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The concept of cryo-conditioning in landscape evolution

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A B S T R A C T

Recent accounts suggest that periglacial processes are unimportant for large-scale landscape evolution and that true large-scale periglacial landscapes are rare or non-existent. The lack of a large-scale topographical fingerprint due to periglacial processes may be considered of little relevance, as linear process–landscape development relationships rarely can be substantiated. Instead, periglacial landscapes may be classified in terms of specific landform associations. We propose "cryo-conditioning", defined as *the interaction of cryotic surface and subsurface thermal regimes and geomorphic processes*, as an overarching concept linking landform and landscape evolution in cold regions. By focusing on the controls on processes, this concept circumvents scaling problems in interpreting long-term landscape evolution derived from short-term processes. It also contributes to an unambiguous conceptualization of periglacial geomorphology. We propose that the development of several key elements in the Norwegian geomorphic landscape can be explained in terms of cryo-conditioning.

Introduction

In contemporary geomorphology, the study of "landforms" constitutes the core of the discipline; however, there is little discussion on how "landform" is defined (Rhoads and Thorn, 1996) or what the basis for *classifying* landforms is. "Landscape" is another fundamental concept that lacks a proper definition in geomorphology. In its simplest sense, landscape is synonymous with topography, and can be considered either a continuous surface in space characterized by morphometric properties (Etzelmüller et al., 2007) or a specific assemblage of individual landforms. On the other hand, landscape as a term also includes biotic and anthropogenic patterns that lead to typical "landscape regions" such as vegetation and/or land-use patterns. Viewing the landscape as either continuous or a sum of discrete objects has very different philosophical implications (Rhoads and Thorn, 1996) and may yield complementary data in a landscape analysis.

Haschenburger and Souch (2004), based on a critical examination of seminal papers, propose six principles that create geomorphic landscapes. Their first principle is that landforms are the basic building blocks, while the remaining principles describe important structural and functional characteristics in a landscape. They state that a landscape is more than just an assemblage of landforms, and emphasize dynamic rather than static classifications. Landforms are essential features of a landscape, but it is not clear *a priori* if the individual landforms that make up the landscape are or must be of the same scale as the landscape itself. Landforms would mainly be considered to be a smaller scale of the landscape even if, e.g. Ahnert (1994, 1996) in his hierarchical structure of landforms, includes all geomorphological objects from erosion rills to mountain chains into the term landform.

The "periglacial" concept was first used by von Lozinski (1912) and has evolved towards a definition of processes relating to "frost action" (Thorn, 1992; French 2004; French and Thorn, 2006), but with indistinct boundaries to azonal processes operating in cold climates. In this paper we refer to periglacial as the processes associated with seasonal and perennial ground ice as recommended by French and Thorn (2006).

The *periglacial landscape* is an interesting case-study of landscape development. First, the *periglacial landscape* is a focal point in science due to anticipated effects and feedbacks in global warming scenarios (French, 2007). Second, cold-climate landscapes have been regarded as being geomorphologically active. Third, the importance of periglacial processes for long-term large-scale landscape evolution has recently been questioned (André, 2003). Fourth, many cold-climate regions intersect with glacial domains in both space and time, thereby providing interesting examples of interactions and controls on landscape development (Zhang et al., 2001; Etzelmüller and Hagen, 2005).

In this paper we aim to develop an overarching concept for analysing cold-climate landforms and landscape evolution and control. The need for such a concept is further substantiated by the problems involved in defining periglacial geomorphology and periglacial landscapes. We argue for the importance of discussing

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the interaction of processes and controls on landscape evolution, rather than static landform assemblages or specific process domains. We claim that the relevant processes in cold-climate landscapes have one *common* control, namely a cryotic ground and surface thermal regime (at timescales ranging from diurnal to perennial [permafrost]). On that basis we suggest *cryo-conditioning* of landform and landscape development as a potential overarching concept, and discuss this within a theoretical geomorphologic framework. Finally, we apply this concept to attempt to explain some elements of the Norwegian landscape.

Periglacial geomorphology and landscapes

Thorn (1992), French (2004), and French and Thorn (2006) argue for a narrow description of periglacial processes and conclude that "the core of modern periglacial geomorphology should concern the study of both perennial and seasonal ground ice and related landscape development" (French and Thorn, 2006, p. 172). Despite the narrow definition of periglacial processes, their understanding of periglacial geomorphology is much broader. They state that "other components of periglacial geomorphology include the impact of seasonal freezing and the roles of seasonal snow and of fluvial, lacustrine, and sea-ice covers. Furthermore, the geomorphology of cold non-glacial regions must embrace (…) also the azonal processes that exhibit distinct behaviour and/or magnitude and frequency distributions" (French and Thorn, 2006, p. 172).

We agree with this holistic view on cold-climate geomorphology, but at the same time find it unfortunate to introduce ambiguity in the term periglacial. "Periglacial" should have the same sense for processes, landforms, landscapes, and environments. Defining periglacial processes in terms of ground-ice processes and conditions implies that periglacial geomorphology is about landforms and landscapes relating *only* to these processes and conditions. When periglacial geomorphologists seem reluctant to follow such a narrow definition, it is probably because, like Pissart (2005), they consider azonal processes to behave with distinctive characteristics in periglacial environments — in other words, that the azonal processes are somehow conditioned by the cold temperatures and ground ice, and that there are important interactions between periglacial and azonal processes.

We attempt to reconcile these perspectives. Glacial processes are also conditioned by cold environments and interact with periglacial processes. Within glaciology, the importance of permafrost conditions for the glacial and glacial geomorphic system is now being recognized (Etzelmüller et al., 1996; Etzelmüller and Hagen, 2005; Haeberli, 2005; Fitzsimons et al., 2008; King et al., 2008). The co-occurrence of permafrost and glaciers in space and time, such as in many high mountains and polar areas, or the former existence of glaciers in present permafrost areas, may cause distinctive characteristics of landforms and sediments. As geomorphologists, we seek explanations to these landforms and sediments. In our view, there should be no reason to include azonal processes in the periglacial domain and at the same time exclude glacial processes.

French (2007) concludes that the few landscapes that experienced cold, nonglacial conditions throughout the Pleistocene can be regarded equilibrium periglacial landscapes, but that they do not show significant development during this time with respect to bedrock topography. Where a clear periglacial imprint is visible in bedrock topography, such as the chalk areas of England and France, the bedrock has been particularly susceptible to frost weathering. Apart from André (2003), no contemporary papers present data in which scale is taken into account in the discussion of process rates against long-term "*periglacial landscape*" development. Where the term "*periglacial landscape*" is used in recent papers, it is mainly to denote a landscape where periglacial processes are or have been operating (e.g., Hättestrand, 1994; Luoto and Hjort, 2004; Fortier and Aubé-Maurice, 2008), or where periglacial landforms are developing (Rossi et al., 2008). When scientists use the term "periglacial landscape" they often relate this to a particular feature such as ice-wedge polygons or rock glaciers. Then, a "periglacial landscape" can be regarded as *a specific association of landforms, superimposed on larger scale topography*. This is in accordance with Haschenburger and Souch (2004, Table 1) principle #2: "*Landscapes are organized assemblages of interconnected landforms*", where they explicitly state that landscapes can include both inherited and exhumed landforms.

It is commonly accepted that periglacial processes do not produce a large-scale topographic fingerprint. This is partly due to the differences in spatial scale that different processes operate upon. Glacial landforms are caused by processes operating at scales up to that of continental ice streams and ice sheets, while periglacial process–form systems do not exceed the scale of rock glaciers, open-system pingos, and thaw lakes, and more often operate on scales below 10^1 m such as in patterned ground. In addition, periglacial processes contribute to sediment production (in the case of frost weathering and thermokarst), but other processes will be responsible for sediment export from the catchment. It is therefore reasonable that any periglacial landscape will exhibit dominant landform elements related to either fluvial or glacial processes. Thus, in a very strict sense, there should be no large-scale "periglacial landscapes".

However, the lack of specific large-scale topography is not necessarily a relevant criterion for determining the importance of periglacial conditions. First, a specific end product of landscape development can generally not be substantiated, given the nonlinear nature of geomorphic systems (e.g., Phillips, 2006). Second, the importance of periglacial processes should be discussed also in terms of geomorphic work, and this is seldom recorded in landforms. Third, an important point for explaining palimpsest landscapes is to clarify what controls inheritance. From a geomorphological point of view, the evolution of this landscape, both regarding the processes involved and the relevant controls, thresholds and other sources of nonlinearity, is more interesting than its present state in terms of landform assemblage.

Cryo-conditioning of landscape development

The concept

In cold-climate regions, slope, fluvial, marine, and aeolian processes exhibit certain "zonal" characteristics (cf. French, 2007). For fluvial processes, permafrost hydrology is a term used (Woo et al., 2008), and hydrological models have been developed specifically for cold regions (Pomeroy et al., 2007). Frozen ground influences hydrological regimes and runoff generation and the interactions with freezing and thawing ground will further influence fluvial geomorphology and sediment yield. Modelling by Boogart et al. (2003) showed that a change from non-permafrost to permafrost conditions leads to network expansion and a (temporary) peak in sediment yield. A freeze–thaw regime may also be very important for riverbank erosion (Yumoto et al., 2006). On slopes, Davies et al. (2001) demonstrate that the stability of frozen jointed bedrock is temperature-dependent, and the importance of cryotic temperature regimes for mass movements from rock walls has been revealed by, for example, Anderson (1998), Gruber and Haeberli (2007) and Hales and Roering (2007). Interconnection between active layer creep (solifluction) and active layer slope failures was demonstrated by Harris and Lewkowicz (2000), and the role of permafrost or seasonal frozen layer in facilitating detachment slides and debris flows is well recognized (Larsson, 1982; Lewkowicz and Harris, 2005). Also in the case of weathering, the ground temperature regime (rather than just freeze–thaw) is considered essential (Hallet, 1983; Hallet et al., 1991; Ødegård et al., 1995; Hall and André, 2001; Hall et al., 2002).

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Glaciers represent distinct parts in many areas of the Arctic and high mountains, and glacial processes interact with the landscape, similarly to the azonal processes discussed above. These interactions include (i) snowdrift, (ii) temporary accumulation and transport of debris deposited on glaciers by aeolian and slope processes (e.g., Heimsath and McGlynn, 2008), (iii) ice-cored moraines on slopes developing into rock glaciers (Barsch, 1996), (iv) the role of glacial meltwater, hydrological regimes, and permafrost for proglacial fluvial processes (e.g., Sidorchuk et al., 2008), (v) paraglacial effects that may be influenced by permafrost conditions (Etzelmüller and Frauenfelder, 2009) such as the alteration of ice-cored moraines by thermokarst processes (Etzelmüller, 2000; Schomacker, 2008; Schomacker and Kjær, 2008), and (vi) direct thermal effects of permafrost conditions on the glacier processes and of the glacier on (subglacial) ground thermal regime (e.g., Kleman and Glasser, 2007).

A common factor in most of the above examples of interactions is *cryotic diurnal, seasonal or long-term thermal conditions*. We consider "cryo-conditioning" a useful concept to appreciate the interconnected nature of cold-climate environments and processes (Fig. 1). We define "cryo-conditioning" in the geomorphic context as *the interaction of cryotic surface and subsurface thermal regimes and geomorphic processes*. This concept underscores the interconnected role of periglacial, glacial, and "azonal" processes in the development of cold region landscapes, by emphasizing that these processes have a crucial *common* control, namely the cryotic surface and subsurface thermal regime.

Cold-climate processes and landscapes are influenced by many factors including ground ice. The ice content is strongly influenced by thermal conditions and the availability of water. At a seasonal scale, freezing and thawing rates are important for ice-lens development and thaw consolidation, thereby impacting solifluction. At a decadal to centennial scale, particularly warm summers will influence the ice-rich transient zone (Shur et al., 2005). Thermal conditions are also a primary control on the stability of buried glacier ice. On the other hand, ice content also significantly influences thermal conditions due to latent heat effects. The advantage of giving cryotic conditions precedence compared to other factors is dual. First, temperature is the factor that defines cold environments. Second, ground and surface temperatures are fairly well known and their distribution and temporal evolution can be modelled.

French and Thorn (2006, p. 171) argue that periglacial geomorphology "lacks a rigorous theoretical base … must be firmly process-based … and needs to sharpen its scientific rigor". The "cryo-conditioning" concept aims at meeting these challenges by providing (1) a theoretical foundation for periglacial geomorphology, firmly embedded in process geomorphology; (2) a unifying core for cryo-geomorphology and (3) a theoretical basis for cryo-geomorphology and its relation to landscape development.

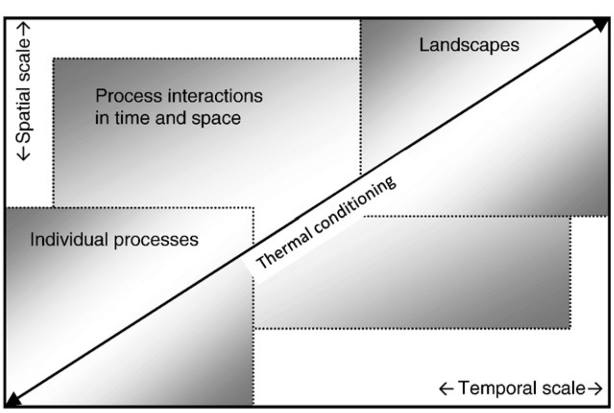

Figure 1. Illustration of the thermal conditioning concept. Thermal conditioning cut across all scales, and applies to individual processes, process interactions and landscape evolution. The boundaries between the different domains are intersecting.

Justification of the concept

The cryo-conditioning concept enables a narrow definition of "periglacial", in line with French (2004), while acknowledging that also "azonal" and glacial processes are influenced by the cold climate and periglacial conditions. Cryo-conditioning is a basic control *beneath* the geomorphic processes operating in cold climates and is therefore a common thread through the relevant geomorphological domains. Therefore, we suggest the term *cryo-geomorphology* to be especially applicable to the landforms and landscapes in these regions that can only be explained by considering the interaction of these processes.

It is increasingly clear that geomorphological explanations occur at various scales (Church, 1996). It has been argued that landscapes are emergent properties of complex systems and thus not explainable from reductionist process studies (Harrison, 2001); in other words, that explanations across scales are inherently impossible. According to such lines of thinking, many landforms themselves may be emergent phenomena. Consequently, any analysis of landscape evolution should be based on theories appropriate for the scale of inquiry. Dixon (2006) reviews the spatial scale issue in periglacial geomorphology and claims that studies of patterned ground, hillslopes (mainly solifluction), and weathering show consistency of form/process relationships across several orders of (spatial) magnitude. Still, if attempts are made to cross spatial scales with respect to geomorphological explanations, this requires a conscious approach (Dixon, 2006).

It is in this respect that the cryo-conditioning concept offers advantages, both in terms of process geomorphology and at the larger scales relevant for landscape evolution (Fig. 1). This is because the thermal conditions have suitable scaling properties, which can be exemplified by the distributional patterns of permafrost in Norway. A number of regional and detailed studies (Isaksen et al., 2002; Etzelmüller et al., 2003; Heggem et al., 2005) show that although permafrost distribution at the local scale is dependent on a number of factors, such as surficial deposits, snow cover, vegetation, and exposure, the regional distribution can be approximated by interpolated mean annual air temperatures. Likewise, for temporal patterns, permafrost ground temperature regimes effectively filter out short-term sub-annual, annual and even decadal temperature cycles. Climatic changes of longer phase are recorded at depth, but the amplitudes are small, and the ground thermal stability is governed by latent heat effects in the transient layer. Thus, ice-rich permafrost is most vulnerable to large and long-term climatic perturbations such as ice-age transitions. Consequently, permafrost influence on small-scale processes and landforms can only be discussed if detailed information on permafrost distribution and characteristics are available, while permafrost influence on the large-scale distribution of landforms and landscapes can be discussed based on long-term climatic changes and cycles. This approach is in line with Harrison (2001, p. 34) who asserts that "the explanations of landscape change employing models of (for instance) climate change […] are at precisely the macroscopic scales with which to understand landscapes. By their very nature, they […] enable us to examine the changing boundary conditions of landform development."

Cryo-conditioned landscape examples

We will briefly discuss a few landscape examples from mainland Norway where we interpret Quaternary landscape evolution as being crucially dependent on the relations between permafrost (subaerial and subglacial), glacial dynamics and thermal processes, and climatic changes through time.

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Preservation of old surfaces

During the Mesozoic and earlier periods of the Cenosoic, one or several planation surfaces were developed in Fennoscandia that collectively have been termed the "Paleic surface" (Reusch, 1900; Gjessing, 1967; Lidmar-Bergstrom et al., 2000). Fennoscandia experienced an asymmetric uplift during the Cenosoic (see discussion in Lidmar-Bergstrom et al. (2000)), lifting the paleic surface to its present elevation. This surface is still a dominant element of the Norwegian geomorphic landscape, despite later incision by both fluvial and glacial processes, and is recognized also by automatic terrain classification (Etzelmüller et al., 2007). Its widespread preservation, regardless of the repeated coverage by Quaternary ice sheets or other glacial configurations, is attributed to cold-based glacial conditions (Kleman and Stroeven, 1997; Lidmar-Bergstrom et al., 2000; Stroeven et al., 2002; Fjellanger et al., 2006; Goodfellow, 2007; Kleman and Glasser, 2007), and the importance of permafrost in this respect has been emphasized (Etzelmüller et al., 2007). Norwegian mountains were probably more often than not underlain by subaerial or subglacial permafrost, considering the expansion of permafrost during onset and retreat of the glaciations and during relatively cold interstadials.

Block fields (felsenmeer) cover large areas of high altitude paleic surfaces and have been regarded as periglacial features, but are often interpreted as preglacial weathering residuals (Roaldset et al., 1982; Rea et al., 1996). This surface cover is clearly important in terms of cooling ground temperatures (high thermal offset) due to advective and/or conductive processes (Hanson and Hoelzle, 2004; Juliussen and Humlum 2007a,b, 2008; Gruber and Hoelzle, 2008). In terms of the cryo-conditioning concept, block fields promote permafrost formation, which again influences the thermal regime of growing glaciers over the area, and thus favor their own preservation; however, modelling is required to investigate to which degree and at what timescales permafrost conditions would determine glacial thermal regimes. The parts of southern Norway interpreted as little or not affected by glacier erosion are larger in area than the glacial landscapes (Etzelmüller et al., 2007). Consequently, the mountains of Scandinavia represent a combination of palimpsest and glacial landscapes that could be explained by considering cryo-conditioning of processes through time.

The co-existence of glacial and paleic surfaces

Alpine or cirque landscapes are commonly found in high mountain massifs where the landscape elsewhere is little modified by glacial processes, despite repeated ice-sheet coverage. The area around Juvvasshøe, Jotunheimen, provides an excellent example (Fig. 2). The paleic surface is easily recognized on all sides of the Kjelen glacier, and here permafrost is present (Ødegård et al., 1992; Isaksen et al., 2001; Isaksen et al., 2002). The cirque in which the probably polythermal Kjelen glacier is situated has been carved during periods without ice-sheet coverage, and the sediments from the cirque have later been removed. Lake-bottom sediments in front of the glacier are very limited in thickness (S.O. Dahl, pers. comm. 2008). Although it is likely that some of the glacial sediments removed from the cirque have been transported and exported by glaciofluvial processes, or thermokarst and fluvial processes during warmer periods, most glaciers at this elevation today are surrounded by well-preserved ice-cored moraines (Østrem, 1964; Etzelmüller et al., 2003). We therefore consider erosion by ice sheets as the most probable mechanism for removing glacial sediments from the front of this and similar cirque and valley glaciers. Even under cold-based conditions, an ice sheet would easily incorporate ice-cored moraines into the basal ice while preserving other surfaces. The landscape development of the high alpine areas thus is the interplay between (i) permafrost conditions, (ii) polythermal local glaciers, and (iii) cold-based ice-sheet processes, and cryo-conditioning is clearly the unifying control.

Fluvial valley development

Fluvial downcutting into the Norwegian paleic surface started in the late Tertiary, due to uplift and colder climate. Landscapes modified by linear glacial erosion follow older fluvial valleys and now form deeply incised glacial fjord or valleys. As discussed by Nesje and Whillans (1994), subaerial processes probably contributed significantly to the development of the fjord and valley sides, and left landforms not obliterated by later glacial erosion. Along many major glacial valleys of Norway one can find v-shaped bedrock valleys in resistant crystalline bedrock more or less adjusted to the present glacial valley floor (Fig. 3), suggesting that fluvial downcutting has commonly been able to keep pace with glacial erosion. We propose that the landscape development along incisions from linear glacial erosion can be conceptualized as the interaction between (i) preglacial relief, (ii) glacial relief development, (iii) fluvial incision, (iv) permafrost development or seasonal frost causing ice segregation in the channel beds, (v) frost weathering of bedrock walls, and (vi) paraglacial adjustments.

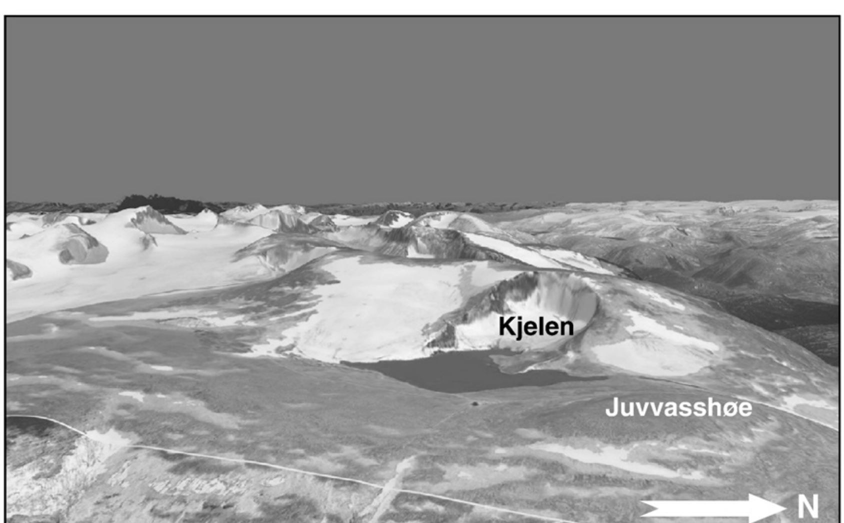

Figure 2. The area around Juvvasshøe, Jotunheimen, Norway shows a coexistence of inherited, paleic surfaces and glacial landforms typical for Norwegian high mountain areas. We interpret this landform assemblage to be caused by erosion by cold-based ice sheets of ice-cored moraine complexes, while other surfaces are mainly left intact. Picture adapted from www.norgei3d.no.

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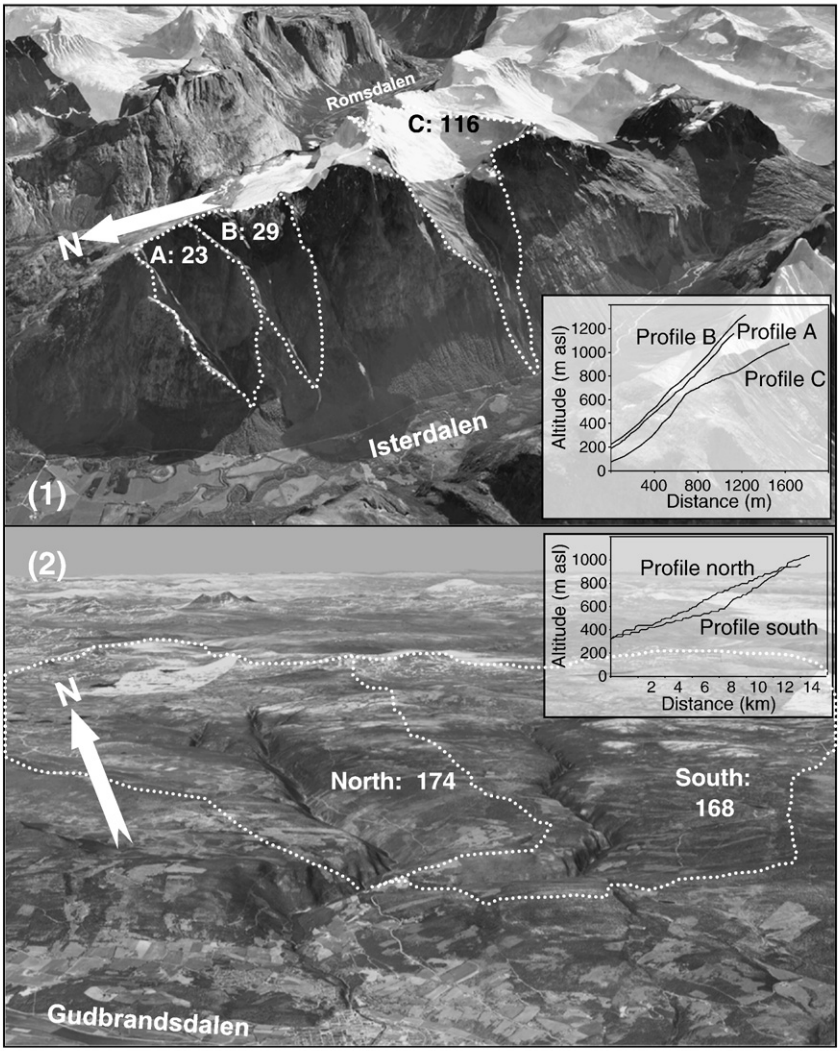

Figure 3. Fluvial valley development in Isterdalen (1) and Ringebufjellet (2). Isterdalen is a side-valley to Romsdalen in northwest southern Norway, while the catchments in (2) join Gudbrandsdalen valley, a large glacial valley in eastern Norway. Dotted lines show the different catchments. The number within each catchment is the calculated annual streampower, averaged along the longitudinal profiles shown in the inserted figure. These profiles extend to catchment boundary for (1) A–B, to the lake in (1) C and to the start of the incisions in (2). The 'north' and 'south' profiles of (2) cross in their upper parts. Note the avalanche snow that is still present within catchments A and B in (1) (pictures taken on Sept. 22, 2006), which points to a cold ground thermal regime even under present climatic conditions. The catchments in Isterdalen cut Precambrian gneiss, at Ringebufjellet late Precambrian sandstones and quartzites. Pictures adapted from www.norgei3d.no.

The total fluvial downcutting amounts to about 0.10–0.25 m/ka on average over the last 2 Ma. Real rates are higher due to periods of glacial coverage. For most such fluvial valleys, average stream power is low due to their limited catchment area (Fig. 3-1), despite very steep longitudinal profiles and narrow channels. The larger catchments in Figure 3-2 have higher average stream power. Little comparative data are available from passive margins (Reusser et al., 2004). The downcutting of these fluvial valleys during the Quaternary does not require extremely high incision rates, but our hypothesis is that an auxiliary process to fluvial erosion better explains at least some of these features. Winter discharge in such valleys will be minimal, and frost action even under present climatic conditions is highly likely. Matsuoka (2008) suggests that slow ice segregation along streams and shores makes such environments very susceptible to frost weathering. If a permafrost environment is present, the effects will be further enhanced by long-term water migration into the transient layer (Shur et al., 2005). Frost weathering and slope/channel coupling also provide continued supply of bedload. Despite being larger, the catchment C in Figure 3-1 does not show any bedrock downcutting, suggesting that other effects than just fluvial erosion may be decisive for incision rates.

Conclusions

We have proposed the term "cryo-conditioning", defined in a geomorphic context as *the interaction of cryotic surface and subsurface thermal regimes and geomorphic processes*, as a new contribution to the discussion on cold-climate landscapes. We also suggest the term *cryo-geomorphology* to denote the geomorphology of cold regions, which especially can be applied to landforms and landscapes where interactions between process domains must be considered.

We are aware that this concept and our examples have a hypothetical baseline, which has to be challenged through further discussions. One approach is to use numerical heat flow models to assess the persistence of permafrost through pre- and post-Weichselian time, especially its interaction with glacial coverage. The cryo-conditioning concept allows the recognition and explanation of wide ranges of cold-climate landforms and landscapes. Cryo-conditioning relate to glacial, periglacial, slope, marine, fluvial and aeolian processes, providing a common control on cold-climate landscape development, highlighting the necessity of considering interaction of processes for explanations of landscape development. We argue that the cryo-conditioning concept bridges the gap

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between small-scale process and large-scale landscape development studies.

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