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Geomorphology 52 (2003) 87–104
GEOMORPHOLOGY
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Aspects and concepts on the geomorphological significance of Holocene permafrost in southern Norway

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Received 14 December 2001; received in revised form 8 May 2002; accepted 14 August 2002

Abstract

This review paper aims at discussing aspects and concepts of the significance of the spatial and temporal distribution of permafrost on glacial and gravitational processes in southern Norway. The study first reviews the distribution of mountain permafrost in southern Norway in comparison with high-relief alpine areas like the Alps, and then discusses the influence of permafrost on gravitational and glacial–geomorphological processes. The basis for the paper is a regional-scale distribution model of mountain permafrost in southern Norway, which is analysed in relation to topographic variations within the same area. The model allows a crude extrapolation to past and future permafrost distribution, which is discussed in relation to geomorphic processes.

Keywords: Permafrost; Slope forms; Glaciers; Scandinavia; Norway; Sediment transport

1. Introduction

The presence of permafrost influences a majority of the surface processes taking place in mountainous environments and is therefore an important regulating factor for the geomorphological process pattern in these environments. Another regulating factor is the topography. Topography varies with space but is, in the time perspective considered here, relatively time invariant. Permafrost distribution varies with both time and space. The types of processes taking place and their relative importance will change with changes in the permafrost distribution, but one may expect that the morphological signal of permafrost is dependent also on the type of topographic shape of the mountain region the permafrost is covering. Compared with lower latitude mountain regions, e.g. the Swiss Alps, high-mountain permafrost areas in southern Norway display an almost absence of permafrost creep features such as rock glaciers (Sollid and Sørbel, 1992).

The basis for the study is a digital elevation model (DEM) with 500-m ground resolution (©Norwegian Mapping Authorities), and a regional empirical model of permafrost distribution (Etzelmüller et al., 1998; Hoelzle et al., 2001) describing the lower limits of mountain permafrost in southern Norway with 1000-m ground resolution. The model uses a digital map of mean annual air temperature (MAAT) derived by Tveito and Førland (1999) to construct a quadratic

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doi:10.1016/S0169-555X(02)00250-7

trend surface through altitude points showing MAAT of about −4 °C. The use of MAAT as a major modelling variable is justified by site investigations in the Jotunheimen and Dovrefjell area of southern Norway (Fig. 1), showing that radiation plays only a minor role on permafrost distribution (e.g. Ødegård et al., 1996, 1999; Isaksen et al., 2002) in these locations. With this assumption, the trend surface could be shifted for simulation of warming or cooling trends of the MAAT. The results were validated by Bottom Temperature of winter Snow cover (BTS, Haeberli, 1973) measurements and DC-resistivity soundings in various locations in southern Norway. Varying snow conditions are not considered in the model, which certainly introduces an error. However, within the accuracy and scale of this model (ground surface resolution of 1000 m and altitude accuracy of ±80 m; Etzelmüller et al., 1998), the results are assumed to reflect the main pattern of permafrost distribution, both at present and during periods of higher or lower MAAT.

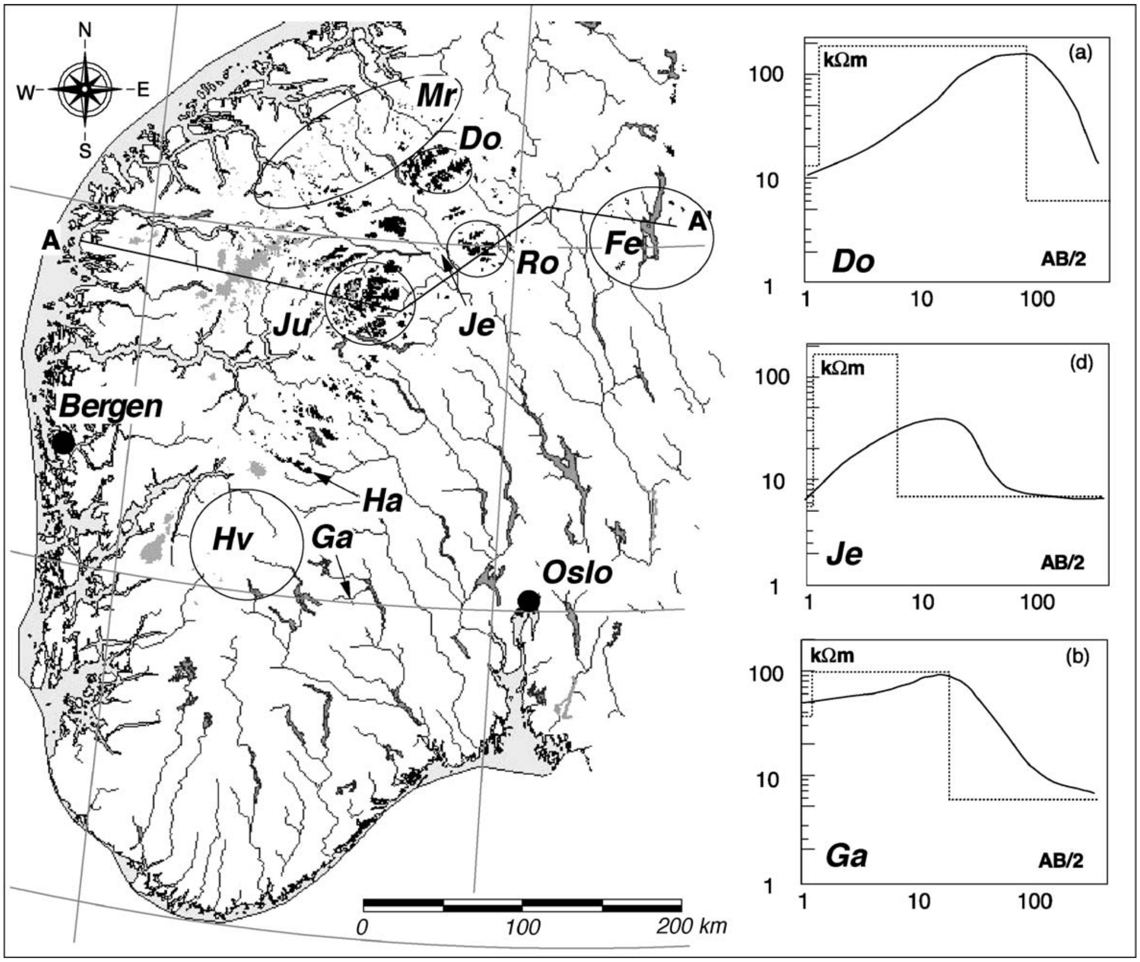


Fig. 1. The distribution of alpine permafrost in southern Norway. Probable permafrost area in dark shading, recent glacier coverage in grey shading. The solid line shows the profile line displayed in Fig. 3. The method of deriving permafrost areas used for southern Norway is described in Etzelmüller et al. (1998). Ju = Juvvass/Galhøpiggen, Je = Jetta mountain, Ga = Gaustatoppen, Do = Dovrefjell, Fe = Femund–Sølen, Ha = Hallingskarvet, MR = Møre and Romsdal, Hv = Hardangevidda. The diagrams show selected one-dimensional DC-resistivity soundings on different locations, indicating permafrost sites. The dashed line in the diagram shows a probable interpretation of the curves, resulting in a three-layer model defining thickness and resistivity of the subsurface.

The objective of the paper is to review and discuss the significance of permafrost on glacial and gravitational processes in high-latitude areas of southern Norway on a regional scale. The influence of permafrost on these processes is related to the presence of permafrost relative to the glacier equilibrium line, and to the topographic shape of the landforms. This paper aims to quantify these relationships and partly compare the results to high-relief alpine areas. The aim is reached by combining the modelled permafrost areas with topographic information and the glacier areas, all on a regional scale. This allowed the analysis of permafrost distribution in relation to changing climatic conditions, glacier equilibrium line altitudes and topographic regions in southern Norway. The analysis was expected to result in a better understanding of geomorphological process and landform pattern connected to mountain permafrost distribution.

2. Permafrost limits and relict permafrost in southern Norway

Alpine permafrost in Norway has been recognised since the turn of the last century. Reusch (1901) found permafrost in Lyngen in northern Norway at 750 m a.s.l. and recognised permafrost as being a normal phenomena at high altitudes in northern Norway. He also suggested that the inner parts of the Finnmarkvidda were underlain by permafrost. During the 1950s, deep permafrost was discovered on Gaustatoppen (1883 m a.s.l.), southern Norway, during construction work of a military radio station (Dons, personal communication 1995). Williams (1959) suggested that a MAAT of about -4 °C was necessary under Scandinavian conditions for widespread permafrost. Liestøl (1965) reported of sporadic permafrost patches as low as 300 m a.s.l. in blocky material near Otta in Gudbrandsdalen valley east of Jotunheimen, southern Norway. First, quantitative mapping approaches were carried out by Barsch and Treter (1976), King (1983, 1986) and Harris and Cook (1988) in the Jotunheimen and Rondane area, using BTS measurements, seismic refraction and DC-resistivity soundings. Both King (1984) and later Ødegård et al. (1996) presented permafrost maps, based on a proposed boundary of MAAT = – 4 °C as the lower altitude limit of alpine permafrost. In the Dovrefjell and Jotunheimen areas, southern Norway, Ødegård et al. (1996, 1999), Sætre (1997) and Isaksen et al. (2002) showed that BTS values could possibly be explained mainly on the basis of altitude, while radiation is of minor importance. This is in contrast to the situation in the Alps where radiation is considered to be more important (Hoelzle, 1992, 1996; Gruber and Hoelzle, 2001).

Recent studies about permafrost (e.g. within the Permafrost and Climate in Europe, PACE, project, Harris, 2001; Harris et al., 2001) have provided increased knowledge of permafrost thickness and spatial distribution in southern Norway (Isaksen et al., 2001) and Svalbard (Isaksen et al., 2000). In Jotunheimen, southern Norway (borehole depth 129 m), and at the Tarfalaryggen, northern Sweden (borehole depth 100 m), permafrost thickness seems to be more than 300 m at 1890 and 1600 m a.s.l., respectively (Sollid et al., 2000; Isaksen et al., 2001). These boreholes showed low-temperature gradients, indicating a severe warming of the permafrost during the last decades (Isaksen et al., 2001). Comparable boreholes in the Alps displayed a similar trend (Harris et al., 2001). In southern Norway, permafrost depth is known from the construction of an elevator inside Gaustatoppen (1883 m a.s.l.). Ice-rich permafrost was discovered above 1600 m a.s.l., and DC-resistivity soundings indicate permafrost below 1500 m a.s.l. on the slopes of this mountain. The permafrost thickness is about 250 m, with a present MAAT on the top of the mountain of – 4 °C. Together with the results from the PACE-drillings in permafrost, this indicates much thicker permafrost in European

Table 1
Area of permafrost in southern Norway according to the map published by Etzelmüller et al. (1998)

	Probable permafrost (km^2)	Glacier area (km^2)
Present situation according to model	2800	1600
One degree cooling of MAAT (“LIA situation”)	6600	>2000
One degree warming of MAAT (“climate warming situation”)	1000	?

The estimates are conservative and do not include areas with patchy permafrost distribution, permafrost under snow patches or permafrost related to palsa mires. The glacier area is estimated based on the N1000-map published by the Norwegian Mapping Authorities. The glacier area for the LIA situation is a crude estimate based on the fact that many glaciers in southern Norway have been reduced in size by about 30% since the LIA maximum.

mountains, in general, than assumed earlier (cf. Ødegård et al., 1992).

Mountain permafrost in southern Norway is mainly concentrated in a 50–100-km-wide zone between Hallingskarvet in the south (Fig. 1) and the Dovrefjell mountains in the north (Fig. 1). According to the model, only small areas east and west of this zone have permafrost. On the western side, glaciers normally cover high-mountain areas. Furthermore, the lower permafrost limit rises to over 1600 m a.s.l. due to increasing maritime influence. Thus, there are few areas where permafrost can exist. On the eastern side of this zone, only small mountain areas or single peaks reach altitudes above 1400 m a.s.l. In the eastern areas, these peaks seems to have permafrost. Preliminary results of a permafrost-distribution modelling applied for the whole Scandinavia and new field investigations indicate even lower alpine permafrost limits down to below 1200 m a.s.l. in the Femund–Sølen area (Fig. 1). The lower limit increases again towards east, possibly due to the climate influence of the Botnian Sea. Recent permafrost field mapping seems to confirm that pattern (Heggem et al., in press). The transition zone of the mountain permafrost might be broad. At Snøhetta/Dovrefjell the zone is located between 1480–1340 m a.s.l. (Sollid et al., in press).

The present extent of highly probable permafrost areas is approximately twice that of the glaciated area (Table 1). Assuming a 1 °C colder situation, the area of probable permafrost was more than doubled during the Little Ice Age (LIA) (Fig. 2a, Table 1). Large areas have probably been subjected to permafrost thaw since the

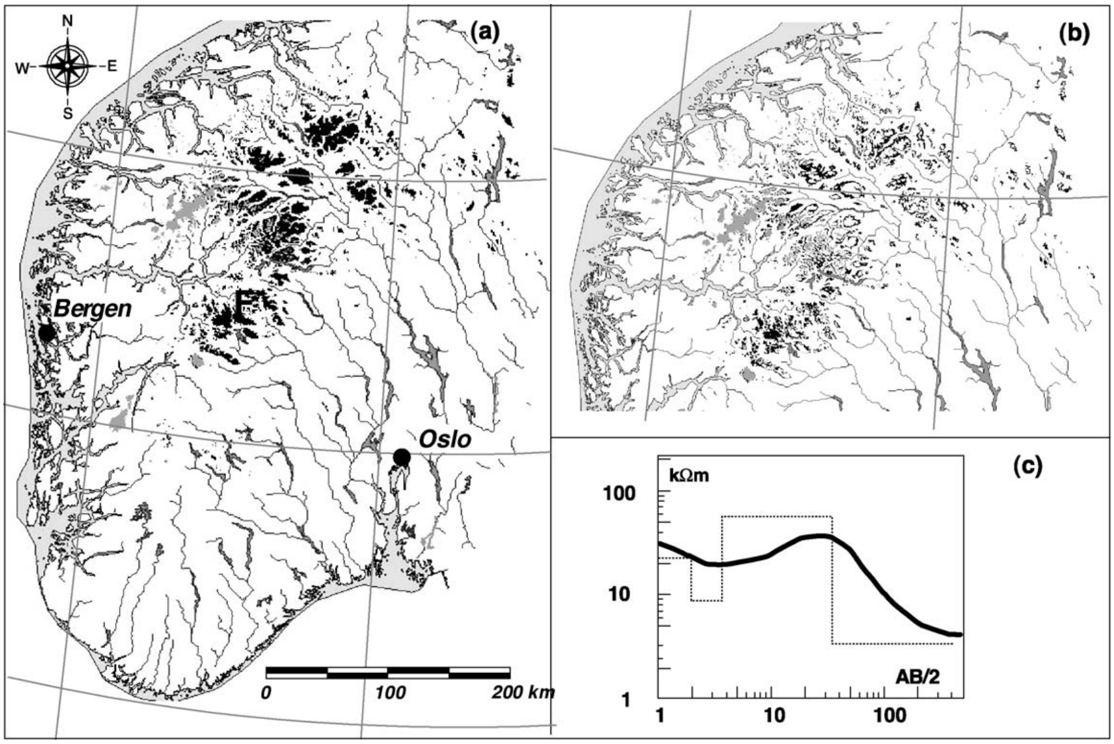


Fig. 2. (a) Estimated distribution of alpine permafrost for a 1 °C cooler scenario, which may have prevailed during the Little Ice Age (LIA) (dark shading in the map). The trend surface was here shifted down slope with 150 m. This number is in accordance with numerical modelling from other areas in Fennoscandia (e.g. Kukkonen and Safanda, 2001). (b) Areas, which are modelled to have been in the permafrost zone during the LIA-scenario, and are not supposed to lie in the permafrost zone during present climate conditions (black shading in the map). These areas are believed to be under permafrost degradation, and may contain considerable areas with relict permafrost. Grey shading denotes recent glacier coverage in both maps. The DC-resistivity diagram (c) show an example from the western Jotunheimen Mountains (Hurrungane). The dashed line in the diagram shows a probable interpretation of the curves, resulting in a four-layer model defining thickness and resistivity of the subsurface.

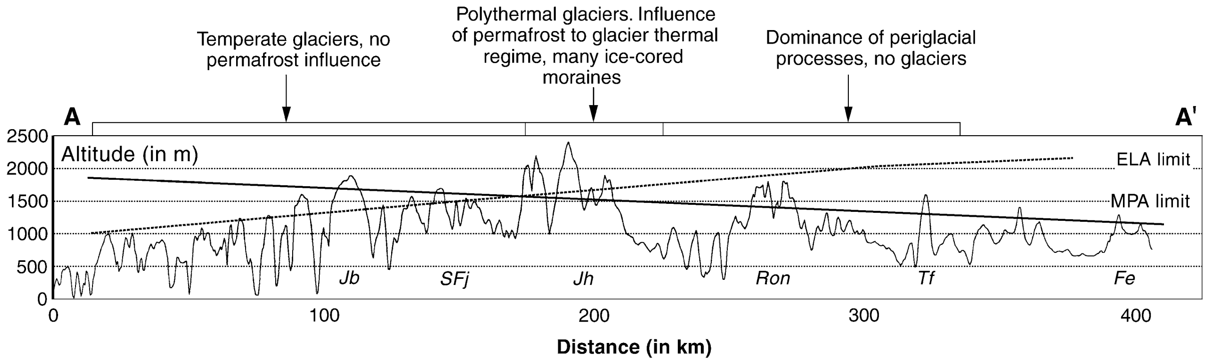


Fig. 3. Profile through southern Norway (A–A', Fig. 1) including the lower altitude of mountain permafrost (MPA) according to the model published by Etzelmüller et al. (1998) and the limits of the ELA. A spatial distribution of the ELA in southern Norway was generated based on an ELA contour map published in Liestøl (1994). The map was digitised and a DEM was constructed using Hutchinson (1989) interpolation algorithm. The profile is interpreted to distinguish three major morphogenetic zones in relation to glacial and periglacial processes. Jb = Jostedalsbreen glacier, SFj = Sognefjellet mountains, Jh = Jotunheimen, Ron = Rondane mountains, Tf = Tron mountain, Fe = Femund mountains.

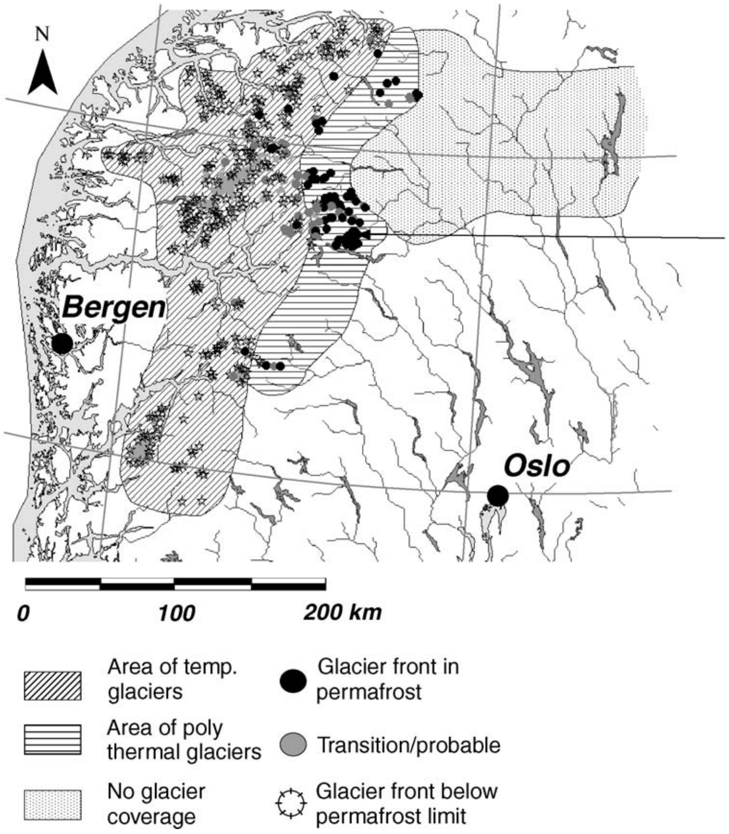


Fig. 4. The possible areal extent of the morphogenetic zones defined in Fig. 3. The point labels denotes the position of recent end moraines in southern Norway. The label signature indicates whether the moraines are situated within the permafrost zone or not, according to the MAAT-based permafrost distribution model. The area signature indicates the morphogenetic regions. The spatial difference was calculated on a cell-by-cell basis using a data set containing the lower altitude of mountain permafrost (MPA) and a data set of the ELA. In the western areas, MPA – ELA > – 50, the central areas, MPA – ELAε[-50 – -300] and in the eastern areas, MPA – ELA < – 300.

LIA (Fig. 2b). As the change of ground temperatures and the eventual melt-out is a slow process due to the damping and delay of surface temperature signals and latent heat effects (Lachenbruch et al., 1988; Williams and Smith, 1989), we can assume relict permafrost in parts of these areas. Several DC-resistivity soundings in this zone (Department of Physical Geography, University of Oslo, unpublished data) indicate thick low-resistivity layers over high-resistivity layers, which are interpreted as possible degrading permafrost (Fig. 2b,c). Ødegård et al. (1996) suggest relict permafrost to exist in Jotunheimen based on resistivity measurements. Isaksen et al. (2002) found signals of upper ground warming in permafrost by temperature measurements in a borehole in Jotunheimen and by resistivity measurements on Dovrefjell.

3. Permafrost limits and equilibrium line altitudes of glaciers

In southern Norway, the lower limit of mountain permafrost altitude (MPA) decreases towards east, while the equilibrium line altitude (ELA) of the glaciers increases in the same direction (Fig. 3), a pattern already proposed by King (1986). We can distinguish here a transition from predominance of glacial processes to predominance of permafrost-related processes (Fig. 4).

In the near and high-altitude regions of the western coast, the ELA is lower or close to the MPA. In these areas, the temperate glaciers are situated (Østrem and Haakensen, 1993). Permafrost may exist on slopes around the accumulation area of the glaciers; however, many of the glaciers are plateau glaciers (Østrem and Haakensen, 1993) where permafrost thus have limited influence. The glacier tongues always end below the MPA. Cold firn areas like those known from high areas in the Alps (cf Suter et al., 2001) probably do not exist in the western parts of southern Norway.

In an intermediate, relative narrow zone ranging from central Dovrefjell to central Jotunheimen, the MPA lies well-below the ELA (Figs. 3 and 4). Here, glaciers and permafrost coexist and most likely affect the temperature regime of the snout of many glaciers. In this area, the ice-cored moraines early studied by Østrem (1964) are situated, indicating the presence of permafrost at the glacier front altitudes. Further east, the ELA is above most of the mountain peaks, and thus permafrost dominates at high altitudes.

4. Permafrost limits and topographic regions

4.1. Spatial distribution

The quantification of elevation data is included within the field of geomorphometry (Pike, 1995), and based on the quantitative analysis of topographic parameters. The topographic parameters related to this concept are normally estimated on the basis of altitude matrixes. In our case, a digital elevation model with a 500-m ground resolution was used. In this part of the study, point parameters are calculated for a single location based on its nearest neighbours. The basic parameters are the *altitude* itself, *slope/aspect* and

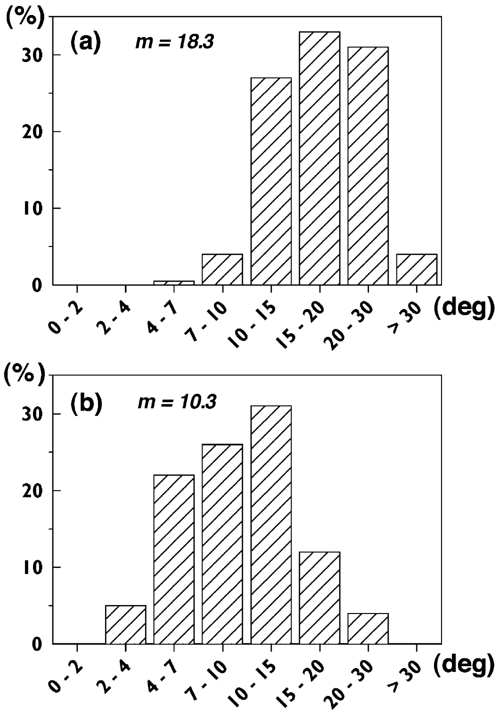


Fig. 5. Slope distribution in permafrost areas for Switzerland (a) and southern Norway (b). The permafrost information from Switzerland is based on Keller et al. (1998).

curvature. The latter is the first and second derivatives of *altitude*, respectively. From these, other parameters are derived, such as statistical measures (e.g. *altitude skew*), relief and hypsographic measures (Evans, 1972; Mark, 1975).

For comparative reasons, the same set of parameters were calculated for southern Norway and the Swiss Alps. In the first step, the frequency distribution of topographic slope within probable permafrost regions was analysed for these areas (Fig. 5). There are clear differences between the situation in Switzerland and southern Norway. This pattern displays the abundance of low-relief ("paleic") mountains and plains in the Scandinavian Mountains (e.g. Reusch,

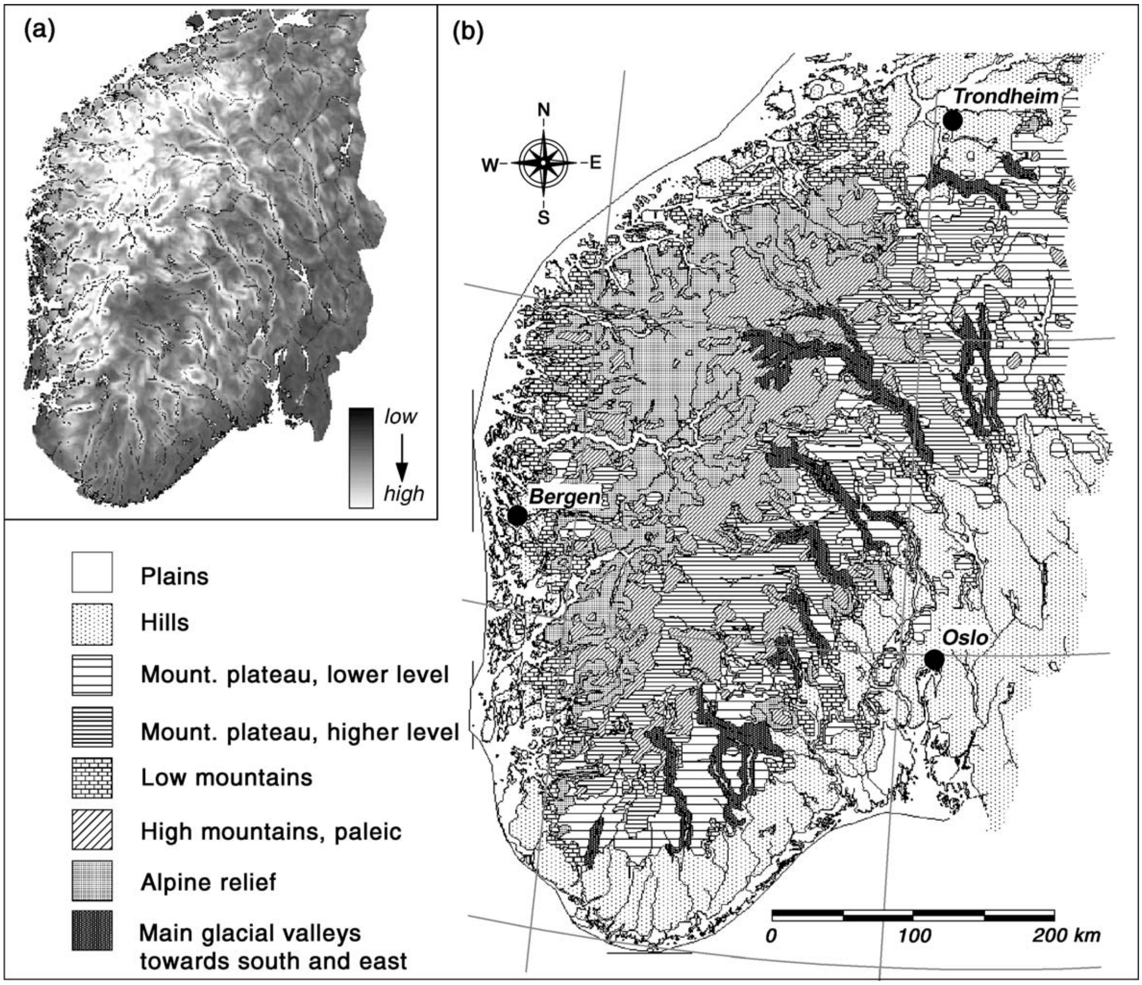


Fig. 6. (a) Distribution of topographic roughness in southern Norway. The topographic roughness map is produced using a digital moving window technique. For each cell position of the DEM, the standard deviation of altitude within a circular window kernel with a 5-km radius is calculated. (b) Topographic regions of southern Norway established based on an automatic, multivariable regional relief classification. The classification is based on a combination of altitude, surface roughness and altitude mass distribution. These are the first three moments of altitude (mean, standard deviation and skewness), which describes the regional aspect of topography. The parameters were calculated as a moving window operation, where the circular window had a radius of 5 km. First, a contextual classification was performed. The contextual classification (cf. Friedrich, 1996) merges classes in the spatial domain using their attribute characteristics. The algorithm starts with as much classes as cells within the study area. Classes are then merged based on similarities of neighbouring cells within the attribute domain. An ISO-cluster algorithm then merges these classes to larger entities.

1901; Gjessing, 1967). In general, really steep alpine topographic settings are rare within the permafrost realm in southern Norway. Only in the Møre Romsdal area of the northwestern part of southern Norway, a fully developed alpine relief exists. However, the terrain is above the lower mountain permafrost boundary only in few locations.

A relief classification was carried out with the parameters *altitude*, *altitude standard deviation* and *elevation–relief ratio*. From this classification, eight major topographic regions were identified (Fig. 6), showing the areal predominance of medium- to low-relief topography in the central and eastern parts of southern Norway. Comparing these results with the modelled permafrost distribution, high-alpine relief represents only 17% of the total permafrost area. Based on these considerations, four major types of permafrost regions were identified (Fig. 7):

4.1.1. The northwestern part of southern Norway

This area consists of alpine landforms with a pronounced relief. The highest peaks reach altitudes of 1800 m. Permafrost patches do exist in some top areas and covers approximately 4% of the modelled permafrost area.

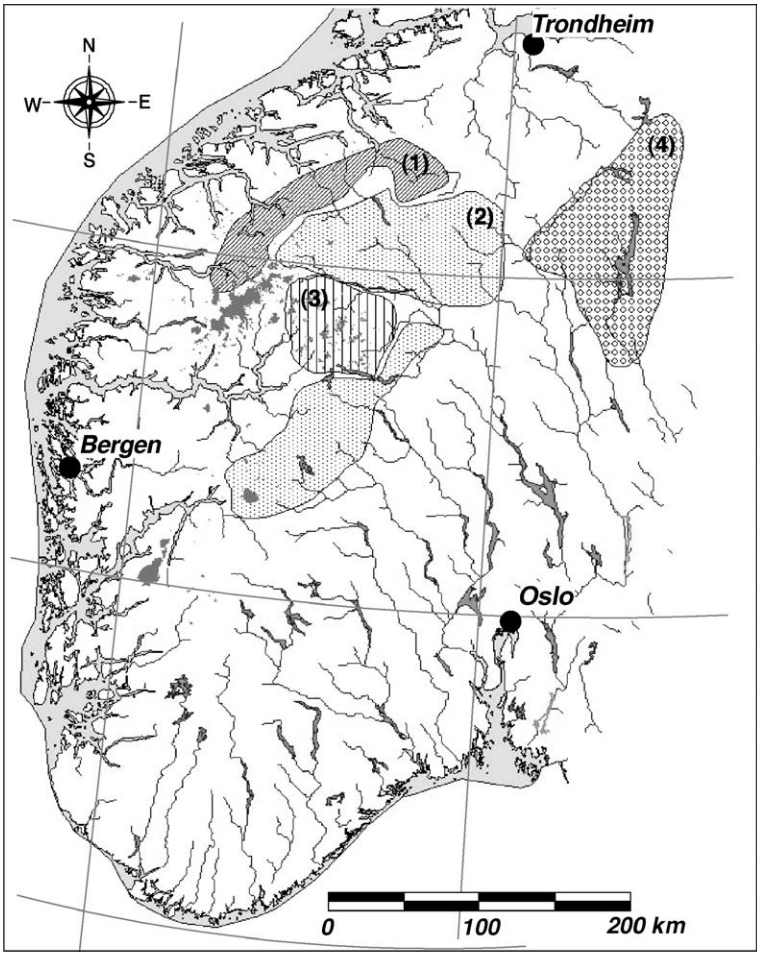


Fig. 7. The major permafrost regions in southern Norway. (1) The northwestern part of southern Norway, (2) the central high-mountain area, (3) the central glacierized high-mountain area of Jotunheimen and Breheimen, and (4) the mountain plateaux.

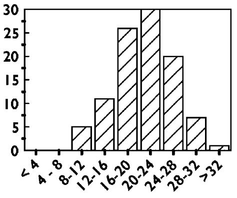
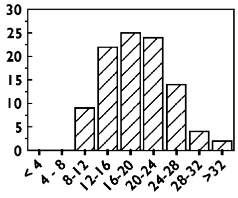
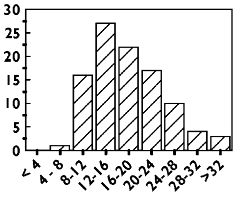
Permafrost and probable permafrost	Climate warming (Future situation)	Present situation	Climate cooling (Little ice-age situation)
Surface roughness (IR)			
	m = 21.0, std = 5.0, rg = 35.0	m = 19.2, std = 5.7, rg = 41.0	m = 17.9, std = 6.2, rg = 42.0
High alpine relief	150 km^2 (16%)	470 km^2 (17%)	1300 km^2 (17%)
Mountain relief	830 km^2 (83%)	2270 km^2 (80%)	5200 km^2 (74%)
High mountain plateaux	<10 km^2 (<1%)	65 km^2 (3%)	620 km^2 (9%)

Fig. 8. Probable mountain permafrost areas seen in relation to topographic surface roughness and topographic regions according to the relief classification shown in Fig. 6b. IR is the roughness index, defined as $R = \sqrt{(\Sigma X_i)^2 + (\Sigma Y_i)^2 + (\Sigma Z_i)^2}$ and $IR = 1 - \frac{R}{n}$, with $X = -\sin y \sin a$, $Y = \cos y \sin a$ and $Z = \sin a$, with y and a being *aspect* and *slope*, respectively. n is the number of samples in the calculation. m = mean, st = standard deviation, rg = range.

4.1.2. The central glacierised high-mountain area of Jotunheimen and Breheimen

In this area, both alpine relief forms and larger areas with paleic surfaces are present. Permafrost is widespread both in top areas and in smaller inter-mountain plateaux. In this area, glaciers and permafrost coexist. This region covers approximately 35% of the total permafrost area.

4.1.3. The central high-mountain area

This area is dominated by paleic relief forms and covers the mountain areas of Dovrefjell, Rondane, Kjølenfjellet and Hallingskarvet. The mountains have larger mountain plateaux, medium relief and are dissected by deep glacial valleys draining towards east. The area is partly influenced by present or former cirque glaciation, and the region covers approximately 56% of the total modelled permafrost area.

4.1.4. The mountain plateaux

This area is dominated by flat mountain plateaux, containing scattered mountain massifs. It is found mainly in the eastern part of southern Norway, but includes also the southern rim of Hardangervidda. Permafrost is found on top of these scattered mountain massifs, such as Gaustatoppen. Scattered degla-

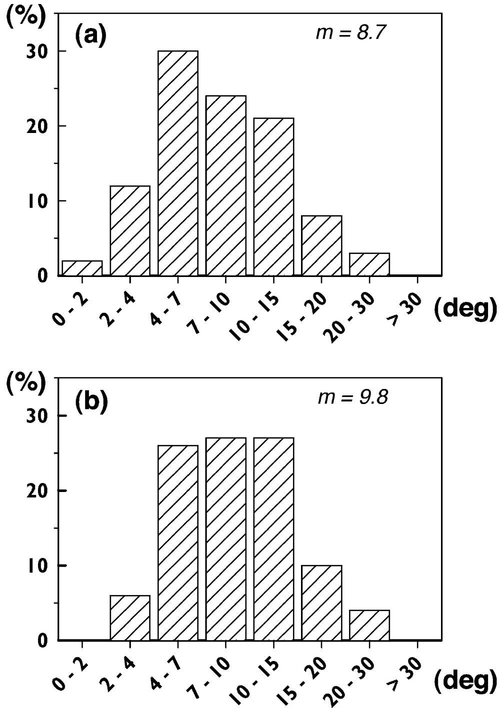


Fig. 9. Slope distribution for areas potentially under degradation since the LIA (a) and potential future degradation due to climatic warming (b). The graph axes denotes slope in degree and percentage of total area. m = mean value of slope (in degree).

ciated cirques are found. Permafrost coverage in relation to the total permafrost area is estimated at 4%.

4.2. Effect of climate change

The distribution of topographic characteristics for the permafrost areas modelled for different climatic settings were analysed (Figs. 8 and 9), only considering MAAT variation. According to this approach, much possible degradation of permafrost has taken place in low-relief areas. Permafrost recently covering flat mountain plateaux may degrade completely during further climatic warming. This means that permafrost has become more restricted to higher-relief areas since the LIA. The exception to this pattern is the alpine areas in the northwestern part of southern Norway (Møre og Romsdal, Fig. 1). In this high-relief alpine area, permafrost always has been restricted to steep slope settings, comparable to the conditions described, for, e.g. the Swiss Alps.

5. Implications of the permafrost distribution on geomorphological processes—a discussion

5.1. Glacial processes

5.1.1. Spatial pattern

Glacier tongues ending on land in a permafrost environment are most probably cold-based, and these glaciers normally have a cold or polythermal temperature regime (cf. Liestøl, 1969, 1977). Polythermal glaciers display a frontal ice-compression zone with shear planes due to the rapid decrease of glacier velocity caused by the reduction of basal sliding towards the glacier front (cf. Weertman, 1961; Boulton, 1972; Hooke, 1973). Cooler ice reduces surface velocities and mass flux, and the restricted basal sliding reduces the influence of subglacial erosion. This results in a characteristic process pattern at the glacier front, with respect to debris entrainment and sedimentation (Fig. 10). In many valley and cirque glacier settings, there is an increased relative importance of external

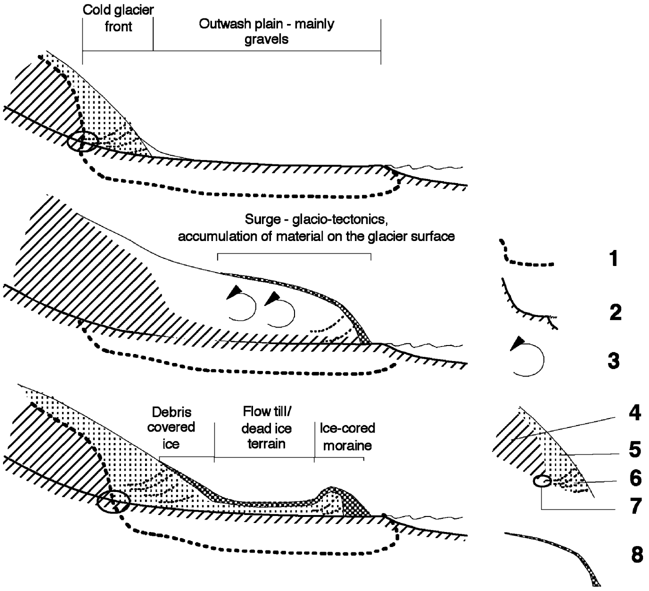


Fig. 10. Principle development of glacier marginal landforms (ice-cored moraines) in permafrost as observed on Svalbard (from Etzelmüller et al., 1996) under the condition of an advance of the glacier over bedrock or frictional, nondeformable sediments. (1) Base of permafrost. (2) Bedrock. (3) Deformed ice during an advance/surge, glacio–tectonical processes. (4) Temperate ice, at the pressure melting point. (5) Cold ice. (6) Shear zone and/or englacial material bands. (7) Transition zone between net melting and net freezing in the sense of Weertman (1961) and Boulton (1972). In this zone, onfreezing of subglacial sediments may take place. Transport of material towards the surface. (8) Debris covered glacier front, material cover preserving underlying glacier ice.

debris input in relation to subglacial material production. In addition, the transition between temperate and cold-based ice favours onfreezing of subglacial sediments, and englacial transport processes relative towards the ice surface in connection to the ice-compression zone (Weertman, 1961; Boulton, 1972). This process causes accumulation of often coarse-grained or even sorted debris in and on the glacier tongue, and leads to the buildup of ice-cored moraines due to accumulation of debris. During glacier advances, stresses from the glacier can be transmitted in the permafrost package over longer distances, resulting in large-scale push moraines (composite ridges) in the glacier marginal distal zone (cf. discussion in Bennett, 2001). Contemporary long retreat phases result in partly down-wasting of ice-underlain glacier marginal zones, resulting in thermokarst features (Sollid and Sørbel, 1988; Etzelmüller, 2000; Lyså and Lønne, 2001).

This pattern is mainly described from polythermal glaciers in the high-Arctic like on Svalbard (Sollid and Sørbel, 1988; Etzelmüller et al., 1996; Hart and Watts, 1997; Boulton et al., 1999; Lyså and Lønne, 2001) and the Canadian Islands (Kälin, 1971; King and Hell, 1993; Bennett, 2001). However, also in southern Norway, a different moraine morphology is described for glaciers ending at higher altitudes than for the temperate western glaciers (Østrem, 1964; Haeberli, 1979). An example is Midtdalsbreen in the Finse area of southern Norway, a temperate outlet glacier of the Hardangerjökull ice cap (Sollid and Bjørkenes, 1977). Here, geomorphological indications and thermistor measurements have shown that the lowermost, up to 20 m thick, area of the glacier front is cold-based (Liestøl and Sollid, 1980; Bø, 1992; Konnestad, 1996). Annual moraines built up since the 1960s show clear melt-out of frozen subglacial layers, and an asymmetric moraine morphology (Andersen and Sollid, 1971). Matthews et al. (1995) describe a similar process in front of Styggedalsbreen, western Jotunheimen.

In southern Norway, the large-scale ice-cored moraines are frequent, especially in the Jotunheimen area (Østrem, 1964) and around the Snøhetta massif in Dovrefjell, indicating permafrost conditions in these areas. To the authors' knowledge, no recent special studies do exist so far explicitly relating the glacial thermal regime to moraine morphology in southern Norway.

5.1.2. Temporal pattern

During the cooler LIA period, more permafrost were probably present (Fig. 2a); however, also the glacier tongues were larger, reaching further down slope. Recent studies estimate the decrease of the ELA in different regions of southern Norway, with numbers varying from more than 100 m on Hardangerjökulen, western Norway (Dahl and Nesje, 1996), to 70 and 25 m at Storbreen and Leirbreen, respectively, in Jotunheimen (Matthews et al., 2000).

With glacier retreat due to climatic warming or changing winter precipitation pattern, the thermal regime of a glacier may change, resulting in a different glacial–geomorphological process pattern. Originally, temperate glaciers retreating into the marginal permafrost zone will develop partly cold glacier tongues. An example is again Midtdalsbreen, displaying a different moraine morphology between recent moraines and LIA moraines (Andersen and Sollid, 1971; Sollid and Bjørkenes, 1977). Polythermal glaciers that are thinning may become cold-based. Examples of this pattern are reported from Svalbard (Hodsen, 1994; Björnsson et al., 1996).

In many areas, permafrost may have been built up in the glacier marginal zones during glacier retreat. The larger glaciers in Jotunheimen ended below the permafrost limit during the LIA, and do now retreat into the permafrost zone. This leads to the buildup of new permafrost in the marginal zone of formerly temperate glaciers. An example is the glacier Memurubreen in central Jotunheimen, where a detailed geomorphologic map exists (Erikstad and Sollid, 1990). The map shows that fluted surface is found up to 1700 m a.s.l., indicating temperate subglacial conditions. Today, these areas lie in the zone of highly probable permafrost, and ice-cored moraines are present at the glacier margins. This process pattern has been observed and mapped in glacier marginal areas by Kneisel (1999). Permafrost aggregation in recently deglaciated terrain changes the process pattern and the geotechnical properties in the area.

5.2. Slope processes

The topographic analysis in relation to modelled permafrost distribution indicates a dominance of relatively low-relief areas affected by permafrost in southern Norway. These patterns are obviously in contrast to high-relief alpine areas, affecting the pattern of permafrost-related slope processes and, thus, landscape development in southern Norway.

5.2.1. Spatial pattern

Rockfall is a commonplace process in Norway, influencing most areas and causing distinct problems with respect to damages on transport infrastructure. Regional maps of geomorphology and Quaternary geology (Sollid and Kristiansen, 1982; Kristiansen and Sollid, 1985; Sollid and Trollvik, 1991) as well as detailed maps (Sollid and Carlson, 1979; Sollid and Sørbel, 1979b; Sollid et al., 1980) indicate that taluses are not particularly well-developed in the main areas of permafrost distribution in southern Norway. In the northwestern part of southern Norway, the areas of talus accumulation are mainly below the permafrost distribution, while steep mountain walls in the Jotunheimen–Breheimen areas mostly are associated with present cirque or valley glaciers. It must be anticipated that the extraglacial material input from slope processes constitutes an important part of the total sediment production within alpine glacier catchments. Effects of snow avalanches often modify the talus slopes found in this area. The main areas for talus development within permafrost in southern Norway are thus deglaciated cirques in the central high-mountain area and structurally determined mountain walls such as along the edges of nappes that overlie softer rocks. The Rondane area is an example of the first situation, and the slopes along the Hallingskarvet mountain massif of the second. To the authors' knowledge, there is no consensus on how permafrost influences rockfall activity. The potential for frost weathering should generally increase, as long as water is available at the surface (Hallet, 1983; Ødegård and Sollid, 1993; Ødegård et al., 1995).

Debris flows are generally a common phenomenon in southern Norway, especially in the western areas (Blikra and Nemec, 1998). Within the permafrost regions, however, they are not particularly usual. In Jotunheimen, they seem to develop beneath the regional permafrost limit. A study from the valley Visdalen in central Jotunheimen indicates that the starting zone of the debris flows in the area seems to be situated close to the permafrost limit (Sørlie, 2002). The lack of debris flows on permafrost may be attributed to the generally thin or lacking material cover on the steeper slopes in these areas. Also, in terrain positions where debris flows normally would tend to develop, slush flows are very common and probably dominant with respect to frequency, local form development and sediment transfer. Sandersen (1997) notes that in the continental parts of Norway, debris flows are either caused by intense snowmelt on unfrozen ground or by convective rainstorms. Thus, conditions leading to debris flows elsewhere might induce slush flows on permafrost. This is due both to a low potential for meltwater infiltration into soil, and to refreezing of meltwater within the snow pack and at the snow/ground interface, which retains water on permafrost slopes until late in the melt season when rapid melting can be expected.

Rock glaciers in the sense of creeping permafrost (Haeberli, 2000) are not common in southern Norway (Sollid and Sørbel, 1992). Although a few examples of smaller permafrost creep features generally can be found (e.g. Sollid and Kristiansen, 1984), rock glaciers are only common in the Rondane area (Barsch and Treter, 1976), where also talus slopes are best developed.

Large rock avalanches and rockslides have been mapped at a large number of locations both in northern and southern Norway (Blikra and Anda, 1997). A number of these have originated in areas where permafrost may have been present. Jonasson et al. (1997) suggest that many such incidents in the north Swedish and the Norwegian mountains may have been triggered in late glacial times. Although such events generally have a complex origin, permafrost may be one of several important factors for their release by its influence or control on rock joint shear strength (Davis et al., 2001). The rock avalanche deposits are sometimes difficult to distinguish from rock glaciers, especially where they are deposited on permafrost (Barsch and Treter, 1976; Dawson et al., 1986).

The described pattern of slope forms that can be related to permafrost presence or degradation seems to reflect the topographical setting and the abundance of permafrost in low-relief mountain areas. A further reason is displayed in the spatial distribution of surficial deposits in the high-mountain areas of southern Norway. The oldest cover deposits are probably the *blockfields* (cf. Sollid and Sørbel 1979a; Sollid and Kristiansen, 1982; Nesje et al., 1988; Sollid and Trollvik, 1991; Dahl, 1992; Follestad, 1995). A preglacial age of these deposits has been suggested, based on vegetation successions (Dahl, 1956); warm-climate, clay-weathering remnants (Dahl, 1954; Roaldset et al., 1982; Rea et al., 1996); and a regional distribution above glacial trimlines in west coastal areas (Sollid and Sørbel, 1979a; Sollid and Reite, 1983; Nesje et al., 1988) or in areas of possible landscape preservation beneath cold-based part of the inland ice sheet (Sollid and Sørbel, 1982, 1994; Nesje et al., 1988). Apart from the blockfields in top areas and colluvium found on scree slopes and talus, the cover deposits seem to be mainly thin and discontinuous in high-relief permafrost regions (Sollid et al., 1980; Sollid and Kristiansen, 1982; Kristiansen and Sollid, 1985; Sollid and Trollvik, 1991).

5.2.2. Temporal pattern

The effect of the variation of permafrost distribution and thickness during time on slope processes must be addressed at different time scales. We consider here only the Holocene, which did become gradually cooler from the warm Atlanticum towards the LIA, with a clear warming trend during the last century (e.g. Dahl and Nesje, 1994; Nesje et al., 2000).

One of the prime concerns regarding the probable mountain permafrost degradation under climatic warming is the potential for slope stability problems in bedrock and nonconsolidated sediments (Haeberli, 1992). Although climatic warming has been going on since the LIA, the rate of temperature changes has been much faster during the recent decades (e.g. Jones et al., 1999). Nevertheless, the period of general warming since the LIA could provide an analogue for the processes likely to take place under possible future climatic warming. No tendency for enhanced debris flow activity can be noted for this period. Increased debris flow activity in Scandinavia is rather associated with colder periods (Nesje et al., 1994; Matthews et al., 1997). The lack of effect of a warming situation is quite probably caused by the dominance of debris flows below the regional limit of permafrost. On the other hand, much degradation of permafrost since the LIA has probably taken place on low-relief areas. It is likely that new starting zones for debris flows may develop, higher up on mountain slopes, as active layer thickness increase. The most important effect of climate change on debris flow activity will nevertheless probably be the anticipated increase in magnitude of precipitation events (Frei et al., 1998).

The only area where permafrost degradation since the LIA has mainly involved steep slopes is the northwestern permafrost region. In this area, large rock avalanches represent a threat to human life and constructions (cf. Blikra and Anda, 1997). The frequency of large rock avalanches is too low to conclude on a relationship to climate. The analyses connected to the permafrost-distribution model presented in this study might offer indications that high-altitude peaks in the northwestern part of southern Norway are subject to permafrost degradation.

5.3. The sediment transport system

The processes within the permafrost zone in high-mountain areas are highly heterogeneous. They should be treated as a sediment cascade system of material transport and sedimentation, where the factor-governing processes, activity states and reaction time on changing constraints will vary in time and space (Caine, 1974, 1986; Barsch and Caine, 1984; Caine and Swanson, 1989). The sediment cascades in high-mountain environments are schematically shown in Fig. 11a. In this concept, the processes are parted in a fine sediment system, a coarse sediment system and a glacier system (Caine, 1974; Barsch and Caine, 1984), where, e.g. talus cones, rock glaciers and moraine ridges are important sediment magazines. These sediment magazines store material and may release considerable amounts of debris during changing environmental conditions, as for instance due to permafrost degradation or during a glacial cycle.

Permafrost seems to be an important regulator of this system as described by e.g. Etzelmüller (2000). In temperate glacier catchments, there is a close relationship between the amount and type of sediments (fluxes) and the existence and size of glaciers within the catchment. Most of the sediments produced in the glacier are evacuated by the meltwater, and the amount of sediments during summer decreases despite of increasing discharge (Liestøl, 1967; Østrem, 1975; Collins, 1979; Repp, 1979; Lawsen, 1993). Thus, there is a close relationship between the existence and size of a temperate glacier and sediment flux (Fig. 11b). In permafrost areas, the glaciers are polythermal,

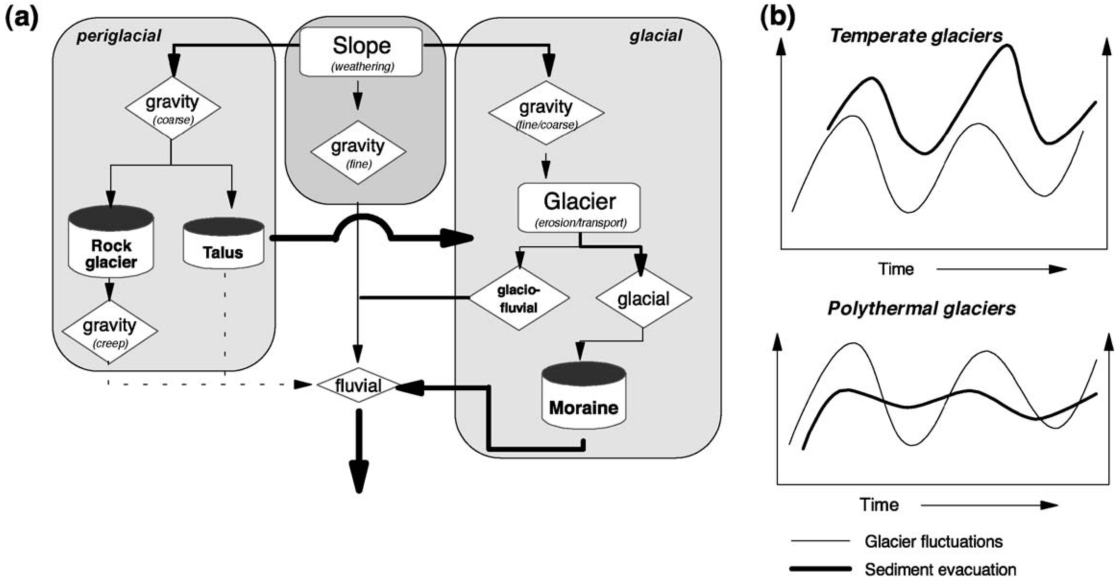


Fig. 11. (a) Conceptional flow chart of the glacial and periglacial particulate material transfer system in arctic glacierized mountains and alpine permafrost areas. The glacial system is an effective transport system, transferring material from the slope to the moraines, which act as sediment magazines. The periglacial slope system is producing sediment magazines, which store material over very long time periods (e.g. rock glaciers). However, coupled with a glacier system, material is effectively removed from the slopes and coupled with the fluvial system. (b) Conceptual illustration of the relationship between glacier variations in time and correspondent particulate material evacuation out of a glacier-dominated catchment. Temperate glaciers show high correspondence between sediment evacuation and glacier activity. In permafrost areas with dominating polythermal and cold glaciers, this signal may be lower and damped.

meltwater discharge is lower, and much erodable material is accumulated under the glacier or in form of ice-cored moraines (Vatne et al., 1995; Hodkins, 1997; Hodsen et al., 1997; Hodsen, 1999; Etzelmüller et al., 2000) and act as a sediment magazine, releasing material also during glacier retreat. Hence, the above-mentioned relationship is locally damped or maybe even reversed in special situations (Fig. 11b). Especially ice-cored moraines play an important role. Material release there is dependent on the removal of material protecting the ice-core. Climate warming increases ice-core melting and thus material release increases from these sediment magazines, while when the glacier retreats and erodes, material production decreases. Thus, glacier variation must not necessarily be in phase with variations in sediment fluxes in permafrost-dominated areas. Actually, small cirque glaciers enhance the periglacial mass-transport system by capturing and transporting material, keeping the slopes steeps and active. Even with low erosional potential, cirque and valley glaciers in cold environments have relatively high material transport and long-term erosion rates measured by meltwater evacuation of solids (Hodsen, 1994; Hallet et al., 1996; Hodkins, 1997). In many cases, the production of the material is predominantly periglacial in a permafrost environment (Etzelmüller et al., 2000).

In previous studies on lake sediments in southern Norway, e.g. on Finse and around Jostedalsbreen, the sediment signal in the lake cores indicate very good correspondence between glacier existence and size and the sediment record (Dahl and Nesje, 1994, 1996; Nesje et al., 2000). These glaciers are temperate, such as Midtdalsbreen (Liestøl and Sollid, 1980), and the lake cores allowed a detailed reconstruction of Holocene glacier and thus climate history.

Permafrost seems to conserve sediment magazines in high-alpine environments over longer time periods, affecting sediment output of permafrost-dominated catchments. Sediment magazines are mobilised during permafrost degradation. On the other hand, coarse-material production on slopes due to frost weathering may be enhanced during colder periods (Blikra and Nemec, 1998; McCarroll et al., 1998, 2001).

6. Concluding remarks

This study reviewed the distribution of mountain permafrost in relation to the topographic setting in southern Norway. On that basis, glacier type and slope-distribution patterns are discussed in relation to permafrost occurrence and its temporal change. From this discussion, the following main conclusions can be drawn:

- Permafrost is predominantly found in non-alpine topography in southern Norway.
- Exceptions are the high-alpine areas of Møre and Romsdal. To the authors knowledge explicit permafrost mapping do not exist in that area so far.
- Sparse sediment cover on steep slopes suggests low permafrost-induced hazards, except for the speculative relationship between large rockslide events and permafrost degradation.

The pattern of increasing ELA and decreasing MPA towards east is assumed to cause a distinct influence of permafrost on sediment transport and thermal regime of glaciers in the central mountain areas.

Acknowledgements

This paper is written based on a presentation held at the 5th International Conference on Geomorphology in Tokyo, Japan, 23–28 August 2001. Parts of the results and observations presented are from the EU-funded PACE project (Permafrost and Climate in Europe, coordinated by Professor C. Harris, Cardiff), headed by Professor J.L. Sollid at the Department of Physical Geography, University of Oslo. Late Professor em. Olav Liestøl (shared professorship) from the same department early realised the importance of permafrost on glacial–geological processes, and his work as glaciologist at the Norwegian Polar Institute (NPI) and teaching at the Department has inspired this paper. Two anonymous reviewers gave constructive comments to an earlier version of the paper. The GIS-work was carried out at the Laboratory for Remote Sensing and GIT at the same department. The temperature and topographic map data were provided by the Norwegian Meteorological Institute (DNMI) and the Norwegian Mapping Authorities (Statens Kartverk), respectively. We want to thank all contributing persons and institutions.

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