

# Classification of sorted patterned ground areas based on their environmental characteristics (Skagafjörður, Northern Iceland)

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## ABSTRACT

A multivariate statistical method (factor analysis of mixed data and hierarchical classification) was used to classify the environmental settings where sorted patterned ground develops in a wet oceanic periglacial area (Skagafjörður, Northern Iceland). A total of 750 periglacial features, distributed over 75 sites, were studied. Nine explanatory variables were assessed by fieldwork and using a digital elevation model, the variables were subdivided into three groups (latitude, topography and soil characteristics) and then integrated into a geographical information system. Furthermore, a correlation between the environmental variables and an intrinsic variable (patterned ground mesh diameter) was determined by a bivariate test. The results show that sorted patterned ground are spread over three homogenous areas, mostly differentiated by altitude, insolation, grain size characteristics and type of drift. In addition, feature diameters differ significantly from one group to another. Finally, it appears that patterned ground diameters are positively correlated with (i) the proportion of clay to medium silt content ( $r=0.35$ ), (ii) altitude ( $r=0.51$ ), and especially with (iii) clast length ( $r=0.97$ ). This strong relationship with clast length is observed in each homogenous patterned ground area at both site and feature scales.

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## 1. Introduction

Sorted patterned ground is geometric features, including circles, nets and polygons, which develop in polar, subpolar and high alpine environments by repeated thawing and freezing cycles (Washburn, 1979). These widespread forms have various dimensions, from miniature patterns (in which mesh diameter does not exceed 20 cm according to the classification of Wilson and Clark, 1991) to large forms (several metres). Sorted patterned ground is composed of a stone area and a raised fine centre, or cell. According to Washburn (1956), a common explanation for these phenomena involves two mechanisms: upfreezing of boulders and raising and expansion of cell soil due to frost heave. The distribution and morphometry of these features depend on (i) various variables that lead to sorting and (ii) frost susceptibility (microtopography, texture of regolith, water content, hydrostatic pressure, and thermal conductivity). Recently, Kessler and Werner (2003) suggested that patterned ground self-organises following a numerical model. They stated that the compression of a confined stone area by adjacent soil redistributes

boulders along the axis of the elongated stone area. According to these authors, polygons form when confinement of the stone area dominates, whereas circles and labyrinths form when sorting dominates.

Most patterned ground studies have focused on their mechanism of genesis (e.g. Washburn, 1956; Chambers, 1967; Ballantyne and Matthews, 1983; Jahn, 1985; Hallet et al., 1988; Krantz, 1990; Van Vliet-Lanoë, 1991; Kling, 1997, 1998; Kessler et al., 2001; Kessler and Werner, 2003; Matsuoka et al., 2003; Peterson and Krantz, 2008), as well as on the environmental conditions associated with their occurrence (e.g. Matthews et al., 1998; Etzelmüller et al., 2001; Luoto and Hjort, 2004, 2005, 2006; Hjort et al., 2007; Feuillet, 2011). These authors show, for instance, the importance of soil moisture (Matthews et al., 1998; Luoto and Hjort, 2004), till presence (Luoto and Hjort, 2005; Feuillet, 2011) and concave topography/wetness index (Luoto and Hjort, 2006) as prerequisite environmental parameters for both patterned ground presence and activity. However, less attention has been paid to the statistical classification of these prone environmental conditions at large scale (Raynolds et al., 2008; Hjort and Luoto, 2009; Treml et al., 2010). Is it possible to classify patterned ground areas into homogeneous groups, as a function of their environmental characteristics such as topography, soil and altitude? Which environmental variables mostly characterise these

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areas? Do intrinsic characteristics of features (dimension) vary significantly according to each homogeneous group? Such issues have never been addressed in depth for Icelandic patterned ground, in spite of their commonality. Previous works (Thoroddsen, 1913; Thorarinsson, 1951, 1953; Bout, 1953; Thorarinsson, 1964; Priesnitz and Schunke, 1983; Krüger, 1994; Dąbski, 2005) have focused on either patterned ground features taken individually, or a non-quantitative description of their distribution. Therefore, the first aim of this study was to describe and attempt to classify different types of environment where sorted patterned ground (active or inactive)

develops along a large fjord (more than 100 km from south to north) located in Northern Iceland. This analysis was mainly based on GIS (geographic information systems) and DEM (digital elevation model) tools, which enabled a set of environmental variables to be associated with each patterned ground site. After collecting the dataset, we selected a particular analysis (factor analysis of mixed data, FAMD) to classify the types of favourable patterned ground setting. FAMD was suitable for this task as it takes into account both qualitative and quantitative variables. Then, groups of environmental settings were defined using a hierarchical classification. Following this

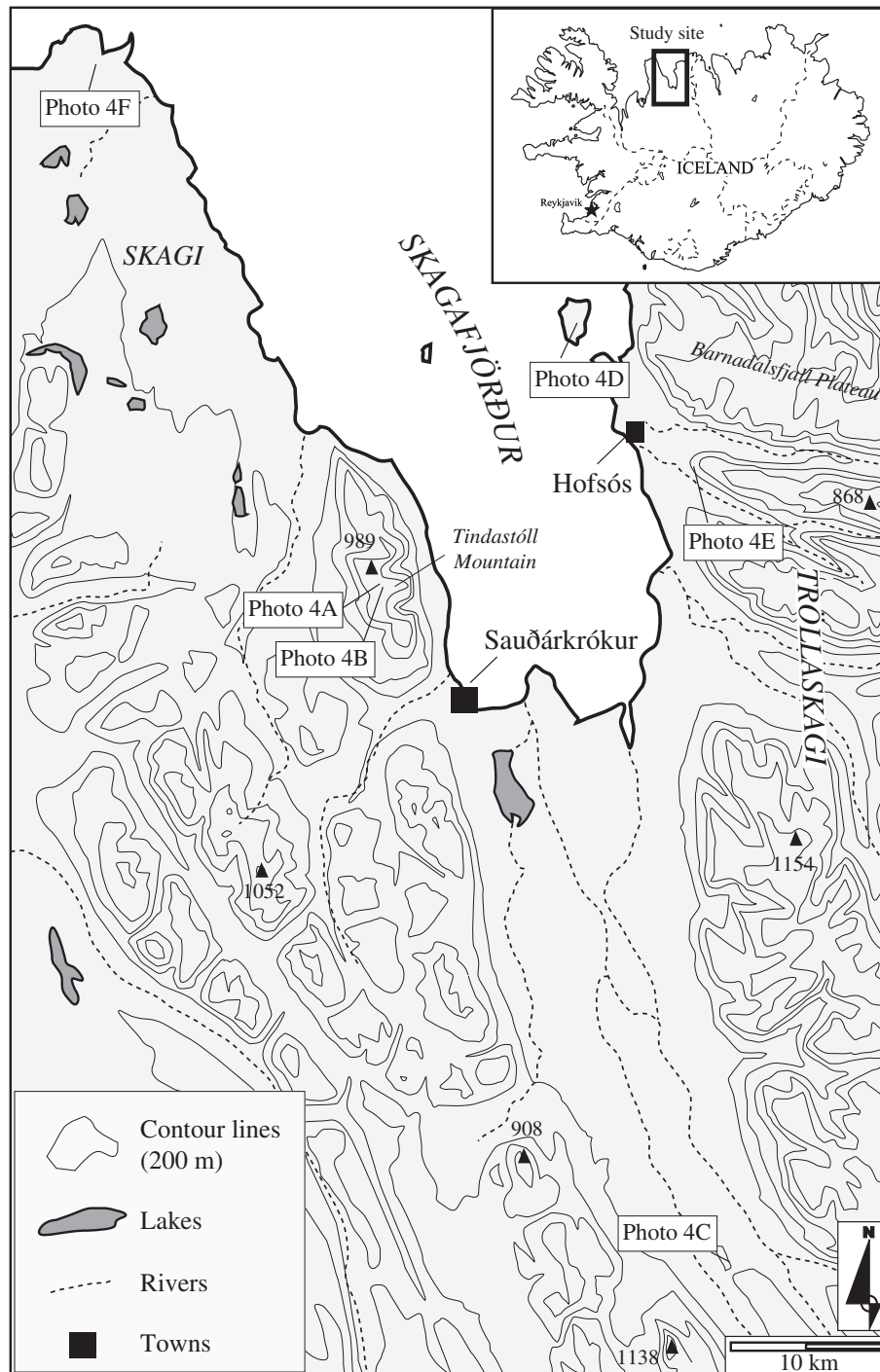


Fig. 1. Location map of the study area.

clustering, the second aim of the study was to determine whether the intrinsic characteristics of patterned ground (mesh diameter) varied significantly between each environmental setting (or cluster). According to the results obtained, the relationships between the patterned ground diameter and the explanatory variables are discussed.

## 2. Study area

The study area is located in Skagafjörður (between 65°20'N and 66°10'N, and between 20°02'W and 19°09'W), in central Northern Iceland (Fig. 1). The fjord has a submeridian direction and extends over 100 km from south to north. The regional maximal altitude is 1381 m a.s.l., but this study was carried out below 1000 m a.s.l. The bedrock is composed of Upper Tertiary basic and intermediate extrusive basalts. The climate is subpolar oceanic, with a mean annual air temperature of 3 °C at Bergstaðir station with recorded extremes of −24.5 °C and 25 °C, and a mean annual precipitation of 634 mm (Decaulne et al., 2007, Fig. 2). Freezing and thawing cycles are particularly numerous and can occur all year-round. At Mánárbakki (Tjörnes, 17 m a.s.l., 100 km east of the study site), 472°-days below 0 °C and 92 days with freeze–thaw cycles have been recorded (period 1965–1979, see Priesnitz and Schunke, 1983). Mountain permafrost is widespread above 800–900 m a.s.l. (Etzelmüller et al., 2007; Farbrót et al., 2007) and small glaciers remain (equilibrium line altitude above 1000 m a.s.l.). The deglaciation chronology of the fjord is not precisely known. According to Rundgren et al. (1997), the dating of several regional raised beaches in the NW part of Skagafjörður (Skagaheiði) from 12000 BP to 9600 BP suggests that the lower part of the fjord was totally deglaciated during the end of the Younger Dryas or Preboreal, although two glacier re-advances occurred between 12.7 and 10.9 ka (Geirsdóttir et al., 2009).

Patterned ground is widespread in Iceland (Bout, 1953; Priesnitz and Schunke, 1983) and was described at an early stage (Thoroddsen, 1913). Basalt rock is conducive to weathering, macro and micro gelivation, and produces large quantities of angular fragments and soils, a prerequisite and basic factor for frost features and processes. According to Priesnitz and Schunke (1983), the lower limit of the larger forms (>0.5 m) is about 650 m a.s.l. in Southern Iceland and near 350 m a.s.l. in Northern Iceland. Active small polygons and circles (<0.5 m) can be found at permafrost-free sea level in Western and Northern Iceland. The largest features observed reach 1–3 m in

diameter (Priesnitz and Schunke, 1983; Krüger, 1994), or even 10 m on the basalt plateaus (600–1000 m a.s.l.) according to Thorarinsson (1951). In Skagafjörður, sorted patterned ground is present at all altitude, but seems to develop preferentially in particular environmental contexts. We have defined three types of geomorphological setting where features are numerous (Fig. 3), based on field investigations. The first type (Fig. 3A) includes raised beaches, present between 10 and 90 m a.s.l. along the fjord, particularly in Skagi (the northwestern peninsula of the fjord, Fig. 1). Active and inactive features are common on these drifts. The second kind of setting includes an association of kame terraces at the foot slopes and fluvio-glacial terraces on the main valley floor (Fig. 3B). Both terraces support patterned ground. This type of context is common in the central and southern parts of the fjord, south of the town of Sauðárkrúkur (Fig. 1). Finally, landslide deposits characterise the last kind of slope (Fig. 3C), especially on the eastern part of the fjord (Fig. 1). These features are mainly rotational or translational mass movements and their surface areas vary from 0.1 to 3.1 km<sup>2</sup>; they were interpreted by Jónsson (1957) and Mercier et al. (2011) as the results of paraglacial adjustment in the early Holocene. Most of them support patterned ground on their benches, although the vegetation cover is sometimes too dense. In the three cases illustrated (Fig. 3), the diamict found on flat terrains (plateaus, benches or veneer between whale backs) is always rich in geometric periglacial features.

## 3. Methods

### 3.1. Sampling strategy

The aim of the sampling was to ensure a regular representation of sorted periglacial features across the fjord. However, two elements were restrictive. First, the extensive surface area and the variety of topographical contexts of the fjord do not provide a perfect and geometric sampling (e.g. one observation for every 500 m). Second, the patterned ground is totally absent in some locations. Indeed, most of the central part of the main valley is subject to cattle grazing or cultivation. In addition, several areas at the valley bottom have a dense vegetation cover and, while there are many thufurs here, features cannot develop. On the contrary, some locations include a high density of features (poorly vegetated benches and plateaus) thus morphostructural control is pronounced. Therefore, the only compromise in order to achieve a regular

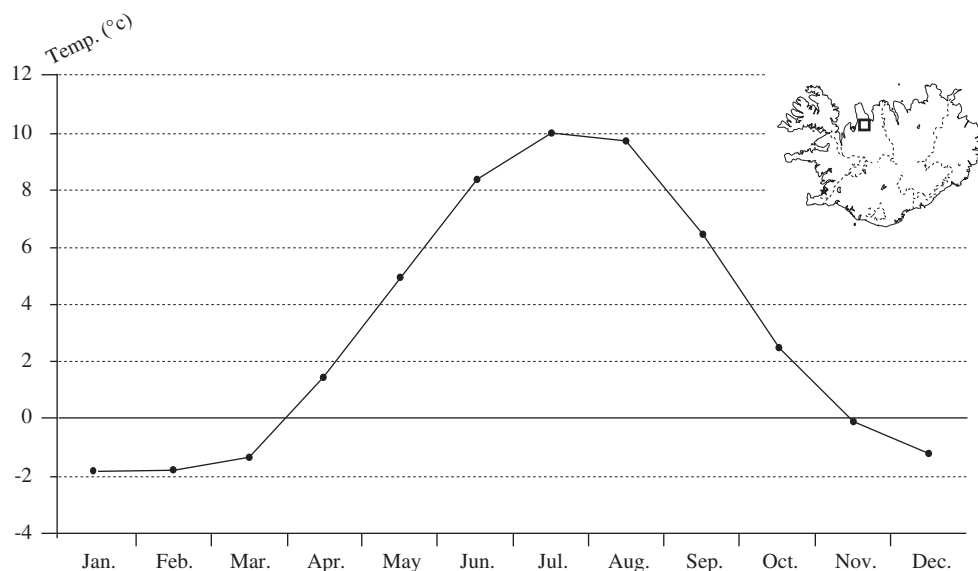
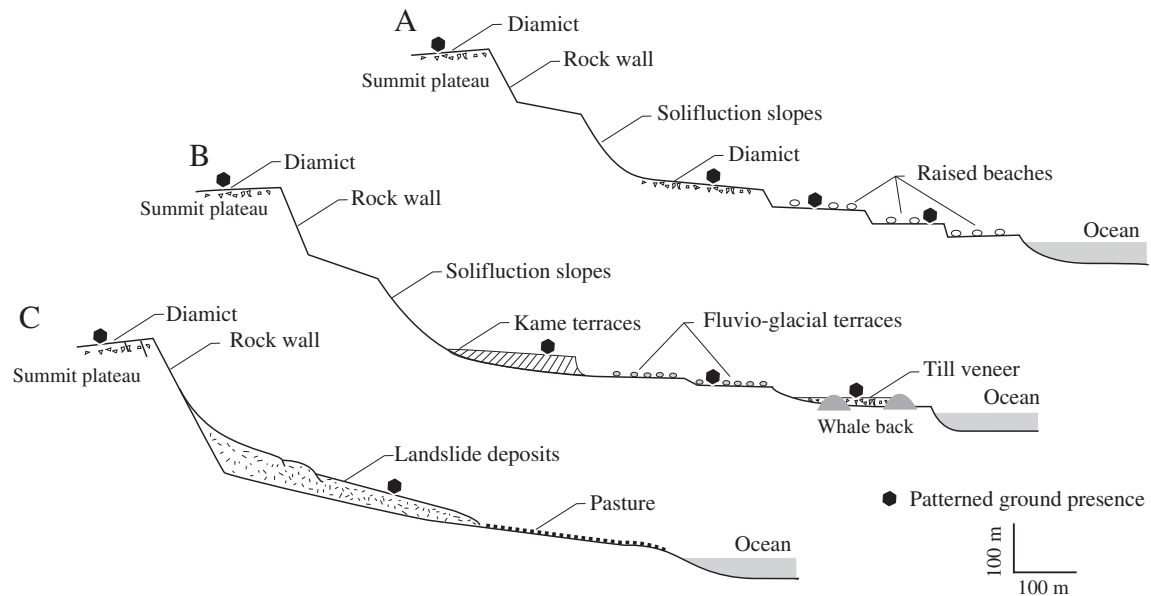


Fig. 2. Mean monthly air temperatures at Bergstaðir station (65°42'N, 19°36'W, 43 m a.s.l.) between 1978 and 2011 (MAAT = 3.1 °C).



**Fig. 3.** Illustration of the three types of geomorphological setting where sorted patterned ground is numerous. A. Slopes including raised beaches (e.g. on Skagi). B. Slopes with kame and fluvio-glacial terraces (e.g. at the central part of the fjord). C. Slopes with landslide deposits (eastern part of the fjord).

sampling at the fjord scale was to divide the study area into equal squares of  $10 \text{ km} \times 10 \text{ km}$ , and to consider that each square had to be represented by at least one patterned ground observation. Each of the 16 squares thus defined ( $160 \text{ km}^2$  in total) was explored from its mid-point (recorded from orthophoto to manual GPS) until finding features. All together, 75 sites of sorted patterned ground were observed in this way, from 15 to 955 m a.s.l. (Fig. 4). Observations per square varied from one to 14, with a mean of 4.8 sites per square. Under-represented squares were located in the central part of the main valley (pastureland), while over-represented squares occurred in the Tindastóll Mountain (west) and the Barnadalsfjall Plateau (east). All the sites were precisely located using a manual GPS procedure (Garmin G60, precision  $< 10 \text{ m}$ ) and then included in the GIS.

### 3.2. Sorted patterned ground sites

A patterned ground site is considered as a location where a continuous sorted feature network develops (Fig. 5). All sites were located on a flat surface ( $< 1^\circ$ ) to avoid the inclusion of the elongated features. Patterned ground sites mostly include sorted polygons (Fig. 5A–D), and sorted circles to a lesser extent (Fig. 5E,F). Beyond the geometrical aspect, Washburn (1956) precised that “in contrast to circles, sorted polygons [...] apparently never develop singly”, yet all the forms studied here are grouped. Since the aim of the study is not dealing with the genesis mechanisms, this distinguishing is here not essential. Finally, the features studied varied in size and were either active or inactive. This characterisation is mainly based on the density of vegetation covering the features and the presence of lichen on clasts. At each site, we selected a  $20 \text{ m} \times 20 \text{ m}$  square including the most regular form network. In these squares, only the ten largest features were taken into account to assess some of the variables described below.

### 3.3. Calculation of mesh diameter

The measured diameter of each mesh corresponds to the longest axis of the soil cell, excluding the stone gutters. This measurement was repeated for the ten largest meshes of each  $20 \text{ m} \times 20 \text{ m}$  square per patterned ground site, i.e. 750 measurements. We calculated the median values to characterise a site; these are more relevant than the mean values as they are less sensitive to outliers.

### 3.4. Explanatory variables

Three groups of explanatory (i.e. environmental) variables, expected to be potentially related to ground freezing and hence associated with sorted form distribution, were used: latitude, topography and soil.

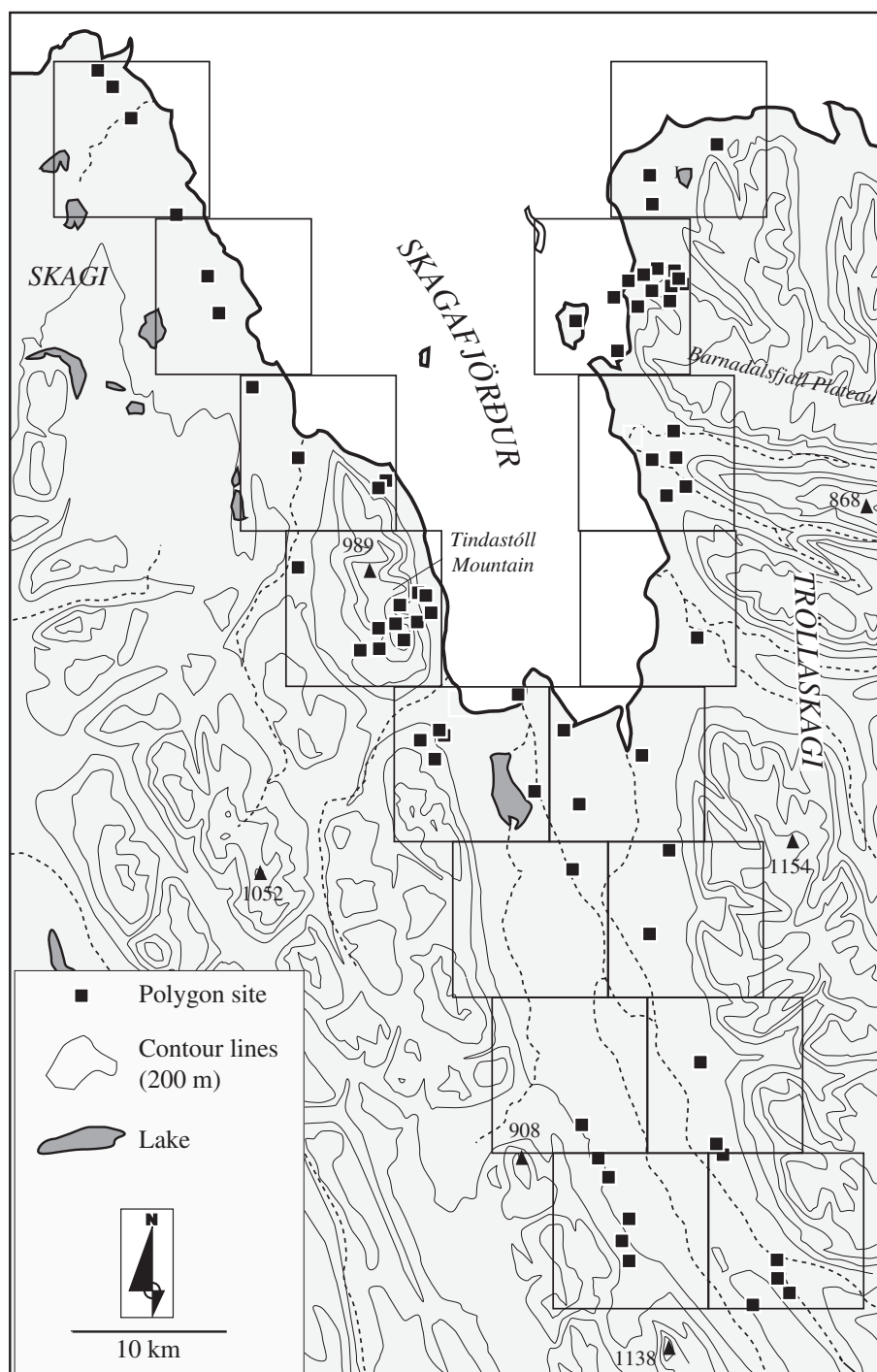
Latitude was determined with the manual GPS. Topographic variables were calculated using a 30-m resolution DEM and SAGA GIS software. This group includes five variables: (i) altitude a.s.l.; (ii) valley depth: this index equals the difference in altitude between the pixel and the upstream ridge, which is similar to a morphometric protection index; (iii) terrain ruggedness index: SAGA GIS calculates this as the sum of the change in altitude between a pixel and its eight neighbouring pixels (Riley et al., 1999); (iv) wetness index: choosing this index excludes the convergence index because of a too high correlation; and (v) potential incoming solar radiation (insolation): this variable is a quantitative equivalent of exposure and provides information on the topo-climatic conditions of the site.

Soil variables were assessed both in the field and in the laboratory. This group includes three variables: (i) type of drift, which is the only qualitative variable of the dataset; it contains six modalities (kame terraces, fluvio-glacial terraces, diamict, beaches, organic soil and landslide deposits); (ii) clast length: this variable concerns only clasts contained in the gutters (stone domain) of features; we measured the longest axis of the five largest stones in each form (3750 values); (iii) proportion of clay to medium silt in the cell ( $p_{20}$ ): considering that the matrix is homogeneous on each patterned ground site, and one sample, weighing about 300 g, was taken from the surface (depth  $< 5 \text{ cm}$ ) of each site. Each of the 75 samples was sifted to keep only particles with a diameter less than 1 mm. Samples were then analysed with a laser granulometer and grain-size cumulative curves were drawn using CULTER® LS software. The proportion of clay to medium silt (depending on the classification, here  $< 20 \mu\text{m}$ ) was determined from these curves. The grain-size threshold of  $20 \mu\text{m}$  was chosen following the conclusions of Beskow (1947) and Kaplar (1974), who stated that particles  $< 20 \mu\text{m}$  are the most susceptible to frost heave.

### 3.5. Statistical methods

To define the homogeneous patterned ground areas (individuals) as a function of the nine environmental variables, factor analyses and



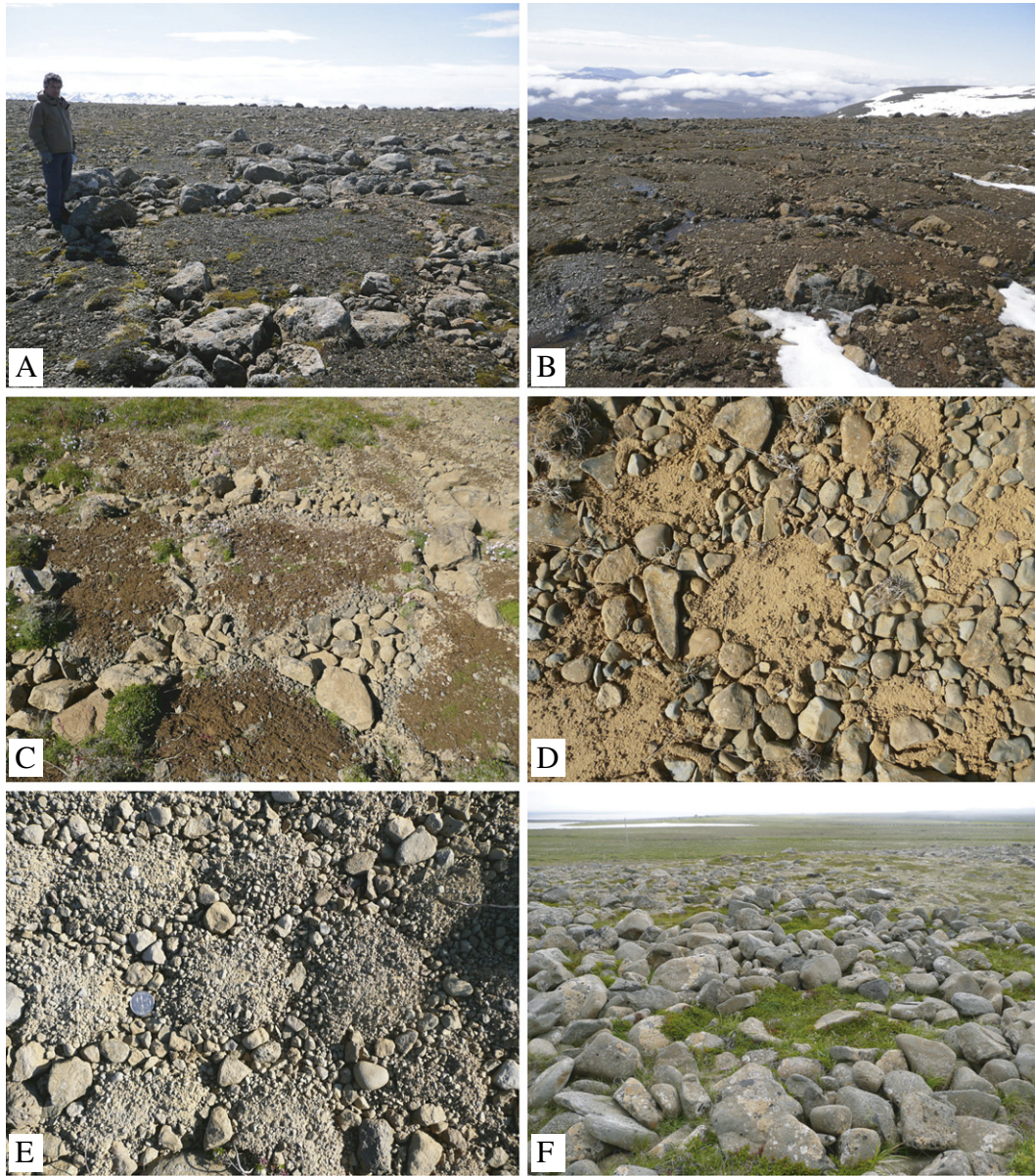


**Fig. 4.** Spatial sampling strategy and location of sorted patterned ground sites. The study area was divided into  $10\text{ km} \times 10\text{ km}$  squares. Each square is represented by almost one patterned ground site. Under-represented squares (central part) are located on rich pastureland areas, where sorted features are scattered.

complementary classification methods are particularly suitable. In fact, they enable all the variables to be summarised in a small number of synthetic variables named principal components. The factorial map, built using these principal components, can then be easily used to assess similarity between two individuals and thus to highlight a typology of individuals. The choice of a precise factor analysis depends on both the number and nature of the individuals and variables. In our case, one of the variables (type of drift) is qualitative, so this is not suitable for a principal component analysis (PCA). Based on the pioneering works of [Escofier \(1979\)](#) and [Saporta \(1990\)](#), [Pagès \(2004\)](#) has recently developed a factor analysis of

mixed data (FAMD) which takes into account the quantitative variables, like a normed PCA, and the qualitative variables, like a multiple correspondence analysis (MCA). According to [Pagès \(2004\)](#), the FAMD is preferable in two cases: when there are few qualitative variables compared to quantitative ones (it is not advisable to code too many quantitative variables) and when the number of individuals is low ( $<100$ ). Our case study meets both criteria, which justifies our choice of this method.

The classification of individuals (patterned ground sites) was then established using a hierarchical classification on principal components (HCPC), i.e. using individual coordinates on principal



**Fig. 5.** Photos of sorted polygon and circle sites. A and B. Largest active polygonal features observed (>3 m) on the Tindastóll Plateau (950 m a.s.l.). C. Large active polygons (1.5–2 m) on diamict (320 m a.s.l.). D. Small active polygons (<30 cm) on diamict (40 m a.s.l.). E. Miniature active circles (<15 cm) on landslide deposits (Hofsós, 190 m a.s.l.). F. Large inherited circles on the Skagi raised beaches (20 m a.s.l.).

components as a basis for classification. Defined clusters can be difficult to interpret instinctively. This is why we used a v-test to characterise them (Escofier and Pagès, 2008). This procedure (so-called *catdes* below), describing qualitative categories by both qualitative and quantitative variables, is based on the indicator  $\bar{x}_q - \bar{x}$ , where  $x$  is a variable and  $q$  is a cluster (or a class). In addition, the v-test puts into perspective the size ( $I_q$ ) of the cluster  $q$  and the standard deviation ( $s$ ) of the variable  $x$ . It is expressed as follows ( $I$  represents the individuals):

$$\frac{\bar{x}_q - \bar{x}}{s_{\bar{x}_q}} = \frac{(\bar{x}_q - \bar{x}) \sqrt{I_q}}{s \sqrt{I - I_q}} \quad (1)$$

Hence, the higher the absolute value of the v-test, the more the variable characterises the cluster.

Having defined the classes, we wondered whether the feature mesh diameter (median value per site) varied according to each homogeneous area. Thus, we analysed the variance to test for significant differences in feature diameter between each group (one-way ANOVA, F test statistic). Finally, statistical associations between mesh diameter and environmental variables were assessed with the Pearson's bivariate correlation test.  $H_0$  (absence of correlation) is rejected if the  $t$ -test statistic  $|t| > t_{\alpha}$  according to Student's  $t$ -distribution, knowing that  $t$  is given by:

$$t = \frac{\hat{r}}{\sqrt{\frac{1 - \hat{r}^2}{n - 2}}} \quad (2)$$

where  $\hat{r}$  is the correlation coefficient in a sample of size  $n$ . All statistical analyses, summarised in Table 1, were performed with R freeware (FactomineR package, see Husson et al., 2008).



**Table 1**  
Summary of statistical methods used in the study.

Step	Method	Description
1	FAMD (Factor analysis of mixed data)	This factor analysis is suitable when the dataset includes both qualitative and quantitative variables. It enables constructing a factorial map based on the principal components (synthetic variables), where each of the 75 patterned ground sites can be visually (on the graph) clustered according to their similarity.
2	HCPC (Hierarchical classification on principal components)	This method enables to classify automatically the 75 patterned ground sites into homogeneous groups (Ward criteria). It is often used in complement of factor analyses. The algorithm groups the most closed individuals (on the factorial map) in pairs, then aggregates the most closed groups in pairs, until reaching only two groups. Here three groups have been held.
3	Catdes (v-test)	This bivariate method is used to interpret the nature of the groups (clusters) defined with the HCPC. Each of the three clusters is described by the nine explanatory variables of the dataset using a v-test. See Eq. (1) for details.
4	One-way ANOVA (Analysis of variance)	One-way ANOVA is used to test significant differences between means of several samples (similar to a t-test when there are only two means to compare). Here, we have used it to test differences between means of feature mesh diameters in each of the three homogeneous patterned ground areas.

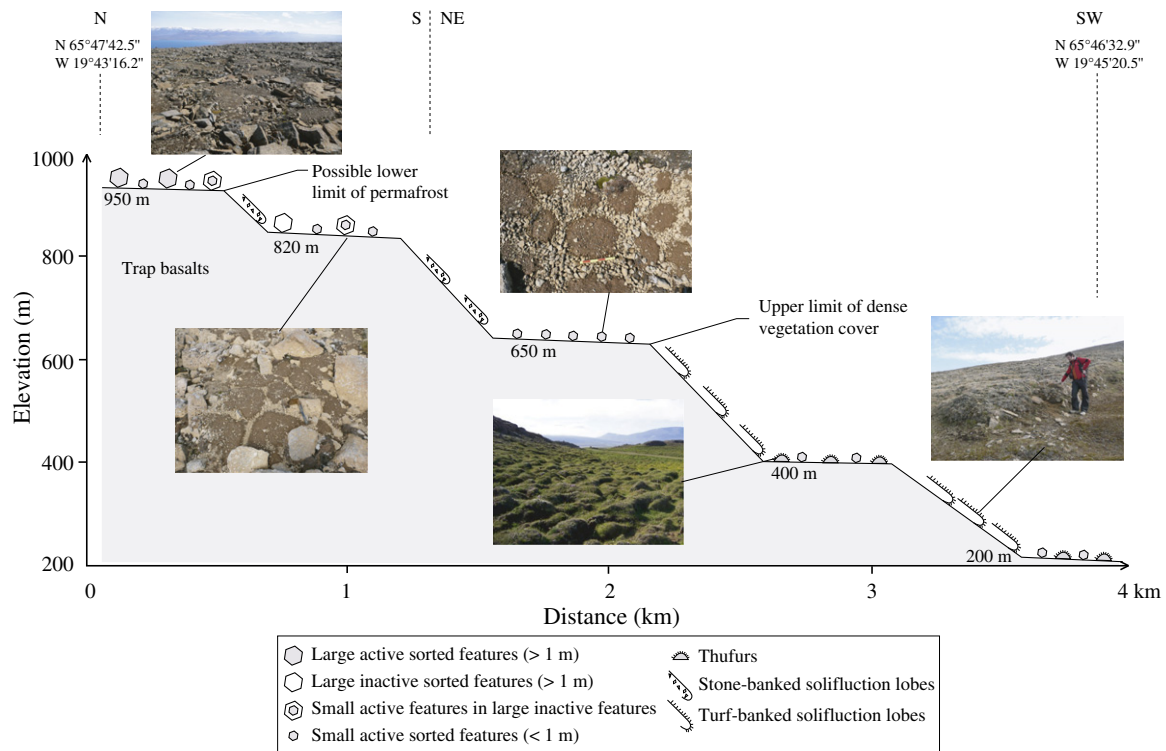
## 4. Results

### 4.1. Characteristics and altitudinal zonation of patterned ground

A total of 750 sorted patterned ground features were measured on 75 sites. Their dimensions (mesh diameters) vary from 4 to 350 cm. The median values per site vary from 7.5 to 235 cm. About 62% of the 75 sites are located on diamict, 15% on beaches and the rest are shared equally between fluvio-glacial and kame terraces, organic soil and landslide deposits. Patterned ground sites occur in an altitudinal belt of 940 m (from 15 to 955 m a.s.l.). Most of them (80%) are located under 500 m a.s.l. The altitudinal zonation of patterned ground is generally visible, for example in Tindastóll Mountain (Fig. 6). In this massif, large (> 1 m, up to 3.5 m) active and inactive sorted patterned ground is present only on the highest benches and plateau (> 800 m a.s.l.), while small (< 1 m) active forms develop at all altitudes. However, large active features (mesh diameter of 2.5 m) were observed under 300 m a.s.l. in the south of the fjord, and large inactive ones (1.7 m) near sea level at Skagi at the north-western study area.

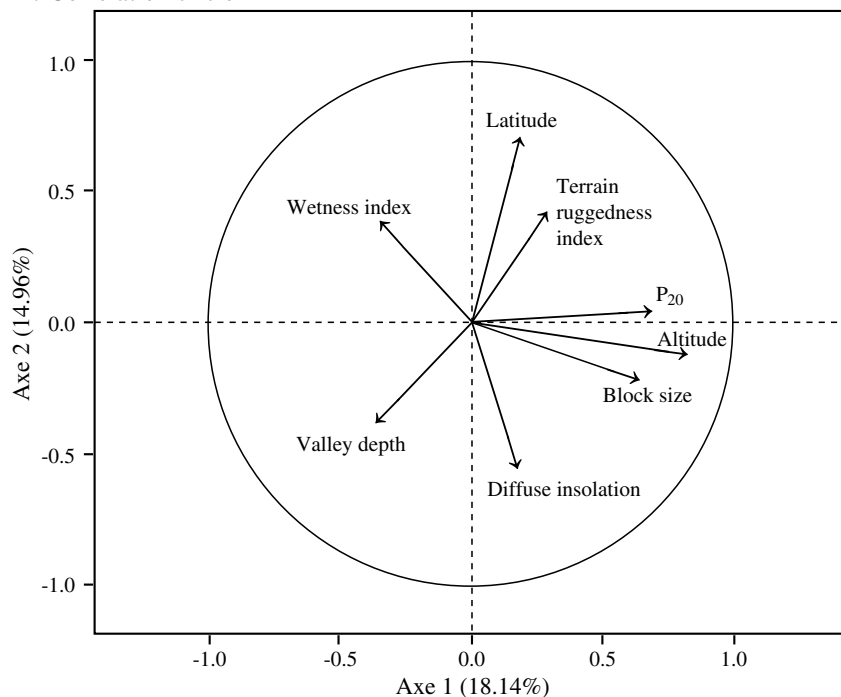
### 4.2. Factor analysis of mixed data and clustering

The first two principal components of the FAMD create an ordination accounting for 33.1% of the variance (Fig. 7A). The first component accounts for 18.1% of the variance, the second for 15.0% and the third for 10.1%. The first ten components explain more than 95% of the variance. The first component is strongly correlated with altitude and, to a lesser extent, with  $p_{20}$  and clast length, but is weakly correlated with types of drift (superficial formations) (Table 2). This component hence represents a complex variable of inter-correlated altitude and soil characteristics. The second component is strongly correlated with latitude and, to a lesser extent, with insolation and types of drift (kame terraces, as shown by the factor map, Fig. 7B).

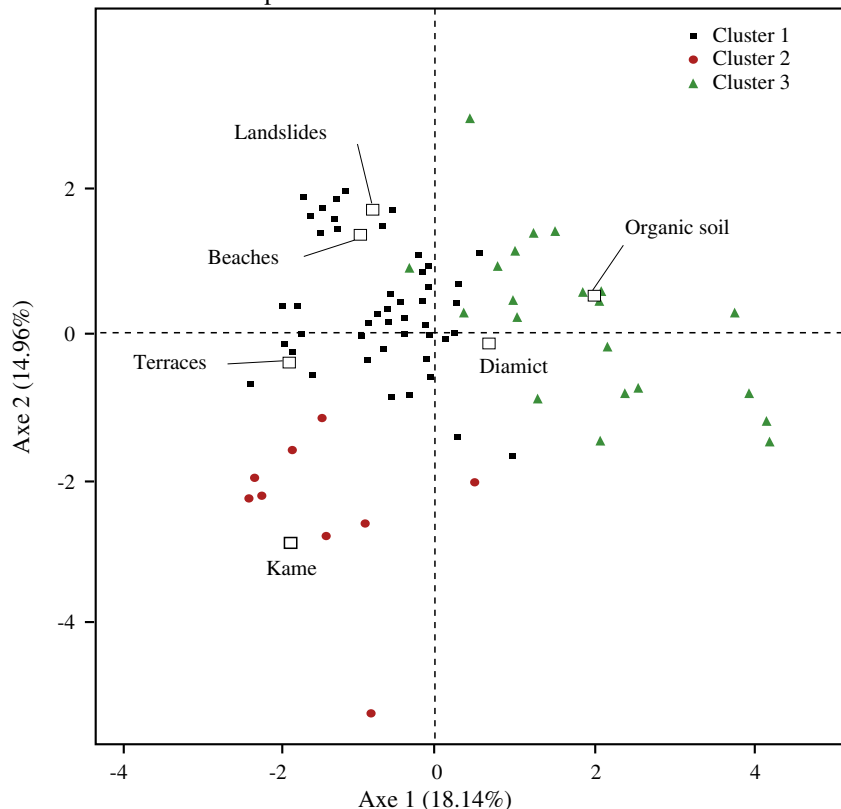


**Fig. 6.** Schematic altitudinal zonation of patterned ground in the Tindastóll Mountain (western part). Large active sorted polygons only occur on the plateau, while small active features develop at all altitude.

## A. Correlation circle



## B. Individual factor map



**Fig. 7.** Graphical results (panel A for the correlation circle and panel B for the individual factor map) of the factor analysis of mixed data. Individuals (sorted patterned ground areas) are subdivided into three homogeneous groups.

This component is mainly based on the north–south feature distribution.

HCPC on the ten first components distinguished three homogeneous sorted patterned ground areas (Fig. 7B). The *catdes* procedure led to the following interpretations (Table 3): the first cluster

( $n=46$ ) is characterised by low altitude, high wetness index, low insolation, small clast length and kame terrace absence. The second cluster ( $n=8$ ) is associated with high insolation, high valley depth, low latitude, low terrain ruggedness and kame terrace presence. Finally, the third cluster ( $n=21$ ) is characterised by inter-correlated



**Table 2**Correlations between the first two components of the FAMD and environmental variables ( $p < 0.05$ ).

First component					
Quantitative variables			Qualitative variables		
	R <sup>2</sup>	p-value		R <sup>2</sup>	p-value
Altitude	0.82	<0.01	Drift	0.41	<0.01
$P_{20}$	0.69	<0.01			
Clast length	0.63	<0.01			
Terrain ruggedness	0.29	<0.01			
Wetness index	−0.36	<0.01			
Valley depth	−0.37	<0.01			
Second component					
Latitude	0.71	<0.01	Drift	0.58	<0.01
Terrain ruggedness	0.44	<0.01			
Wetness index	0.39	<0.01			
Valley depth	−0.38	<0.01			
Insolation	−0.56	<0.01			

high altitude, low valley depth, low wetness index, large clast length, high terrain ruggedness, high  $p_{20}$ , diamict presence and beach absence. Thus, the two main patterned ground areas (1 and 3) are distinguished overall by their altitudes and hence correlated variables (wetness index, insolation and valley depth). The second area is not characterised by altitude, but by its association with kame terraces, in the southern part of the fjord.

#### 4.3. Feature diameter according to cluster and environmental variables

The mean form diameter is 27.1 cm in cluster 1, 32.9 cm in the second one and 85.0 cm in the third one. According to ANOVA tests, these deviations are significantly different ( $p < 0.001$ ). Thus, we can state that the first patterned ground area, characterised by a low altitude, corresponds to small features, while the third area (high altitude) includes the largest features. Pearson's correlation test (Table 4) confirms this positive relationship between altitude and form diameter ( $r = 0.51$ ). Yet, these tests highlight overall a very strong positive correlation between form diameter and clast length ( $r = 0.97$ ). This correlation is strong in all three patterned ground areas ( $r$  always above 0.93). To a lesser extent, the proportion of clay to medium silt ( $p_{20}$ ) is also positively correlated with form diameter ( $r = 0.35$ ).

Finally, we investigated whether this strong relationship between clast length and feature diameter was at all sustainable at the feature

**Table 3**Correlations between the three clusters (patterned ground areas) and environmental variables ( $p < 0.05$ ).

Quantitative variables			Qualitative variables		
	v-test	p-value		v-test	p-value
Cluster 1					
Wetness index	2.51	<0.01	Kame terraces	−2.46	<0.05
Clast length	−3.33	<0.01			
Insolation	−3.97	<0.01			
Altitude	−6.00	<0.01			
Cluster 2					
Insolation	5.36	<0.01	Kame terraces	4.51	<0.01
Valley depth	3.29	<0.01			
Latitude	−2.00	<0.01			
Terrain ruggedness	−2.09	<0.01			
Cluster 3					
Altitude	7.26	<0.01	Diamict	3.64	<0.01
Clast length	3.82	<0.01	Beaches	−2.06	<0.05
Terrain ruggedness	3.40	<0.01			
$P_{20}$	2.92	<0.01			
Wetness index	−2.04	<0.01			
Valley depth	−2.55	<0.01			

**Table 4**Correlations between feature diameter and environmental variables ( $p < 0.05$ ).

	Correlation	p-value
Clast length	0.97	<0.01
Altitude	0.51	<0.01
$P_{20}$	0.35	<0.01
Wetness index	−0.29	<0.05
Valley depth	−0.24	<0.05

scale (i.e. for the 750 forms, to be distinguished from the site scale) and in each patterned ground area. The results revealed strong correlations for all forms ( $r = 0.91$ ,  $p < 0.001$ ) and in each of the three areas (0.86, 0.87 and 0.90 respectively,  $p < 0.001$ ). We conclude that feature diameter is linked to clast length, whatever scale (site or feature) or environmental context is considered.

## 5. Discussion

### 5.1. Fundamental role of altitude

These results show that altitude plays a fundamental role in two ways: first, in differentiating the homogeneous patterned ground areas and hence being more discriminant than the other environmental variables; second, in being linked to feature diameter. Actually, altitude is indicative here of climate cooling and, in particular, of frost severity. Yet, the diameter of the sorted patterned ground is recognised as being indicative of freezing depth (Hallet and Prestrud, 1986) and freezing depth is correlated to both frost severity and snow cover. It is therefore consistent to observe that cluster 3 includes most of the largest features studied, located on the summit plateaus. Furthermore, such plateaus, submitted to strong deflation, are less snow-covered than concave or leeward surfaces. This relative lack of snow explains a greater freezing depth, as well as more thermal fluctuations promoting frost cracking and polygon formation (Washburn, 1956; Wilson and Sellier, 1995; Treml et al., 2010).

However, both active and inactive features were studied here. We could expect that large relict polygons and circles, dating probably from colder Holocene climates, would occur at low altitude (which is also the case, but just for a small number of them, situated on raised beaches). Two possible explanations can be highlighted: (i) most Holocene inherited features are invisible because of their degradation by washing erosion or colluviation, so only a few remain visible, like on raised beaches; (ii) the coldest Icelandic Holocene climates were not severe enough to cause widespread development of large sorted forms at low altitude (July air temperatures were only 3–4 °C below nowadays in Northern Iceland at 10.2 ka cal. yr BP and increased rapidly afterwards, according to Caseldine et al., 2006), except on exceptionally favourable sites. This is the case of raised beaches. For instance, Dutkiewicz (1967) showed in Spitsbergen that polygons could have evolved during the entire Holocene on raised beaches. This hypothesis is possible because the fjord has passed rapidly from a glacial environment to a wet oceanic periglacial context, without very cold temperatures compared to more continental areas.

### 5.2. Are large features indicative of permafrost occurrence?

The largest active polygons (3.5 m) observed on the Tindastóll Plateau (950 m a.s.l.) could be associated with permafrost occurrence, even if patchy. During June 2011, the subsurface was frozen below a depth of 5 cm. Thus, the soil surface was quite thixotropic and characteristic of a mollisol. In any case, this altitude of 950 m corresponds to the values given by Etzelmüller et al. (2007) and Farbrøt et al. (2007) as sufficient for discontinuous permafrost occurrence but is probably close to its lower limit because of the latitude of the plateau (high oceanic influences compared to more continental Icelandic

Highlands). Except on this summit plateau, no doubt remains that all the observations were carried out in permafrost-free contexts. This issue dealing with regional permafrost limits presents a high scientific interest for further studies. Indeed, thermal measurements would provide evidence (i) to test the hypothesis of permafrost occurrence and (ii) to associate it with patterned ground development.

### 5.3. Feature diameter/clast length relationship

The strong correlation highlighted between feature diameter and clast length is in agreement with other studies in different areas (Barbaroux, 1968; King and Buckley, 1969; Goldthwait, 1976; Tremblé et al., 2010). According to Goldthwait (1976), the larger the stones in the area, the greater the spacing (the ratio lies between 1:5 and 1:10). In our case, the ratio between the 750 meshes measured and the median value of the five largest clasts for each form varies from 1.2 to 9.9. Clearly, it was expected that small sorted forms would be absent from the large boulder regolith. However, this strong correlation, whatever the feature size and environmental conditions of the area in which the feature develops, is of interest. This result must now be confirmed in other types of environment which have not been studied here, like for instance in proglacial areas.

### 5.4. Methodological considerations

We have shown to what extent the factor analysis of mixed data was particularly suitable for our issues and our dataset. However, another possibility could be used in the multivariate analysis, by adding the type of drift (the qualitative variable) as a supplementary variable in a normed principal component analysis. This implies that the qualitative variable does not contribute to the construction of the PCA axes. We tested this particular PCA and the results revealed no great changes compared to the FAMD. The first component is still linked to altitude, while the second component is more associated with terrain ruggedness and insolation than latitude. The HCPC also revealed three homogenous groups, which differ for only a few individuals compared to the FAMD. Clusters 1 and 3 are again mostly differentiated by altitude, while the second one is only strongly associated with high insolation.

## 6. Conclusions

This study of Icelandic sorted patterned ground highlighted much information about the environmental conditions (latitude, topography and soil) of their development and about the relationships between their dimension and nine environmental variables.

Three types of patterned ground area were identified based on a hierarchical classification of principal components. The first group is characterised by low altitude, low insolation and high wetness index. The second group is mainly associated with high insolation and inter-correlated high valley depth/presence of kame terraces. The last group includes areas where altitude, terrain ruggedness, proportion of clay to medium silt, and clast length are high, as well as presence of diamict. Thus, altitude is of primary importance as a discriminator of the two main areas (1 and 3) and, to a lesser extent, topography and grain-size characteristics.

We have also shown that feature diameter varies significantly by group (ANOVA). The first two groups, located at lower altitude than the third one, include the smallest features, while the third area includes the largest ones. Bivariate correlation tests confirm a significant positive relationship between altitude and feature diameter ( $r=0.51$ ). This relation highlights climate cooling with altitude, which favours an increase in sorting depth. The topographical conditions of summit plateaus reinforce this idea since they are subject to strong deflation and therefore probably do not have a significant snow cover.

The variable most correlated with feature diameter appears to be clast length ( $r=0.97$ ). We highlighted that this positive correlation is confirmed whatever the patterned ground area and scale considered (site and feature scales).

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