Automatic regional classification of topography in Norway

Bernd Etzelmüller, Bård Romstad and Jakob Fjellanger

The objective of this study is to apply a combined region-growing and classification method for a first automatic landform segmentation of Norway at a regional scale. The classification is based on primary topographic point parameters, generated from a 500 m digital elevation model (DEM). The automatic regional landform segmentation resulted in a division of Norway into 25 classes, merged into ten major topographic types. At the regional scale the resulting classes could be related to the influence of broad-scale land-forming mechanisms such as planation and uplift. Regions related to Quaternary glacial and periglacial processes, such as the magnitude of Pleistocene glacial erosion and the distribution of mountain permafrost, could be defined. The classification method, or variations of it, is usable for different purposes including the generation of new information, such as in geohazard zonation studies. This classification might serve as a basic constraint for further analyses within the TopoScandia framework, and for application to present-day processes such as rapid mass movements or as a basic constraint for further analyses aimed at highlighting the relation between land surface topography and offshore sedimentary stratigraphy.

Introduction

Topography is the result of, and thereby contains information on, previous geomorphic processes, and is critical for the interpretation of present-day exogenic processes. Therefore the quantitative description and classification of the terrain (“geomorphometry”) is an important part of landform analysis. One basic assumption in geomorphometry is that a close relation exists between surface processes and surface characteristics (e.g. Pike 2000). This relation is assessed by defining sets of digital elevation model (DEM)-derived parameters or topographic indices, and relating them to geomorphic process areas, soil properties or the presence of certain landforms by means of statistical techniques (Etzelmüller et al. 2001; Hjort & Luoto 2006; Luoto & Hjort 2004; Luoto & Seppälä 2002; McBratney et al. 2003). The approach taken here is the concept of homogenous topographic units, where we assume that a process acquires a certain deterministic or stochastic pattern, or that a distribution pattern of certain landforms can be related to these units. The topographic units then describe a sort of topographic constraint, linking the potential existence of a landform or a process to a defined topographic setting (Etzelmüller et al. 2001). Topographic units can be defined through a classification of terrain parameters. If an empirical or physical relationship between the topographical units and certain surface processes can be established, terrain classification can then be used as a tool for the spatial modelling of these processes (e.g. Lapen & Martz 1996; Pachepsky et al. 2001).

Pike (1988) introduced the concept of landform description by geometric signature. He showed that disparate landforms can be distinguished by a set of measures that describes the topographic form. The numerical description of surface geometric or topographic characteristics, coupled with the relationship between topography, process and sediment cover facilitates a more consistent set of rules for landform delineation (e.g. Burrough et al. 2000; Dikau 1989; Schmidt & Andrew 2005). This synthesis can be approached objectively by generalising multivariate data by means of statistical analysis and classification. Relief data, however, most commonly represent a continuum that has few distinct class boundaries. In order to address this challenge methods like fuzzy classification (Burrough et al. 2000; Irvin et al. 1997; Park et al. 2001; Ventura & Irvin 2000) or image-segmentation algorithms (Friedrich 1996; Miliareis 2001; Romstad 2001) of the terrain are proposed.

This study applies a combined region growing (or iterative cell-grouping, see also Jensen 2005), and subsequent classification technique to segment objectively landform types on a regional scale, delineating broad-scale landform patterns for Norway and assessing their relationship to past and present geomorphological processes. As a first application the paper interprets the results in relation to (a) broad-scale bedrock geomorphology, (b) Pleistocene landscape development and (c) mountain permafrost distribution.
Setting

Norway is situated along the western margin of the Baltic shield with a cover of Caledonian nappes in the west (Fig. 1). The bedrock of the Baltic shield is dominated by Precambrian basement rocks (e.g., granites, gneisses, amphibolites and meta-sediments) in the southern and south-eastern part of the country and the Caledonian nappes by Precambrian rocks and metamorphic Cambro-Silurian sediments in the central and western parts. Cambro-Silurian sedimentary and Permian volcanic rocks occur within the Oslo Graben (Fig. 1, Ramberg et al. 2006). The subaerial relief is 2500 meters in southern Norway, and the overall development of the gross-geomorphology in the region can be summarized as one of erosion and planation during the late Palaeozoic and Mesozoic; major uplift during the Cenozoic with maximum uplift in the western areas (e.g., Lidmar-Bergström et al. 2000; Ren et al. 2003; Riis 1996; Stuevold & Eldholm, 1996), and glacial erosion during the Pleistocene (e.g., Fredin 2002; Nesje & Whillians 1994; Riis 1992). Norway comprises a variety of landscapes dominated by glacial erosion and surfaces, where the effect of glacial erosion is limited or absent. The term “Paleic surface” was introduced by Reusch (1901) to describe the gentle elevated surfaces in contrast to the deeply incised and clearly younger valleys and fjords. It is assumed that the Paleic surface pre-dates the latest uplift surface developed under warmer climatic conditions than at present (e.g., Gjessing 1967; Lidmar-Bergström et al. 2000). High-elevation surfaces have, especially in eastern settings of the Scandes, escaped glacial erosion during the Pleistocene, possibly due to cold-based ice sheets (Fjellanger & Sørbel, this issue; Kleman 1994; Kleman & Bergström, 1990; Sollid and Sørbel 1982b; Sollid & Sørbel, 1988; Sollid and Sørbel 1994). Different views and summaries concerning the regional landform development in Norway are given by Peulvast (1985) and Rudberg (1988), and discussed more recently by others (e.g., Bonow 2004; Bonow et al. 2003; Fjellanger 2006; Fjellanger & Etzelmüller 2003; Fjellanger & Sørbel this issue; Lidmar-Bergström 1999b; Lidmar-Bergström et al. 2000).

Methods

The study consists of three major steps. First, morphometric variables are defined and calculated. Second, interrelations between the variables are quantified and diagnostic variables selected. Finally, the classification process of the topography is applied (Fig. 2).
**Principles and morphometric variables** - Conceptionally, topography can be described by six basic characteristics (Table 1). (1) **Vertical location** as a discretisation of the continuous topographic surface; (2) **Elevation amplitude** or local variability of elevation; (3) **absolute and relative surface inclination**; (4) **hypsography** as the relation between elevation distribution and surface area or the **vertical distribution of topography** (e.g. Evans 1972); and finally, (6) **topographic texture or spacing** as a measure of the spatial autocorrelation **range** of topography. These topographic characteristics can now be quantified by topographic (relief) parameters or attributes, derived from digital elevation models (DEM).

The topographic attributes described in Table 1 were calculated from a 500 m DEM that contained 1.32x10⁶ grid cells for the landmass of Norway. The basic measures are the derivatives of elevation (**slope**, **aspect** and **curvature**). These were calculated by an algorithm of Zevenbergen & Thorne (1987), which fits a higher order polynomial to a 3x3 window in the DEM and derives the obtained local polynomials. The algorithm was implemented in the ArcInfo environment. Direct, point-based gradient parameters describing the local inclination of the topography like **slope**, **aspect** or **curvature** are meaningless because of noise in the coarse data sets, and the fact that slopes estimated from such data can produce significant underestimates of the true slope. To describe relief amplitude and surface inclination for a larger area, parameters and their statistical moments calculated over a local neighbourhood were used. Evans (1972) early showed that the second statistical moment of **elevation** and **curvature** are reliable estimates for surface roughness or relief variability. Hammond (1964) and later Dikau et al. (1995) used **local relief** (Table 1) and a slope parameter, indicating the area of gentle slope defined as <8% (c. <4.6°) within a local neighbourhood.

The hypsography of a landscape was early used to describe qualitatively the maturity of topography in the sense of Davis’ (1899) concept of cyclic landform development. As a measure of local hypsometry the elevation-relief ratio (cf. Mark 1975; Pike & Wilson 1971; cf. Wood & Snell, 1960) was introduced (Table 1), ranging between 0 and 1. Low values describe the dominance of plains (most areas within low elevations), while higher values denote elevated plains and mountains (most areas at high elevations). Hammond (1964) introduced a “profile-type” measure and calculated the area of gentle slopes within high or low elevations, respectively.

The local area of parameter estimation, or window size, was defined by the mean **grain** for Norway. If we assume the topography as being described by harmonic functions, the **grain** is defined as the longest significant wavelength of topography (introduced by Wood & Snell, 1960). The measure is related to the overall valley spacing and can be estimated using semivariogram analysis (Mark & Aronson 1984; Pike et al. 1989). In this study **grain** was determined with a simplified algorithm that calculates the local omnidirectional semi-variance in every grid cell for different lags between 1 km and 20 km (Fig. 3a). A plot of this semi-variance as a function of the lag yields a graph showing the semi-variance or elevation variance at different lags. For each grid cell the **range** can then be estimated by finding the knick point on this graph. The knick point was defined as the first location where the slope between two consecutive semivariogram points fell below a certain threshold, as described in Pike et al. (1989). In this study we used 0.015 as the threshold, which is assigned subjectively (Fig. 3a). If the threshold value is not reached, the range was set to 20 km. The **nugget** of this graph is the point where the graph crosses the y-axes. High nugget denotes sub-cell variability and thus roughness. The **sill** displays the elevation variance at the **range** and is the total variability of elevation. In this study **grain** for the attributes was estimated to vary between c. 3 km and >16 km for southern Norway (Fig. 3b). A **grain** of 7 km was applied for the whole of Norway as an average value for this preliminary study.

**Selection of variables** - For the regionalisation of a terrain to be successful, the selected attributes should have a smaller variation within the terrain units of interest than between them. In addition the attributes should not...
Table 1. Principle topographic characteristics and topographic parameters calculated for this study

<table>
<thead>
<tr>
<th>Topographic characteristic</th>
<th>Topographic parameter</th>
<th>Description, expression and interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location (vertical)</strong></td>
<td>Mean of elevation</td>
<td>1st moment of elevation; height above mean sea level (potential energy for gravitational processes)</td>
</tr>
<tr>
<td>Elevation amplitude</td>
<td>Local (“relative”) relief (1)</td>
<td>Elevation range in a local neighbourhood - MAX(elevation)-MIN(elevation)</td>
</tr>
<tr>
<td></td>
<td>Local (“relative”) relief (2)</td>
<td>Relief (“sill”) at distance (“range”) derived from spatial autocorrelation</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of elevation</td>
<td>2nd moment of elevation, local variability</td>
</tr>
<tr>
<td><strong>Surface inclination (absolute)</strong></td>
<td>Slope</td>
<td>Maximum gradient, change of elevation toward steepest descent (Zevenbergen and Thorne, 1987)</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of slope</td>
<td>Variability of slope gradient</td>
</tr>
<tr>
<td><strong>Surface inclination (relative)</strong></td>
<td>Area in gentle slope (&lt;8%)</td>
<td>Area of slope &lt; 8% in a local neighbourhood (“roughness” parameter of Hammond 1964); area best for human use</td>
</tr>
<tr>
<td></td>
<td>Surface curvature</td>
<td>Rate of change of slope gradient and aspect, concave (&lt;0) and convex (&gt;0); shape of local terrain</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of curvature</td>
<td>Variability of surface curvature; curvature magnitude regardless of sign</td>
</tr>
<tr>
<td>Hypsography (relief distribution)</td>
<td>Elevation skewness</td>
<td>3rd moment of elevation; distribution of mass by elevation; inverse of ER (Wood and Snell, 1960) and hypsographic integral (Strahler, 1952)</td>
</tr>
<tr>
<td></td>
<td>Elevation-relief ratio (ER)</td>
<td>$ER = \frac{\text{MEAN(elev.)}-\text{MIN(elev.)}}{\text{MAX(elev.)}-\text{MIN(elev.)}}$; \text{mathematically identical to hypsometric integral}</td>
</tr>
<tr>
<td></td>
<td>Profile type</td>
<td>Amount of gently sloping terrain (&lt;8%) in lowland or upland; measure of local mass distribution (Hammond, 1964)</td>
</tr>
<tr>
<td>Spacing (“texture”)</td>
<td>Topographic grain</td>
<td>Range of relief semivariance at value of the “sill”; characteristic valley spacing derived from spatial autocorrelation</td>
</tr>
</tbody>
</table>

be correlated to each other. A correlation matrix calculated for the parameters revealed high correlations ($r>0.7$) within groups of attributes identifying elevation amplitude and inclination variation (e.g. elevation standard deviation, local relief, curvature standard deviation) or hypsography (e.g. Hammond’s profile type, elevation-relief ratio, elevation skewness), while relatively lower correlations were obtained between these groups of attributes and with mean elevation ($r<0.45$) (Table 2). These three parameter groups are described by the first three moments of elevation (mean, standard deviation and skewness), and express the regional aspect of topography: (1) Mean elevation; describing the overall surface elevation level and a measure of potential energy for gravitational processes; (2) standard deviation of elevation, a measure of local relief variation or amplitude (Evans 1972); and (3) elevation-relief ratio, a measure of the hypsography or elevation mass distribution (Mark, 1975; Pike & Wilson 1971) (Fig. 4). These three parameters were used for the further classification.

Classification process – Segmentation of landforms was achieved using first an iterative region-growing algorithm, first implemented by Friedrich (1996) and later modified by the authors. Region growing is a specific cell-grouping process, where neighbouring cells are merged to larger units based on the similarity of their attributes. Prior to the region-growing process, the attributes were normalised between 0 and 1, but not weighted. The basic unit in the procedure is the distance vector between two classes. This vector is calculated as the Euclidian distance between each neighbouring region in the dataset as $d = \sqrt{\sum (a_i - b_i)^2}$, where $d$ is the total number of attributes, and $a_i$ and $b_i$ are the values of attribute $i$ in region $a$ and $b$ respectively. The two neighbouring regions with the shortest vector distance between them are then merged. New attribute values are then calculated for the new region, and the distance vectors between the new region and its neighbours are updated before the procedure is iterated. The degree of generalisation chosen will act as a halting criterion for the growing process. A suitable degree of generalisation will primarily depend on the scale of the data relative to the scale of the features being classified. We defined the halting criteria to 99.5% generalisation, which for southern Norway resulted in 9200 merged groups of cells (Fig. 5a).

To classify the relief units into more general landscape types, an iterative unsupervised cluster analysis was used.
Fig. 3: (a) Calculation principles for estimating topographic autocorrelation and topographic “range”. Around each cell the variation is defined as $\gamma(h) = \frac{1}{2N} \sum (Z(x) - Z(x + h))$, where $N$ is the number of cells, $Z(x)$ is the elevation value at position $x$ and $h$ is the distance between two elevations. Pairs of values are sampled symmetrically around the central cell position with given $h$, resulting in one semivariance value for each $h$. (b) Map of obtained “range” classes for a central part of southern Norway.

Table 2: Correlation coefficients between selected topographic parameters calculated for southern Norway (for nomenclature, see Table 1).

<table>
<thead>
<tr>
<th></th>
<th>Mean elevation</th>
<th>Elevation standard dev.</th>
<th>Relief at “sill”</th>
<th>Relief at “nugget”</th>
<th>Hammond’s slope parameter</th>
<th>Local relief</th>
<th>Hammond’s profile type</th>
<th>ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean elevation</td>
<td>1</td>
<td>0.45</td>
<td>0.30</td>
<td>0.12</td>
<td>-0.59</td>
<td>0.46</td>
<td>-0.10</td>
<td>0.52</td>
</tr>
<tr>
<td>Elevation standard dev.</td>
<td>1</td>
<td>0.76</td>
<td>0.67</td>
<td>-0.86</td>
<td>0.99</td>
<td>0.12</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Relief at sill</td>
<td>1</td>
<td>0.61</td>
<td>-0.56</td>
<td>0.75</td>
<td>-0.09</td>
<td>-0.01</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Relief at nugget</td>
<td>1</td>
<td>-0.49</td>
<td>0.67</td>
<td>-0.85</td>
<td>-0.07</td>
<td>-0.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hammond’s slope parameter</td>
<td>1</td>
<td>1</td>
<td>-0.85</td>
<td>0.75</td>
<td>-0.01</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local relief</td>
<td>1</td>
<td>0.13</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hammond’s profile type</td>
<td>1</td>
<td>-0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ER</td>
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<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Fig. 4: Examples of the three principle parameters used to sub-divide southern Norway. (a) mean elevation (local mean averaged over circular radius of 7 km), (b) elevation standard deviation, (c) elevation-relief ratio.

Fig. 5: (a) Topographic types after segmenting southern Norway into approx. 9200 units and then (b) 25 classes using a combined cluster and maximum-likelihood (ML) classification. The distribution of the 25 classes by parameter is illustrated in Fig. 6. The colours in (a) are randomly chosen in order to illustrate the clusters. The colour legend for (b) is chosen to represent the major topographic areas defined in Fig. 7.
The selected terrain attributes resulted in several layers of continuous data. Each of these layers was then averaged over the relief units generated by the region-growing, producing a new layer for each attribute. The cluster analyses on the resulting stack of data revealed 25 significant classes. The data set was then classified using a maximum likelihood (ML) classification based on the resulting variance-covariance matrix from the cluster analysis (Fig. 5b). The 25 classes were later merged manually into 10 regional topographic units for visualisation and interpretation.

Results and first interpretation

The region-growing procedure resulted in an irregular pattern of small landscape units (Fig. 5a). As this is a local process, clusters with similar geometric signatures are not joined during this process. The clustering and ML-classification of each resulted in 25 major classes (Fig. 5b), which still show a heterogeneous distribution of major landforms. When plotting the class means for the chosen parameters against each others it is evident that mean elevation and elevation standard deviation show the lowest interrelation. Thus, the general categories are mainly distinguished by the mean elevation and elevation standard deviation of each class while the elevation-relief ratio varies considerably within the categories (Fig. 6). This is not surprising as for high-mountain plateaux for example the classes show high elevation-relief ratios along the perimeter, but low values in the interior, resulting in an intermediate average. The elevation-relief ratio is therefore more suited to define sub-classes within the suggested categories than it is for delineation of the categories themselves. For a more spatially coherent regional picture, the 25 classes are merged into 10 classes, which reveal a homogenous and easy interpretable distribution of landform classes for Norway. This merging was done entirely subjectively, by merging nearby classes based on the class mean distribution in Fig. 6c, and in addition trying to obtain a similar

Fig. 6.: The 25 class means (dots) of mean elevation, elevation standard deviation and the elevation-relief ratio plotted against one other (a, b, c). The standard deviation around the class means is indicated. (c) shows a confining triangle of the class means. The sides of the triangle are interpreted to indicate certain landform characteristics and process domains (see text). The dotted lines roughly and subjectively delineate landforms dominated by glacial erosion from landform preservation. This division was subjectively chosen, and other divisions might enhance a different pattern. The colours correspond to the classification legend in Fig. 7 and display the 10 major topographic types in Norway.
basic landform pattern like those published by Rudberg (1960) and Klemsdal & Sjulsen (1988). The 10-class result outlines first-order topographic regions of the area, and the nomenclature in Fig. 7 is inspired by the qualitative classifications of Klemsdal & Sjulsen (1988) and Gjessing (1967). The following description focuses mainly on southern Norway (Fig. 5).

**Coastal plains and strand flats (1)** – mostly flat to somewhat hilly terrain, dominates the southern and south-western coast line, and covers about 5% of the total land area of southern Norway.

**Hills (2, 3)** – comprises lowland hills and hilly terrain with more accentuated relief, surrounding the mountain areas of central southern Norway and in south-eastern Norway.

**Upland hilly terrain and table lands (4, 5, 6)** – these areas are flat highlands at varying elevations. During the classification three major levels were identified, with ranges around 400-600 m a.s.l., 700-900 m a.s.l. and 1000-1200 m a.s.l., respectively. Much of these areas fall within the
Paleic surface (after Gjessing 1967), with the possible exception of class 4 (Lidmar-Bergström 1999b). These surfaces seem mostly to have escaped glacial erosion (Sollid & Sørbel 1982a; Sollid & Sørbel 1994). In total, these areas comprise almost 40% of the total land area in southern Norway, and form the dominant landscape type in Finnmark in northern Norway.

Glacially-scoured low mountains and valleys (7) – the class describes the transition between the central upland mountains and the coast-near lowlands in southern Norway, and is dominated by glacial erosion.

Upland mountains with moderate slopes (8) – this class summarizes the central mountain areas of Norway between the highland plateaux in the east and the alpine relief in the west. Much of these areas is dominated by moderate slopes and the Paleic mountains (Klemsdal & Sjulsen 1988). However, large parts of more glacially affected mountain areas like eastern and central Jotunheimen, Rondane, Dovrefjell and Trollheimen are also included here (class 8).

Alpine relief or glacial relief (9, 10) – is characterised by high relief, and dominates the westernmost mountain areas. In the east and north large valleys that drained the inland ice are over-deepened, showing topographic characteristics similar to the westernmost mountain chains (e.g. in Telemark county). Numerous cirque glaciers dissect the landscape today, and slope and permafrost-related processes dominate. Thus, these areas have been extensively reshaped during the Pleistocene.

Selected applications

Topographic regions and landform development. The regional classification illustrates the overall first-order landform pattern. For southern Norway this pattern is related to uplift history and the work of Pleistocene glaciations. When plotting the 25 class centres of mean elevation and elevation standard deviation the point cloud is constrained within a triangle (Fig. 6c). It is here suggested that the sides of the triangle are related to uplift, planation and glacial erosion, respectively. However, it remains to be investigated if this pattern is common for several mountain areas, or specific for the morphogenetic conditions of Scandinavia.

We can use the confining triangle in Fig. 6c to analyse each class relation to the three processes. Areas with little or no glacial erosion are identified along the lower part of the triangle, while glacial erosive landforms lie closer to the upper corner. In southern Norway it is widely accepted that areas with few signs of erosion were either ice-free (e.g. Nesje et al. 1988) and/or were overlain by cold-based ice during several Pleistocene glaciations (Sol- lid and Sørbel, 1994). This has the important implication that our map may actually indicate the areas where we could expect dominantly cold-based ice conditions, or ice-free areas during parts of the Pleistocene glaciations (Fig. 8). The similarity between our results and maps of expected frozen-bed areas during the last glacial maximum (Kleman & Hättestrand 1999; Sollid and Sørbel 1994) is consistent with our hypotheses. An interesting feature is the high proportion of relatively gentle landscapes at high elevations in southern Norway. They may
reflect a late Cenozoic uplift of southern Norway (Huuse 2002; Japsen and Chalmers 2000; Lidmar-Bergström 1999b; Riis 1996).

Hills of low relief and at low altitude (class 2 and 3) roughly correspond to the exhumed, deep weathered Mesozoic relief mapped by Lidmar-Bergström (1999a). These surfaces with gentle slopes occur at different levels and are prominent features in south-eastern Norway, the Trondheim area and eastern Finnmark. The analysis revealed three major elevation classes of planation surfaces centred at around 500 m, 800 m and 1100 m a.s.l. in southern Norway. These levels correspond roughly with the regional levels described by Lidmar-Bergström et al. (2000) and Fjellanger & Etzelmüller (2003). These surfaces have been interpreted as developed by etch processes on a landscape controlled by lithostructural features and by fluvial processes being controlled by sea level and may indicate separate discrete uplift events (e.g. Bonow et al. 2003; Fjellanger & Etzelmüller, 2003).

**Topographic regions and mountain permafrost** – Permafrost is defined by the thermal state of the sub-surface, with freezing maintained throughout at least two subsequent years. In contrast to alpine mountain chains, such as the Alps, we find an imbalance between mountain permafrost existence and alpine topography in Scandinavian mountains (Etzelmüller et al. 2003). The abundance of mountain permafrost increases with elevation and continentality. In the westernmost mountains, climate is more maritime, and the higher elevations are occupied by glaciers. Furthermore, the highest regions in westernmost Norway are not necessarily the most alpine because of the enhanced linear erosion by valley and inland glaciers. This means, in general, that steep alpine topography is rare within the permafrost realm. Comparing the results from the topographic classifications with modelled permafrost distribution (Fig. 9), high alpine relief contributes little to the total permafrost area in Norway.

Based on these considerations Etzelmüller et al. (2003) identified four major regions with permafrost in southern Norway (see Fig. 9): (1) The north-western part, which consists of alpine landforms with a pronounced relief, where permafrost patches exist in some summit areas. (2) The central glaciized high-mountains (mainly Jotunheimen), which have both alpine relief and large areas with paleic surfaces. Permafrost is widespread both in summit areas and in smaller inter-mountain plateaux. (3) The central high mountains (Dovrefjell, Rondane, Kjølenfjellet and Skarvheimen) are dominated by paleic relief forms. These large mountain plateaux of medium relief are dissected by deep glacial valleys draining towards the east. (4) The central and eastern mountain plateaux dominated by upland plateaux with scattered massifs (inselbergs). These are found mainly in the eastern part of southern Norway, but include also the southern rim of Hardangervidda (not shown in Fig. 10). Permafrost is present on the summits of these scattered mountain massifs.

The distribution of permafrost in relation to topography has geomorphological implications. First, recent active rock glaciers, defined as perennial frozen and creeping permafrost bodies covered with coarse blocky material
(Haeberli 2000), are seldom found in Norway. Rock glaciers are instead abundant as fossil features in northern Norway, being related to permafrost conditions at alpine, coast-near sites during and shortly after the last glacia-
tion (Sollid & Sørbel 1992). Secondly, present permafrost is widespread in areas where glaciations were initiated
during the Pleistocene (e.g. Etzelmüller et al. 1998; Heg-
Thus, much glacier build-up has taken place over perma-
frost, affecting the basal thermal regime of the growing
ice sheets (e.g. Etzelmüller & Hagen 2005). At high and
flat locations, ice movement is limited and has a vertical
component, keeping sub-glacial temperatures below the
pressure melting point. Thirdly, landscape development
in these regions seems to be pre-glacial or periglacial in
origin. Accordingly, we have a mechanism whereby gen-
tle elevated topography with permafrost inhibited glacial
sculpturing of the landscape. The pattern has been stud-
ied in more detail in northern Scandinavia (Fabel et al.
2002; Kleman & Stroeven 1997; Naslund et al. 2003; Stro-
even et al. 2002).

Discussion

Classification process – The process here follows the prin-
ciples of geometric signatures defined by Pike (1988),
using morphometric variables as independent variables
in a classification. Hammond (1964) used a similar set of
parameters; however, in contrast to our study he concen-
trated on elevation amplitude, relative surface inclination
(“roughness” measure) and hypsographic measures. His
classification therefore could not delineate larger plains
at high elevations, which is an important component of
Scandinavian topography. In later studies, it has become
evident that the elevation itself, the surface roughness
and the surface hypsography or elevation mass distribu-
tion are major measures for regional relief classification
(cf. Evans 1972; Mark 1975; Wood 1996; cf. Wood and
parameters related to these three measures as those most
descriptive for landform delineation in Italy. The same
is found in a more recent study by Miliåresis (2001),
who used the 30’-resolution (c. 1 km) GTopo DEM for
identifying mountain areas, where roughness and hyp-
sographic measures were important. At a higher resolu-
tion (< 100 m), more drainage-dependent parameters
have increased importance, especially in relation to con-
vergent and divergent drainage patterns. Dikau (1989)
applied the concept of form elements based on slope and
plan/profile curvatures (e.g. Richter 1962; Ruhe 1975)
for landform classifications from DEMs. This has been
used for landslide risk mapping and landform character-
defined morphometric classes that were obtained from
the numeric analysis of the change in gradient of a cen-
tral point in relation to its immediate neighbours. This
was later used in other studies (e.g. Bolongaro-Creveenna
et al. 2005). For the scale of these studies the parameters
related to the second derivative (e.g. curvature) or near-
est-neighbour relations (e.g. flow routing) would be too
noisy and produce too many uncertainties (Florinsky
1998) for a statistical classification process.

The use of automatic classification procedure based
on region growing has recently increased in geomor-
phometry. The resulting landscape segmentation clearly
results in better spatial coherence (e.g. Romstad 2001),
and now replaces earlier attempts of clustering of multi-
dimensional data sets on a cell-by-cell basis (Guzzetti &
Reichenbach 1994; Weibel & DeLotto 1988). Many stud-
yes on a regional scale, including ours, use unsupervised
classification where classes are defined automatically by
explorative analysis (clustering). Before the user had to
manually assign properties to the classes. Ideally, the clas-
sification should be designed to delineate specific land-
forms.

A topic addressed in too few studies is the estimation of
the topographic spacing or grain (e.g. Pike et al., 1989).
Semivariogram analysis has been used in several recent
papers (Sung & Tsaa 1992; Sung & Chen 2004; Zhang
et al. 1999), especially for the fractal property of topog-
phy in one and two-dimensions (DeJong 1995; Mark
& Aronson 1984; Outcalt et al. 1994; Polidori et al. 1991;
Sulebak 1999; Sung & Tsaan 1992; Sung & Chen 2004).
The first approach used in our study is rather general as
(1) local trend removal was not carried out, (2) the semi-
variogram analysis was omnidirectional and (3) a mean
value was used for the whole of Norway. These points are
certainly weaknesses. However, grain estimation is here
quantitative, which increases the reliability of the result,
even if the use of variable grains would certainly enhance
the quality of the classification.

Assessment and comparison with earlier qualitative clas-
sifications. In general, the classification is an objective
unsupervised classification. This means, the classifica-
tion result was not influenced by earlier manual classifi-
cations, such as those published by Rudberg (1960) and
Klemsdal & Sjulsen (1988). We are aware that the reduc-
tion into 10 classes is subjective, and another choice of
the merging principle would probably enhance topo-
graphic patterns different from those shown in this
paper. The merging of classes was only based on the
relation between mean elevation and elevation standard
deviation. The ER parameter was not included, which
means that the local hypsography only plays a limited
role in the final 10-class result. It is obvious that fur-
ther analyses must be carried out to assess the obtained
classes better and evaluate their relevance to geomor-
phological and geological processes.

In Rudberg’s (1960) map, the number of major classes is
less than in our study. The map is generalised, so direct
comparisons are difficult. Concerning major landform
patterns, the alpine relief in Rudberg’s map includes
small massifs with local glaciation, which in our case is more smoothed and included in the elevated mountain class. The high-plateaux areas correspond well, while lower plateaus (our classes 5 and 6) are part of a general “fell” or “pre-montan” class, together with our classes 7 and 8. Ruberg’s “Undulating hilly relief” is mostly covered by types 2 and 3, even if wider valleys in south-eastern Norway have also been related to these classes (“Pre-montan” in Rudberg’s map). The map by Klemsdal & Sjulsen (1988) is a regional overview, enhancing the major landform classes in Norway. They based their classification on genetic interpretations of landforms, while we made an automatic classification. The advantage is that with our method we can reveal conditions that may not have been noted before. The lowland areas with plains and hills correspond fairly well with our classification, as does the low-relief upland classes (“mountain plateaux”). Differences are related to Klemsdal & Sjulsen’s class “upland hills”, which are included in our class 5 and 6. A further difference is related to the mountain forms, where Klemsdal and Sjulsen (op. cit.) distinguish between “alpine”, “glacial” and “paleic” mountains based on the qualitative abundance of steep slopes in relation to smoother older surfaces. Our classification also uses this nomenclature, but relates to topographic amplitude rather than local inclination.

Summary and conclusions

This study represents a quantitative relief classification of Norway on a regional scale. The study’s main objective is to present a principle methodology, combined with some selected applications ranging from bedrock geomorphology via the problem of landform preservation during glaciations to permafrost-topography relations. From this first automatic classification attempt the following conclusions can be drawn:

• Automatic regional landform segmentation resulted in a division of Norway into ten major topographic types.
• At the regional scale the resulting classes could be related to the influence of broad-scale land-forming mechanisms such asplanation and uplift.
• Regions related to Quaternary glacial and periglacial processes, such as the magnitude of Pleistocene glacial erosion and the distribution of mountain permafrost, could be defined.
• The classification method, or variations of it, can be used for different purposes including the generation of new information.

As an example, landslide hazard zonation might be mentioned: topography is, together with geologic and climatic settings, a major constraint for landslide distribution. Therefore, a regional relief classification may play a role when identifying regional landslide hazard zones. Future foci of research should also include coupling of the obtained classes with geological lineaments and bedrock types. Furthermore, this study can serve as a basic constraint for further analyses aimed at highlighting the relation between land surface topography and offshore sedimentary stratigraphy.

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