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Classification of Patterned Ground Based on Morphometry and Site Characteristics: A Case Study from the High Sudetes, Central Europe

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ABSTRACT

About 750 examples of patterned ground forms at 25 sites in the High Sudetes mountains (Czech Republic) were classified using morphometric characteristics and environmental parameters. Simple parameters such as length, width and height of patterned ground were measured in the field, with additional variables of elevation, intensity of deflation and regolith grain size. The surface morphometry of patterned ground, comprising relict sorted polygons and sorted nets and active earth hummocks, was strongly influenced by site characteristics. Sorted net dimensions were affected by the intensity of deflation, which determined the micro-relief (positive correlation), and regolith coarseness, which negatively impacted the diameter of landforms. For sorted polygons, opposite relations concerning diameter and regolith coarseness were observed. The use of both morphometric and environmental variables within canonical linear discriminant analysis was successful in classifying almost 95 per cent of landforms. The advantage of combining the two types of predictors was demonstrated by the presence of both earth hummocks and sorted polygons at wind-swept sites, but with significantly different morphometric and regolith requirements. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: patterned ground; classification; High Sudetes; central Europe; morphology; discriminant analysis; spatial modelling

INTRODUCTION

Patterned ground is a large group of periglacial landforms which form variously shaped and sorted geometric structures. Such landforms are most frequently described as sorted and non-sorted polygons, circles, nets, stripes and steps (Washburn, 1979; van Everdingen, 1998). Alternative terminology used for certain types of non-sorted circles includes earth, peat or stone hummocks and frost boils (Van Vliet-Lanoë and Seppälä, 2002; Grab, 2005; Walker *et al*., 2008).

The development of patterned ground is driven by several interconnected processes linked to freeze/thaw cycles. Geometric surface structures are established through differential frost heaving, cracking (thermal or desiccation induced), clast heaving, and changes in the water table or hydrostatic pressure (Washburn, 1956; Ballantyne and Matthews, 1983; Van Vliet-Lanoë, 1991; Grab, 2005; Hallet and Prestrud, 1986; Peterson and Krantz, 2008). Regular microtopography, clast size and/or vegetation patterns are probably formed by self-organisation due to the complex non-linear interactions of underlying processes (Krantz, 1990; Kessler and Werner, 2003).

Freezing depth, depth of the water table and textural properties of the regolith are considered to be important determinants of both patterned ground distribution and morphology (Van Vliet-Lanoë, 1998; Kling, 1998; Francou *et al*., 2001; Kessler and Werner, 2003; Peterson and Krantz, 2008). These characteristics are strongly affected by bedrock type and topographic position of the site (Etzelmüller *et al*., 2001). Different bedrocks give rise to regoliths that vary in the basic characteristics necessary for patterned ground formation such as frost susceptibility, thermal conductivity, water permeability and salt content (Gold and Lachenbruch, 1973; Konishchev and Rogov, 1993; Williams and Smith, 1989). Furthermore, the local relief affects patterned ground formation through terrain-related patterns of snow depth, drainage and solifluction (Van Vliet-Lanoë and Seppälla, 2002; Hjort *et al*., 2007; Raynolds *et al*., 2008).

The effects of topographical variables on the occurrence of patterned ground can be successfully used as input data

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for predictive geomorphological mapping (e.g. Luoto and Seppälä, 2002). With increasing resolution of remote-sensing data it is also possible to classify the types of patterned ground automatically but this method requires their morphometric parameters. In this study, we focus on whether it is possible to determine typical morphometric and site characteristics for different types of patterned ground, and examine the influence of regolith properties and local topography on these parameters. While the effects of topography on the presence/absence of patterned ground have been already analysed for some study areas (Luoto and Hjort, 2006; Hjort *et al*., 2007; Etzelmüller *et al*., 2001), less attention has been paid to the direct influences of topography or bedrock geology on the morphology of patterned ground (e.g. Vitek, 1978; Kling, 1998). Our research was focused on both relict patterned ground (sorted polygons, sorted nets) and on recently active alpine forms of earth hummocks in the High Sudetes (central Europe, Czech Republic).

STUDY AREA

The study area is situated in the alpine belt of the High Sudetes Mountains, which are part of the Hercynian Mountains of central Europe, in the Czech Republic (Figure 1). The study area includes the central parts of the Krkonoše Mts (English toponym Giant Mts), Králický Sněžník Mts and Hrubý Jeseník Mts. These ranges comprise crystalline rocks and are characterised by planated surfaces at elevations of 1300–1550 m a.s.l.. Patterned ground is widespread (Sekyra and Sekyra, 1995; Křížek, 2007),

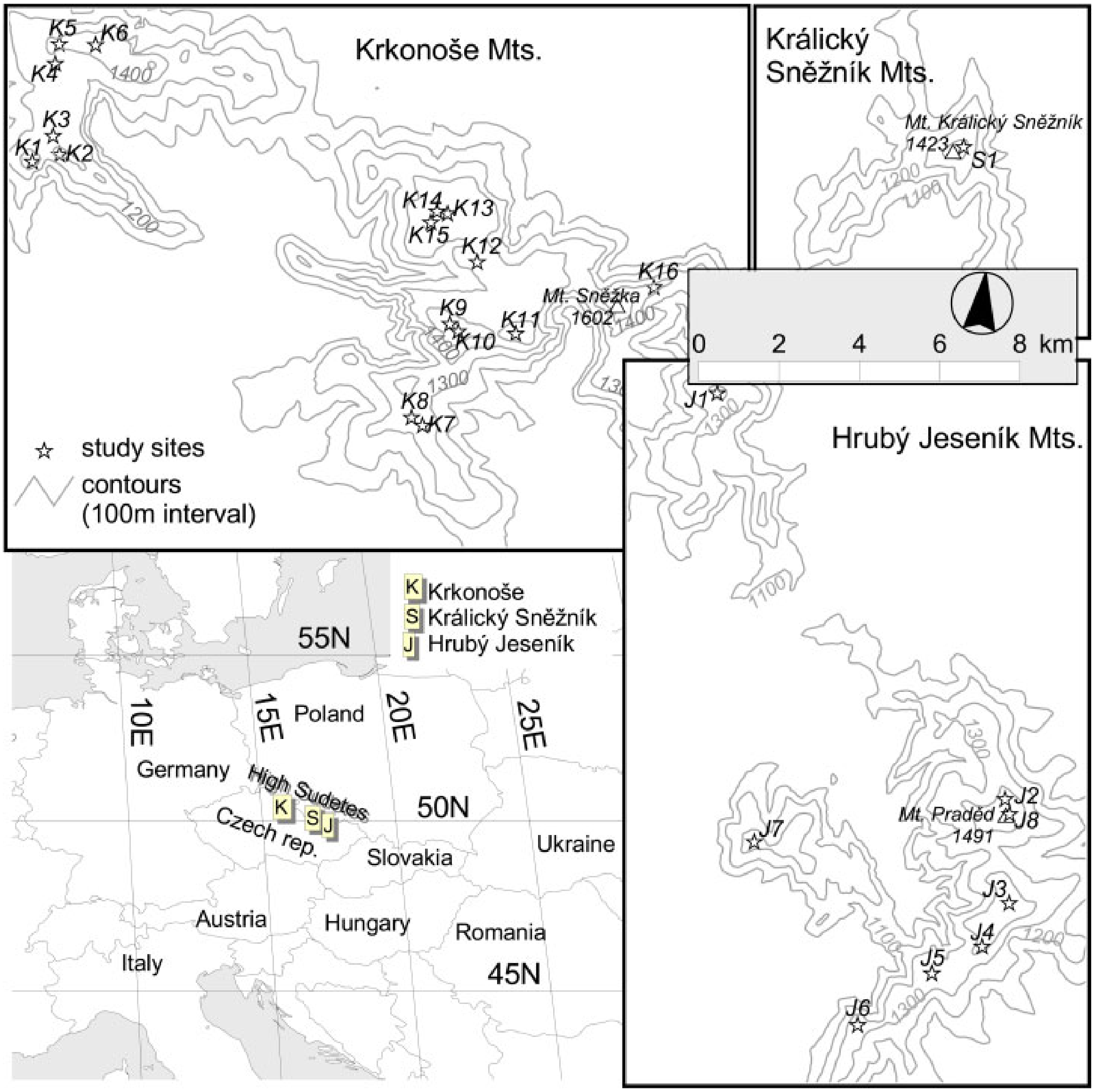

Figure 1 Geographical location of the study area. Site codes are used further in the text.

mainly consisting of inactive sorted polygons and nets formed at the end of the Last Glacial or during colder periods of the Holocene (Traczyk and Migoń, 2003; Kociánová, 2002). In addition, recently active sorted circles (Klementowski, 1998) and alpine forms of earth hummocks (Treml *et al*., 2005; Kociánová *et al*., 2005) can occasionally be found in deflation areas with low snow cover (Figure 2). Relict patterned ground forms have been partly or fully overgrown by graminoids, but in sorted forms, large clasts emerge from tussocks at the boundaries of individual cells.

The studied part of the Krkonoše Mts consists of two different geological units: fine to coarse-grained granites and a complex of metamorphic rocks represented by mica schist, phyllites, erlans and quartzites (Chaloupský *et al*., 1989). The Králický Sněžník Mts and Hrubý Jeseník Mts are built by gneiss, mica schist and phyllites, though quartzites are also present (Opletal, 1997). Soils in the summit areas of the High Sudetes consist of various types of spodosols and entisols (Němeček and Tomášek, 1983) according to the US Soil Taxonomy (Soil Survey Staff, 2003).

The mean annual temperature ranges from 0 to 3°C in the study area (Květoň, 2001), while annual precipitation usually totals 1300 to 1500 mm. Summit plateaus are characterised by strong westerly winds which transport snow to leeward slopes (Jeník, 1961). Deep seasonal freezing and intensive regelation are facilitated in these wind-swept areas (Harčarik, 2002), with seasonal frost reaching depths of 30 to 60 cm (V. Treml and M. Křížek, unpublished data, 2003–2008). Snow cover usually develops in mid-November and persists to the beginning of May, but it ablates earlier at wind-swept summit sites.

METHODS

Morphometry and Environmental Parameters

Twenty-five field sites (Figure 1) situated on flat surfaces or gentle slopes (up to 2°) within areas of previously mapped patterned ground (see Křížek *et al*., 2007) were selected for the current study. Simple morphometric parameters were measured for 30 randomly selected landforms located approximately in the centre of each of the patterned ground areas: length of the long axis, length of the short axis, height (difference between the lowermost and uppermost point of the landform) and height/width index (ratio between the height and the length of the short axis). The short rather than long axis was included in the index because the latter is more influenced by surface inclination and thus does not

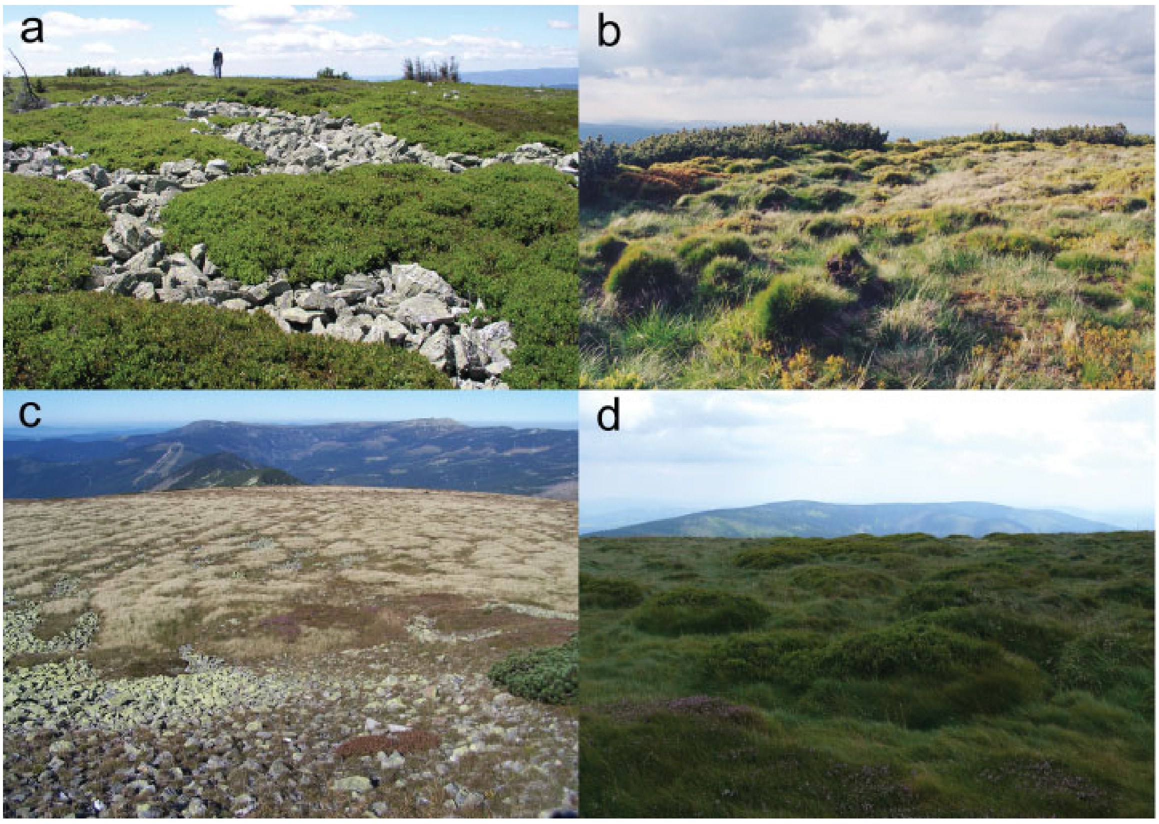

Figure 2 Individual types of patterned ground in the High Sudetes: (a) Sorted polygons, (b) earth hummocks, (c, d) sorted nets.

necessarily reflect other factors of patterned ground formation (e.g. Büdel, 1960).

In order to examine site characteristics which might influence patterned ground dimensions, variables such as elevation, regolith type and deflation were determined for each site. The values of elevation and deflation were derived from a digital elevation model with 20-m resolution created using the TopoGRID function (ESRI, 2005); input elevation contour intervals were 5 m.

Site elevation was chosen as an explanatory variable because it affects basic processes enabling patterned ground formation such as temperature and the snow cover duration and timing of snow melt.

Deflation was modelled as an index describing the uneven distribution of snow and therefore the variable potential for deep freezing of the ground. Snow distribution in the High Sudetes is strongly influenced by westerly winds which transport snow from windward western slopes to leeward east-facing slopes. Deflation index was defined as:

$$D = asp + curv + el\_dif\_inv$$

where asp is the orientation of the locality relative to the east (folded aspect with 0° towards the east); curv is the curvature of the surface (ESRI, 2005); and el_dif_inv is the inverse value of the altitudinal difference between the given locality (pixel) and the highest point on the maximum slope line which intersects the pixel (locality). All variables included in this deflation model were standardised (the same size of minimum and maximum). This deflation index reaches its highest value at sites with the lowest snow depths. The index was verified using snow measurement data conducted by Janásková (2007), who analysed snow depths across deflation gradients in the Krkonoše Mts during the winters 2004–05 and 2005–06. The correlation coefficient (Spearman rank R) between modelled values of the deflation index and snow measurements on random control points is -0.73 ($p < 0.05$, $n = 70$). Index values also correspond to patterns of snow melt analysed by Klimešová (1993) on the main ridge of the Hrubý Jeseník Mts.

According to Sekyra and Sekyra (1995), wind directions in the Late Glacial and Early Holocene were approximately the same as at present. In our analyses, the deflation index was therefore assumed to be applicable for sorted polygons, sorted nets and earth hummocks, even though these landforms may have originated in different periods.

Regolith properties were evaluated using median grain size for the regolith at the individual sites, by sieving the B/C horizons sampled from excavated profiles.

Statistical Analysis

Before performing statistical evaluations, values of both morphometric parameters and environmental variables were checked for normality using the Shapiro-Wilk test (Shapiro and Wilk, 1965). In order to meet the criterion of normality, values of the height/width index were root-square transformed and log transformation was applied to grain sizes.

Next, mean values and standard deviations of morphometric parameters were determined. Morphometric variables were analysed with respect to patterned ground type to test for significant differences (one-way ANOVA, F-test). Using mean morphometric parameters for individual sites, tree clustering (Rencher, 1995) was applied in order to assess similarities among the individual patterned ground areas. This resulted in a classification into morphologically similar groups of landforms, regardless of the patterned ground type.

Subsequently, discriminant analysis helped to interpret the position of groups with respect to the environmental variables (elevation, index of deflation and regolith properties). We used stepwise canonical linear discriminant analysis (Leps and Smilauer, 2003) in order to search for the most powerful morphometric and environmental parameters that would enable classification of patterned ground into individual types. The significance of individual parameters (i.e. discriminators) was checked using a Monte Carlo permutation test at a probability level of 0.01 (Ter Braak and Smilauer, 1998). The effect of single parameters was evaluated by means of discrimination loadings. Classification performance was cross-validated by dividing the analysed sample into two subsamples, the first used for estimation of classification function, the second for evaluation of classification performance (Meloun *et al.*, 2005; StatSOFT, 2004).

To contend with the highly uneven representation of objects in individual types of patterned ground, linear discrimination analysis was applied to randomly selected subsamples containing 90 sorted polygons, 90 earth hummocks and 136 sorted nets. This analysis was repeated four times with different subsets of sorted nets and polygons. Since discrimination analysis is vulnerable to multicollinearity in explanatory variables (Meloun *et al.*, 2005), a correlation matrix between all variables was calculated. Just one of the highly correlated variables was then included in the analysis.

The effect of environmental variables on patterned ground dimensions was tested for sorted nets, which were the most frequent type of patterned ground. We used stepwise redundancy analysis (Ter Braak and Smilauer, 1998) to evaluate the influence of elevation, deflation index and regolith grain size on morphometric parameters. The statistical significance of both variables included in the model and the first two canonical axes (explaining most variability in the data) was tested by Monte Carlo permutation tests. Finally, variance partitioning enabled an evaluation of the effect of single environmental variables on morphometric parameters (Leps and Smilauer, 2003).

Statistical analyses were performed using CANOCO (Ter Braak and Smilauer, 1998) and Statistica software (StatSOFT, 2004).

RESULTS

Patterned Ground Morphometry

The largest patterned ground landforms were sorted polygons (Table 1, Figure 3). Earth hummocks were the

Table 1 Mean values of morphometric parameters and environmental variables.

Patterned ground type	Length (cm)	Width (cm)	Height (cm)	Height/ width index	Elevation (m a.s.l.)	Index of deflation	Median grain size (mm)
Sorted polygons	374	304	17	0.06	1467	28.9	1.50
Sorted nets	281	224	27	0.12	1416	25.5	0.73
Earth hummocks	167	123	37	0.32	1429	27.9	0.31

smallest, as were sorted nets at the Králický Sněžník site (S1, Figure 3; Table 1). Earth hummocks were characterised by the most prominent hummocky topography. Less-raised centres were characteristic for sorted nets, with the exception of dome-shaped landforms at sites K10, K13, K14 and K15 ($h = 27 \pm 10$ cm). Sorted polygons were the flattest landforms. Earth hummocks had the highest height/ width index and sorted polygons the lowest (Table 1). There were significant differences in all morphometric parameters tested for individual patterned ground types (ANOVA, $p < 0.001$).

Using cluster analysis, six groups of patterned ground were defined on the basis of the sizes of the long and short axes, the centre height and the height/width index. In some cases, the groups established include two types of landforms (Figure 4). The first group (Cluster 1) consists of both sorted polygons and the largest sorted nets. These sites are situated on either quartzites (sorted polygons) or mica schists (sorted nets) and are characterised by a high intensity of deflation. Earth hummocks (J1, J2, J8) and one site with sorted nets (S1) form the next group (Cluster 2). This group includes localities on phyllites and gneiss which are characterised by

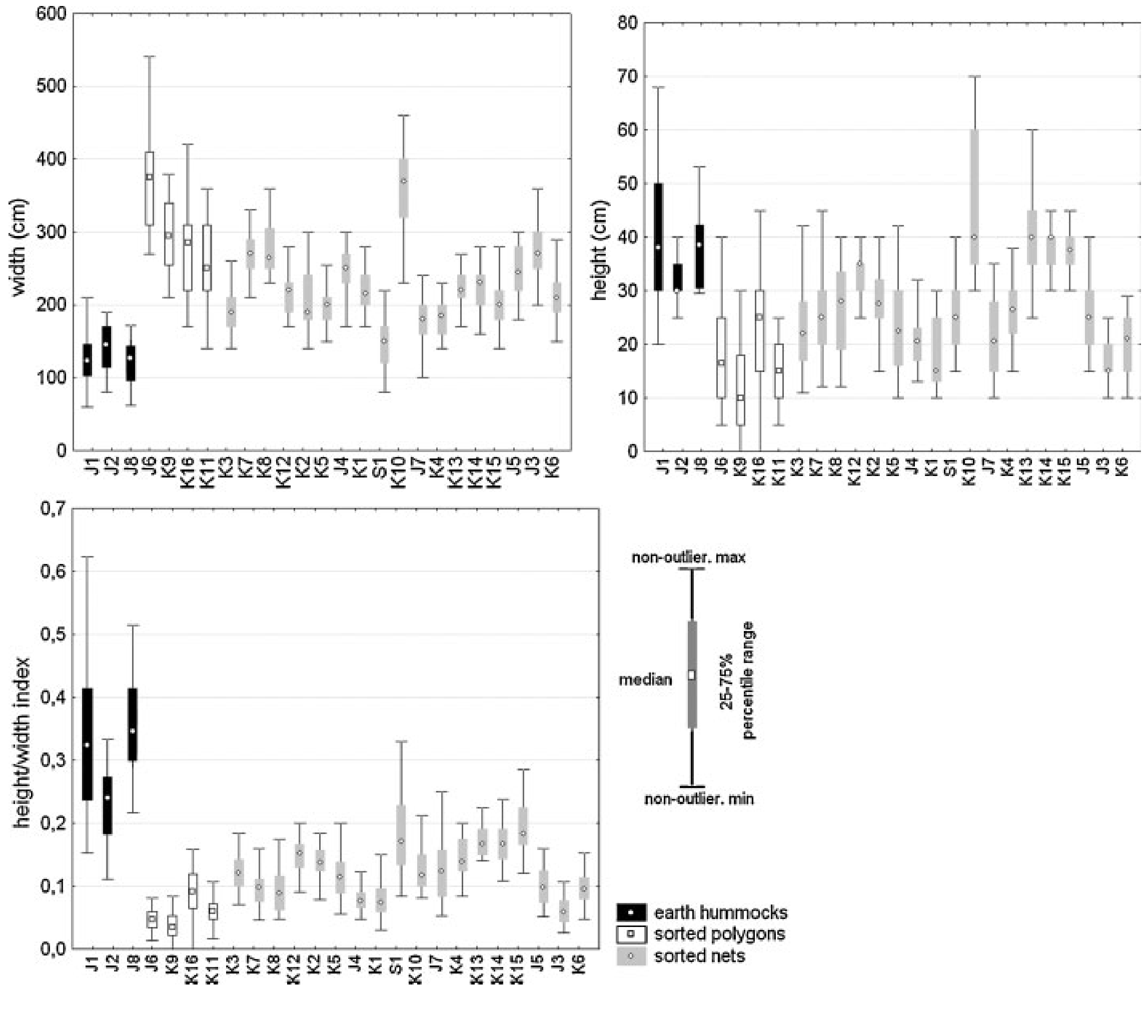

Figure 3 Morphometric parameters of patterned ground. Every site is represented by 30 landforms. For the location of study sites see Figure 1.

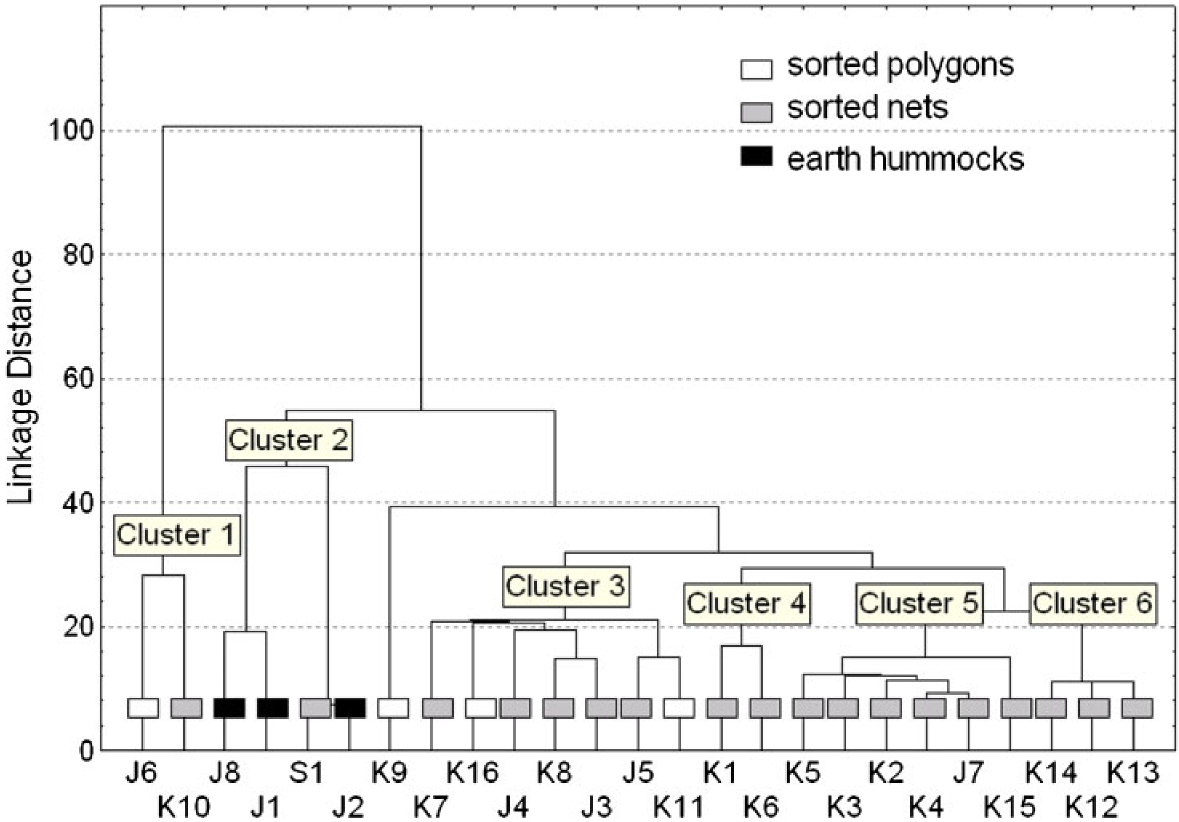

Figure 4 Tree cluster of sites based on patterned ground morphometry. For the location of individual sites see Figure 1.

moderate to high rates of deflation. Cluster 3 contains both sorted nets and sorted polygons situated on phyllites and mica schists. Low deflation is generally characteristic for sorted nets belonging to Cluster 3. The remaining groups include sorted nets developed on phyllites where the deflation index is high (Cluster 4), and sorted nets on granites and gneisses in areas with a low (Cluster 5) or predominantly high deflation (Cluster 6).

Classification of Patterned Ground based on Morphometry and Site Characteristics

In order to evaluate the relationships between individual variables and patterned ground types, we classified patterned ground using both site characteristics and morphometric variables.

The number of explanatory variables was reduced, so as to avoid strong correlations. Only width, height, index of deflation and grain size were entered into the statistical analyses. Classification proved to be very successful: 95 per cent of landforms were correctly assigned to their patterned ground type (Table 2). Sorted polygons and earth hummocks had no classification errors, while sorted nets partly overlapped with other patterned ground types (Table 2; Figure 5a). According to the classification loadings, grain size, deflation and width of landforms are the strongest discriminators (Figure 5b). Sorted polygons are characterised by large widths, low height and affinity to coarse-grained regolith on wind-swept sites. Earth hummocks also preferably occur on wind-swept sites but on fine-grained regoliths, and exhibit both low widths and high heights. Sorted nets occur mainly at sites with low deflation.

Morphometric parameters alone classified individual patterned ground types with a success rate of 78 per cent. Incorrect classifications occurred especially for sorted polygons versus sorted nets and sorted nets versus earth hummocks. There were no cases of earth hummocks incorrectly classified as sorted polygons or vice versa (Table 2). Similarly, the use of environmental variables to classify patterned ground into individual types was possible, reaching an 87 per cent success rate. Classification of earth hummocks and sorted polygons was always correct. Incorrect classifications again occurred in the case of sorted nets (Table 2).

Effects of Site Characteristics on Sorted Nets

Sorted nets are the most frequently encountered type of patterned ground across the High Sudetes, occurring in a wide range of environments. This makes it possible to analyse the direct effect of site characteristics on sorted net dimensions. Stepwise redundancy analysis showed that all

Table 2 The classification matrix of discriminant analysis. Only the worst performance results from all iterations are presented.

	Per cent correctly classified	Earth hummocks	Sorted polygons	Sorted nets
1. Morphometric variables (width, height)				
Earth hummocks	84.4	76	0	14
Sorted polygons	73.3	0	66	24
Sorted nets	77.9	13	17	106
Total	78.4	89	83	144
2. Environmental variables (grain size, index of deflation)				
Earth hummocks	100.0	90	0	0
Sorted polygons	100.0	0	90	0
Sorted nets	70.6	17	23	96
Total	87.3	107	113	96
3. All variables together (width, height, grain size, index of deflation)				
Earth hummocks	100.0	90	0	0
Sorted polygons	100.0	0	90	0
Sorted nets	89.7	8	6	122
Total	95.5	98	96	122

tested environmental variables (elevation, deflation, grain size) significantly add to the percentage variance of morphometric parameters explained, although elevation and deflation are correlated. The first and second canonical axes explain 20 per cent of the variance in morphometric parameters as directly related to environmental variables, and 72 per cent of this variance is covered by the first canonical axis. Some of this explained variance can be divided into variance governed by elevation and deflation (13.2%) and by grain size (6.3%). The rest of the variance cannot be ascribed to any individual factor.

The index of deflation as well as elevation evidently affects the centre height of sorted nets (positive correlation, Figure 6). The diameter (width) of sorted nets is negatively correlated with regolith grain size. The height/width index is positively related to both deflation and grain size. In other words, the largest sorted nets develop on fine-grained regoliths (such as mica schists) and high-elevation sites subject to strong deflation. Sorted nets with the greatest micro-relief tend to occur on wind-swept sites underlain by coarse-grained regolith (such as coarse-grained granites).

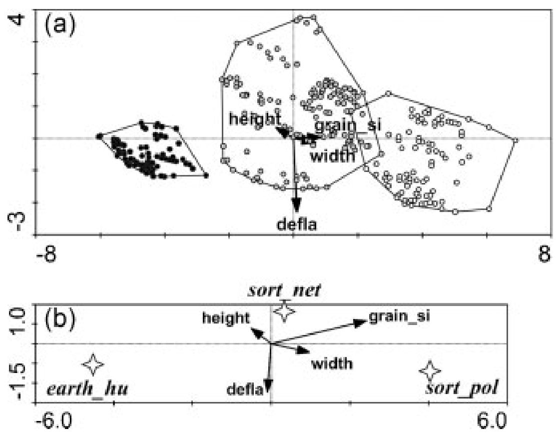

Figure 5 Ordination scheme of the canonical linear discriminant analysis. (a) Discriminators plotted against samples (i.e. individual landforms); (b) discrimination loadings of individual discriminators plotted against patterned ground types (i.e. species in CANOCO terminology).

DISCUSSION

It was expected that patterned ground type and dimensions would be associated with local topography and bedrock properties, since these characteristics affect processes relating to ground freezing (Washburn, 1979; Ballantyne, 1996; Matsuoka *et al*., 2003). The classification techniques applied do indeed show that individual patterned ground types are roughly characterised by similar morphometric parameters as well as particular site conditions.

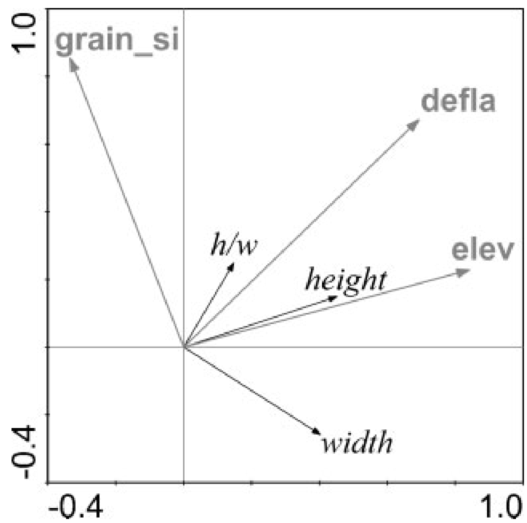

Figure 6 Ordination scheme of the redundant discriminant analysis. Morphometric parameters (thin) are plotted against environmental variables.

Earth hummocks have small horizontal sizes and a pronounced high dome-shaped centre. They occur in areas of fine-grained regolith (frost-susceptible silts to fine sands) as recognised elsewhere (e.g. Grab, 2005). In addition, earth hummocks are preferentially found on convex, deflated sites, which seems to be unusual in comparison with arctic or alpine tundra areas, where they occur predominantly in depressions or the lower parts of slopes (Van Vliet-Lanoë and Seppälä, 2002; Niessen *et al.*, 1992). The deflation at convex sites, however, enables deeper ground freezing, which appears to be essential for recently active earth hummocks in the snow-rich High Sudetes (Treml *et al.*, 2005).

Sorted polygons are the largest of the studied patterned ground types and are characterised by a low height/width index, which is in agreement with data from other areas (Kling, 1998; Raczkowska, 2003; Ballantyne, 2007). They occur most commonly at the most wind-swept sites on coarse sand to gravel regoliths. The latter are derived from resistant quartzites and form the most elevated parts of the relief, which in turn are exposed to wind and accumulate little or no snow, and which are therefore characterised by the greatest thermal fluctuations. Such site properties facilitate frost cracking and promote polygon formation (Washburn, 1956; Ballantyne and Matthews, 1983). In addition, hexagonal to quadrilateral landforms tend to form on coarse-grained, less compressible regolith under increased differential frost-heave action (Kessler and Werner, 2003).

The purely morphometric classification of patterned ground was not very successful in the case of sorted nets. These are characterised by intermediate relief and diameter, and typically occur at sites with low deflation. They are present in a wide variety of environments, which probably results in broader morphometric variability and more frequent morphological similarities with other types of patterned ground.

Regolith properties and deflation both statistically influenced the morphometric parameters of sorted nets. The largest sorted nets occurred on phyllites and mica schists where the regolith has a considerable fine grained and frost-susceptible fraction (silts to medium-sized sands). The smallest landforms were located on porphyric granites where the regolith is medium- to coarse-grained sand. This contradicts previous statements that generally larger sorted patterned ground develops on granites (see Sekyra, 1960; Traczyk and Migoń, 2003). On the other hand, the largest polygons were located on quartzite bedrock, while smaller ones occurred at sites underlain by fine-grained regoliths formed on phyllitic mica schists. In addition, some sites with relict sorted polygons longer than 10 m were excluded from the analyses because they were too few in number and poorly preserved (e.g. on quartzite and coarse granite regolith at the Větrná louka and Vysoké kolo sites; Křížek *et al.*, 2007).

A similar pattern of size differences occurs in northern Sweden where larger sorted polygons are present on granites rather than on mica-garnets, whereas the reverse size-geology relation was found for sorted circles (Kling, 1998). We presume that such opposite tendencies may be explained by different processes contributing to the two types of patterned ground (Ballantyne, 2007; Kessler and Werner, 2003; Peterson and Krantz, 2003). Variations in polygon diameter may also related to clast size (Goldthwait, 1976), since the largest polygons were observed at sites where coarse-grained regoliths contain predominantly large boulders. However, such a trend was not seen in the case of sorted nets in the study area.

The diameter of sorted forms of patterned ground is indicative of sorting depth (Gleason *et al.*, 1986; Hallet and Prestrud, 1986), which usually ranges between 0.3 to 1 m in the High Sudetes (Sekyra and Sekyra (1995); Sekyra, 2002; Křížek *et al.*, 2005). Corresponding diameter/sorting depth ratios roughly equal 3. According to this ratio, exceptionally high sorting depths would need to occur in the largest sorted polygons on coarse-grained regoliths (up to 2.5 m). We suggest that frost heave, lateral confinement of clasts and/or convection-related processes (Hallet and Prestrud, 1986) must have been supplemented by frost cracking in order to form such large landforms.

The relief of sorted nets was positively linked to deflation. The highest landforms prevailed at the most extreme sites (highest elevation, most wind-swept), where frost action is enhanced. The dimensions of sorted nets thus result from the effects of both bedrock properties and site position in the terrain. This can be seen in the classification of patterned ground into clusters according to morphometric similarity (Figure 4). For instance, Clusters 3–6 clearly differ in either geology (cluster 3) or deflation index (Clusters 4–6).

The variable morphometry of sorted nets may also be linked to the polycyclic/polygenetic development of some landforms. There may be successive environmental changes favouring the formation of different patterned ground types at a given site (Van Vliet-Lanoë, 1991, 1998), or intermediate or uneven characteristics of both the regolith and topography enabling the formation of features specific for various patterned ground types (e.g. Matthews *et al.*, 1998). At least two possible examples of transitional landforms were identified at our sites. Sorted nets with some straight margins of the dome-shaped central part (sites K10, J3), resembling those of sorted polygons, may be the product of regolith properties. These sites are underlain by phyllitic mica schists with a considerable proportion of quartzites, and are similar to locations where sorted polygons occur. The small sorted nets on the top of Králický Sněžník Mt (site S1) are similar to earth hummocks in both relief and diameter according to their morphology but their inner structure is sorted. The pronounced relief may be due to either the fine-grained, frost-susceptible regolith or a possible two-phase development: initially developing as sorted nets, and then when overgrown by vegetation, their fine-grained centres, now rich in organic matter, developing as alpine earth hummock forms (Van Vliet-Lanoë, 1998).

Our analysed sites are situated throughout almost all major areas of patterned ground within the High Sudetes. The relationships of studied landforms with environmental variables differ from those found in several studies from Scandinavia (e.g. Hjort and Luoto, 2006; Niessen *et al.*, 1992; Harris, 1982). We found deflation to be a much more important factor than elevation, even though these factors are correlated. The former, which determines the occurrence of patterned ground in convex parts of a terrain, was also observed as important by Matthews *et al.* (1998) on surfaces which were freshly exposed due to glacier retreat. The types of patterned ground analysed in our study area are usually located on either flat or convex parts of the terrain. In active periglacial areas, however, active patterned ground usually develops in concave locations with sufficient moisture (e.g. Van Vliet-Lanoë, 1998; Luoto and Hjort, 2004). This contradiction can be explained by the degradation of relict patterned ground by rillwash erosion or its burial by colluviation. Either or both could have occurred during the Holocene in concave parts of the High Sudetes, and so may explain the observed distribution of patterned ground.

CONCLUSIONS

Surface morphometric and site characteristics enabled the correct classification of almost 95 per cent of the studied patterned ground landforms in the High Sudetes. This methodology therefore appears to be useful for geomorphological mapping based on high-resolution remote-sensing data, digital terrain models and geological maps.

The results obtained show that sorted polygons are reliably characterised by large planar dimensions, low height/width indexes and wind-swept locations on coarse-grained regoliths. Earth hummocks are also found at wind-swept sites, but on frost-susceptible, fine-grained regoliths. They are characterised by a small horizontal size and a significantly raised hummock centre. Sorted nets are typically situated at less deflated sites and have intermediate morphometric values that relate to the intensity of deflation and regolith properties. The horizontally largest sorted nets are located on bedrocks that yield a fine-grained regolith. In contrast, where the proportion of coarse grains/clasts is greater, the sorted polygons are larger. This contradiction is likely caused by different types of processes prevailing in the formation of individual patterned ground types.

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