—Plenary Paper—

Alpine and Polar Periglacial Processes: The Current State of Knowledge

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Abstract

Recently the traditional view on the geomorphological evolution of periglacial landscapes has been questioned. The geomorphological processes considered most important for landscapes in periglacial regions, in general, are not unique for periglacial environments. On the other hand, there is a suite of geomorphological processes which may be seen as characteristic for periglacial environments. Based on what the author considers characteristic periglacial phenomena and landforms, this paper attempts to identify what might be conceived as the main characteristic periglacial processes. Seasonal or perennial freezing and conspicuous landforms such as extensive talus sheets, polygonal networks, and large-scale patterned ground, dominate descriptions of periglacial regions. Phenomena controlling bedrock disintegration, rockfall, thermal contraction cracking, and sorting of sediments are therefore all seen as the means to identify characteristic periglacial processes. Each of these periglacial processes is shortly described, and the present state of knowledge, or the lack of such, is outlined.

Keywords: climate; geomorphology; modeling; monitoring; periglacial; permafrost.

Introduction

Periglacial regions at high latitude or high altitude experience rapid changes in the ground thermal regime in response to daily and annual as well as long-term climatic variations. Changes in the ground thermal regime and the associated growth or decay of permafrost may destabilize rock slopes or mobilize sediment slopes, possibly leading to major geomorphic changes, accompanied by natural hazards (e.g., Harris et al. 2001, Haeberli and Burn 2002). One practical priority issue of periglacial geomorphology should therefore by to improve understanding of the climatic controls on geomorphic processes, to predict potential hazards. The ultimate scientific aim of periglacial geomorphology, however, remains the formulation of models for cold-climate landscape evolution (French and Thorn 2006).

By tradition, alpine and polar periglacial landscapes are regarded as characterized by efficient frost-driven geomorphological processes. The importance of frost shattering and related processes was equally emphasized. Hence, the geomorphology of periglacial areas was long regarded as controlled primarily by processes driven by freeze–thaw mechanisms.

Originally, the term periglacial was used to describe the climatic and geomorphic conditions of areas peripheral to Pleistocene ice sheets and glaciers. Modern usage refers, however, to a wider range of cold climatic conditions regardless of their proximity to a glacier, either in space or time. In addition, many, but not all, periglacial environments possess permafrost; but they appear all to be dominated by frost action processes (Dylik 1964, French 1976, Washburn 1979, French 2007). In line with this view, the English version of the Multi-Language Glossary of Permafrost and Related Ground-Ice Terms compiled by the IPA's Terminology Working Group (Everdingen 1998), defines the term periglacial as the conditions, processes and landforms associated with cold, nonglacial environments.

Periglacial landscapes

The origin of periglacial landscapes as traditionally defined is recently becoming a theme for renewed debate. The relationship of landscapes to climate is a topic which has simultaneously been regarded as a focus for research in geomorphology and an approach which has fruitlessly occupied the time of geomorphologists over the past several decades. The former view has characterized research by many French and German geomorphologists, whereas the latter has prevailed among Anglo-American researchers. There is little doubt that major differences in climate have a profound effect on landscape development. Disagreement comes with the finer distinctions between degrees of climatic differences evident in past attempts to identify morphoclimatic zones. For instance, if we examine a range of landscapes in periglacial environments, landscape diversity is often more apparent than uniformity. A further problem is the diversity of conditions under which apparently similar landforms can develop. Perhaps the most intractable problem in periglacial geomorphology is the logical temptation of explicit linking of a particular landform with a specific set of climatic conditions. The observation of periglacial phenomena such as, e.g. ice-wedge casts, in climatic environments in which they could not have developed obviously raises the question of climatic change in landform interpretation.

Any modern periglacial landscape should be considered as consisting of a number of landforms currently adjusting according to present climate, and a number of relict features, produced under past climatic conditions. Whether a climatic change is of geomorphic significance depends on its magnitude and duration, and on the properties of the landform considered. The larger or more resistant a landform, the longer, in general, it takes to adjust to a change in climate. In addition, the broad features of landscapes in periglacial environments are also highly influenced by lithological differences.

The validity of the traditionally view on the evolution of a typical periglacial landscape has therefore been questioned in recent times: The importance of geomorphological processes like chemical weathering, rainfall-induced slope processes and river action are emphasized, even though they are not unique for periglacial environments, but occur also in many other climatic settings. For example, Rapp (1960) in his classical study on weathering in northern Sweden demonstrated that solution was more important than mechanical processes. Later Thorn (1992) suggested that frost action may have been overestimated in relation to explaining the geomorphology of periglacial regions. Weathering and transport processes not related to frost may often modify the landforms resulting from frost action, or even preside over landform evolution in many periglacial environments. The action of wind and running water may be two important examples of such ubiquitous processes not limited to cold regions. This development in 2003 lead André to ask the pertinent question: Do periglacial landscapes evolve under periglacial conditions? The significance of this question was emphasized by French and Thorn (2006). On this background we might even begin to wonder what is understood by periglacial processes.

Periglacial processes

The André (2003) paper was published in a special issue of the journal Geomorphology, presenting a selection of papers originally presented at the general session ‘‘Glacial and Periglacial Geomorphology’’ of the Fifth International Conference on Geomorphology held in Tokyo, Japan, in August 2001 (Matsuoka et al. 2003). A study of these papers provide some assistance in identifying what is understood as periglacial processes at the beginning of the 21st century. Broadly the papers could be categorized into four themes: effects of diurnal frost, mountain permafrost, paleo-periglaciation and nonfrost processes in periglacial environments.

This suggests that many periglacial geomorphologists still have their research focus on frost-related processes. Low temperatures as a driving mechanism apparently remain a valid criterion for defining periglacial processes, even though the evolution of landscapes in periglacial environments may be controlled by other azonal processes. Also the steady interest in fossil periglacial features as indicators of past cold environments, points toward this conclusion. The validity of paleoclimatic indicators depends on precise description of, among other things, the climatic control on processes responsible for the landform or sedimentary structure studied. Otherwise, the periglacial feature observed would clearly be of little use as indicator for past cold environments.

So, at the beginning of the 21st century periglacial geomorphologists apparently are defining key periglacial processes as those related to seasonal or perennial frost, a point of view supported by French and Thorn (2006). At the same time, it is recognized that landscapes in periglacial regions are not always dominated by such periglacial processes, but quite often by more omnipresent processes such as wind and running water. On this background it might be considered if the future use of the term periglacial should be limited to describe processes and environments, rather than landscapes?

Having identified the modern implication of periglacial processes, we may proceed towards identifying a number of especially important or characteristic processes. To achieve this goal, we must first consider what is generally seen as characteristic landforms in periglacial environments. Due to space limitations, this will clearly not represent a comprehensive analysis, but will focus on a few landforms and phenomena, by the present author seen as characteristic for landscapes in periglacial environments.

Characteristic periglacial landforms and processes

The perhaps most obvious and impressive landforms in periglacial environments are those associated with steep slopes. In many mountain areas, glacial over-steepening, combined with weathering has led to rock slope instability and the production of large volumes of debris. Outside Holocene permafrost environments, a fundamental distinction is often recognized in valleys partly filled by glacier ice during Stadials of the last ice age. Within the former glacier limits, volumes of talus are limited relative to those at the foot of slopes outside the limits. By implication, the greater volumes of debris reflect the more severe periglacial conditions that prevailed during the Stadial and perhaps also during the deglaciation. Indeed, the impressive size of talus accumulations in periglacial highlands environments has led many researchers to conclude that rockfall is particularly pronounced under cold-climate conditions, due to release of debris from cliffs by frost wedging.

Low-relief periglacial areas are characterized by extensive polygonal networks, patterned ground and different types of frost mounds. All these phenomena are related to temperature induced volume changes of bedrock, sediments, ice, or mixtures of thereof. A highly diversified terminology is attached to the description of the surface expression of such phenomena. For example polygonal networks may appear in the literature under the headings of tundra polygons, frost-fissure polygons, ice-wedge polygons, and sand-wedge polygons, just to mention a few.

These observations suggest that frost-related non-glacial processes leading to rock disintegration, rockfall, rupturing by thermal contraction, and the deformation and sorting of thawed soil may be among what might be seen as characteristic periglacial processes. This assumption will provide the basis for the discussion below.

Characteristic Periglacial Phenomena

Rock disintegration

Evidence suggests that frost action is not the only weathering process leading to rock decay in periglacial environments. Cold-climate weathering is caused by the broader concept of cryogenic weathering, a collective term for a combination of little known physical and chemical processes which cause the in situ breakdown of rock under cold-climate conditions. Pressure release, salt weathering, chemical weathering, biological activity or thermal shocks may all play a role. In fact, chemical weathering (Roberts, 1968, Dixon et al., 2002) and biological processes (André, 2002) are more and more often considered as important actors in cold environments.

Field data on rock temperature and moisture content is essential for improved understanding of rock weathering in periglacial environments and for setting up realistic laboratory experiments. Unfortunately, such data are scarce in literature. In recent years, however, this situation is beginning to change through the publication of such data (e.g., Hall 1997, Hall 2006, Hall et al. 2002, Prick 2003).

This new accessibility of high-quality field data has provided the background for conducting realistic laboratory experiments, investigating the importance of ice segregation for low temperature bedrock breakdown under permafrost conditions (Murton et al. 2001). This experiment demonstrated that ice segregation, frost heave and brecciation in artificial permafrost formed in moist chalk are fundamentally similar to the processes associated with the growth of natural permafrost formed in frost-susceptible sediment. Similarities between the experimentally formed brecciation and naturally brecciated bedrock in areas of contemporary and former permafrost suggest that ice segregation during perennial and seasonal freezing is an important weathering process of frostsusceptible bedrock. By implication, the coarse, angular debris produced by ice segregation in bedrock during cold Quaternary periods was suggested being the sediment source for many of the coarse periglacial slope deposits. It is also very likely that bedrock fracture by ice segregation is significant for rockwall stability in regions of mountain permafrost, and for landform development in such areas in general. On this background Büdel's (1977) original 'Eisrinde' hypothesis absolutely deserves renewed research interest.

Rockfalls

The term rockfall describes the fall of relatively small (< 10 m^3) fragments of rock debris that are released from bedrock cliffs. By tradition, rockfall in periglacial environments has been widely attributed to frost wedging, the widening of cracks and joints by ice during freezing and detachment of debris from cliffs during thaw. Frost wedging is, however, only one of several processes operating on cliff faces (André 2003). Rockfall may also be triggered by stress-release, progressive failure along joints, or build-up of hydrostatic pressure within a rock mass. Indeed, some researchers view the role of freeze-thaw in rockfall as trivial in comparison with intrinsic controls such as stress release, weathering and build-up of joint-water pressures.

The timing of rockfalls remains the main reason for seeing frost wedging as the foremost cause of rockfall in cold environments. Rapp (1960) noted that rockfall at high latitudes is most frequent in spring and autumn, when cliffs was assumed to experience a maximum frequency of freeze-thaw cycles. Rockfall inventories in the Arctic and the Alps (e.g. Luckman, 1976, Coutard and Francou 1989) suggest maximum activity during the spring thaw. In Japan, Matsuoka and Sakai (1999) observed peak rockfall rate 5-15 days after meltout of the cliff face, when seasonal thaw reached an estimated depth of 1 m. Other rockfall inventories, however, emphasize diurnal variations, rather than seasonal trends. This is observed at alpine cliffs with frequent diurnal freeze-thaw cycles penetrating to depths of 50 cm (Coutard and Francou 1988). Rockfalls may also coincide with summer rainstorms, implying that build-up of joint-water pressures is also instrumental in releasing debris. Conversely, Matsuoka and Sakai (1999) in Japan found that intensive rockfall activity is rarely associated with either diurnal freeze-thaw cycles or precipitation events. So it is actually difficult to confirm the hypothesis regarding frost wedging as the main trigger of rockfall in periglacial environments.

Wind action

Due to the general lack of trees, many periglacial regions experience high wind speeds (Seppälä 2004), leading to the formation of different types of deflation surfaces. The vegetation, soil and fine material debris is removed to leave an armoured surface where large clasts are embedded within a matrix of finer sediment. Grains of sand and fine gravel can often be observed in motion during strong winds, blasting vegetation and rock surfaces. Sand dunes or sand sheets may occur downwind of such areas (Ballantyne and Harris 1994, Humlum and Christiansen 1998), but often much of the debris seems not to accumulate as dunes or sheets. Some may become temporarily resident in the snow pack, to thaw out in spring. Some probably finds its way into lakes and rivers on valleys floors. Some may be transported into the sea suspended in the air.

Another characteristic feature related to wind action in periglacial environments is wind-facetted blocks or wind polished bedrock surfaces (Christiansen and Svensson 1998). The wind-eroded surfaces are identified from their smooth and polished surfaces, together with facets and grooves (Christensen 2004). Blowing snow at low temperatures has apparently been the abrading agent for several examples of periglacial bedrock windpolish (Fristrup 1953).

Snowblow

Snowblow by wind is important in most periglacial environments, partly because of the typical absence of high vegetation providing lee at the ground surface, partly because many periglacial regions are found at high latitudes or high altitudes, where wind speed may be high.

The process of snow drifting is important in low-relief periglacial terrain, where the resulting distribution of snow controls heat exchange between atmosphere and the ground surface during the winter, for example on palsas (Seppälä 2004). The thermal importance of the snow cover for permafrost is well demonstrated by the efforts put into determining the n-factor, describing the thermal insulation provided by the snow cover (Smith and Riseborough 2002). In high-relief areas, snow accumulation on steep slopes contributes to the release of avalanches, especially on slopes downwind of extensive mountain plateaus (Humlum et al. 2007).

At low temperatures, the hardness of snow crystals increases, and wind transported snow may act as an efficient abrasive agent in relation to boulders and bedrock (Fristrup 1953). In addition, wind induced accumulations of snow are important as sources of water during the summer, as precipitation generally is low in periglacial environments.

Bagnold (1941) provided much of the groundwork for current steady-state models of sand drift (e.g. Sørensen 1991). The same physical basis has been applied to existing numerical models of snowdrift, such as SnowTran-3D (Liston and Sturm 1998) and the snowdrift index in SNOWPACK (Lehning et al. 2000, 2002a, 2002b). Snow drift prediction models using weather station data have also been developed for meteorological services (e.g., Li and Pomeroy 1997a, 1997b). These models, however, tend to consider snow drift as a probabilistic event and relate conditions to a measurement height, rather than to surface conditions.

Snow avalanches

Snow avalanches represent a periglacial transport process especially important during winter and spring. Although many shallow or midwinter avalanches contain only snow, deeper and late winter avalanches frequently incorporate and transport varying volumes of rock debris. As avalanches tend to follow gulleys, this debris accumulates on valley floors at the mouths of these gulleys in the form of avalanche boulder lobes (Rapp 1960), protalus ramparts (Ballantyne and Harris 1994), or rock glaciers (Humlum et al. 2006).

The meteorological control of snow avalanches represents a research theme in its own right, highly developed especially in Switzerland, Austria, USA and Norway. Several factors affect the likelihood of an avalanche, including weather, temperature, slope steepness, slope aspect, wind direction, terrain, vegetation, and the general snowpack conditions. Different combinations of these factors can create low, moderate or extreme avalanche conditions. Despite the existence of large databases with observations on avalanches, avalanche safety rules still are based mainly on empirical rules of thumb, rather that on strict meteorological-geotechnical analysis.

Another way of investigating the climatic control on avalanches is through analysis of avalanche deposits accumulated during the Holocene (e.g., Blikra and Selvik 1998). Such analyses, however, important as they are, only indicate that avalanches become more frequent during cold periods with frequent snow precipitation, but do not provide the means of detailed insights into meteorological controls on avalanche release. Indeed, some attempts at analysis simply assumes that the presence of what is interpreted as avalanche-derived debris indicate past periods with cold and snowy conditions.

Thermal contraction of frozen ground

Periglacial thermal contraction phenomena such as ice-wedge casts are widespread in periglacial environments. Fossil features in the form of ice-wedge casts are often used to estimate palaeotemperatures, specifically the maximum values of the mean annual air temperature or the mean air temperature of the coldest month (e.g., Washburn 1979, Vandenberghe et al. 1998). The now common use of ice-wedge casts as palaeotemperature indicators arose from an influential study by Péwé (1966a, 1966b) of ice-wedges in Alaska. As later pointed out by Murton and Kolstrup (2003), however, the validity of such attempts at reconstructions still remains uncertain because of limited knowledge of the frequency of thermal contraction cracking under contemporary permafrost environments. In addition, the perhaps complex controls other than meteorological on cracking are still incompletely understood. In fact, snow thickness appears to represent a decisive factor on ice-wedge cracking near the Western Arctic coast of Canada (Mackay 1993). Also the role of surface vegetation still needs to be quantified (Murton and Kolstrup 2003).

Progress in knowledge on thermal contraction cracking requires detailed field observations, supplemented by laboratory and numerical experiments, using real-world meteorological data on climate, landforms and sediments. A numerical modeling experiment on ice-wedge formation was recently presented by Plug and Werner (2001). This attempt at modeling ice-wedge growth turned out to be premature, because of lack of insight in real world conditions (Burn 2004).

Examples of how to expand knowledge on thermal contraction cracking of frozen sediments is given by careful field studies such as, e.g., Mackay (1993) and Christiansen (2005), in great detail describing meteorological and snow conditions related to thermal cracking of frozen ground.

Sediment sorting

Sorting of near-surface sediments in periglacial areas is responsible for the distinct, and often symmetrical geometric shapes known under the general heading patterned ground. The details of the sorting process and the origin of patterned ground has remained elusive for ages, despite much research effort.

Patterned ground is perhaps the most striking feature of the periglacial landscape, and can be found in a variety of forms: Polygons, circles, nets, steps, and stripes. The individual surface forms may range in size from a few centimeters to several meters in diameter. Typically, the type of patterned ground in a given area is related to the amount of larger stones present in local soils and the frequency of freeze-thaw cycles.

Polygons, circles and nets normally occur on level or gently sloping surfaces, while steps and stripes are found on steeper gradients. Both sorted and non-sorted varieties are recognized. The sorted varieties are typically outlined by coarse, stony material, and so are termed “stone circles,” “stone polygons,” “stone nets,” “stone steps,” and “stone stripes.”

The origin of patterned ground involves a complex interaction of several geomorphological processes, including differential frost heaving and mass movement. Recurrent freezing and thawing of water is usually believed to be critical for the development of patterned ground. In permafrost regions and non-permafrost regions affected by seasonal frost, repeated freezing and thawing of soil water transports larger stones toward the surface as smaller soils flow and settle underneath larger stones. At the surface, areas that are rich in larger stones contain less water than highly porous areas of finer grained sediments. These water saturated areas of finer sediments have greater ability to expand and contract as freezing and thawing occur, leading to lateral forces which ultimately pile larger stones into clusters and stripes. Through time, repeated freeze-thaw cycles form the common polygons, circles, and stripes of patterned ground.

There is still much debate as to the detailed mechanisms involved in freeze-thaw sorting, but it is widely agreed that the large scale patterned ground reflects the former existence of permafrost (Ballantyne 1996). Recurrent freezing and thawing of ground is also considered important for other periglacial phenomena such as solifluction and ploughing blocks.

The way ahead for periglacial geomorphology

Periglacial geomorphology is very special. It usually requires some mastery of geology, meteorology and geophysics to plan and carry out efficient investigations of complex geomorphological problems in periglacial environments. On the other hand, especially Quaternary geologists can in a very real sense be seen as applied periglacial (and glacial) geomorphologists. This relation emerges because periglacial (and glacial) geomorphologists combine the historical perspective so dear to geologists with an accentuated awareness and interest of contemporary geomorphological processes. In my opinion, it is exactly this study of geomorphological processes in periglacial environments which provides periglacial geomorphology with integrity, and upon which periglacial geomorphology relies for future scientific credibility.

Geomorphological processes clearly unique to periglacial environments relate to seasonal or perennial freezing, including the growth of segregated ice and associated frost heaving. Many of these processes operate in the near-surface layer subject to seasonal freezing and thaw; the active layer in permafrost regions. Ground seasonally frozen experience a range of special conditions associated with pore-water expulsion and thaw consolidation (French and Thorn 2006). On sediment slopes, this may promote rapid mass failures. On bedrock slopes, disintegration of exposed rock by mechanical frost weathering and several still poorly understood physical and biochemical processes may lead to rock falls. In addition to such characteristic periglacial processes the enhanced effect of wind in periglacial regions clearly deserves further study (Seppälä 2004).

Any study contributing to increased knowledge on geomorphological processes in periglacial environments are by definition important, no matter the specific theme chosen. From a strategic point of view, however, it appears that improved understanding of especially processes related to seasonal or perennial freezing should be seen as having tactical research priority within future periglacial research. Rock weathering in periglacial environments may be considered the mother of many types of sediments, and therefore a key factor for a range of other processes and landforms. Rock weathering in periglacial environments definitely deserves a concerted research effort, along with research on thermal contraction cracking and sediment sorting. These three phenomena together typify landscapes in most periglacial environments.

What is needed within periglacial geomorphology is a detailed monitoring scheme of meteorological parameters and geomorphological processes. Clearly, the use of dataloggers and other automatic equipment will have an important role in this development (Matsuoka 2006).

In this context, the organization in 2004 of a new Working Group (WG) on ‘Periglacial Landforms, Processes and Climate’ under the International Permafrost Association (IPA) may prove helpful. This WG is aiming at making a database for temporal and spatial variability of periglacial processes with special attention to meteorological controls and the impact of climatic change. To achieve this goal, the WG attempts to establish a global network for monitoring periglacial processes (Matsuoka and Humlum 2005, Matsuoka 2006), highlighting geomorphological processes associated with ground thermal regimes, inside and outside permafrost regions.

The recommended parameters to be measured depend primarily on the purpose of the study and the spatial scale. A cold-climate drainage basin is subjected to a variety of geomorphic processes, including glacial, periglacial, fluvioglacial, nival, gravitational and eolian processes. One research approach may focus on the mechanism of a specific process like rock fall, solifluction or ice-wedge growth, whereas other may aim at evaluating the sediment budget for the whole catchment. Whatever the approach chosen, the search for knowledge on past and present processes influencing landform evolution in periglacial regions is becoming increasingly influenced by more and more refined monitoring protocols, relying upon automatic and sophisticated equipment.

To the present author the common denominator for future periglacial research appears to be a coordinated research scheme embracing mapping, monitoring, experiments, and modeling, with focus on geomorphological processes relating to seasonal or perennial freezing.

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