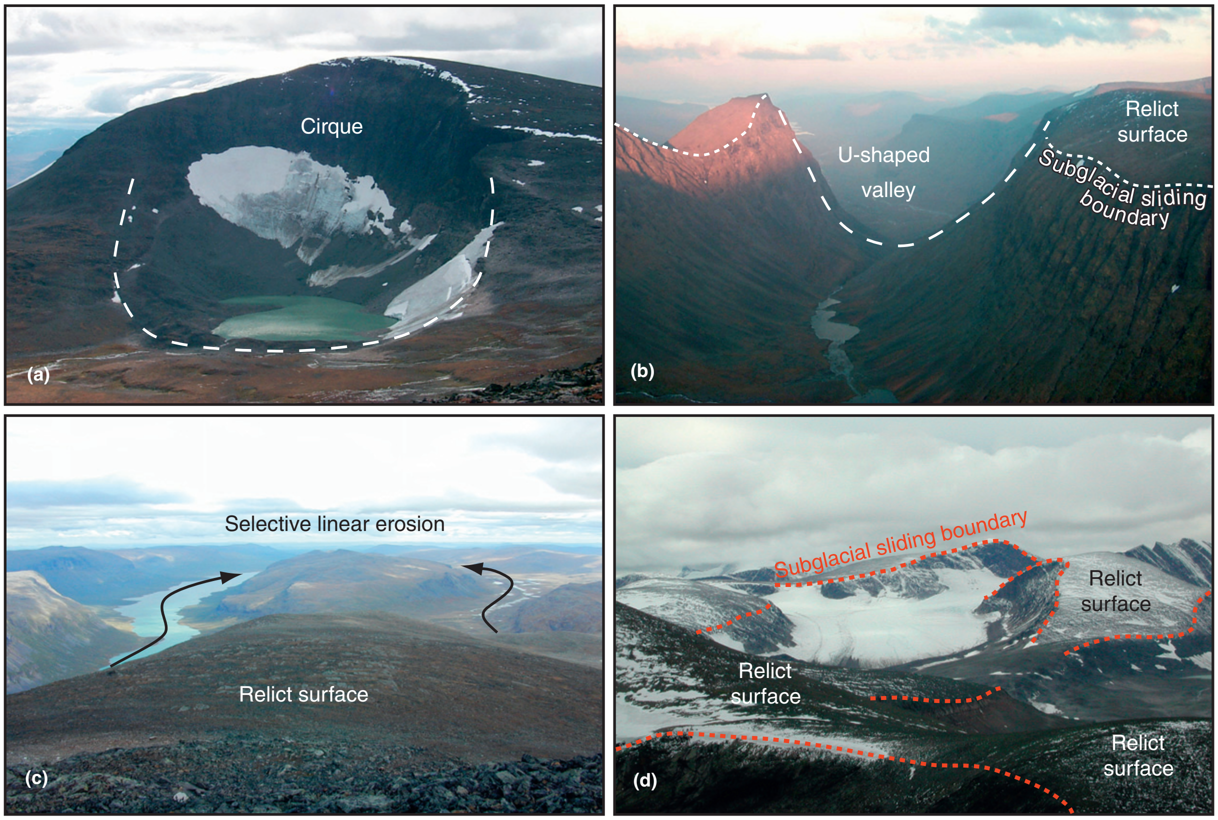

Figure 2 Photos of glacial landscapes from the northern Scandinavian/Swedish mountains. (a) Cirque with a steep backwall and a lake-filled depression (tarn). (b) U-shaped valley with clear upper margins marking a subglacial sliding boundary of the ice sheet stages. (c) Selective linear erosion with two glacially eroded valleys on both sides of an elevated relict surface in the center of the photo. (d) Relict surfaces characterized by smooth convex–concave slopes and preserved under cold-based ice. The relict surfaces are outlined by subglacial sliding boundaries, which also mark the edges of glacially eroded regions.

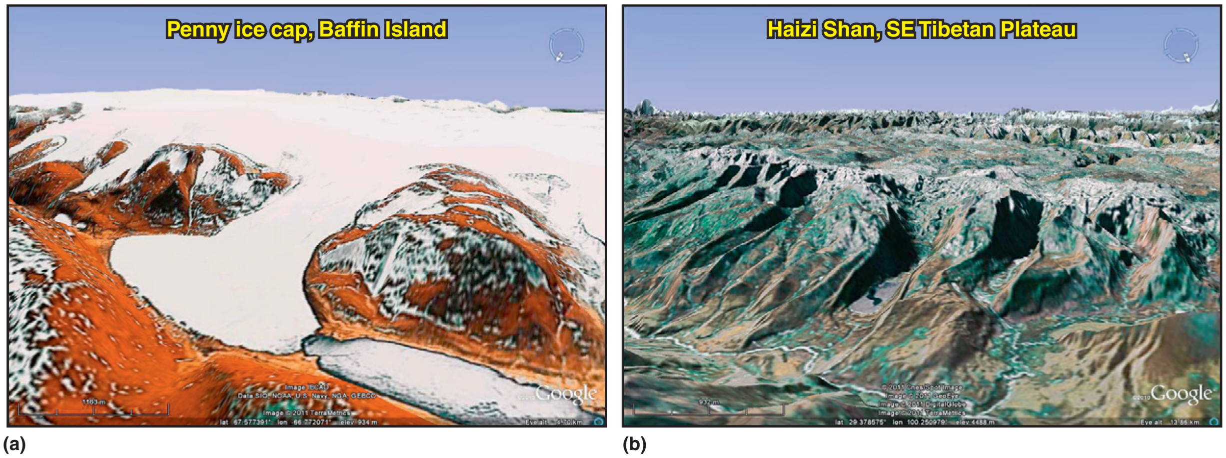

Figure 3 Google Earth imagery showing landscapes of a contemporary and past ice cap with outlet glaciers. (a) Penny ice cap on Baffin Island, Canada, with an outlet glacier flowing down a valley (Image © 2011 Google, Image © 2011 TerraMetrics). (b) The Haizi Shan plateau on the southeastern Tibetan Plateau (Fu et al., 2011) with glacial valleys cut into the plateau and lacking cirques, indicating formation by outlet glaciers from an ice cap (Image © 2011 Google, Image © 2011 Cnes/Spot Image, Image © 2011 Geoeye, Image © 2011 DigitalGlobe, Image © 2011 TerraMetrics).

by ice flowing up-gradient along preexisting valleys. Such instances occur, for example, where ice descending from higher mountain ranges flanks and intrudes into unglaciated valleys radiating from neighboring lower mountain ranges or where ice cap or ice sheet margins protrude into unglaciated highlands.

Glacial valleys in alpine settings are typically deeper than they are wide (Hirano and Aniya, 1988). Glacial troughs, on the other hand, are significantly wider than glacial valleys and sometimes much wider than deep. Glacial valleys form in response to glaciers deepening and widening preglacial precursor valleys, but also by headward erosion (Shuster et al., 2011). Because the precursor valleys were mostly fluvial valleys, and because ice flow was controlled by topography, glacial valley patterns also inherit the dendritic outline, which is a hallmark of fluvial landscapes. However, glacial valleys are typically straighter than fluvial valleys because glaciers tend to eradicate and truncate another key component of the fluvial landscape, their valley spurs.

8.9.3 Landscapes of Regional and Continental Glaciation

In ice caps and ice sheets, ice flow is driven by the ice surface topography, and the processes, rates, and patterns of erosion are determined by subglacial conditions, which, because of the massive scale and differences in subglacial topography, can differ significantly along flow-lines and between different ice sheet sectors. Significant erosion only occurs where basal temperatures attain the pressure melting point away from ice dome areas, predominantly in areas in the vicinity of the equilibrium line. Erosion by detachment may be particularly effective in areas where the condition of subglacial freezing is replaced by subglacial melting (Hättestrand and Kleman, 1999); scouring occurs predominantly in the subglacial melting zone; and plucking occurs in areas where the condition of subglacial melting is replaced by subglacial freezing. Distinct spatial patterns of subglacial melting and freezing have led to typical landscapes of glacial erosion, that is, selective linear erosion, areal scouring, and little or no erosion (**Figure 4**).

8.9.3.1 Landscape of Selective Linear Erosion

Landscapes of selective linear erosion develop under ice caps and ice sheets that cover upland terrain and involve conditions where corridors of subglacial melting, largely parallel to the regional ice-flow direction, occur adjacent to regions of subglacial freezing (Sugden, 1968; **Figures 1(b)** and **2 (c)**). The surface expression of this subglacial thermal organization was one of ice streams forming within the ice sheet. As the ice overrode the mountains, it established zones of subglacial melting over valleys where the ice thickness was greatest, that is, the deepest valleys, and that were oriented largely parallel to the imposed ice-flow direction. During the first ice sheet glaciation, the ice would have preferentially deepened the major preglacial fluvial valleys parallel to ice flow. This imposed a positive feedback, because subsequent ice sheets then experienced deeper valleys to funnel ice into, and thus continued erosion enhanced differences in local relief, resulting in a juxtaposition of deep glacial valleys with shallower valleys where glacial erosion was less effective or absent (Briner et al., 2006; Kessler et al., 2008).

One of the most extreme landforms associated with landscapes of selective linear erosion are fjords, where concentrated erosion by ice steams has deepened valleys terminating offshore to depths of more than 1 km below current sea level (Andersen and Nesje, 1992; Nesje and Whillans, 1994; Näslund, 2001). Another characteristic landscape assemblage containing several landforms associated with landscapes of selective linear erosion are preserved uplands in between corridors of intensive deepening (Dahl, 1966). Such uplands are commonly characterized by suites of nonglacial landscape forms such as convex–concave slope profiles, regolith, and tors (Sugden and Watts, 1977; Kleman and Stroeven, 1997; Stroeven et al., 2006). Tributary valleys of glacial and fluvial origins in the preserved uplands are left hanging by intense deepening of the main valleys.

Landscapes of selective linear erosion occur along extensive sections of coastal uplands in all formerly and currently glaciated regions. Prominent examples occur along the former margins of the Innuitian, Laurentide, and Cordilleran ice sheets in easternmost Queen Elisabeth Islands, Baffin Island (Sugden, 1978), and British Columbia (Stumpf et al., 2000), respectively, the Greenland ice sheet along much of its northern and northeastern margin (Sugden, 1974), the former Fennoscandian ice sheet along much of its western margin in the Norwegian and northern Swedish mountains (Goodfellow, 2007; Goodfellow et al., 2008; Kleman et al., 2008), and in coastal sectors of Antarctica (Drewry, 1983; Drewry et al., 1982; Näslund, 2001; Sugden et al., 2005).

8.9.3.2 Landscape of Areal Scouring

Landscapes of areal scouring occur where an ice sheet has removed the preexisting cover of loose material, including

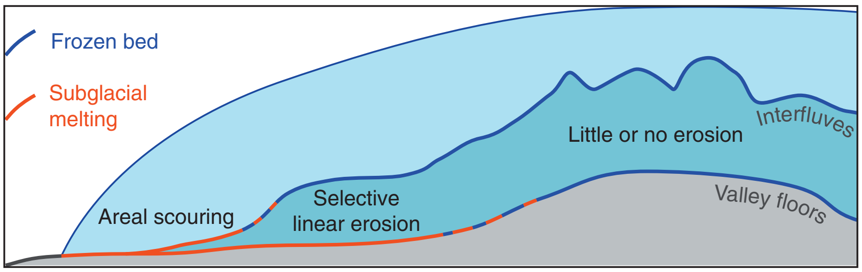

Figure 4 Schematical figure of an ice sheet cross-section with subglacial melting (red) and frozen bed (blue) conditions. Central and high-elevation locations are favorable for frozen bed conditions and subglacial preservation, resulting in little or no erosion or selective linear erosion. Subglacial melting is favored by either thick ice cover or by rapid ice flow that typically occur toward the margin under the equilibrium line. Modified from the original figure by Clas Hättestrand. Reproduced from Ebert, K., Hättestrand, C., Hall, A.M., Alm, G., 2011. DEM identification of macroscale stepped relief in arctic northern Sweden. Geomorphology 132, 339–350.

regolith, and eroded into bedrock over large areas (**Figure 1(c)**). Subglacial melting conditions prevailed across the entire scoured landscape because ice removed the preexisting loose material from high-points as well as depressions, despite differences in relief. Thus, the relief was below a critical level required to induce subglacial freezing conditions on summits and subglacial melting conditions in depressions (and create landscapes of selective linear erosion). Areas of areal scouring in Greenland (Sugden, 1974) and Fennoscandia (Kleman et al., 2008), for example, tend to occur at the heads of fjords and embayments, where ice started to accelerate over wide areas as it converged into large depressions (Briner et al., 2008). However, areal scouring is not limited to these conditions as much of the central area of the Laurentide ice sheet has been classified as a landscape of areal scouring (Sugden, 1978), although even here areas of scouring also flank the heads of fjords and other depressions.

Landscapes of areal scouring are characterized by rounded and plucked hills (roches moutonnées) and depressions filled with lakes or bogs. Several studies in such regions have indicated that despite the appearance of pervasive glacial erosion, the total depth of ice sheet erosion involved in creating this landscape may have been restricted to the simple removal of preglacial weathering material and slight rounding, smoothing, and plucking of the preexisting topography. A classic area of glacial scouring in southwestern Sweden has been shown to have formed by only minor glacial erosion; the exhumed sub-Mesozoic etch surface (relative relief 20–135 m) underwent enough erosion to become rounded (stoss) and plucked (lee; **Figure 5(a)**) but the magnitude was not enough to remove detailed etchforms in protected positions (Johansson et al., 2001; Olvmo and Johansson, 2002; Olvmo et al., 1999). In another classic region of areal scouring, on the topographic divide between Sweden and Norway at Riksgränsen, where ice was funneled into Rombakfjorden, the total impact of erosion by the last ice sheet was in the order of only 2 ± 0.4 m of bedrock (**Figure 5(b)**; Stroeven et al., 2002a).

Kleman et al. (2008) examined the distribution of regions of areal scouring in Scandinavia and concluded that regions that border the Norwegian mountains (such as at Riksgränsen) may have experienced periods of scouring over multiple glaciations during the entire Quaternary (Kleman and Stroeven, 1997), whereas similar regions in southern and eastern Sweden and southern Finland may have only been formed during the last 1 million years or so under the influence of full-grown ice sheets. In fact, considering the limited amounts of ice sheet erosion required to form these landscapes, it is possible that any of these regions may have formed purely as a result of erosion during one glaciation.

8.9.3.3 Landscape of Little or No Erosion

Despite extensive evidence for the presence of ice, some formerly glaciated areas include pockets, areas, zones, and regions characterized by an absence of glacial erosion (**Figure 1(d)**). This includes sites where neither erosion nor deposition occurred, as well as depositional zones around the terrestrial margins of the former ice sheets (Kleman et al., 2008; Sugden, 1978). Areas of little or no glacial erosion or deposition include nonglacial landforms such as fluvial river valleys and drainage networks (**Figure 1(d)**), such as on Jamieson Land in eastern Greenland (Sugden, 1974; Sugden and John, 1976), unmodified large-scale landscape characteristics of weathering and stripping (Lidmar-Bergström, 1997), including the survival of lowland tors (Hättestrand and Stroeven, 2002), and uplands characterized by convex–concave slope profiles, regoliths, and tors (Goodfellow, 2007; Kleman and Stroeven, 1997; Sugden and Watts, 1977; **Figure 2(d)**). Although the recognition of such areas as

(a) (b)

Figure 5 Two locations in Sweden with a landscape of areal scouring. (a) Plucked bedrock slabs and rounded surfaces indicate glacial erosion in a region of southwestern Sweden where detailed etchforms remain in protected positions (Johansson et al., 2001; Olvmo and Johansson, 2002; Olvmo et al., 1999). (b) The topographic divide between Sweden and Norway at Riksgränsen where ice was funneled into Rombakfjorden. Cosmogenic exposure dating of this site has shown that the erosion by the last ice sheet was in the order of only 2 ± 0.4 m of bedrock. Reproduced from Stroeven, A.P., Fabel, D., Harbor, J., Hättestrand, C., Kleman, J., 2002a. Quantifying the erosional impact of the Fennoscandian ice sheet in the Torneträsk-Narvik corridor, northern Sweden, based on cosmogenic radionuclide data. Geografiska Annaler 84 A, 275–287, with permission from Wiley.

nonglacial regions that survived ice sheet glaciation with little or no modification has a long history (Wråk, 1908), more wide-spread acceptance of the possibility that extensive areas under ice sheets underwent little or no erosion has resulted from the use of cosmogenic nuclide techniques to back-calculate depths of erosion produced by recent glaciations (Bierman et al., 1999; Briner et al., 2003, 2005; Fabel et al., 2002; Stroeven et al., 2002b, 2002c). The main explanation for the preservation of nonglacial features despite extensive ice cover is that the region had basal temperatures below the pressure melting point for much or all of the period of glaciation.

Landscapes of little or no erosion are commonly described as relict or palimpsest landscapes. As the recognition of the extent of landscapes of little or no erosion is relatively recent, and these landscapes are not discussed in much detail in other standard texts, they are discussed more extensively here. We present three perspectives for the zonation of glacial conditions that give rise to patterns of erosion and preservation beneath an ice sheet: a topographic perspective, a landform perspective, and a process perspective. These perspectives are based on analyses of relict landscapes worldwide, but in particular on studies of relict surfaces with weak glacial imprints in the uplands of the northern Swedish mountains (Clarhäll, 2002; Goodfellow, 2007; Harbor et al., 2006; Kleman, 1992; Kleman and Borgström, 1994).

In a case where an area known to have been covered by an ice sheet has a relict surface with weak glacial imprints, an important initial question to address is whether the imprint is weak because subglacial melting conditions: (1) were not sufficiently intense, (2) had low frequency, (3) were short lived, or (4) some combination of these reasons. In northern Sweden, weakly glacially modified patches that occur on some relict surfaces include glacial landforms conformable with ice-flow patterns of the last deglaciation (Kleman, 1992). Erosional and depositional landforms delineating the boundaries of these relict surfaces are also directionally compatible with inferred deglacial ice flow. Thus, relict surfaces and their boundaries in northern Sweden appear to reflect basal temperature conditions of a late stage of deglaciation (a short-lived event). Cosmogenic dating (Harbor et al., 2006) restricts the occurrence of subglacial melting conditions on a relict surface in the study areas in northern Sweden to only the last deglaciation (an example of an infrequent or a rare event). Finally, because erosional patches in northern Sweden are not lower than the surrounding relict terrain, this suggests that the event that produced the glacial imprint was of low intensity. Thus, in one extensively studied area of relict surfaces with weak glacial imprints, the periods of subglacial melting conditions that produced the glacial imprints were low intensity, low frequency, and short lived.

8.9.3.3.1 Topographic perspective

Relict patches occur over a range of sizes (Kleman et al., 1999) depending on the scale and detail of the mapping effort (Goodfellow et al., 2008). In northern Sweden, typically, the size of individual relict patches is in the range of a few square kilometers (Kleman and Stroeven, 1997; Fabel et al., 2002). In high-relief landscapes, topography has a self-stabilizing effect on the basal thermal regime (discussed in **Section 8.9.3.1**) that can lead to relict areas on broad interfluves that contrast with intense erosion in main valleys (landscapes of selective linear erosion). However, relict areas also occur on upland plateaus of medium to low relief amplitude (<200 m). Here, basal temperature conditions over reasonably level ground would either be frozen or melting, with small transition regions between these end members, and would fit within the larger context of regional patterns of basal thermal regime for the ice sheet. However, in the case of upland plateaus in the northern Swedish mountains, topography still appears to have exerted a control on the general location of relict surfaces (on hills) and glacially modified terrain (on the lee-side of hills and in depressions). The relict area boundaries are irregular and are, in some places, located on level ground (Clarhäll and Kleman, 1999; Harbor et al., 2006; Kleman and Borgström, 1994). This indicates that in the case of a subglacial region with a short-lived transient state close to the transition from frozen to melted, local topography plays a part in controlling the details of the boundaries of relict areas and the locations of small patches of glacial modification within relict areas.

8.9.3.3.2 Landform perspective

In a landscape with a binary distribution of relict and subglacially eroded land surfaces, the boundaries between the two deserve special attention. They are commonly strikingly sharp and prominent (e.g., Harbor et al., 2006) and are therefore important discontinuities in land-surface morphology. Provided that the assumption that relict surfaces represent sustained basal freezing conditions is correct, these surface discontinuities also mark locations for important discontinuities in the glacial system. These surface discontinuities are delineated by a predictable suite of landforms (Kleman and Borgström, 1994), such as transverse lee-side scarps, lateral sliding boundaries, and stoss-side moraines, depending on whether ice was leaving a frozen patch, flowing parallel to a frozen patch, or entering a frozen patch, respectively.

Transverse lee-side scarps (Clarhäll and Kleman, 1999) occur on the distal end of relict surfaces where temperature changed from up-ice frozen to down-ice thawed conditions. These erosional forms have considerable topographic expression due to the removal of a substantial amount of sediment and rock. Transverse lee-side scarps are generally located across or just down-ice of a hill summit (Clarhäll and Kleman, 1999; Kleman et al., 1999). Lateral sliding boundaries are flow-parallel boundaries separating relict and subglacially modified surfaces (Dyke and Morris, 1988). Some lateral sliding boundaries have no topographic expression, which indicates a balanced subglacial sediment budget, and may point to subglacial sediment deformation as the predominant mode of transfer (Harbor et al., 2006). The formation of a moraine-like deposit may occur when ice enters a cold-based zone (Kleman et al., 1999). Hence, some proximal boundaries of relict surfaces are delineated by stoss-side moraines (Clarhäll, 2002; Kleman and Borgström, 1994). Subglacial transport of sediment appears to have ceased at these locations, resulting in sediment thickening and formation of a series of ridges that are parallel to each other.

8.9.3.3.3 Process perspective

Prolonged basal freezing conditions are a prerequisite for the presence of landscapes of little or no erosion. Hughes (1981) postulated that the transition from frozen to melting basal conditions starts with small areas of basal melting that gradually grow larger (**Figure 6**). Ice flow accelerates over melting patches, and more deformation heat is released, which creates a positive feedback that expands the size of the melting patch. These melting patches coalesce upon expansion, which results in the isolation of frozen patches and their final eradication to produce a bed with pervasive melting. Formerly glaciated areas with patches of relict surfaces must have experienced only partial basal melting; subglacial melting conditions started in some areas, but propagation of these melting conditions was discontinued before the bed was entirely transformed.

The distribution of relict surfaces in northern Sweden (Fabel et al., 2002; Goodfellow et al., 2008; Kleman and Stroeven, 1997; Kleman et al., 1999) fit an intermediate snapshot of the binary mosaic of subglacial temperature conditions postulated by Hughes (1981). However, because the spatial distribution of relict surfaces does not illustrate a process but rather the time-integrated result of processes, the mosaic of relict surfaces must either reflect a stable topographically induced temperature distribution or a reversion to frozen basal conditions before the entire bed reached the melting state. A reversal to frozen basal conditions, at a time close to deglaciation, was demonstrated for one such upland by Harbor et al. (2006); here, reversal to frozen basal conditions occurred under the influence of a frozen perimeter, a feature known from both contemporary ice caps and ice sheets (even for relatively temperate climates such as in southernmost Iceland (van der Meer et al., 1999)) and numerical models (Hooke, 1977; Moran et al., 1980; Payne and Dongelmans, 1997; Sugden, 1977).

8.9.3.4 Landscape Distributions, The Temporal Perspective

The distribution of erosional landscapes is related to the establishment and duration of melting-bed conditions over time. These conditions may have occurred repeatedly and persistently, such as in alpine landscapes, most landscapes of selective linear erosion, and some regions of areal scouring, especially those flanking trough heads, and may have occurred over areas of considerable size (up to 10^5 m^2) and attained large erosional magnitudes (in excess of 10^3 m). However, these conditions may also have occurred only infrequently over small areas (below 10^3 m^2), and had sufficient impact to leave only a small erosional imprint. This latter situation produces landscapes of little or no erosion.

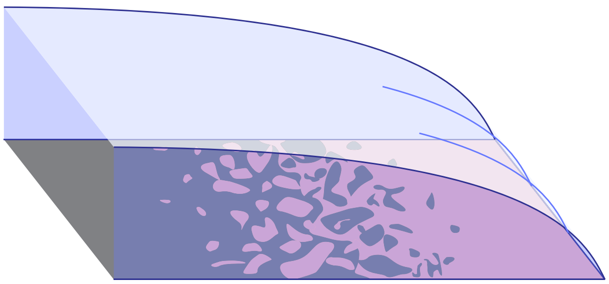

Figure 6 Transition from a completely frozen ice bed, over a zone with patches of frozen bed and frozen ice bed, to a completely melted ice bed.

Once formed, alpine landscapes and landscapes of selective linear erosion have been persistent features during the Quaternary. This is because the amount of glacial erosion, and relief enhancement, was large enough that (1) it was impossibly fully eradicated by subsequent interglacial processes such as mass wasting (Hovius et al., 1997; Jarman, 2009) or fluvial deepening and widening; (2) it could not be masked by deposition of sediments be they of glacial or of nonglacial origin; and (3) the relief enhancement formed a positive feedback for glacial deepening during subsequent glacial erosional events. Landscapes of areal scouring, on the other hand, have not necessarily been persistent and recognizable features of the landscape after first appearance because younger sediments could entirely mask this low-relief landscape. Hence, such landscapes, and, more generally, lower relief surfaces beyond the high mountains domains, are usefully situated to record the complexity of glaciation. For example, such a location may have been in the marginal zone of valley glaciers or been in the subglacial preservation zone of a subsequent regional ice sheet and then underwent erosion under a continental scale ice sheet and deposition during final deglaciation as part of one glacial cycle. Because sequences of conditions similar to those described may have occurred several times during the Quaternary (Kleman et al., 2008), it is the integrated impact of each of all these phases that determines whether a landscape may be recognized as erosional or not.

Glaciated landscapes that may have undergone multiple periods of glacial erosion and deposition therefore display features that have been only partly erased or modified by later events, and thus have a complex mix of landforms of different ages and different degrees of modification. This is generally described as a palimpsest landscape. The occurrence of palimpsest forms in fragmented glacial landscapes and the occurrence of glacial erosion on relict surfaces indicate that insufficient time was available for expansion of subglacial melting patches to develop to melting conditions regionally. A range of evidence suggests that such glacial erosional conditions were established during short-lived periods of deglaciation. Ice sheet margins, which were cold-based, retreated as the ice sheet shrank. Meanwhile, ice divide regions, which also remained cold-based, migrated to their final positions during deglaciation. A zone of melting basal conditions, in a zone near the equilibrium line (Hooke, 1977), migrated therefore also across the landscape as ice sheets shrank. The extent of the melting zone diminished during deglaciation, and was eventually minimized so that basal melting was only partial. Landscapes with a patchy pattern of relict surfaces are located in areas that were affected only by partial melting. A gradual shrinkage of the melting zone during deglaciation is supported by the wider distribution of relict landscapes toward areas that hosted the last ice remnants, such as in the northeastern Scandinavian mountains, central Baffin Island, and north-central Québec (Clarhäll and Jansson, 2003; Clark et al., 2000;

De Angelis and Kleman, 2008; Jansson et al., 2002; Kleman, 1992; Kleman and Hättestrand, 1999; Kleman et al., 1997).

8.9.4 Landscape Development and Interpretation

In introducing this section on landscapes of glacial erosion, we noted that a recognizable landscape is produced when a set of processes and their patterns, driven by a specific set of environmental conditions, operate with sufficient intensity or time to produce a distinctive assemblage and pattern of landforms. The components of this definition provide a framework for understanding how researchers have used landscape studies to examine issues of landscape development, rates and styles of landscape change, and the ways in which landscapes can provide an insight into paleoglaciological and paleoenvironmental conditions and chronologies.

A recognizable landscape 'includes an assemblage and pattern of landforms that is distinct from contrasting landscapes.' For example, the alpine landscape produced by glaciation described earlier in this chapter stands in marked contrast to the fluvial upland landscape that may have preceded it, a landscape that might have been characterized by V-shaped river valley cross sections, interlocking spurs, and convexo–concave interfluve slope profiles. Time sequences of landscape change as a result of changes in dominant environments can be derived in several ways, including comparisons of landscapes in different places at different stages of transformation, and numerical modeling of long-term landscape development. In such sequences, it is clear that a preexisting landscape is progressively modified to create a new landscape type (**Figure 7**); thus, at present, one should expect to see landscapes that are both clearly recognizable as glacial and landscapes that have glacial landform assemblages as well as vestiges of landforms related to a prior environment (palimpsest landscapes). This is particularly apparent in: (1) landscapes of selective linear erosion, because a key characteristic of the landscape is the contrast between areas that have been strongly eroded by glacier ice (valley glaciers and ice streams) and intervening areas that are little modified and thus that include landform assemblages of the preglacial landscape; and (2) formerly glaciated landscapes that are rapidly consumed by fluvial erosion, for example, on the margin of the Tibetan Plateau, where glacial valleys are deepened and gradually lose their glacial characteristics (U shape) in favor of fluvial characteristics (V shape; e.g., Stroeven et al., 2009). Rarely does one attempt to define a specific point (in time, or space) at which one type is declared to have changed to another.

A change in landscape type requires that the processes 'operate with sufficient intensity or time' to produce the new

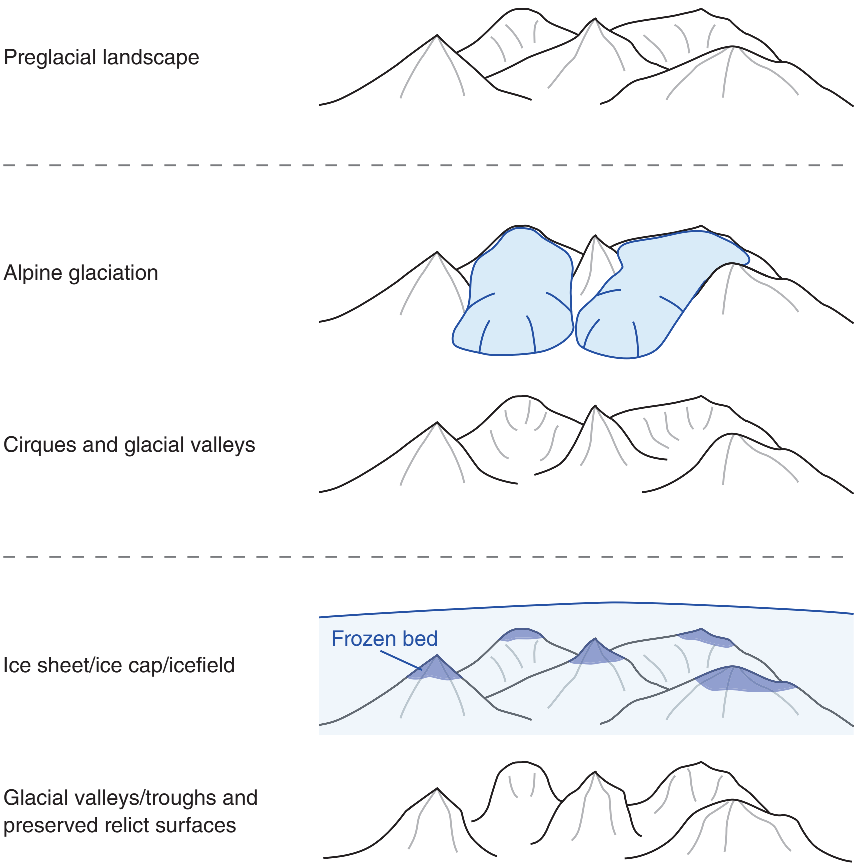

Figure 7 Schematic figure of landscape development with alpine and ice sheet/ice cap/ice field-style glaciation. Although alpine glaciation typically produces cirques and glacial valleys, ice sheet glaciation commonly preserves the highest elevation regions due to cold-based, nonerosive ice, and can create a complex landscape with clear marks of glacial erosion as well as intervening patches showing a preglacial signature.

distinctive assemblage and pattern. This requirement could be met with changes that occurred over repeated glaciations with glacial erosion of low intensity or frequency remolding the landscape incrementally. At the other end of the spectrum, a single glaciation with glacial erosion of high intensity could also change the landscape sufficiently enough to result in a new landscape type. Glacial landscapes that formed incrementally with low-intensity glacial erosion can be identified in some places because palimpsest forms cross-cut each other, demonstrating their incompatibility with a single event formation. Distinguishing a landscape formed by a single event from an incrementally formed landscape may be difficult because repeated glaciations with low-intensity erosion of glaciers expanding to the same limits may result in a landscape similar to that formed by a single event glaciation of high-intensity erosion. Cosmogenic nuclide-based rock erosion rates, however, can be used to demonstrate that topography formed over consecutive glacial cycles rather than during one erosive event (Hättestrand et al., 2004; Stroeven et al., 2002a). Estimates of glacial erosion rate and formation duration come from quantitative volume–time considerations, numerical modeling, and direct observations through sediment yield, cosmogenic nuclide, and thermochronometry measurements. Nesje et al. (1992) analyzed the bedrock volume eroded from Sognefjord, western Norway, and arrived at glacial erosion estimates of 1–3 mm $year^{-1}$ considering a glaciation duration of 600 000 years. Experiments using numerical models of valley erosion and landscape development have yielded estimates of the duration required to produce a distinct glacial landform ranging from 10^4 to 10^6 years (Harbor, 1992; Kessler et al., 2008; MacGregor et al., 2000). Direct observations through sediment yield, cosmogenic nuclide, and thermochronometry measurements have yielded glacial erosion rates ranging from as low as 10^{-3} to more than 10^3 mm $year^{-1}$ (Hallet et al., 1996; Koppes and Montgomery, 2009). Collectively, the wide range of these estimates illustrates the variety of glacial landscape formation time scales. In particular, the application of cosmogenic nuclide exposure measurements to quantify glacial erosion has revolutionized our abilities to confirm concepts and establish patterns of glacial erosion. For example, conceptualized patterns of glacial erosion across valley cross-sections (Harbor, 1993), where the highest rates of erosion occur at or near the valley bottom and diminish up the valley wall, have been confirmed in the field across U-shaped valleys (Fabel et al., 2004; Li et al., 2005). These findings confirm the theoretical basis of the process leading to landscapes of selective linear erosion and numerical modeling studies. Further, a large and rapidly growing dataset of cosmogenic nuclide measurements from bedrock of, and erratics covering, relict surfaces (Briner et al., 2003, 2005, 2006; Fabel et al., 2002; Phillips et al., 2006; Stroeven et al., 2002c, 2006; Sugden et al., 2005), have confirmed that preservation under cold-based ice has been a common feature during the last glaciation (Kleman and Hättestrand, 1999; Kleman et al., 1997).

A recognizable landscape is 'produced by a set of processes and their patterns, driven by a specific set of environmental conditions.' In this definition, a 'set' of environmental conditions can include a distinctive range and sequence of environments, such as those that occur during the advance and retreat of an ice margin or a basal thermal zone. Such large-scale changes of subglacial conditions are driven by external forcing, such as changes in global temperature, precipitation patterns, and global sea level, and these too could be considered as part of 'driven by a specific set of environmental conditions.' We are generally interested in first explaining or understanding the existence of glacial landscapes in terms of (erosion) processes and their patterns (Hättestrand et al., 1999; Hättestrand and Kleman, 1999), and then subsequently using the existence of specific landscapes to infer past processes and patterns over geologic time. This is in fact one of the motivations for studying complex landscapes – to unravel and reconstruct the past spatial and temporal sequence of environmental conditions that were required to arrive at the landscape we see today (Kleman et al., 2010).

The recognition that for parts of an ice sheet bed a frozen base can protect rather than erode the landscape has added an important dimension regarding past glacial processes and patterns and the 'specific set of environmental conditions' that result in preservation under cold-based ice. With relict areas that have been spared from glacial erosion through the Quaternary, and with preserved landforms indicating glacial configurations different from the final glaciation, we are one step closer to revealing the processes, patterns, and environmental conditions creating the landform assemblages. Ultimately, ice sheet modeling with tuning of the controlling environmental conditions could reproduce the spatial and temporal patterns of glacial erosion (and lack of erosion) as revealed by field evidence.

Glacial erosional landscapes include a wide range of landforms and occur in a variety of styles and patterns, ranging from distinct alpine landscapes with cirques and U-shaped valleys as their hallmark landforms to landscapes of little or no erosion that are primarily of nonglacial origin but may carry a faint and patchy glacial imprint (with transverse lee-side scarps, lateral sliding boundaries, and stoss-side moraines as their hallmark landforms). Such a wide variety of glacial landscapes also reflects a similarly wide variety of glacial processes and patterns, subglacial environmental conditions, and external environments (climate, sea level), and illustrates the complexity of the glacial system. The dominant patterns and styles of glacial landscapes described offer some important insights into past glacial processes over landscape formation time scales for which there are no better proxies or methods. Although the effectiveness of glacial erosion has been recognized for a long time (fjord erosion in excess of kilometers, the wide-spread occurrence of areal scouring landscapes), the main contribution in glacial geomorphology of the last 30 years has been the recognition that glacial preservation has been an important component in limiting ice sheet erosion, both spatially and temporally, such that, despite 2 million years of glacial history, relict surfaces still form an important feature of the current landscape. This recognition has offered important insights into the complexity of glacial landscapes and, although superficially complicating glacial landscape interpretations, landscape preservation now offers the potential to reveal a much more complete paleoglaciological picture (e.g., Kleman et al., 2010) with significant implications for important topics such as past ice volume, responsiveness, ice dynamics, and paleoclimate.

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Biographical Sketch

Arjen Stroeven, Dutch by birth, has completed his education in physical geography at Utrecht University 1982–88, thus becoming one of the first glaciologists of the country. He then pursued his career further in the country where he learned to love and study the glaciers, Sweden. He changed his focus from glaciers to glaciated landscapes during his MSc from the University of Maine and PhD at Stockholm University on Tertiary Antarctic glaciation (1991–96). He has since been part of the development of the field of paleoglaciology with studies in the Russian and Canadian Arctic, northern Fennoscandia, Yukon Territory, and, most recently, on the Tibetan Plateau and in central Asia. The principal objective of these studies has been to demonstrate the extent, thickness, volume, and timing of former ice expansion as well as the properties of the subglacial environment by means of cosmogenic nuclide studies, that is, demonstrate the efficiency in some places, and inefficiency in other places of glacier erosion.

Jonathan Harbor's early fascination with glacial landscapes acquired from hiking through the English Lake District has turned into a very enjoyable career in research and teaching. His early enthusiasm was encouraged and developed by great mentors at Cambridge University (BA), the University of Colorado (MA), and the University of Washington (PhD), and by exceptional collaborators internationally as well as at his home institution, Purdue University. The projects, which Harbor was involved with his students, have ranged from detailed field investigations of basal sliding and glacier internal structure, numerical modeling of ice flow and landform development, and using cosmogenic nuclides in conventional and novel ways to reconstruct glacial chronologies, extents, and erosion patterns. This has provided opportunities for study in a wide range of locations, including many parts of North America, the Alps, northern Fennoscandia, the Tibetan Plateau, and central Asia.

Jakob Heyman, Captured by the beauty of glaciers and glacial landscapes on Svalbard in 2001–02, finished his undergraduate thesis focusing on marginal moraines in the Swedish mountains at Stockholm University 2005. He then shifted his focus on the glacial history of the Tibetan Plateau, which was the topic of his PhD project (2005–10). Since February 2011, he has been working as a postdoc at Purdue University focusing on glaciation and erosion of the Tibetan Plateau. The tools he has used to resolve the history of past glaciations include remote sensing (geomorphological mapping from satellite imagery and DEM), field investigations, cosmogenic exposure dating, and numerical modeling.