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Factors Controlling the Distribution of Mountain Permafrost in the Northern Hemisphere and Their Influence on Sediment Transfer

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Abstract

The distribution of mountain permafrost in the northern hemisphere depends on topographic and climatic factors, ranging from the maritime conditions of Iceland over transitional conditions in southern Norway to continental conditions in Mongolia, and from alpine mountains to paleic mountains. This study discusses the different environmental factors that govern permafrost distribution based on personal studies and a literature review. It is hypothesized that the thermal state of the ground is an important parameter to understand the time and spatial scale of sediment transfer and landscape development in cold mountainous regions. This is exemplified for the cases of rock walls, glacier forefields, rock glaciers, and the case of sediment remobilization due to glacier advance. The authors propose that thorough knowledge of the ground thermal regime is an important basis for addressing sediment budgets in space and time.

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Introduction and Background

Permafrost in mountains is a comparably new scientific topic. During recent years mountain permafrost gained increasing attention due to its influence on the occurrence of geotechnical hazards (e.g. Haeberli, 1992; Harris et al., 2001; Arenson et al., 2003) and due to its role as a freshwater supplier in arid mountain chains (Corte, 1976; Schrott, 1998). Mountain permafrost is special for two main reasons: First, it is extremely heterogeneous. The transition between permafrost patches and continuous permafrost can be located along a single slope, with correspondingly great variability of ground temperatures, unfrozen water content, and geotechnical properties of the ground over short distances (e.g. Hauck et al., 2004). Second, most mountain permafrost areas are characterized by relatively "warm" ground temperatures (i.e. temperatures close to 0 °C), making these areas extremely sensitive to climate change impacts (cf. Haeberli et al., 1993).

Permafrost is defined as a certain thermal state of the ground. The term "periglacial" addresses this domain, even though permafrost is not a prerequisite. Geomorphological processes in permafrost areas mainly relate to products of annual freeze-thaw cycles (patterned ground), gravitational processes (solifluction, creep), and landscape-forming processes associated with valley building and cryoplanation. The role of permafrost in a sediment budget concept, and its influence in general landscape development, is less elaborated in the literature, and mainly related to the influence of rock glaciers (e.g. Jäckli, 1957; Barsch et al., 1979; Frauenfelder, 2006; Berthling and Etzelmuller, 2007).

It is evident that mountain permafrost is an important factor for processes related to sediment production, mobilization, and deposition. High mountains in Europe (e.g. the Scandes, Alps), North America, and Central Asia (e.g. Himalaya, Pamir, Altai, etc.) were glaciated to a varying degree and in varying extents during the Pleistocene and Holocene, in contrast to more continental areas in, for example, the northern Yukon and parts of Siberia/Russia and Alaska. In these formerly or presently glaciated mountain chains most of the sediment availability and mass flux can be described within the concept of paraglacial sediment adjustment (see overview in Ballantyne, 2002). The exhaustion rate of sediments within this framework is dependent upon different factors, such as bedrock geology, topography, and climate (Ballantyne, 2002). As a consequence of certain climate factors, the evolution or prevalence of permafrost after the early Holocene glacier retreat is affecting time-dependant sediment budgets in core areas of many mountain chains.

The term "paraglacial" does not refer to a certain process domain but is an expression for transitional processes, in this case caused by glaciations, adapting to a new equilibrium. This is also known for other geomorphological processes, such as the periglacial weathering-cover or loess accumulation in, e.g., Central Europe (Büdel, 1982; French, 1996), planation and tropic soil accumulation throughout the Tertiary in Central Europe (cf. Büdel, 1982), or rapid land uplift and associated erosion and accumulation processes in tectonically active continental margins (cf. Summerfield, 1991). The term "paraglacial" explicitly addresses the geomorphologic imbalance caused by glaciations in terms of erosion and accumulation of debris, available for non-glacial processes.

In terms of the understanding of process interactions and landform development, the paraglacial concept opens up an interesting connection between the glacial and the periglacial realm, especially a coupling of the "glacial system" and the "coarse debris system" according to the morphogenetic definitions of high mountain process areas (cf. Caine, 1974; Barsch and Caine, 1984).

The *motivation* for this paper is to formulate and discuss concepts of the relationship between permafrost and sediment transfer in cold mountain areas within the framework of the IAG SEDIBUD working group (Beylich et al., 2008). We suggest that the thermal state of the ground and thus, mountain permafrost distribution, is an important factor for the sediment transfer and subsequent landscape development in cold mountainous regions, as schematically illustrated in Figure 1. The *objective* of this paper

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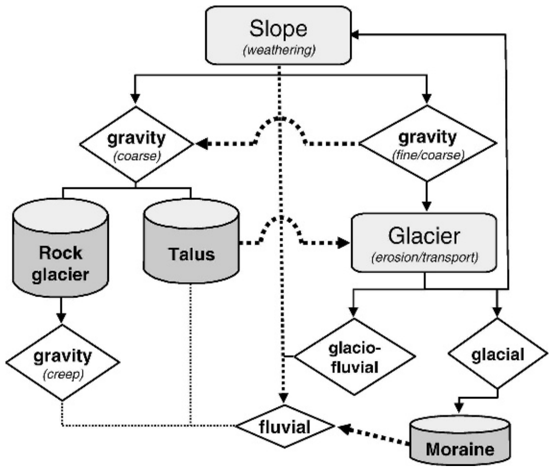

FIGURE 1. Sediment cascade system in mountainous areas. The relative importance of the arrows indicating paraglacial sediment fluxes are highly influenced by the ground thermal regime (based on Etzelmüller, 2000).

is to highlight process patterns based on a conceptional, geomorphological understanding by a modification of the paraglacial exhaustion model with consideration of permafrost conditions especially for the glacier sediment system and the coarse (and thus paraglacial) sediment system in the sense of Barsch and Caine (1984), neglecting frost-driven creep processes and fluvial dynamics. This paper outlines mountain permafrost in relation to the factors influencing its distribution in different environmental settings, and its influence on glaciers. Mountain ground thermal regimes are then coupled conceptionally and discussed based on their influence on selected aspects of the paraglacial concept and the sediment transfer system.

Factors Affecting Mountain Permafrost in Different Environmental Settings

TOPOGRAPHY

Topography is one of the major constraints for the existence of mountain permafrost. At present no clear consensus exists about how to define a mountain range. Geomorphologists normally use a morphometric definition in terms of elevation variability within a certain spatial range (cf. Barsch and Caine, 1984), which is, for example, easily implemented using digital elevation models (DEMs) (Fig. 2). Such morphometric characteristics are important to understand mountain permafrost distribution and associated geomorphologic processes. Permafrost in Scandinavia is, for instance, related to other topographic settings than permafrost in the Alps. In Scandinavia, relatively high, but smooth mountains (paleic surfaces) dominate within the permafrost realm, while this type of smooth topography is absent in the Alps (Fig. 2). This causes different landform assemblages, e.g. the scarcity of rock glaciers in southern Scandinavia (cf. Etzelmüller et al., 2003).

CLIMATE, SURFACE WETNESS, SNOW, VEGETATION, AND SURFACE COVER

Haeberli et al. (1993) has distinguished mountain permafrost into more maritime and more continental realms early-on. In many mountain ranges there exist continuous transitions between maritime- and continental-dominated climate conditions because of the rain-shadow effect of mountain ranges. There, both an increase of the equilibrium line altitude of glaciers (ELA) and a decrease of the lower permafrost limit towards the rain-shadow direction can be observed. This is documented, for example, for Scandinavia (Fig. 3) (Etzelmüller et al., 2003), the Yukon mountains (Lewkowicz and Bonnaventure, 2008), and Iceland (Etzelmüller et al., 2007).

In mountain areas, the relationship between permafrost existence and topographic and climatic factors has been widely used to map permafrost distribution, and conceptually outlined using precipitation-temperature diagrams like the one shown in Figure 4 (Haeberli and Burn, 2002). In these studies the distribution of certain permafrost landforms, such as rock glaciers (e.g. Frauenfelder et al., 2001), or ground temperature parameter proxies, such as the bottom temperature of the snow cover (BTS), were statistically related to permafrost temperatures or, simply to its existence/absence (e.g. Hoelzle, 1992; Gruber and Hoelzle, 2001; Isaksen et al., 2002; Lewkowicz and Ednie, 2004; Heggem et al., 2005; Lewkowicz and Bonnaventure, 2008). Altogether, such studies document certain prevailing dependencies (Table 1), which are summarized in the following:

Elevation and *topographic aspect* are the most important factors governing permafrost distribution, and are proxies for the energy balance near the ground surface. Topographic aspect is normally substituted by incoming solar radiation, calculated using DEMs. However, many studies demonstrate that the influence of topographic aspect increases with continentality and slope inclination. In maritime areas like the western Yukon (Lewkowicz and Bonnaventure, 2008) or western Norway (Isaksen et al., 2002), permafrost distribution can be explained quite adequately by elevation alone, while in more continental areas, like the eastern Yukon (Lewkowicz and Bonnaventure, 2008), eastern central Scandinavia (Heggem et al., 2005; Juliussen and Humlum, 2007b), or Mongolia (Etzelmüller et al., 2006; Heggem et al., 2006; Sharkhuu et al., 2007), topographic aspect gains increasing influence. In high-relief regions, such as the Alps, topographic aspect is a key parameter for the assessment of the permafrost distribution pattern (Hoelzle, 1992; Gruber and Hoelzle, 2001; Lewkowicz and Bonnaventure, 2008).

Snow cover decouples the atmosphere from the ground in terms of energy exchange, and the degree of decoupling is governed by snow thickness (Goodrich, 1982). According to Smith and Riseborough (2002), the snow cover delineates the transitional area between discontinuous and continuous permafrost. In mountains, however, snow cover is extremely heterogeneous due to topography and wind redistribution, and important in all settings (e.g. Mittaz et al., 2002).

Surface wetness and *high soil water content* act differently in maritime and continental settings. In more maritime mountains, permafrost is restricted to high-alpine zones with cool summers and low vegetation coverage. Wet areas act as a heat source due to latent heat and accumulation of snow in such areas (Heggem et al., 2005). In continental areas, summer temperatures are higher and allow denser vegetation in terms of biomass and consequently the build-up of associated organic material. Here, the vegetation damps summer temperatures, while the winter cold can penetrate easily into the ground due to the higher thermal conductivity of frozen versus thawed organic material (Williams and Smith, 1989). Thus, wet areas are positively correlated with permafrost existence in more continental environments, while the opposite is true in maritime settings (Etzelmüller et al., 2006).

It is only in continental mountain environments that *vegetation* is important. In arid continental mountains, permafrost

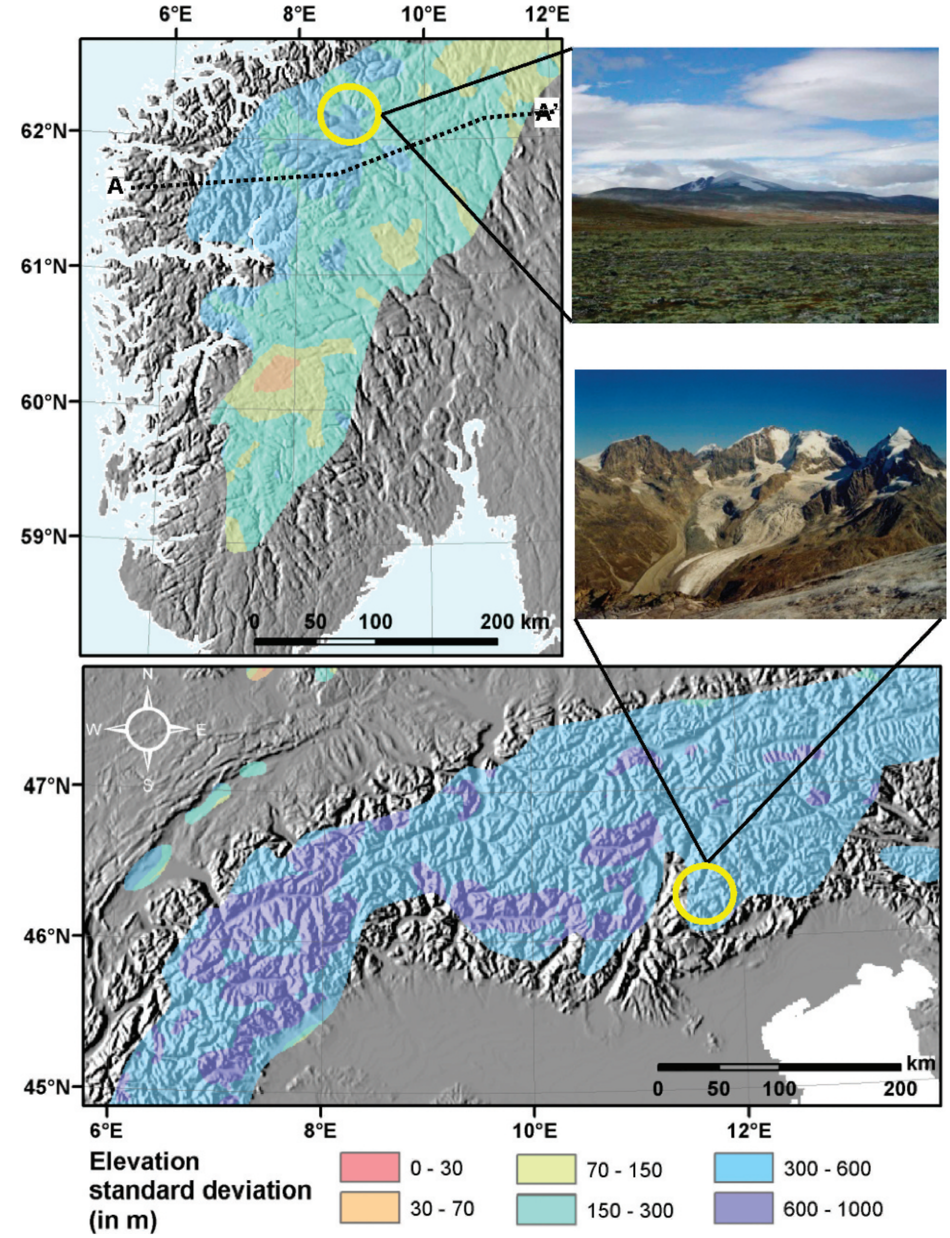

FIGURE 2. The figure illustrates the topography variability in the permafrost areas of southern Norway and the Alps. The topographic variation is expressed as the *standard deviation* of *elevation* within a 10 km radius from each point (cell in a DEM) in the map. The colored areas denote the areas potentially underlain by permafrost according to Brown et al. (1995). While the mountains of southern Norway are dominated by an *elevation standard deviation* of below 300 m, the corresponding value for the Alps is above 300 m, with large areas above 500 m. The photographs display the difference of paleic and alpine landscapes, exemplified for southern Norway (Dovrefjell) and Switzerland (Engadin). The dotted line shows the position of the profile of Figure 3.

may be the reason for denser vegetation as compared to non-permafrost areas, due to the fact that the active layer keeps the water close to the surface during summer and, therefore, makes it available for vegetation. The large influence of vegetation cover on permafrost distribution in, e.g., northern Mongolia has been demonstrated by Sharkhuu et al. (2007). In other, more moderate, continental areas like Finnmark county, northern Norway, vegetation may have the opposite effect, by maintaining a stable snow cover and, thus, preventing permafrost aggradation (Isaksen et al., 2008).

Surficial sediments are highly heterogeneous in mountains. According to Smith and Riseborough (2002), organic material determines the limits of sporadic permafrost in lowland permafrost areas. This is also valid for many mountain areas and manifested in the distribution of palsas. Examples can be found in northern Scandinavia, where we can observe palsas close to sea level in Finnmark (Svensson, 1964), while the lower limit of discontinuous mountain permafrost is found at elevations between 400 and 500 m a.s.l. (Farbrot et al., 2008). A similar pattern is documented for the Abisko area, Sweden (Zuidhoff and Kolstrup, 2005), northern Finland (cf. Seppälä, 1997; Luoto and Seppälä, 2002), and Iceland (Etzelmüller et al., 2007).

An additional factor in mountains is *coarse, block-rich material*. It has been widely shown that the surface offset between "surface temperatures" and "top of permafrost temperatures" is high in such material due to advective heat transport (cf. Gorbunov et al., 2004; Harris and Pedersen, 1998), because of high surface roughness, preventing the accumulation of enough snow to cover blocks during winter (e.g. Juliussen and Humlum, 2008) or simply due to low thermal conductivity of the upper block-rich layer (Gruber and Hoelzle, 2008). Many studies clearly show the cooling effect of block fields, both on slopes and on planes (Delaloye et al., 2003; Juliussen and Humlum, 2007b, 2008). This means that block-rich surface layers in mountains, in the form of block fields, rock glaciers, or block streams, play a similar role as organic material. Block-rich material depresses the lower limit of mountain permafrost. Locally, steep blocky slopes in shaded topographic settings may display patches of permafrost or permafrost islands far below the regional permafrost limit (e.g. Delaloye et al., 2003; Luetschg et al., 2003).

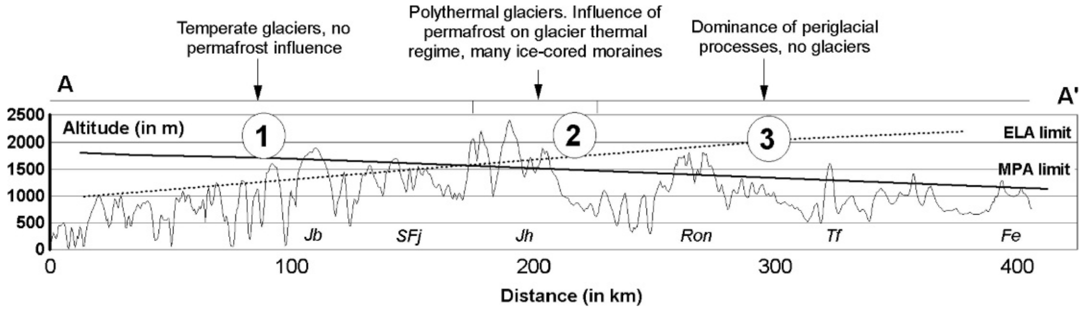

FIGURE 3. **Example of the relation between equilibrium line altitude of glaciers (ELA) and lower limit of discontinuous mountain permafrost (MPA) along a west–eastern transect in southern Norway (based on Etzelmüller et al., 2003, modified). The shaded areas denote locations of palsa mires as a morphological expression for sporadic permafrost. The numbers indicate: (1) the zone of dominating glacier coverage, (2) the zone of co-existing glaciers and permafrost, and (3) the zone of periglacial dominance and the absence of glaciers. Jb = Jostedalsbreen, SFj = Sognefjell, Jh = Jotunheimen, Ron = Rondane, Tf = Tronfjell, Fe = Femund area.**

Permafrost and Glaciers

Permafrost and glaciers co-exist in the transitional area between maritime-dominated and continental-dominated climatic settings in mountain areas. In addition, several mountain areas within the continuous and discontinuous arctic permafrost zone are partly glaciated with glaciers ending in permafrost environments (e.g. East-Canadian Arctic Islands, Svalbard, Franz-Josef land, etc.).

A comprehensive overview on glacier-permafrost relations is given in, e.g., Haeberli (2005) and Etzelmüller and Hagen (2005) (Fig. 5). The basic assumption thereby is that glaciers ending in the permafrost zone will always have at least parts of their tongues frozen to the bed. Thus, glaciers in the permafrost zone are polythermal with partly cold-based margins. It is evident that permafrost at glacier margins (1) enhances basal marginal on-freezing of debris (basal freezing conditions) (cf. Boulton, 1972), (2) leads to enhanced transport and accumulation of debris onto the glaciers' surface (cf. Weertman, 1961), (3) favors the development of long-term ice-cored moraine land systems (if the debris cover is thicker than the regional active layer) (e.g. Souchez, 1971), and (4) is thermally unstable (e.g. Etzelmüller, 2000; Sletten et al., 2001; Schomacker and Kjaer, 2008).

Deposited in sloping terrain, such frozen debris deposits may start creeping, resulting in rock glacier–like landforms. Such "moraine-derived" creep deposits may contain ice of different origin (glacier ice, segregation ice, interstitial ice) but even so require permafrost conditions for their long-term maintenance. While creeping sediment deposits originating from rock wall processes are closely related to their debris-supplying headwalls

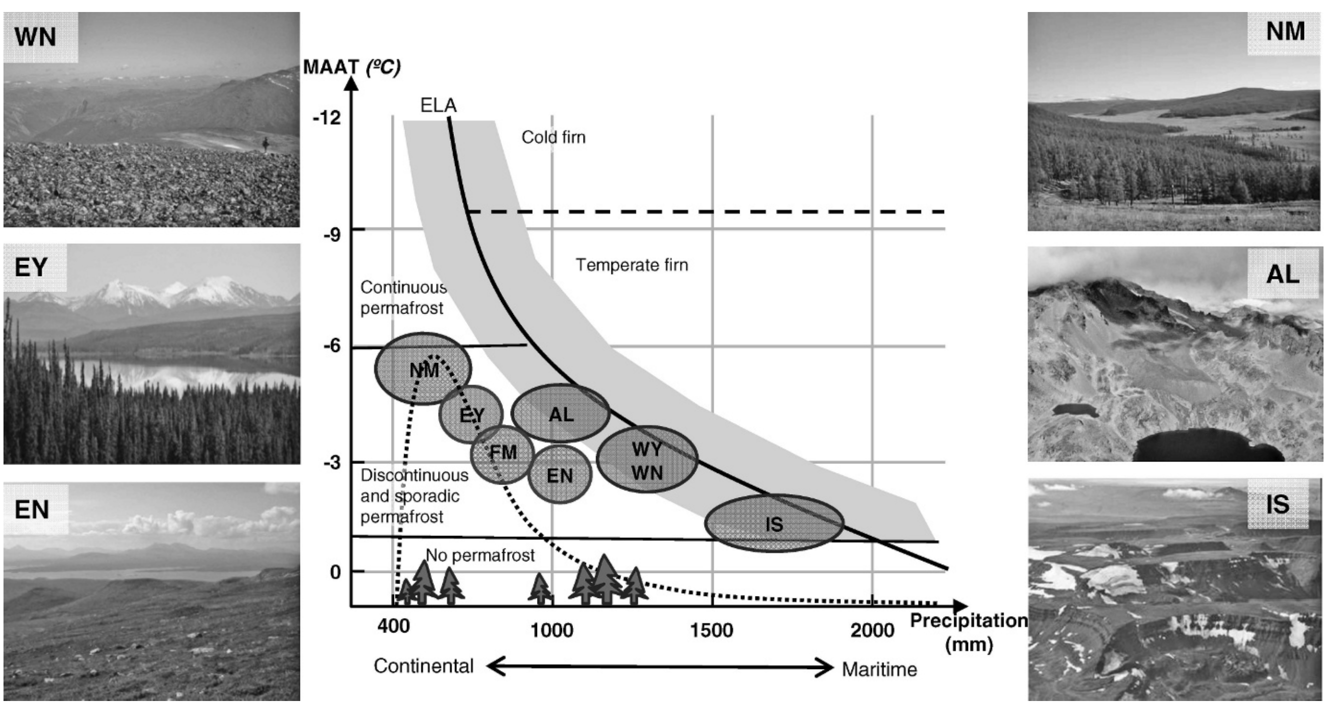

FIGURE 4. **Conceptual diagram showing the relation between precipitation (continentality), temperature, glacier equilibrium line altitude (ELA), and permafrost ("cryosphere model," modified based on Haeberli and Burn, 2002). The shaded area denotes the zone where interactions between glacial processes and permafrost are to be expected. The dashed line marks the approximate transition between cold and warm firn. The dotted line crudely denotes the timberline. The circles indicate areas mentioned in this paper. NM = northern Mongolia, EY = eastern Yukon, WY = western Yukon, WN= western Norway, EN = eastern Norway, FM = Finnmark county in northern Norway, IS = northern and eastern Iceland, AL = Alps. The pictures illustrate the diversity of mountain permafrost settings throughout selected sites in the northern hemisphere.**

TABLE 1

Statistical relation between environmental factors and permafrost existence in different mountain settings. The relations are extracted from literature, and mainly based on linear or logistic regression analysis of permafrost proxies (bottom temperature of the snow cover [BTS], rock glaciers) and permafrost existence. ++/−− = strong positive or negative statistically significant relation, +/− = statistically significant relation, 0 = weak or no statistical significance.

	Continental		Maritime	
	Alpine	*Paleic*	*Alpine*	*Paleic*
Elevation	+	+	++	++
Topographic aspect/incoming radiation	−−	−−	−	0
Surface wetness/soil water	+	++	0	−−
Snow, topographic curvature	−	−−	−−	−−
Vegetation	+	++	0	0

through a direct process chain linking frost weathering, rockfall, and debris displacement by permafrost creep, the development of moraine-derived landforms contains an additional, both spatially and temporally, complex transport module (including the whole glacier history). A moraine-derived rock glacier is, thus, not fed primarily by continuous debris input but evolves out of an already existent debris "reservoir." Consequently, the characteristics of this debris are significantly different from the original, weathered material accumulated before glacial transport.

Retreating glaciers (e.g. due to climate forcing) can trigger permafrost aggradation in recently deglaciated glacier forefields (ground cooling) (Kneisel, 2003; Kneisel, 2004; Etzelmüller and Hagen, 2005), while the advancing of glaciers into permafrost normally leads to a warming of the ground and possible talik development (ground warming). Hence, there is an imbalance between the air and ground temperature signals, and the corresponding responses may differ for decades to millennia. The time difference in response time of the signal is a major driving factor, influencing the sediment transport system. At the temporal and spatial interface between glaciers and permafrost this leads, in addition, to the frequent triggering of catastrophic events, such as ice-rock avalanches, glacier-lake outburst floods from moraine-dammed lakes, etc. (e.g. Richardson and Reynolds, 2000b; Kääb et al., 2005; Schneider, 2005).

Sediment Mobilization and Transfer under Permafrost Conditions

The paraglacial concept, based on Church and Ryder (1972) and recently further discussed by Ballantyne (2002), tries to quantify the time- and process-dependant mobilization of sediments after glaciations in form of a sediment-exhaustion model (Fig. 6a). Ballantyne's (2002) exhaustion model follows in principle a linear stationary impulse-response function of the form

$$S = S_0 \, e^{-(k*t)} \qquad (1)$$

where S is the amount of material left which is unstable or can be evacuated, t is time, k is an adjustable parameter related to the speed of sediment evacuation, and S_0 is the starting volume of available sediments or process frequency. This equation is widely known for hydrological modeling, describing the linear emptying of hydrological magazines.

The exhaustion rate of sediments within this framework is dependent upon different factors, such as bedrock geology, topography, and climate. As a consequence of certain climate factors influencing the evolution or prevalence of permafrost after early Holocene glacier retreat in core areas of many mountain chains, we can expect a severe impact of the ground thermal regime on the ability to mobilize material. Thus, we hypothesize that k is also dependent on ground temperature. In the following paragraphs, we attempt to defend this hypothesis with examples for material entrainment during glacier advances under the influence of permafrost, rock wall processes, debris-mantled slopes and glacier forelands, and hazard related processes.

PROCESSES RELATED TO PARAGLACIAL MATERIAL ENTRAINMENT DURING GLACIER ADVANCES

A major discussion in this context is the incorporation of proglacial debris during glacier advances. A major input into the glacier system is pre-glacial loose debris incorporated during glacier advances, in addition to subglacial processes. In a cold-based system this input is lower, subglacial erosive processes are less pronounced or even absent (Humlum et al., 2005), and external material entrainment is relatively more effective. The material accumulation during glacial activity develops a sediment magazine, which serves as the initial impulse for the paraglacial exhaustion model (Fig. 6c).

Many sediment magazines are not connected to the fluvial system, thus surviving a whole deglaciation period. In a frozen context, these landforms will not serve as sediment sources during new glacier advances. This has become more and more evident during recent studies, e.g. on Svalbard, where plant remnants were found undisturbed by glacier advances (Humlum et al., 2005). Such findings can also help to better understand landscape development in, e.g., Scandinavia (cf. Kleman and Hättestrand, 1999; Fredin, 2002) and Canada (Kleman and Hättestrand, 1999). Cold-based glaciers neither produce much sediments, nor do they largely influence pre-glacial sediments; these are basically left "untouched," as, for example, block-rich material which, as has been discussed above, favors stable permafrost conditions due to its large thermal offset (Juliussen and Humlum, 2007a). Thus, from a paraglacial point of view, the paraglacial period in terms of an adjustment to a pre-glacial state of sediment transport, does not exist or is highly restricted (Fig. 6d).

PROCESSES RELATED TO GLACIER FORELANDS AND DEBRIS-MANTLED SLOPES

Glacial sediments in permafrost regions are frozen, and, therefore, not available for intense erosion except for the active layer. As long as the active layer is undisturbed, such landforms and sediment covers are stable, and often ice-rich. Erosion is effective at uncovering the active layer, initiating differential melting and sediment redistribution (Østrem, 1964; Driscoll, 1980; Etzelmüller, 2000). This makes glacier forelands in the permafrost zone a constant source of sediment supply during short periods of

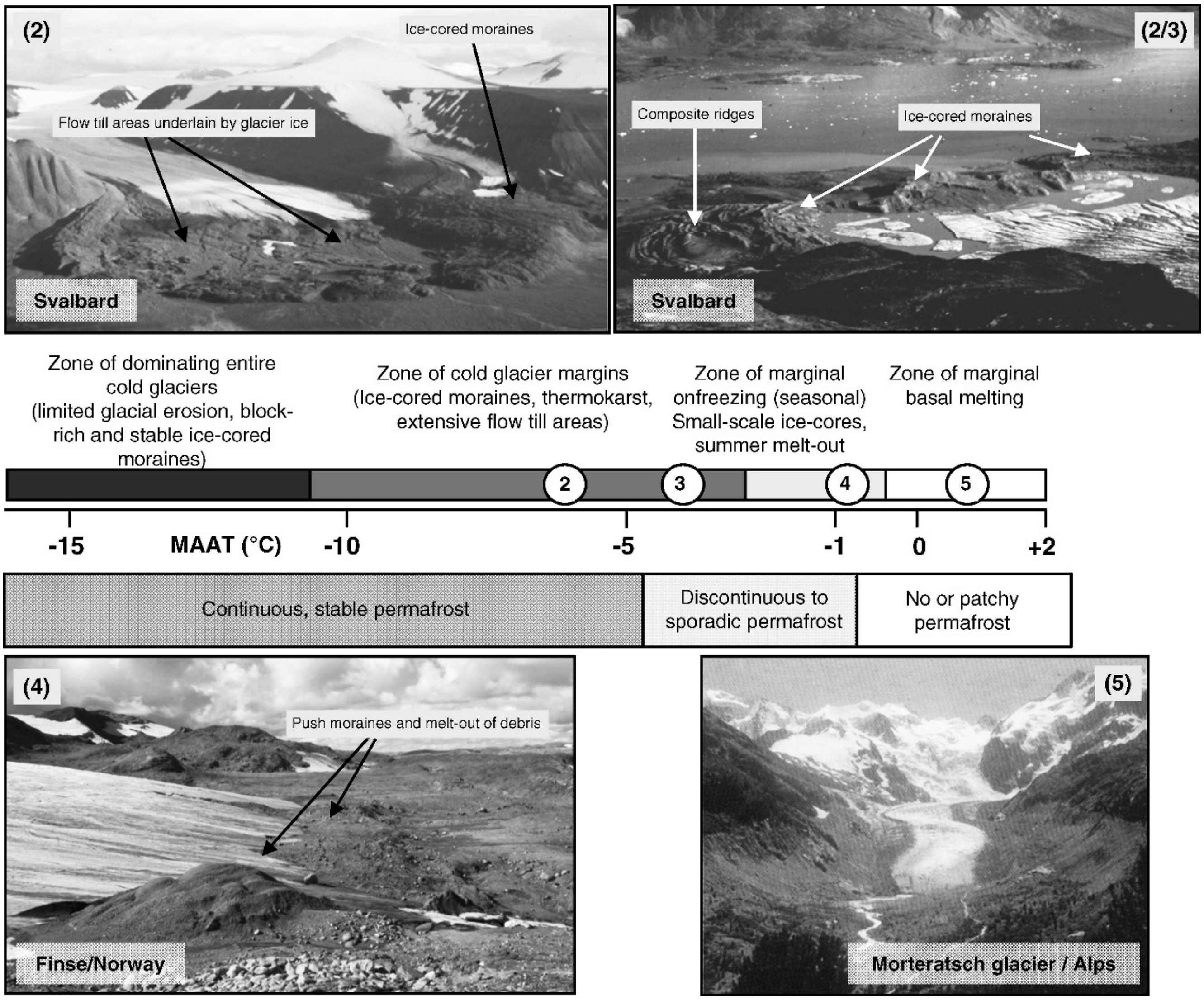

FIGURE 5. Conceptual diagram indicating the relation between climate (mean annual air temperatures), permafrost, and landform assemblages in the glacier marginal zone (modified based on Etzelmüller and Hagen, 2005). The numbers on the pictures relate to the numbers on the diagram and display glacier marginal land systems in different ground thermal regimes.

the year, but the amount of debris mobilized is limited due to a short melting season. This process would speed up, however, under conditions of climate forcing and during an enhanced melt of the ice cores.

This pattern obviously has a large effect on the fluvial sediment evacuation system from glacier-dominated environments. In temperate environments with a stabilized pro-glacial river network, sediment concentration is high during spring, subsequently decreasing during summertime. There is no or low correlation between river discharge and sediment concentration and normally a negative hysteresis effect can be observed (e.g. Lawson, 1993). In polythermal glacier margins and permafrost dominated environments, however, sediment supply is present throughout the season, and we find a good correlation between discharge and sediment concentration (Vatne et al., 1995, 1996; Bogen and Bønsnes, 2003). The reason for this pattern is related to the glacial drainage systems and sub-glacial sediment availability. In temperate glacier systems total discharge is higher and channelized through sub-glacial tunnels. Material produced during the previous year is evacuated and the sediment storage emptied. In polythermal and cold glacier systems discharge is lower and sediments are usually available closer to the front due to onfreezing processes in the transition zone between temperate and cold ice (Weertman, 1961; Boulton, 1972) and thus available for fluvial evacuation.

This implies that degrading permafrost or enhanced melt of ice-cored sediments would speed up sediment evacuation during the paraglacial period. In contrast, stable permafrost conditions or permafrost aggradation in recently deglaciated terrain would lead to the bonding of sediments and to reduced evacuation (Fig. 6e).

PROCESSES RELATED TO GLACIALLY OVER-STEEPENED ROCK WALLS

It is well-known that glacier activity leads to oversteepening of valley sides and destabilization of bedrock. After deglaciation, an increased frequency of rock slope failures due to stress release and erosion can, therefore, be observed.

The relation between permafrost and rock slope stability is also documented in the literature. Permafrost in rock walls leads to ice-fillings in rock joints, and influences the rock hydrology and the hydrostatic pressure. Steep temperature gradients at the

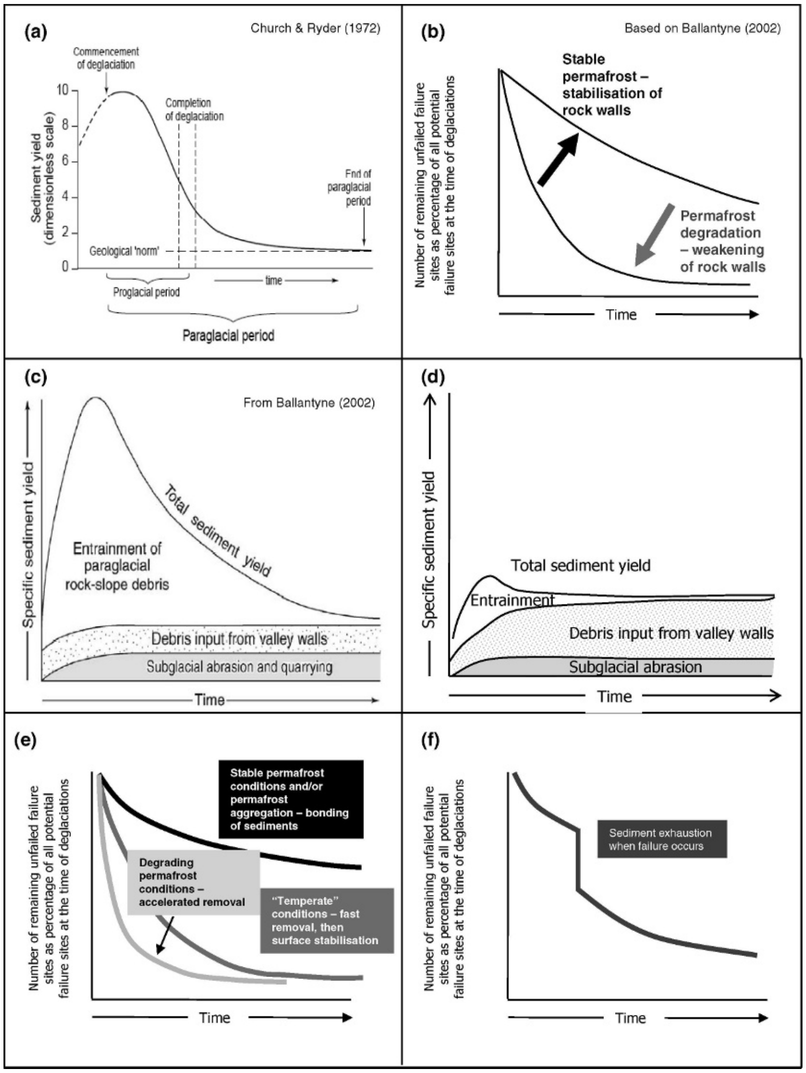

FIGURE 6. Conceptual diagrams illustrating the relation between the paraglacial exhaustion model and the ground thermal regime. (a) Principle of the paraglacial exhaustion model based on Church and Ryder (1972). The model follows the principles of an impulse-response function, where the impulse is the sediment accumulation due to glaciations, and the response is the evacuation or mobilization of these. (b) Influence of permafrost on the stabilization or weakening of rock walls. (c) Material accumulation due to glaciations in a temperate glacier setting. (d) Same as (c) but under permafrost conditions. (e) Conceptional sediment exhaustion rate of debris-mantled slopes under different ground thermal conditions (from Ballantyne 2002). (f) Sediment exhaustion in the case of rapid sediment evacuation due to failure (natural hazard).

surface zone cause the transport and refreezing of free water and subsequent growth of ice lenses. The resulting increase in pressure is able to destabilize the rock locally (Haeberli et al., 1997; Wegmann et al., 1998). With a rise in temperature, frozen rock joints reach minimal stability at temperatures between –1.5 °C and 0 °C, i.e. even before thaw, as shown by Davis et al (2001) through centrifuge modeling in the laboratory. Additionally, the hydrostatic pressure within the rock wall might change. As a consequence, enhanced rockfall activity and rock avalanches are expected in particular at the lower boundary of permafrost distribution (Nötzli et al., 2003; Gruber et al., 2004). While cold permafrost stabilizes rock walls, it may also enhance frost-weathering related processes and, subsequently, the production of smaller-grained debris (Fig. 6b). In summary, frozen rock walls delay sediment exhaustion.

In general, slope deposits form important sediment magazines which are available for, e.g., fluvial evacuation. However, permafrost bonds these sediments. On the other hand, ice content can be so large that creep processes start, bringing a talus slope closer to a media for material evacuation. Active rock glaciers, for example, creep down-slope with velocities in the order of centimeters to decimeters per year, and despite this comparably slow movement, can be seen as efficient debris transport agents (Jäckli, 1957; Barsch, 1996). It is evident that rock glacier creep can delay or even prevent the covering of rock faces by talus material and thus extend the period for frost shattering. Thus, rock glacier development may enhance rock wall retreat locally. However, these processes are extremely slow, delaying sediment exhaustion over millennia.

Discussion and Conclusive Remarks

PERMAFROST, CLIMATE CHANGE, AND SEDIMENT TRANSFER

As permafrost is defined by ground temperature and, thus, depends on the surface energy balance, it is evident that climate change and presently observed climate forcing have a severe influence on the distribution of mountain permafrost. The thickness of the active layer is reacting more or less instantaneously to climate warming by an increased thaw depth, thus potentially making more sediments available for erosion and transport. Gruber et al. (2004) reported thaw depths of more than 10 m in rock walls in Switzerland during the unprecedented warm summer of 2003 . It can, therefore, be concluded that increasing ground temperatures in ice-rich permafrost are likely to cause thaw-related slope instabilities in mountain areas (Harris et al., 2001; Haeberli and Burn, 2002) as well as in the continuous permafrost zone of the Arctic (e.g. Lewkowicz and Harris, 2005). The latent heat effects of an ice-rich transient layer immediately

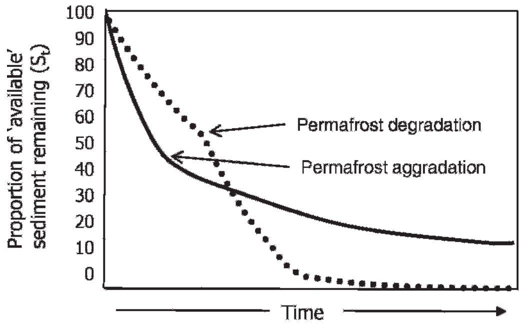

FIGURE 7. Theoretical and simulated exhaustion rates calculated with a time-dependant $k(T)$ from Equation 2. In the "permafrost degradation" case, k changes linearly from 0.1 to $0.25\ ka^{-1}$ between a certain time period. In the "permafrost aggradation" case, k changes linearly from 0.25 to $0.1\ ka^{-1}$.

below the permafrost table reduces thaw penetration (Shur et al., 2005), but also increases the volume of meltwater released, thereby increasing the risk of landslides in areas with finer-grained soils.

In contrast to rock walls, block field areas in high mountain ranges or sites with thick organic surface layers in more continental areas will show a much slower reaction because of their internal thermal buffering effects (Harris and Pedersen, 1998; Gorbunov et al., 2004; Yi et al., 2007). Therefore, we can expect different responses in more continental areas where a climate warming signal of the permafrost is not clearly visible, and thus sediment transport reaction might be different (Burn and Nelson, 2006; Lawrence et al., 2008).

Sediment mobilization through polythermal glaciers and creeping permafrost is extremely slow, delaying sediment exhaustion over millennia notwithstanding climate variability. Nonetheless, this leads—over time—to the accumulation of considerable sediment bodies. One example is the influence of these delay mechanisms on the intensification of processes when failure occurs. The sediment exhaustion concept is, therefore, also of importance for the understanding of alpine geohazards, such as debris flows and glacier outburst floods (GLOFs). Rock glaciers, for instance, act as enhanced reservoirs of potentially unstable debris, increasing potential debris flow starting volumes within debris flow initiation zones (Hoelzle et al., 1998). Where a rock glacier has advanced onto steeper ground, rockfall along the steep rock glacier front may increase (Bauer et al., 2003; Kääb and Reichmuth, 2005). If the ground falls steeply away below the rock glacier, rockfall, slides, and subsequent debris flows may affect considerably larger areas (Kaufmann and Ladstädter, 2003; Roer et al., 2005; Kääb et al., 2007). These processes are accelerated during climate warming episodes, because the internal ice warms up which may lead to velocity increase of such landforms (Kääb et al., 2007). Thus, in the case of failure, large sediment volumes would be released within a short time, leading to a step-wise exhaustion of the sediment magazine (Fig. 6f).

Ground thermal conditions in moraines are often a crucial factor in the damming of moraine lakes. Permafrost or near-permafrost conditions support the long-term preservation of dead ice bodies, which may leave cavities when melting (Richardson and Reynolds, 2000a, 2000b). Sudden release of meltwater stored in such cavities may lead to significant hazard, causing GLOFs. Differential thaw settlement is frequently associated with the formation of thermokarst lakes, which continue to develop through positive feedback mechanisms of water convection and latent heat effects, leading to further ground ice melt (Kääb et al., 2005). In such unstable terrain, sudden lake drainage is likely.

A TEMPERATURE-DEPENDANT PARAGLACIAL EXHAUSTION MODEL

Based on the above considerations it seems evident to incorporate temperature into sediment exhaustion model equations. Such a model would then take a form like:

$$S = S_0\, e^{-k(T)*t} \tag{2}$$

following the principle of Equation 1, as proposed by Ballantyne (2002). Here, $k(T)$ indicates the temperature dependence of the exhaustion rate coefficient (Fig. 7). It is obvious that permafrost aggradation would lead to a flattening of the exhaustion curve, while the opposite is true for permafrost degradation in relation to a non-permafrost situation.

CONCLUSIVE REMARKS

As in glaciology, the understanding of the thermal regime of the ground has a key importance also in a sediment transfer context within the paraglacial framework. It is evident that the thermal regime of glacier margins highly governs glacial land systems (cf. Benn and Evans, 1998), and, therefore, also influences sediment budgets related to this environment, such as paraglacial exhaustion rates. Permafrost plays an important role for more episodic events and, thus, within a geohazard context, e.g. by stabilizing slopes or accumulating debris due to permafrost creep. Permafrost degradation can trigger the failure of sediment storage bodies. Climate change directly governs the ground thermal regime and surface ice coverage, and therefore, even though not in phase, influences sediment mobilization and transport within cold mountainous environments. With this in mind, it is important to explicitly address the thermal components in catchments, also in the ground, when trying to monitor and quantify sediment transfer processes in mountainous regions.

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