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Factors Controlling Spacing Distances of Sorted Stripes in a Low-Latitude, Alpine Environment (Cordillera Real, 16 °S, Bolivia)

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ABSTRACT

A total of 1500 spacing distances of sorted stripes were measured on 30 alpine sites in the Bolivian Andes with distinct slope angles, elevations and aspects. Additionally, the geometric evolution of stripes was systematically analysed along a slope with varying inclinations and morphology. We dealt with mainly small-sized stripes (<40 cm). The scatter observed in the distribution of spacing distances suggests that the factors controlling the geometry of sorted stripes are complex. Among them, we point out the role of slope inclination and coarse sediment supply. They imply that stripe geometry does not depend exclusively on processes operating in soils such as frost heaving and sorting, but also on the dynamics of the flux of coarse materials along the sloping surface. This analysis questions models which assume that sorted stripes are organized according to a strict periodicity whose origin depends on specific physical processes. Particularly, it appears that recent convective models cannot explain the characteristics and the evolution of patterned slopes in this environment. Copyright © 2001 John Wiley & Sons, Ltd.

RÉSUMÉ

On a mesuré 1500 largeurs de stries réparties sur 30 sites se différenciant par la pente, l'altitude et l'exposition. Par ailleurs, on a analysé systématiquement l'évolution des stries le long d'un versant de pente et de morphologie variables. On confirme que dans ce type de milieu où dominent les cycles de gels-dégels journaliers les stries sont en majorité de petite dimension (<40 cm), mais la dispersion de la distribution suggère que les facteurs qui déterminent l'espacement des stries sont complexes. Parmi eux se détachent l'inclinaison de la pente et la morphologie du haut du versant, laquelle intervient par la quantité de produits clastiques parvenant au sol strié. Cela implique que la géométrie des sols striés ne dépende pas seulement des mécanismes du gel dans le sol, comme le gonflement et le tri qui lui est associé, mais aussi de la dynamique du flux de matériel grossier tout au long du versant. Cette étude remet en question les modèles qui partent de l'hypothèse que les sols striés sont organisés selon une stricte périodicité, dont l'origine est attribuée à un processus physique particulier. Il apparaît notamment que les modèles construits à partir de la convection ne parviennent pas à rendre compte des caractères et des évolutions observés sur les sols striés dans ce type de milieu. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: sorted stripes; patterned ground; tropical Andes; Bolivia

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INTRODUCTION

Sorted stripes are believed to form by differential frost-heaving: cells of fine soil are ejected at the surface amid a clast pavement (Washburn, 1956, 1979; Pissart, 1973, 1987; Goldthwait, 1976; Van Vliet Lanoé, 1991). Heaved together with fine soil, any coarse material migrates progressively towards adjacent borders, thereby enriching these borders with porous materials (Pissart, 1973, 1977). Once the pattern is established, the textural contrast between borders and frost-susceptible fine cells tends to increase: this enhances the sorting in parallel stripes and perpetuates the pattern. Pissart (1977) and Washburn (1979) point out the presence of parallel troughs on both sides of the central dome which trap clasts while they migrate diagonally to the slope. Needle ice is considered to play a major role in the sorting process (Troll, 1944; Pissart, 1977; Washburn, 1979; Pérez, 1987, 1992). Pattern geometry, particularly the spacing between stripes, seems to be directly controlled by the magnitude of frost heaving, depending itself on the depth of the recurrent freezing in the ground. This explains why small-sized (<50 cm) patterned ground is the most frequent in regions of superficial freeze-thaw cycles of daily occurrence (Troll, 1944; Graf, 1971; Furrer and Freund, 1973; Schubert, 1973; Hastenrath, 1977; Van Vliet Lanoé and Francou, 1988; Pérez, 1992), while regions with seasonal and deep freeze-thaw cycles, including eventually permafrost, frequently have stripes 1.0 m wide or more (Washburn, 1956; Mackay and Matthews, 1974; French, 1996; Pissart, 1987). However, exceptions have been reported, such as large sorted patterns in the tropics (Furrer and Freund, 1973; Hastenrath, 1977), and small-size stripes in the polar countries or the mid-latitude mountains (Washburn, 1979). Small-scale sorted patterned ground has been commonly reported outside of periglacial areas in regions where winters are marked by frequent freeze-thaw cycles, as in Western Europe (Caine, 1963; Warburton, 1985; Wilson, 1992; Ballantyne, 1996; Warburton and Caine, 1999). Sorted stripes are described as originating from closed, sorted patterns, as polygons, nets or circles, which deform with slope and open progressively (Cotton, 1948). Thus, most authors believe that the sorting mechanisms involved in both patterns could be the same (Pissart, 1987). On the other hand, the origin of the regular geometry of some patterned ground is less understood and still controversial. Indeed, many authors have stressed, from either qualitative observations or from specific measurements, that the succession of fine and coarse stripes responds to a strict periodicity. To explain this periodicity, several physical models have been proposed, several of them involving convection mechanisms in the ground. We mention below only the model based on the free convection of Bénard-Rayleigh which assumes that regular cells develop in the superficial water-saturated ground when an unstable stratification of melt-water of different densities exists (Ray *et al.*, 1983; Gleason *et al.*, 1986). At depth, the convective cells tend to melt irregularly the frozen level and transform it to an undulating surface. When freezing, this surface drives the sorting processes and gives birth to a regular pattern. The great interest of this model is to link two variables that can be measured in the field—the sorting depth and the width of stripes (Ray *et al.*, 1983). However, up to now, except for a few field analyses such as that conducted by Warburton (1987), the geometry of stripes has not been either widely documented or subject to statistical analysis. For example, it is not known if the spacing of stripes is specific to vast regions characterized by the same frost regime, or whether it is susceptible to wide variability from one site to another, or even locally along the same sloping surface. If this latter situation were the case, it is interesting to identify the variables involved.

In this paper, the question is examined by reference to a homogeneous periglacial environment in a low-latitude, mountain area in Bolivia. Daily freeze-thaw cycles are dominant, and the sorted stripes are widespread enough to make it possible to collect data from a variety of sites. Three variables, easy to quantify at every site, have been considered: elevation, aspect and slope morphology. At the same time, analysis has focused on one site in order to identify the variables determined previously from a case study. The aim is to better understand the organization of sorted stripes in this environment.

STUDY AREA AND LOCATION OF SORTED STRIPE FIELDS

Close to La Paz, in the Cordillera Real, sorted stripes are the most common features along sloping surfaces, together with stone-banked lobes and sheets (Graf, 1971; Francou, 1990). All these features are found in Palaeozoic sedimentary and metamorphic terrain which produces a great quantity of fine and frost-susceptible materials: 40–60% of small-grained particles (<2 mm) are <50 μm (silts, mostly). Sorted stripes are active above 4700 masl and continue to be found in the vicinity of glaciers at 5200–5400 masl. Specific geocryological processes have been analysed in detail by Francou (1988,1989), Bertran *et al.* (1995) and Francou and Bertran (1997). The number of effective freeze-thaw cycles exceeds 200 at >4900 masl during a year but the ground never freezes more than 20 cm in depth. During the wet months, which correspond to the summer season and last from October to April, freezing is superficial (<10 cm) and gives rise to intense needle-ice activity. Displacement rates of the ground surface are high and depend on slope gradient and clast size (Francou and Bertran, 1997). During the dry period (May–September), ice lenses grow where moisture persists. These microstructures have been clearly identified at depths of up to 15–20 cm (Van Vliet and Francou, 1988; Bertran *et al.*, 1995). The ice lenses induce slow frost creep whose specific displacements have been differentiated from those caused by needle ice (Francou and Bertran, 1997). With a mean annual air temperature (MAAT) close to 0 °C at 4900 masl and an equilibrium line altitude of glaciers between 5200 masl and 5400 masl, depending on aspect (Ramirez *et al.*, 2001), the periglacial environment is relatively expanded in altitude and permafrost may exist locally above 5400 masl (Francou *et al.*, 1998). As in Peru (Francou, 1988, 1989), the effect of aspect is significant and divides north and east slopes, which receive the maximum radiation input at the annual scale, from south and west slopes, where colder conditions allow glaciers to extend 200–300 m lower in elevation. Sorted stripes are present on all sloping surfaces that may be less than 5° and up to a maximum of 35° in angle. They may cover slopes over several hundred metres without any discontinuity, or be present intermittently on the surface of stone-banked sheets. They are only absent below active rock faces which provide great amounts of coarse materials and which work as talus slope deposits. Generally, sorted stripes are generated on sloping surfaces from more or less continuous clast pavements. Rarely do they develop from polygons or nets by an opening of the borders when the slope angle increases. Moreover, polygons and nets are seldom represented in this environment (Graf, 1971), whereas nubbins (occasionally named 'mud cakes' or 'erdkuchen') of 15–30 cm diameter are very common.

METHODS

Two kinds of measurements were performed. First, the distance between the centre of two successive coarse stripes was measured along a line perpendicular to the stripes (Figures 1 and 2). The plot line is located on the middle-distal section of the slope, at a fractional distance of 50–80% from the summit. At this distance, the sorted stripes are commonly in their maximum development stage. Accuracy was generally within 3 cm. Second, slope gradient was measured along a 5 m long segment perpendicular to the line and above it, with an accuracy of half a degree. We recorded elevation with an altimeter calibrated on the map of IGM-Bolivia at 1 : 50 000. For convenience, we rounded up/down to the closest 100 m. Aspect was noted only by four direction classes coded, from 'coldest' to 'warmest' sites, 10, 20, 30, and 40 respectively. These classes correspond to the following ranges (in degrees): 10 = N180-N270; 20 = N135-N180 and N270-N315; 30 = N90-N135 and N315-N360; and 40 = N0-N90. On each plot, 50 pairs of stripes were measured, for a total sample of 1500 spacing distances. The plots and variables are presented in Table 1. This data set is assumed to represent the slopes of the Cordillera Real: slope angles range from 32° to 11°, aspects from 10 to 40 and elevations from 5400 masl to 4800 masl. The elevation range represents about 4 °C of MAAT considering the lapse rate of 0.7 °C for 100 m.

The three variables, elevation, aspect and slope, were tested by correlation in order to estimate their possible inter-dependence. It was found that slope gradient and elevation were poorly correlated at $p < 0.05$ ($R^2 = 0.31$), implying a statistical dependence which limits our ability to construct a model based on multiple regression. The 1500 spacing distances were analysed to characterize the shape of the distribution, with a resolution of 10 cm. We looked for the best correlation (at $p < 0.05$) between spacing distances and the different plot variables. Plots were also analysed separately according to sites ≥5000 masl, sites <5000 masl, 'warm' sites (aspects coded 30–40), and 'cold' sites (aspects coded 10–20).

A second stage of analysis focused on the importance of gradient and morphology of the upper slope surface as factors controlling stripe geometry. Here, we selected a 150 m long plot surface on the south slope of the Milluni-Tuni pass. The slope is concave with a summit at 5000 masl. Stripes were measured along four lines perpendicular to the slope. The left side (downslope) of the slope lies below a 10 m high rock face which supplies a high quantity of clasts, whereas the right side is connected to a gentle and smooth ridge where coarse elements are scarce (Figure 3). The four lines commence at distances of 10 m, 30 m, 60 m and 100 m from the top and lie at angles of 22°, 26°, 24° and 19° respectively. On this plot fine and coarse stripes were surveyed separately, within the same degree of accuracy as

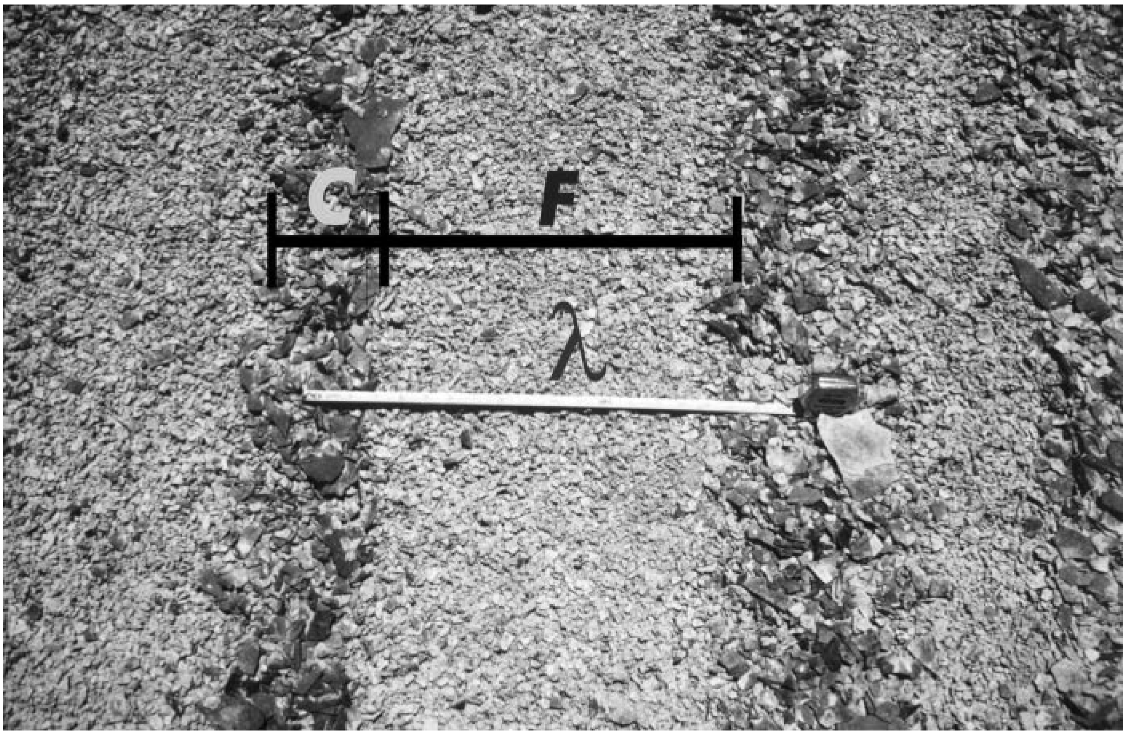

Figure 1 Methods for measuring the spacing distances of stripes. The tape meter indicates the distance used for the extensive sample (n = 1500). λ = width from centre to centre of the coarse stripes; F = fine stripe; C = coarse stripe.

Figure 2 Method for measuring the spacing distance of stripes from a fixed line. Cerro Visuya, 5200 masl.

Table 1 Characteristics of the 30 plots. Slope gradient in degrees. Aspect coded from the 'coldest' (10) to the 'warmest' ones (see text). Elevation in masl.

Plots	Slope	Aspect	Elevation
CB1	11	30	4800
CB2	19	30	4800
CB3	14	10	4800
CB4	20	10	4800
CB5	15	20	5000
CB6	22	40	5000
CB7	20	30	4800
CB8	11	20	4800
CB9	11	20	4800
CB10	14	10	4800
CB11	15	10	4800
MT1	26	40	5000
MT2	31	40	5000
MT3	20	20	5000
MT4	32	20	5000
MT5	31	10	5000
MT6	31	30	5000
MT7	28	10	4900
MT8	28	10	4900
MT9	28	20	5000
MT10	23	30	5000
MT11	23	30	5000
MT12	18	30	5000
CH1	21	40	5400
CH2	29	30	5200
CH3	28	10	5200
CH4	25	10	5200
CH5	32	10	5200
CH6	26	40	5200
CH7	25	40	5200

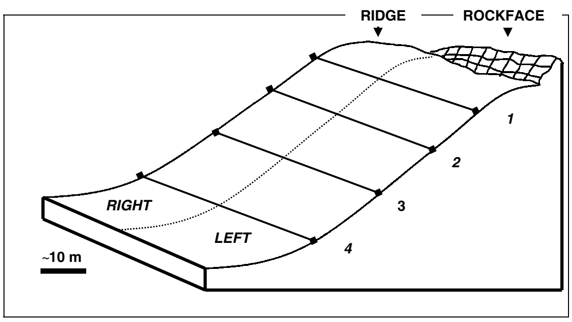

Figure 3 The case study of the Milluni-Tuni pass. Solid lines and diamonds: measured profiles. Dash line: limit between left and right plots.

before, along fixed distance of 40–50 m. Thus, the number of measured stripes changes according to the lines, varying from a maximum of 118 pairs (line 1) to a minimum of 94 (line 2). Since the sample is small and not necessarily normally distributed, kurtosis and skewness were used as criteria to determine the shape of the distribution. The non-parametric Kolmogorov-Smirnov test was systematically applied to compare the coarse/fine stripes. This process was extended to both directions: 1) *lengthwise* along the four lines, in order to clarify the effect of the slope inclination on the stripe organization, and 2) *crosswise* to point out the role of the upper surface morphology, which controls the supply of coarse materials. For this, each line was divided into two segments, one on the left side influenced by the rock face, another one on the right side (Figure 3). Finally, we did not measure systematically the depth of sorted materials. This observation, linked to the spacing distance, is important to the validity of the convective model (Gleason *et al.*, 1986; Warburton, 1987). From earlier fieldwork in this environment, we believe that materials are mainly sorted by solifluction and stratification mechanisms (Francou, 1988; 1989; 1990; Bertran *et al.*, 1995). The latter involve frost-heaving, needle-ice, frost-creep and burial of openwork front banks below advancing fine layers. They explain the strong variability of the sorted layer thickness (5 cm to 30 cm and more), since the freezing depth is much more constant (5 cm to 15 cm). Thus, the depth factor is not the only relevant indicator of frost heaving and for these reasons, it was not considered in this study.

RESULTS FROM THE EXTENSIVE SAMPLE (n = 1500)

Spacing distances show a clear positive skewness and fit a log-normal distribution (Figure 4). The mode is scattered through a large range of values (20–40 cm) with a median at 35 cm. Large spacing distances (40–70 cm) total 30% of the population, very large ones (70–110cm) total 10% and small-size stripes (<20 cm) total 13%.

Median values, upper and lower quartiles, and extreme values are scattered, both within and between plots (Figure 5). Plots have been classified in ascending slope gradient. The spacing distances tend to become larger and more variable as slope gradient increases. Indeed, slope gradient is the only factor significantly correlated with stripe spacing ($p < 0.05$). But the coefficients of determination (R^2) between all spacing distances (i.e. medians, means, maximums, minimums, ranges, standard deviations) are low (always $R^2 < 0.25$).

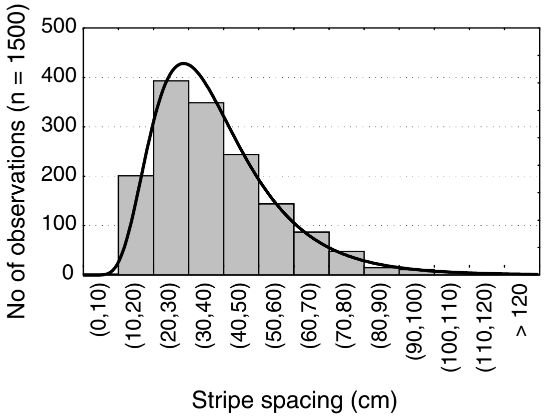

Figure 4 Distribution of spacing distances of the stripes with a log normal fit. Mean = 38.3 cm; Median = 35 cm; Skewness = 1.0; Kurtosis = 0.9; n = 1500.

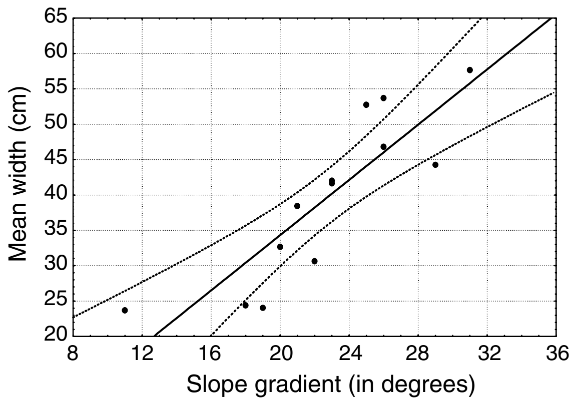

Figure 6 Relationship between the mean widths (cm) and the slope gradients (degrees) on the 'warm' sites (30 + 40 aspects). $R^2 = 0.722$, n = 13.

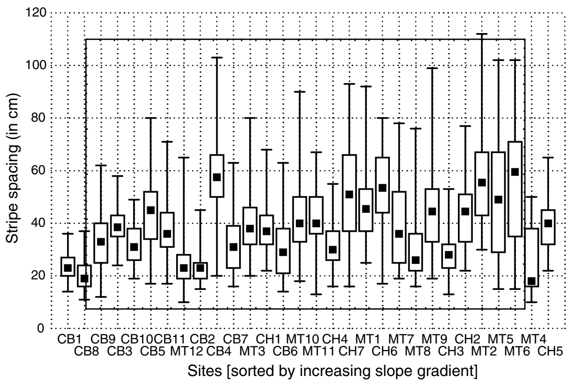

Figure 5 Spacing values (median, quartile, extremes) of 1500 stripes from 30 plots (50 stripes by plot). Plots are sorted from the left by increasing slope gradient.

Correlations with other factors, such as elevation or aspect, are poor and not significant. Thus, although the steeper the slope (>20°), the more frequent become large (>70 cm) spacing distances, the explained variance is low (25%). At the same level of significance, we can state that the scatter of spacing distances tends to grow when the slope gradient increases.

Further analysis consisted in dividing the plots into two elevation, groups: those ≥5000 masl (n = 19) and those <5000 masl (n = 11). The results show no correlation between spacing distances and slope angles. But, once 'warm' sites (30 + 40, n = 13) and 'cold' sites (10 + 20, n = 17) are processed separately, slope gradients and mean spacing distances of the 'warm' sites appear to be reasonably correlated, with $R^2 = 0.722$ (see Figure 6). Conversely, on the 'cold' sites, the correlation is not significant. Field observations explain this discrepancy: the 'warm' sites, which were not covered by glaciers during the Little Ice Age, have less massive and steep rock walls than 'cold' sites. This difference limits the quantity of coarse material which supplies the patterned ground. As a consequence, stripe-spacing distance and slope angle on these 'warm sites' are more closely correlated.

A CASE STUDY OF SORTED STRIPES AT THE MILLUNI-TUNI PASS

Four lines were located along a slope profile of variable inclination, being steep in its upper section (1–2), and decreasing in angle in the lower parts (3–4) (Figure 3). Stripe widths were measured individually, first a fine stripe then the next coarse stripe and so on. Data are presented on Figures 7a–d. The evolution of medians, upper and lower quartiles are synthesized on Figure 8.

These data suggest that the widths of the fine stripes decrease as slope angle declines. In contrast, the coarse stripes are narrow and more constant throughout the sloping surface. Figure 8 shows that the scatter of the fine stripe widths decreases downward. This is confirmed by a decreasing coefficient of variability on the four lines (drops from 0.85 to 0.72, 0.54 and 0.51 on lines 1, 2, 3 and 4 respectively). This means that the stripes formed on the upper slope are the most

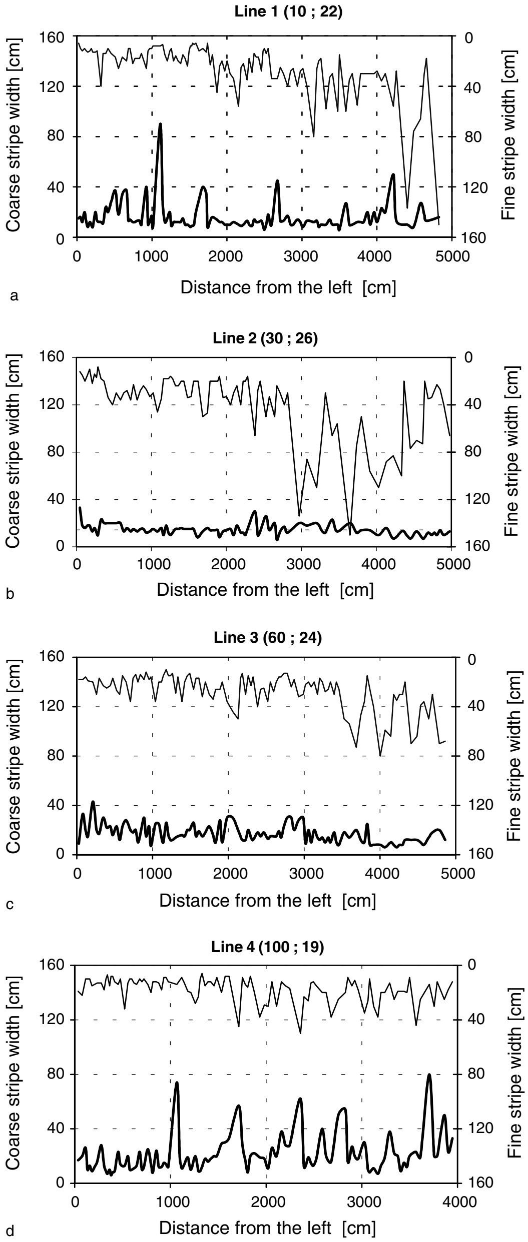

Figure 7 Measurements at the Milluni-Tuni pass. Width of individual coarse stripes (heavy line) and fine stripes (thin line) across the slope. In brackets, distance from the top (in metres) and dominant slope gradient (in degrees). (a) line 1; (b) line 2; (c) line 3; (d) line 4.

irregular, then they become progressively more uniform lower down the slope. This trend is also apparent on the coarse stripes but is less clear.

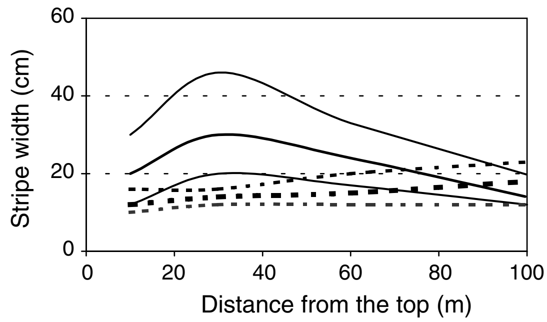

Figure 8 Stripe width evolution according to the distance upslope: median, upper and lower quartiles. Solid lines: fine stripes, dotted lines: coarse stripes.

Figure 7 shows an important lateral change occurring in the stripe geometry at a distance of about 30 m across the slope. This change is linked to the variable morphology of the upper surface (see Figure 3). The sector where the stripes increase in width is precisely where the rock wall is missing and where there are few clasts arriving from the top.

To analyse changes occurring in stripe geometry both downslope and across the slope, the non-parametric Kolmogorov-Smirnov test was used to reject the Null hypothesis. Using the $p < 0.05$ level of significance, the following conclusions were drawn:

1. Across the upper slope (line 1), the differences between the fine stripe widths of the left sector (i.e. with the rock face) and the right sector (i.e. without the rock face) were found to be significant.
2. On the steepest middle section (line 2), the coarse stripe widths remain constant in both directions while the fine stripe widths expand both on the left and right sectors. Despite this trend, differences between the widths of the fine stripes across the slope remain significant.
3. On the lower slope (lines 3 and 4), the differences across the slope remain significant because the pavement expands more rapidly on the left sector in relation to the abundant coarse materials supplied by the rock face.

The Kolmogorov-Smirnov analysis confirms that two variables control the evolution of stripe geometry: 1) the slope inclination, and 2) the quantity of coarse materials available, this factor depending on the morphology of the upper surface. This confirms earlier analysis performed on other slopes of the same morphology (Le Méhauté,1998; 1999).

DISCUSSION

From the extensive sampling, it can be demonstrated that daily frost environments do not produce exclusively small-scale sorted stripes. Although the majority of spacing distances have values <50 cm, the population does not display a sharp mode. The distribution tends to be skewed towards the higher values of spacing distances and a number of occurrences of widths >40 cm have been measured. The geometry of stripes does not show a striking periodicity: the scatter of spacing distances is important on all sites, as evidenced by the high standard deviations, quartiles and ranges. The scatter is partly the result of an instability of stripe geometry along the sloping surfaces. The steeper the slope, the more frequent become the wide stripes (>50 cm), a linkage observed more systematically on slopes where the upper morphology limits in quantity and size the availability of clasts. As fine stripes are the most sensitive to changes, coarse stripes being more stable, their geometry mainly depends on the extinction of coarse stripes.

Elevation does not have a significant influence. This may be because the range considered in the sampling is too small (5400–4800 m), but, more probably, it is because the daily frost regime is dominant on all situations. Aspect is important, not because it induces a change of the frost regime in soils, but rather because clast availability on the 'warm' sites is limited due to the morphology of the upper surfaces.

It is also observed in this environment that stripes do not evolve from the polygons formed on flat surfaces. They develop from cells of fine soils that are ejected at the surface through a clast pavement, then move downslope and progressively coalesce to form parallel small sheets.

These observations lead us to discuss the general processes involved in the origin of the geometric organization of the sorted stripes.

Origin of the 'Primary' Stripes

Considering that the organization of stripes changes with the slope, we believe that it is justified to distinguish 'primary stripes', formed first, from 'secondary stripes' which are subjected to reorganization downslope. In accordance with observations made elsewhere in the same kind of environment (Troll, 1944; Pérez, 1992), the first stripes originate from an extrusion of elongated fine mud patches (nubbins) which form a continuous stripe (Figure 9). These primary stripes are narrow (<30 cm), because they

Figure 9 Primary stripes formed through a continuous pavement. Early in the morning, the mud patches (nubbins) are still frozen. Chacaltaya, 5250 masl. β = slope direction.

cannot expand across the slope for two reasons: 1) depth of frost penetration in this area is superficial (<20 cm), and limits the magnitude of heave; and 2) heaving and the displacement of coarse materials towards the borders on both sides of the central dome generate an accumulation of porous materials whose poor frost-susceptibility prevents needle ice formation. The slope inclination favours the opening of the pavement by reducing its thickness, which increases the probability for fine materials to be ejected through it (Figure 10). At this stage, the random presence of slower-moving block-size elements may deflect the coarse material flux and allow the onset of fine stripes on their downslope face. The fine stripes formed in this way attain the width of the blocks. Once formed, they move downslope as small stone-banked lobes pushing coarse materials on the borders. When there is no pavement on the upper slope, stripe width depends strictly on the quantity of coarse materials available: if there are few, the primary fine stripes are wide; if they are absent, the stripes do not form. Once the primary stripe has formed, the slope becomes the principal agent of evolution.

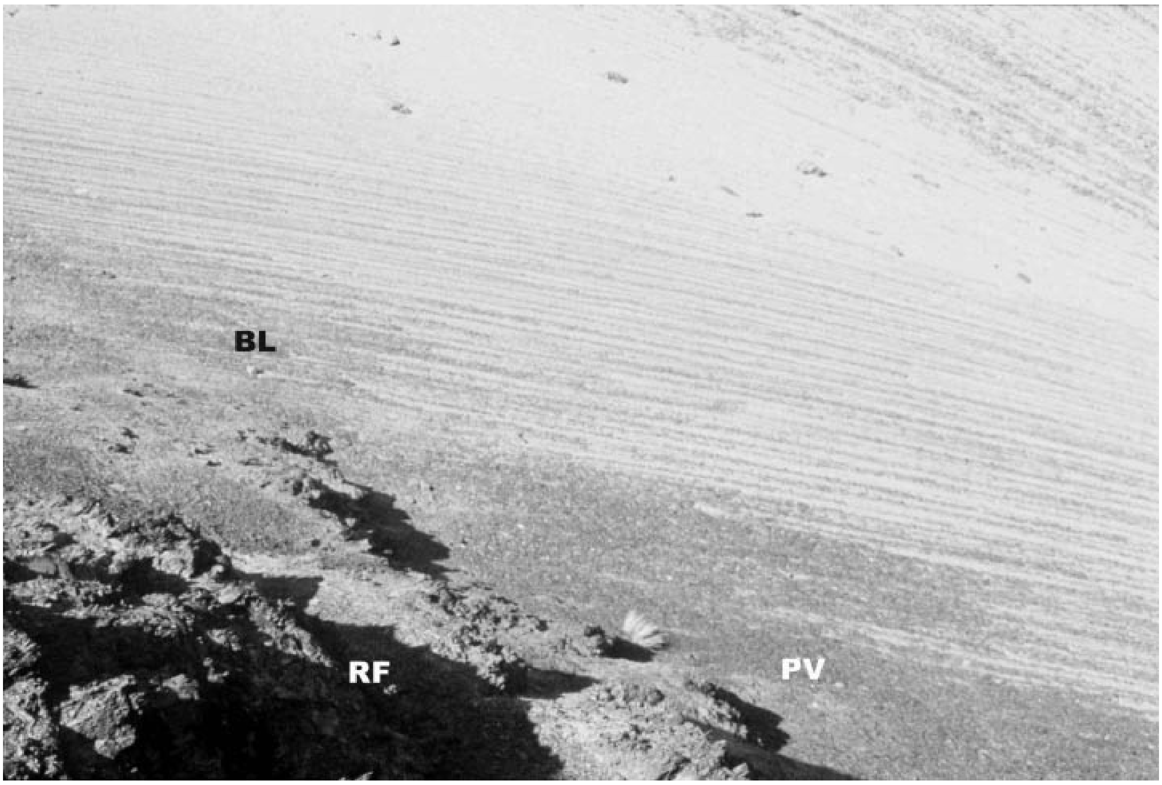

Figure 10 Formation of stripes from a continuous pavement. Note the effect of the block-size clasts (BL) in the genesis of fine stripes. Milluni-Tuni plot, 5000 masl. RF = rock face ; PV = stone pavement.

The slope factor

The slope inclination increases the displacement rates of materials at the surface. From a series of measurements conducted during five years at Chacaltaya, in the same area, Francou and Bertran (1997) found a correlation (r = 0.73) between displacement rate and the slope angle. With 25°–30° slopes, rates of displacement of 10 cm-long clasts can be as high as 100 cm.a^{-1} on fine stripes and 30 cm.a^{-1} on coarse stripes. These rates are typical of needle-ice activity. Other measurements in the same area show that the coarse stripes do not move in a homogeneous way. As a result of a pronounced lateral sorting (small materials on the borders and block-sized ones lying along the centre of the bands; see also Pérez, 1992), the fine debris moves considerably faster that the blocks because they are directly supported by a matrix where needle-ice can grow. The coarse fragments move more intermittently by frost creep and their velocity, in accordance with this process, is less than 10 cm.a^{-1}. This explains partly the relative stability of the coarse stripe geometry when slope gradient is high, because these stripes cannot expand as long as needle ice is active on the borders. As cracks are absent and cannot stabilize the coarse bands, unlike observations reported in alpine regions (e.g. Pissart, 1977), if their width decreases to less than 10 cm, they behave like a frost-susceptible surface and may disappear. It is in this way that two adjacent fine stripes can join and form a new and wider stripe. According to measurements for coarse stripes, it is likely that, for displacement rates close to 20–30 cm.a^{-1}, width ranges of about 15–20 cm represent a minimum. This is because, if the velocity increases, the risk of break-up of the stripe becomes very high. When the coarse stripes include a quantity of block-size elements (>15 cm), mean velocity decreases and the stripes survive for a longer distance downslope even if the slope increases. In this way, it can be explained why, in the large sample (n = 1500), the small spacing distances (~20 cm) are frequent even on steep slopes (Figure 5); this maintains the poor correlation between slope angle and spacing. In the same way, we can understand why on the 'warm' aspects the fine stripes are systematically wider on the steep inclinations: due to the morphology of the top surface, the production of clasts is less abundant and reduced in size compared with the 'cold' aspects where massive rock faces are frequent. With these conditions, many coarse stripes can be eliminated as slope gradient increases and fine stripes expand.

Our analysis demonstrates that, in this kind of low-latitude, alpine environment, the geometry of stripes is variable. This variability is not a consequence of a change in the frost regime in the ground, but rather a response to a clast velocity. Considering that the width of coarse stripes is almost constant, a velocity which increases implies, for the continuity of the flux of coarse materials along the slope, that the coarse stripes decrease in number. This leads to the lateral expansion of the fine stripes. A decreasing slope angle produces the opposite effect by a drop in the displacement rates: the coarse stripes expand and new coarse stripes appear in the centre of fine stripes, generated by accretion from the down-slope pavement. Thus, the superficial geometry of this patterned ground can be considered as being controlled by a ratio between the quantity of coarse materials that has to be transported along the slope, and the mean rate at which these materials move.

The convective models

This section questions the models which postulate that all sorted stripes are organized as regular wave-length patterns, that implies a physical process producing this periodicity (e.g. Ray *et al.*, 1983). Although we did not estimate the width:depth ratio in this environment, we stress that our observations conflict with these models: 1) spacing distances, particularly of the primary stripes, are too irregular to be determined by a single process deriving from frost activity in the ground; 2) stripes are more regular in the middle section due to a process of reorganization—consequence of the slope inclination, which is independent of a change occurring in the frost regime in the ground; 3) depth of freezing, in the order of 5–20 cm depending on the season, is constant in this area, as neither elevation nor aspect affects it appreciably; and 4) the depth at which the soil appears to be sorted (the assumed depth of the freezing front) is variable on slopes of the Cordillera Real. We believe that this variability does not depend only on the frost-heaving process operating on the site.

CONCLUSION

Considering the homogeneity of the environment of the Cordillera Real, where daily freeze-thaw cycles are dominant, we believe that the results of our analysis can be extrapolated to other similar environments.

As expected, the spacing distances of stripes are small, generally <40 cm, but the absence of a sharp mode, the scatter of the distribution and the presence of wide stripes (>50 cm) suggest that the factors which control stripe geometry are complex and vary between and even within sites. The geometry of primary stripes is irregular. This irregularity partly depends either on the quantity of clasts available from the upper slopes or random factors such as the presence of block-size elements. Further down the middle slope, as displacement rates increase, the fine bands tend to expand by a process of selective extinction of the coarse stripes. In the distal sector, as a consequence of decreasing displacement rates, the stone pavement tends to re-form by either the expansion of existing coarse stripes or by the formation of new coarse bands. Consequently, the geometry of sorted stripes in this environment is not the exclusive consequence of frost mechanisms in the ground. The dynamics of clast materials throughout the sloping surface have to be considered. Factors that depend on the morphology of the slopes, clast availability on the upper surfaces, and displacement rates along the slope profile cannot be disregarded.

Further research on sorted stripes should systematically observe the geometric variability of patterned ground along sloping surfaces. Particular attention should be paid to extra-tropical regions to verify if the evolution observed in Cordillera Real is specific to low latitudes or whether it occurs in other environments.

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