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Statistical Analyses of Active Patterned Ground Occurrence in the Taillon Massif (Pyrénées, France/Spain)

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ABSTRACT

Statistical approaches were used to describe and explain the presence or absence of active patterned ground features in a mid-latitude alpine area. The relative rarity of these landforms can be problematic for such analyses but this issue was resolved by a novel spatial sampling strategy that considers only terrain within circles drawn around each observed patterned ground feature, which is then subdivided into a grid. This strategy focuses only on fields with potential patterned ground occurrence and can be used for all statistical studies concerning the occurrence of scattered features over extensive areas. These data were examined using factor analyses (multiple correspondence analysis and hierarchical ascendant classification) blended with a complementary bivariate method to associate patterned ground occurrence with eight environmental variables (elevation, exposure, height-distance ratio, drift, glacier influence, vegetation cover, slopewash and lithology). The absence of active patterned ground is associated with low elevation, glacier absence, no slopewash, a low height-distance ratio and talus fans. Zones where active patterned ground features are present are divided into three homogeneous subzones and are mostly associated with glacier influence, a large height-distance ratio and an absence of vegetation. Their location is controlled by the presence of till from different glacial sequences so that the former and current presence of glaciers favours the development of patterned ground features at the landscape scale. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: periglacial geomorphology; patterned ground; factor analyses; bivariate analyses; mountain

INTRODUCTION

Patterned ground features include circles, polygons, nets and stripes, which develop in surficial materials subjected to freezing (Washburn, 1979). Each landform can be sorted or non-sorted. Patterned ground is very common in periglacial environments, but has also been attributed to some non-frost-related processes (Van Vliet-Lanoë, 1991). Studies of the origin of patterned ground features relate them to deformation of the ground caused by differential frost heave and thaw consolidation (Matsuoka *et al.*, 2003; Bertran *et al.*, 2010). Patterned ground development in the altitudinal periglacial environment is restricted by a lower limit below which freezing is rare, and by an extremely high upper limit above which thawing can no longer occur or snow and ice cover is perennial. The distribution of these landforms reflects particular morphoclimatic thresholds because processes generate the landforms *in situ*. Patterned ground is therefore a useful marker of periglacial conditions.

Most studies of patterned ground features in Western Europe have been undertaken in the Alps. There are a limited number of surveys in the Pyrénées from both the French side (Cailleux and Hupé, 1947; Philberth, 1961; Höllermann, 1967; Soutadé, 1980; Bertran *et al.*, 2010) and the Spanish side (Boyé, 1952; Garcia Ruiz *et al.*, 1990; Serrano *et al.*, 2000, 2001; Garcia-Ruiz and Marti Bono, 2001). Höllermann (1967) defined the lower limit of patterned ground as close to 2600 m a.s.l. and an upper limit at the elevation of the highest Pyrenean peaks (3300 m a.s.l. close to Monte Perdido), but Feuillet and Sellier (2008) observed active sorted patterned ground features at around 2300 m a.s.l. in the French central Pyrenees.

Statistical approaches can be used to study environmental factors controlling the distribution of natural phenomena. In recent years, a variety of quantitative methods, including generalised linear models and multivariate analyses, has been used to describe or predict the location of periglacial landforms (e.g. Matthews *et al.*, 1998; Luoto

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and Seppälä, 2002; Luoto and Hjort, 2004, 2005; Ridefelt and Boelhouwers, 2006; Hjort *et al.*, 2007; Castillo-Rodríguez *et al.*, 2007; Marmion *et al.*, 2008; Hjort and Luoto, 2008; Hjort and Marmion, 2009; Ridefelt *et al.*, 2010). The conclusions reached in these studies depend in part on the methods and spatial resolution. For instance, Matthews *et al.* (1998) concluded that moisture availability is the most important physical environmental control on patterned ground distribution at the local scale. Luoto and Hjort (2004) noted an increase in the activity of patterned ground forms with increasing soil moisture and the proportion of concave topography at the landscape scale. For Luoto and Hjort (2005), till presence and soil moisture were correlated with active sorted patterned ground occurrence. Hjort *et al.* (2007) and Hjort and Marmion (2009) associated sorted solifluction features with elevation and slope angle. Finally, Ridefelt *et al.* (2010) added the vegetation index, annual incoming potential radiation and wetness index to explain the occurrence of turf-banked solifluction lobes in northern Sweden.

Almost all of the studies on patterned ground distribution have focused on arctic or subarctic areas where climatic conditions and terrain factors differ from those in alpine terrain. First, the climatic conditions of mid-latitude mountains are characterised by a weaker seasonal freezing cycle than in arctic climates, with the possibility of thawing even in winter. At the same time, diurnal freezing-thawing cycles are more common (Bertran *et al.*, 2010). Precipitation is also greater in mid-latitude mountains, so snow cover plays an important role. Second, the periglacial features of these areas are often associated with seasonally frozen ground rather than with permafrost. Third, scale analysis is different for arctic zones because periglacial features may be widespread even at low elevations. In alpine areas, periglacial landforms are sporadic and often confined to a narrow altitudinal zone. These differences explain why arctic studies are not directly transferrable to mid-latitude areas.

The aims of this paper are: (1) to augment knowledge about patterned ground features in the Pyrenees; (2) to propose spatial sampling and statistical methods for scattered landforms that complement those developed for arctic areas; and (3) to identify locations favourable for active patterned ground forms. I emphasise that this approach should be usable in all high mountain areas.

STUDY SITE

The Pyrénées are a massif located between Spain and France, culminating at 3404 m a.s.l. (Pico Aneto). The range extends for about 430 km from the Atlantic Ocean to the Mediterranean Sea.

The study site, the Taillon Massif (Figure 1), is located in the northwestern portion of the Pyrénées (42°N, 00°W) and reaches 3144 m a.s.l. The site is mainly composed of sandstone, limestone and sandy limestone from the Mesozoic and Cenozoic eras. This portion of the range is characterised by an oceanic climate generating high moisture levels (due to rain and snow) and weak annual thermal amplitude (temperate winters and cool summers). The mean annual air temperature (MAAT) was -1.3°C at 2880 m a.s.l. (Pic du Midi de Bigorre, 1959–84, data measured by Météo France) but increased to -0.2°C between 1994 and 2007. Unfortunately, there are no data available between 1984 and 1994. At this elevation, the coldest month is February (-7.5°C) and 7 months have average temperatures, <0 °C. The regional annual lapse rate is 0.59°C/100 m (Feuillet and Sellier, 2008). Precipitation is about 1000 mm/year in the foothills, more than 2000 mm/year on summits, and is seasonally concentrated between October and May. At 2450 m a.s.l., snow cover starts in November and ends in June, being present for 220 days/year (1995–2007) and reaching up to 3 m in thickness. As is typical of mid-latitude mountains, ground temperature cycles are mainly superficial and often daily, which leads to a depth of sorting of only a few centimetres or decimetres. However, annual cycles can reach depths of a few decimetres (Bertran *et al.*, 2010). I observed a mean of 26 freeze-thaw cycles at -1 cm, nine cycles at -10 cm and four cycles at -30 cm on the Spanish side of the massif at 2750 m a.s.l. (2004–07). On the northern slope for the period 2008–09, I observed 12 cycles at -5-cm depth and 19 cycles at -15 cm. Minimum temperatures are often close to 0°C.

On the northern side (Figure 1B and C), the timberline does not exceed 1700–1800 m a.s.l. and the treeline is around 1950 m a.s.l. These relatively low elevations are due to the oceanic character of the climate, and particularly strong winds. Nevertheless, these limits are higher in granitic massifs. The upper limit of continuous alpine grass is around 2300 m a.s.l. on the northern slope where it is correlated to rock wall proximity and glacier influence, and around 2400–2500 m a.s.l. on the southern slope (Figure 1B and D). Patches of grass can occur up to 2800 m a.s.l. on the southern slope.

During the Last Glacial Maximum, one of the longest Pyrenean glaciers stretched from Taillon to the foothills (Lourdes, 60 km in length). There are currently three small glaciers remaining in the massif, all located on the northern slope: the Gabiétous Glacier (8.5 ha), the Taillon Glacier (11.6 ha) and the Brèche de Roland Glacier, which is on the verge of disappearing and less than 2 ha. The southern slope hosted a small glacier during the Little Ice Age (LIA). Thin tills covering a large portion of this slope are undated. At these high elevations, a glacier probably covered this slope during the Younger Dryas (see Pallàs *et al.*, 2006). The difficulty is knowing whether Holocene neoglacial events, defined by Gellatly *et al.* (1992) in the Cirque de Troumouse as occurring around 4950–4650 ^{14}C BP, or early Holocene readvance concerned the studied slope. I only know that at 2750 m a.s.l., there was no glacier after 4600 ^{14}C BP, according to ^{14}C dating from a palaeosol located under a stone-banked solifluction lobe (unpublished data). Given the uncertainty, these drifts are considered as pre-LIA moraines.

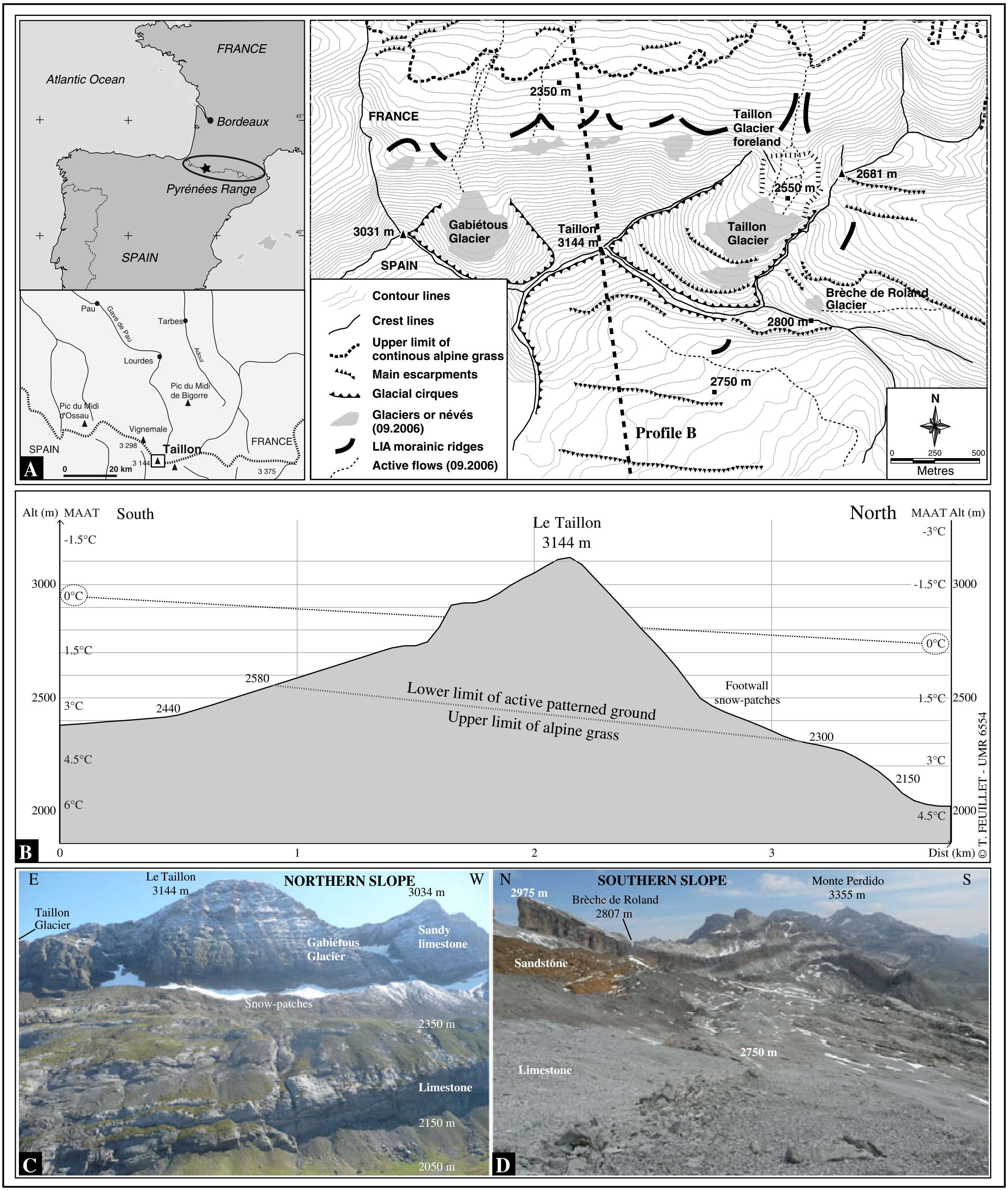

Figure 1 Study site. (A) Location map. The Taillon Massif is located in the central western portion of the Pyrénées range. (B) North-south profile and lower limit of active patterned ground features on the Taillon Massif. (C) View of the northern slope of the study site (September 2008). (D) View of the southern slope of the study site (September 2008). Abbreviations are given in the text. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

There is a variety of active patterned ground features on both slopes. The majority of landforms are smaller than 1 m in size. Flat terrain (<3°) displays mostly circles (Figure 2A), nets and polygons (Figure 2B), sorted or non-sorted. Slopes (>3°) display elongated landforms: stripes, steps and stone-banked solifluction lobes. These slope landforms are directly derived from circles, nets or polygons (Washburn, 1979; Bertran *et al.*, 1995).'

METHODS

Spatial Sampling Strategy

Active patterned ground features were visually defined in the field (September 2008 and September 2009) in an area of 5 km² on the northern and southern slopes of the Taillon Massif (Figure 3A). Except for the largest stone-banked lobes, these landforms are too small to be identified from aerial photos. Only a portion of the extensive southern slope was explored to even out the distribution between the two sides. Landforms with no vegetation on borders were considered to be active. Each landform was mapped with a GPS 60 Garmin and included in a GIS (MapInfo 8.5 software) based on high-resolution (2.5 m²/pixel) ortho-rectified aerial photos (September 2006) of 1 × 1 km areas.

Figure 2 (A) Geolocation of sorted circles with Garmin GPS (20 cm in length), Taillon Glacier foreland, 2550 m a.s.l., lithology: sandy limestone (August 2009). (B) Small sorted polygons, southern slope, 2750 m a.s.l., lithology: limestone (September 2008). This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

For the statistical analysis, a grid with equal-sized squares (50 × 50 m) was created (Figure 4). Each square is characterised by the absence or presence of patterned ground. Large portions of the slopes do not exhibit patterned ground forms because active landforms are rare. To avoid a high disproportion between absence- and presence-squares, the studied fields were limited to circular regions, 200 m in diameter, around each observed patterned ground feature (Figure 3B). These circles were then subdivided into 50 × 50 m squares (Figure 3C). Squares located on glaciers and rock walls were ignored so that the focus was only on fields with potential patterned ground occurrence.

The patterned ground sampling method used must include errors, but these are difficult to evaluate. Small, isolated landforms may have been missed. However, even if these constitute 10 per cent of the total, this does not imply an equivalent error level because some may have occurred in squares already characterised by the presence of active patterned ground features.

Matrix Constitution: Choice of Variables

The first analytical matrix contains one dependent variable to describe patterned ground absence or presence and eight mixed explanatory variables: elevation, exposure, lithology, height-distance ratio, drift, slopewash, glacier influence and vegetation cover. Each variable represents one matrix column while squares are matrix rows (total of 642 rows). To homogenise the data, numerical variables (elevation and height-distance ratio) were grouped into three nominal clusters. The second matrix is a portion of the first, containing only the squares where patterned ground features are present (67 rows).

- Elevation is based on the mean elevation of each square, determined using a digital elevation model. It contains three categories of equal sample size: alt1 (2220–2400 m a.s.l.), alt2 (2400–2660 m a.s.l.) and alt3 (2660–2860 m a.s.l.).
- Exposure contains four categories: north (N), northeast (NE), southeast (SE) and south (S). Other exposures were excluded because there were no observations on west- and east-facing slopes.
- Lithology contains two categories: limestone (LI) and sandy limestone (SLI). Data come from the regional geological map and field observations.
- Height-distance ratio index (DEI) is a novel variable. It is based on the ratio between the distance of the square midpoint to the nearest rock wall (numerator) and the height of the rock wall (denominator). So, a low index results in a high height-distance ratio. This variable

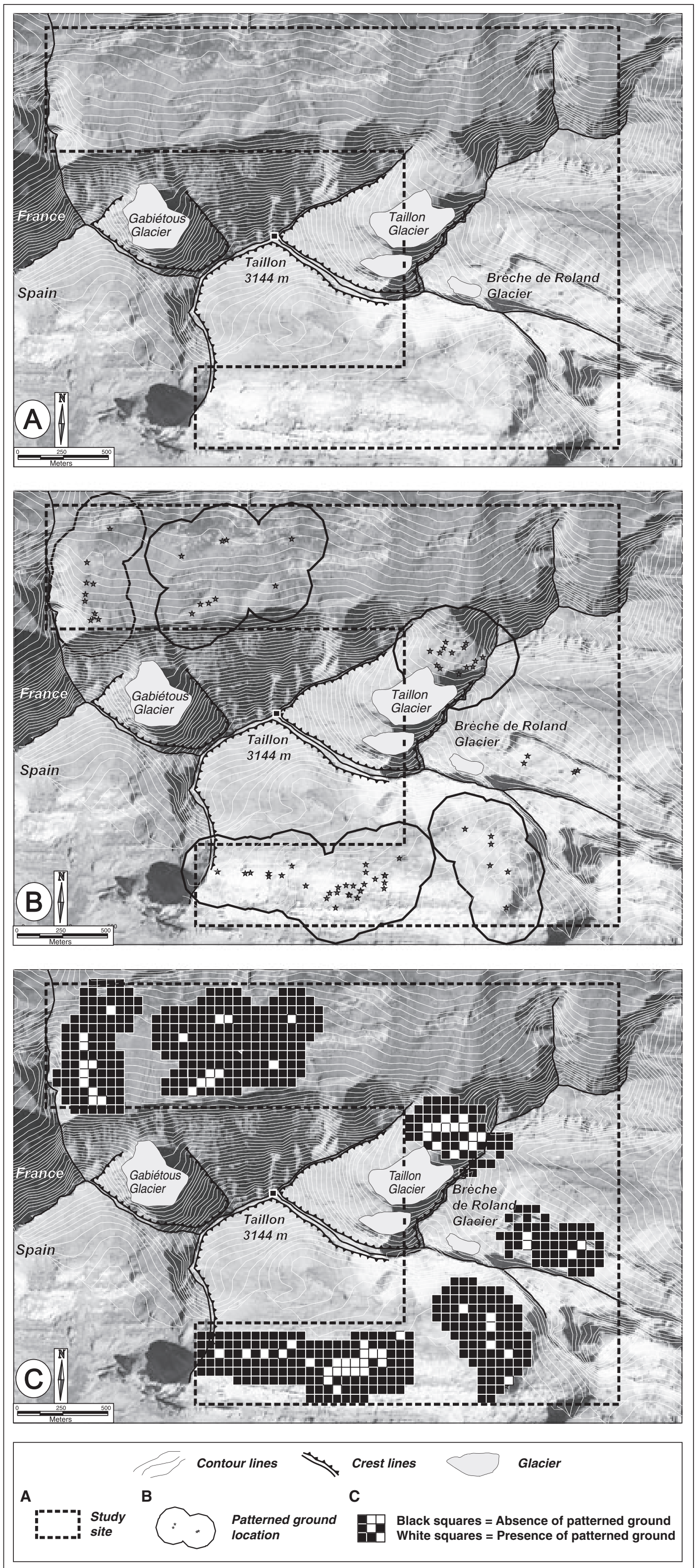

Figure 3 Methodological approach. (A) Demarcation of observation sites. (B) Location of all observed active patterned ground features in the study zone. Circles of 200-m diameter are drawn around each point to limit the considered terrain. (C) In each circle, a grid cut into 50 x 50 m squares is created. Cells featuring rock walls and glaciers are ignored. Each square is characterised by the absence (black) or presence (white) of active patterned ground.

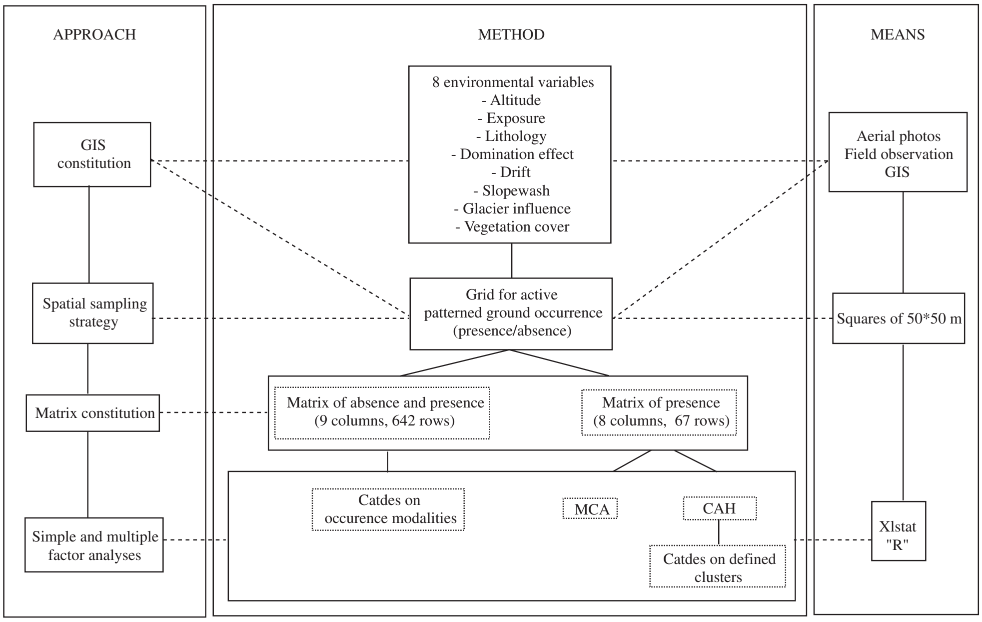

Figure 4 Diagram of the methodology used. Abbreviations are given in the text.

contains three classes: DEI0 (no height-distance ratio, i.e. no rock wall), DEI1 (low height-distance ratio, index >0.42) and DEI2 (high height-distance ratio, index <0.42). The 0.42 cut-off value was chosen so that low height-distance ratio (DEI1) and high height-distance ratio (DEI2) have equal sample sizes.

- Drift contains six classes: till1 (Till1), till2 (Till2), fluvio-glacial deposits (FGdep), reworked drift (SubautD), talus fans (TF) and rockfall deposits. Source data come from aerial photos (resolution of 2.5 m²/pixel) and field observations. Till1 comprises thin pre-LIA moraines (Lateglacial? Holocene?) covering roches moutonnées and is located exclusively on the southern side. The till2 category comprises glacial deposits from the LIA and current glaciers. Subautochtonous drifts are mostly regosolic in nature and often subject to solifluction. Rockfall deposits are composed of large blocks related to rockfalls and paraglacial dynamics.
- Slopewash has four classes: no wash (W0), unconcentrated wash (W1), concentrated wash (W2) and sheetwash (W3). The difference between unconcentrated wash (W1) and sheetwash (W3) is based on the density of the sheet with sheetwash (W3) squares characterised by extensive sheetwash. Data come from aerial photos taken in September 2006. Summer 2006 was particularly warm, so only the largest snow-patches persisted. Thus, the slopewash variable takes into account only wash derived from the melt of the largest snow-patches and glaciers and not wash during spring snowmelt.
- Glacier influence has three categories: no glacier (Glac0), former proglacial zone or current proglacial zone but not directly influenced by the melting of ice (Glac1) and current proglacial zone directly influenced by the melting of ice (Glac2). Data come from aerial photos and field observations.
- Vegetation cover contains three classes: no vegetation (Veg0), patchy cover (Veg1) and continuous cover (Veg2). Note that squares with vegetation cover can include active patterned ground where vegetation is absent on the landforms themselves. Data come from aerial photos and field observations.

Statistical Methods

Correlations between patterned ground occurrence and environmental parameters were examined using the catdes (categories description) procedure, a bivariate method that enables a qualitative variable to be described by quantitative and/or qualitative variables (Escofier and Pagès, 2008). This analysis is based on a v-test estimation and is used to characterise clusters of homogeneous individuals. The test shows if the category value is significantly different from 0, and the higher the v-test, the more the class explains the category. The catdes is thus tested on both the presence and absence classes. This method was implemented using ‘R’ freeware with the FactomineR package (Husson *et al.*, 2008).

In a second step, multiple correspondence analysis (MCA) (Benzécri, 1980; Greenacre, 1984), a particular type of exploratory multivariate analysis, was applied to the second matrix (presence of patterned ground). This technique is an extension of correspondence analysis and enables the pattern of relationships of several categorical variables in a matrix to be analysed. MCA is used to describe I individuals (patterned ground) by J qualitative variables (environmental parameters), as opposed to the quantitative variable analysis provided by principal component analysis. This method was chosen as the variables are mostly nominal. MCA produces a graphical display in which the rows and columns of the matrix are depicted as points. It constructs factorial axes that enable each category and each individual to be positioned according to their coordinates on the selected factorial plane. Its interpretation is based on the distance between category points and individual points. Two points (category and/or individual) close together are indicative of association. MCA was performed only on the presence matrix to analyse relationships between all the variables associated with the presence of patterned ground.

To identify potential homogeneous patterned ground areas, a hierarchical ascendant classification or cluster analysis (HAC) (Ward method and Euclidian distance) was used. This implements the clustering of individual points using a dendrogram by combining the observations sequentially and reducing the number of clusters at each step until all individuals belong to one cluster only (Almeida *et al.*, 2007). The HAC can be combined with the MCA graph as it is based on the complete disjunctive table (a matrix in which each category is coded as 1 or 0, i. e. as dummy variables). These multivariate methods were carried out using XLSTAT software.

Finally, catdes was again used to characterise clusters (homogeneous patterned ground areas) defined by the HAC (Figure 4).

RESULTS

Catdes of Absence/Presence Classes

Catdes relates categories to the absence or presence of active patterned ground. The selected results are for $p < 0.05$ (Table 1). They show that six classes mainly characterise the absence of patterned ground: low height-distance ratio, low elevation, no glacier influence, talus fan, no wash and northern exposure. At $p < 0.01$, wash and northern exposure are dropped. Classes characterising patterned ground presence are direct glacier influence, high height-distance ratio, mid-elevation and no vegetation, with only direct glacier influence remaining at $p < 0.01$. Finally, three variables appear in both catdes: glacier influence, height-distance ratio and elevation. I conclude that glacier influence, mid-elevation and a high height-distance ratio index are favourable for the presence of active patterned ground. Conversely, glacier absence, low elevation and a low height-distance ratio are unfavourable.

MCA of Patterned Ground Presence

MCA was performed on the second matrix where all the squares with active patterned ground presence were represented ($n = 67$). The first two factors explain 82 per cent of the sample variance, which is significant (Figure 5). The factor plane F1/F2 shows the classes and the individuals. First, it is clear that some classes are located far from individual points: low height-distance ratio, talus fan, patchy vegetation cover and continuous vegetation cover. This shows that these classes are not associated with patterned ground presence and confirms previous results. The vegetation absent class is close to 0 which means that all individual observations are affected by it. Some groups of individual points are associated with particular classes. This is especially the case on the right side of the plot, which contributes to factor 1 (Figure 5). Two other clusters appear with negative coordinates on the left side.

HAC of Patterned Ground Presence

An HAC was based on the second matrix complete disjunctive table to estimate clusters of individuals (squares characterised by patterned ground presence). Three main clusters (1, 2 and 3) were identified, confirming the MCA interpretation (Table 2).

Catdes of the Three Defined Clusters

The new clustering was added to the second matrix as a new column. Catdes ($p < 0.05$) was then applied to characterise each cluster (Table 2). Cluster 1 (23 individuals) is associated with the southern slope. This is characterised by limestone outcrops, reworked drifts, high elevation, no glacier influence, no rock wall and no significant slopewash. Cluster 2 (30 individuals) is associated with a high height-distance ratio, northeastern exposure, glacier influence, moraines, sandy limestone outcrop and medium elevation. This corresponds to the Taillon Glacier proglacial zone. Cluster 3 (14 individuals) is associated with a medium height-distance ratio, southeastern and northern exposure, absence of glacier and fluvio-glacial drift.

Table 1 Catdes results for the occurrence (presence/absence categories) of active patterned ground ($p < 0.05$).

Absence		
	p-value	v-test
DEI = DEI1	<0.01	3.4790
Elevation = alt1	<0.01	3.4168
Glacier = Glac0	<0.01	3.2929
Drift = TF	<0.01	3.2762
Wash = W0	<0.05	2.5636
Exposure = N	<0.05	2.2460
Presence		
Glacier = Glac2	<0.01	3.6779
DEI = DEI2	<0.05	2.3433
Elevation = alt2	<0.05	2.1996
VegCov = Veg0	<0.05	2.0374

Note: The higher the v-test, the more the category characterises the presence or absence classes. Abbreviations are given in the text.

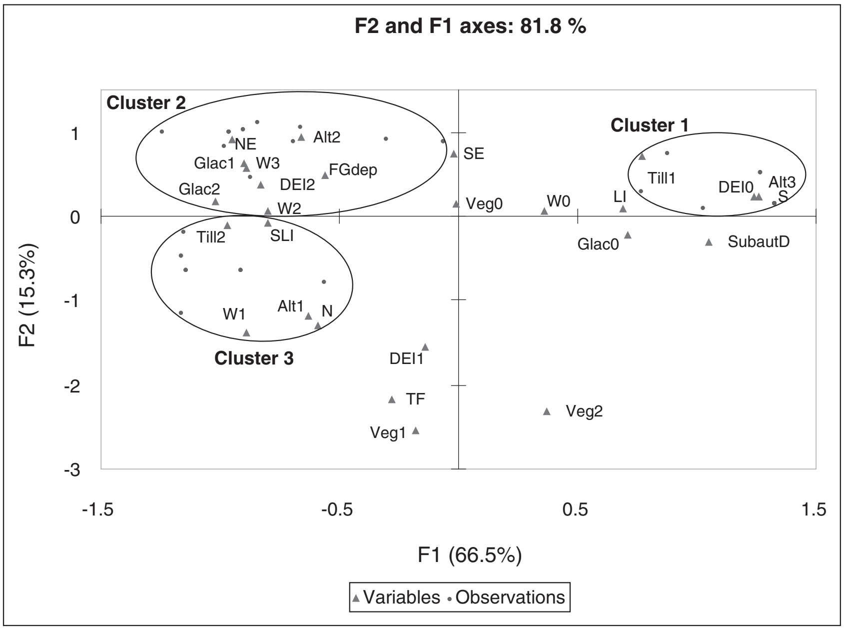

Figure 5 Multiple correspondence analysis factorial plane F1/F2 on the second matrix. Note that not all of the 67 individuals are visible because many points have identical coordinates. Abbreviations are given in the text.

These results reveal that different environments are favourable for the presence of active patterned ground features at the scale of the massif. Most features are found in two main areas: the southern slope and the proglacial zone of the Taillon Glacier with the latter being the most important (30 of 67 grid cells). A third group includes all the other occurrences of active patterned ground.

DISCUSSION

Favourable Conditions for Patterned Ground Development

Patterned ground is present in two well-defined sites and in a third grouping that is not spatially clustered:

1. The Taillon Glacier foreland (2550 m a.s.l.) exhibits numerous well-developed patterned ground features, especially sorted circles and nets. These can be related to a number of influences. Glacial meltwater ensures a consistent moisture supply and the grain size distribution includes many glacially derived fines. The proglacial zone is confined by a rock bar which allows only the slow evacuation of fines and the glacier is topographically confined (i.e. the height-distance ratio is high). This effect is correlated with the duration of snow cover which melts only from June to July while it does so a month earlier at the same elevation on other slopes. This late melt is another source of moisture and also leads to a reduced growing season. Vegetation cover is negatively correlated with the presence of patterned ground, both acting as an indicator and helping to stabilise deposits.
2. The southern slope (2700–2800 m a.s.l.) is also characterised by numerous patterned ground features but environmental conditions are different. There is no glacier, little drainage and zero height-distance ratio, while gentle slopes (3–10°) and drifts (pre-LIA till and reworked drift) are particularly favourable for the development of stone-banked lobes. Circles and nets are also present but to a lesser extent and only close to late-lying snow-patches. There are many inactive landforms which have been colonised by vegetation and this suggests that the current climatic and moisture conditions are less suitable for patterned ground activity than in the past. Active landforms are confined to most favourable sites (presence of fines, moisture due to snow melt) while inactive ones are widespread. Outside the study area, on the upper portion of the Taillon slope (>2900 m a.s.l. to 3100 m a.s.l.), active patterned ground forms are also very common, probably because of the more severe climatic conditions. Thus, 2750 m a.s.l. seems to correspond to the approximate current lower limit of active patterned ground features on this southern slope with only a very few active landforms observed down to 2600 m a.s.l.
3. Other areas of active patterned ground are present on the northern and southeastern slopes. On the northern slope, a few sorted circles are active on LIA moraines down to elevations of 2300–2400 m a.s.l. This is about 300 m lower than active patterned ground features on the southern slope. Activity is particularly pronounced close to the footwall snow-patches which provide fines and moisture at a local scale and are linked to a high height-distance ratio. On the southeastern slope (2600–2700 m a.s.l.), the only observed active patterned ground

Table 2 Catdes results for the three clusters.

Cluster 1		
	p-value	v-test
Exposure = S	<0.01	8.6855
DEI = DEI0	<0.01	8.6855
Elevation = alt3	<0.01	7.8607
Drift = SubautD	<0.01	5.6096
Glacier = Glac0	<0.01	5.2624
Lithology = LI	<0.01	4.4126
Wash = W0	<0.01	3.2439
Cluster 2		
DEI = DEI2	<0.01	6.6624
Glacier = Glac2	<0.01	6.1036
Drift = Moraines	<0.01	6.1036
Lithology = SLI	<0.01	5.9938
Exposure = NE	<0.01	5.6257
Glacier = Glac1	<0.01	3.1222
Elevation = alt2	<0.01	2.9757
Cluster 3		
DEI = DEI1	<0.01	4.5926
Exposure = SE	<0.01	4.0120
Glacier = Glac0	<0.01	3.6082
Drift = FGdep	<0.01	2.6103
Exposure = N	<0.01	2.1243

Abbreviations are given in the text.

features (circles, steps and stone-banked lobes) are located near active streams.

The majority of active patterned ground features in the three types of site develop on glacial drift. However, it is not necessarily the melting of glaciers that is the most important factor, but the fact that glaciers deposited fines-rich till, which was then subject to cold conditions. A paraglacial system is thus favourable for patterned ground development. In the current proglacial zone of the Taillon Glacier, landforms are particularly well developed, even a few decametres from the glacial front. This supports the conclusions of Haugland (2004) that very recently deglaciated terrain can quickly develop patterned ground features, sometimes only 10–20 years after exposure. On the southern slope in former Lateglacial or Holocene proglacial zones, numerous patterned ground features also exist due to the presence of favourable glacial drift, but they are smaller and starting to appear inactive as indicated by vegetation colonisation.

Methodological Approach

The methodology developed could be used to study the occurrence of sparse landforms or processes in any environment. MCA and HAC were applied to the presence grid cells because I wanted to identify homogeneous areas of patterned ground features, and factor analyses are suitable for this. It should be noted that the same spatial sampling and data collection could be applied with other statistical methods.

The environmental explanatory variables used are certainly inter-correlated. The MCA factorial plane shows these correlations (Figure 5) which are indicated by two variable points located close together. For example, this is the case between glacier presence and slopewash, and between glacier presence and current moraines, where it is known that glacier presence is the causal factor. At the same time, a high height-distance ratio does not systematically explain the presence of glaciers. The inter-correlation does not affect the bivariate analysis (catdes) because each variable is used independently of the others, so the results remain the same even if a variable is removed. These causality relations, however, need to be taken into account during the interpretation of the results. In this case, the presence of glaciers (Glac2) is the best variable to explain the presence of patterned ground. Logically, this means that the presence of current till is one too. Concerning the multivariate analysis results (MCA and HAC), they are affected by these inter-correlations to a certain extent as they give more relative weight to a group of correlated variables. I consider that these results are still interpretable, however, because the correlations between each linked category are not very strong (<0.7).

The grouping of the quantitative variables elevation and height-distance ratio into three nominal classes resulted in a loss of information. For the height-distance ratio, this was the only way to avoid a disproportionately large number of cells in the zero height-distance ratio class. However, the three classes of the elevation variable are essentially arbitrary and could affect the results so the MCA and HAC were run again with a matrix containing four approximately equal classes (2300–2440, 2440–2580, 2580–2720 and 2720–2820 m a.s.l.). Given the sample size (67), more classes were not appropriate. The MCA factor map showed groups of individuals better because of more scattering of the scatter plot (increase of total variance). This was particularly the case for cells on the southern slope of the Taillon because the fourth class (alt4- 2720–2820 m) was composed solely of them. The complementary HAC again defined three clusters, but some changes appeared. Previously, the third cluster included the northern and southeastern cells whereas the latter were now included in the first cluster, while the northern cells form a small distinct cluster. Cluster 2 was unchanged. I maintain that these changes do not have important consequences on the interpretation of the patterned ground areas. Subsequently, four elevation classes (2220–2340, 2340–2590, 2590–2720, 2720–2860 m a.s.l.). were tested in the first matrix but the catdes results were the same. With five classes of equal size, one change occurred in the classes characterising the presence of patterned ground: elevation 2400–2660m a.s.l (alt2) disappeared while till2 (Till2) appeared.

Perspectives

Patterned ground features depend on the rhythm and depth of freeze-thaw cycles and snow cover exerts an influence as thermal insulation, as a source of moisture during the melt and on the vegetation cover. These factors could be incorporated into the matrix to refine the analyses. However, a major drawback would be the need to install numerous dataloggers to generate a reliable dataset. Given the heterogeneity of the high mountains, only multiple spatially distributed measurements over several years would be useful.

This study focused on a single massif and this choice of scale partly determined the required precision of the environmental variables. A scaling-down would allow the inclusion of more precise soil characteristics, slope angles, etc. It would be complementary and useful to apply the factor analyses approach at a very local scale. The results show the importance of current proglacial zones in terms of active patterned ground development, so the recently deglaciated environment could be the subject of a local analysis. It would enable examination of the time elapsed since the disappearance of the LIA glaciers as a variable which can only be included at this scale. Several studies have already shown a correlation between this parameter and patterned ground development (Ballantyne and Matthews, 1982; Matthews *et al.*, 1998; Haugland, 2004, 2006; Haugland and Beatty, 2005). The Taillon Glacier foreland would be a perfect site to study this for two reasons. First, many patterned ground features are present, especially sorted circles and nets. Second, the deglaciation chronology since the LIA is well known (Gellatly *et al.*, 1994). This is also the case for the Pays Baché Glacier foreland in the Pic Long Massif. Thus, at least two productive directions are available for further work.

CONCLUSIONS

This study contributes to improving the knowledge of Pyrenean periglacial features and proposes an original spatial sampling particularly suitable for analysing the occurrence of scattered landforms in alpine environments. This methodological approach could be used in other heterogeneous landscapes.

Factor analyses enabled significant conclusions to be drawn regarding the environmental controls of active patterned ground development. I have also shown some of the benefits of complementary bivariate and multivariate analyses. The catdes enabled to associate the absence of patterned ground features with a low height-distance ratio, low elevation, absence of glacial influence, talus fan sites and an absence of slopewash. MCA analysis of patterned ground presence revealed two main findings. First, talus fans, low height-distance ratio and vegetation cover points are far from individual points. This means that these variables are not associated with the presence of landforms. Second, groups of homogeneous individuals appear, interpreted as different densely patterned ground zones. I applied a hierarchical clustering to identify these areas. It revealed three groups of individuals associated with particular variables. The catdes was again used to define these variables. This suggested that the first group corresponds to the southern slope and is characterised by high elevation, no glacier, reworked drift and zero height-distance ratio. The second group, which contains the majority of individuals, corresponds to the Taillon Glacier foreland (strong glacier influence, moraine presence and high height-distance ratio). The third group contains the remaining individuals (northern and southeastern slopes).

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