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A Multivariate Analysis of Clast Displacement Rates on Stone-banked Sheets, Cordillera Real, Bolivia

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ABSTRACT

Clast movements of stone-banked sheets were measured for five years at Chacaltaya (5200 m ASL) in the Bolivian Andes (16°S). This environment is characterized by frequent surficial freeze–thaw cycles and high displacement rates, up to 100 cm a^{-1} on the sheets and 30–40 cm a^{-1} on the stone banks. Multivariate analysis makes it possible to identify slope gradient, clast size, type of clast substratum (fine- or coarse-grained material) and clast morphology as the main factors controlling the movement. The material in the sheet appears to move faster than the stone bank and the stone banks have a greater velocity than the stone pavement located in the front of them. As a consequence, downslope surfaces are progressively overrun by the banks. This analysis allows quantification of the mechanisms which explain the stratified nature of slope deposits in an Andean periglacial environment. © 1997 John Wiley & Sons, Ltd.

RÉSUMÉ

On a mesuré pendant cinq ans à 5200 m d'altitude à Chacaltaya dans les Andes de Bolivie le déplacement superficiel des fragments rocheux à la surface de coulées à front pierreux qui génèrent un dépôt stratifié. Dans ce milieu à cycles de gel superficiels et fréquents, les déplacements moyens sont rapides: jusqu'à 100 cm a^{-1} à la surface des coulées et 30–40 cm a^{-1} sur les fronts de coulées. Une analyse multivariée fait ressortir le rôle majeur qu'exercent la pente, la taille des éléments, leur support (fin ou grossier) et leur forme sur les vitesses de déplacement. La coulée apparaît comme étant plus rapide que le front pierreux, et lui-même plus rapide que les éléments du pavage situés à l'aval. Les surfaces aval se font donc recouvrir progressivement par celles de l'amont, ce qui confirme les mécanismes qui sont à la base de la stratogénèse dans le milieu périglaciaire des Andes centrales. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS: stratified slope deposits; slope processes; quantification; Bolivia

INTRODUCTION

One model to explain the formation of stratified slope waste deposits in periglacial environments concerns the mechanisms occurring in stone-banked sheets (SBS) (Francou, 1988; Van Steijn *et al.*, 1995). The basic geocryological processes involved are needle-ice, frost creep/gelifluction and the frost sorting of clasts (Francou, 1990; Bertran *et al.*, 1995a). Previous studies in different periglacial environments have shown that optimal

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conditions for stratification include frequent freeze–thaw cycles in the upper 20 cm of the ground (Bertran *et al.*, 1995a). Characteristic sedimentary structures may be identified in ancient deposits, for example the Pleistocene *grèzes litées* of Western Europe (Bertran *et al.*, 1995b; Van Steijn *et al.*, 1995). In the tropical Andes, the stratified slope waste deposits have been recently used as indicators for palaeoenvironmental reconstruction (Heine, 1996).

Over the last 40 years, rates of stone displacements on sloping surfaces have been measured in a number of periglacial areas. Some of these studies concern environments characterized by frequent freeze–thaw cycles ($\geqslant 200\ a^{-1}$), such as the tropical Andes in Peru (Francou, 1989) and Venezuela (Pérez, 1987; 1993). In these high mountains, runoff plays a minor morphogenetic role because of the infrequence of rainy events, and debris transport is mainly due to frost-induced movements, as by pipkrakes, frost creep and gelifluction. To date, no systematic data have been obtained from SBS to estimate the mobility of surface debris in these environments. More specifically, it has not been possible to use direct measurements to quantify the stratification mechanisms inferred from other observations (Francou, 1990; Bertran *et al.*, 1995a), namely: (i) the formation of an openwork stone bank by sorting of a diamict and (ii) the burial of a stone bank and a downslope pavement by a matrix-rich sheet. This paper presents a series of measurements in the Andes of Bolivia over a five-year period that documents these processes.

METHODS

Measurements were restricted to the pebbles and small boulders which move on the sheet and form the bank. Three representative SBS showing evidence for different degrees of mobility (CH1, CH2ab and CH2c) were selected. Painted markers consisted of clasts with a axis > 4 cm. Sets of ten markers were identified with different colours and scattered in various sectors of the SBS, including (1) the upslope area (*sheet*), where dominantly fine-grained material is covered by a discontinuous stone pavement, (2) the *stone bank*, characterized by an openwork texture, (3) the downslope stone pavement overlying a matrix-rich material (Figure 1). The three clast axes were measured in

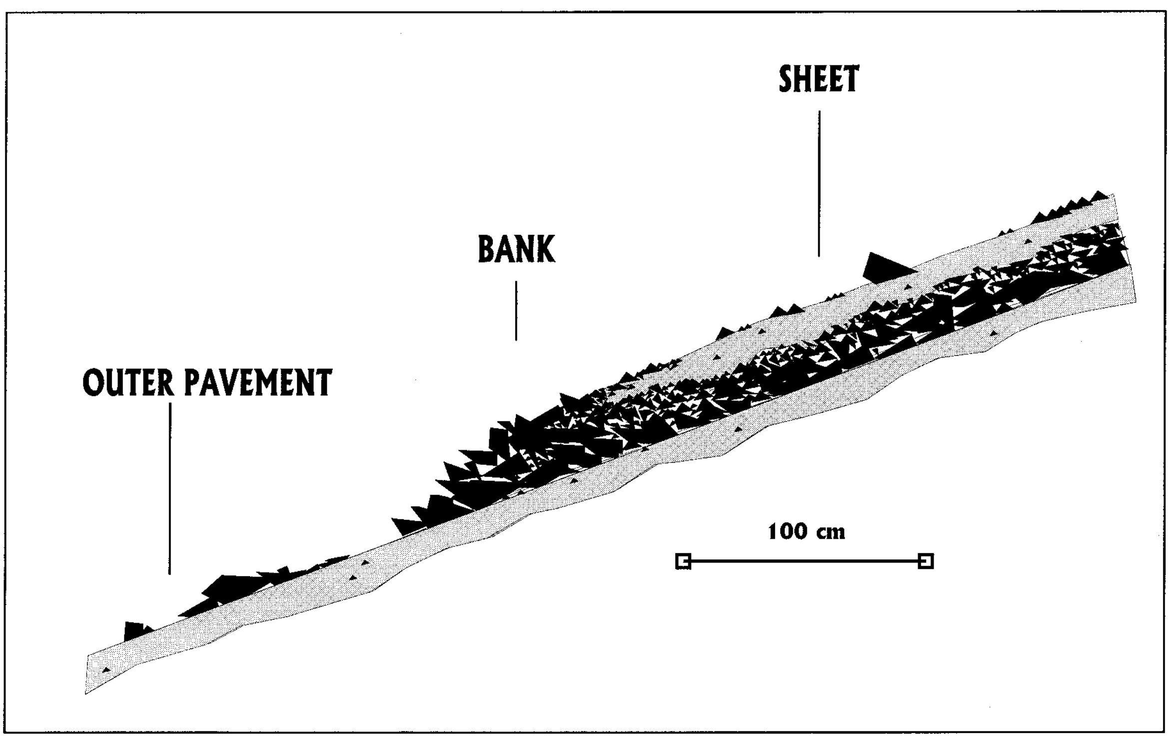

Figure 1 Stone-banked sheet: the three distinct units with painted markers.

order to calculate the geometric mean $(abc)^{0.333}$ (GM), the elongation a/b and the flatness index $(a + b)/2c$ (FLAT). The slope gradient (BETA) was taken using a two-metre rule set on the ground close to each clast and a Suunto clinometer. The nature of the substratum (SUP) was classified as either coarse (gravel to pebble: noted 1) or fine (matrix-dominant: noted 2). Table 1 presents the periodicity of the surveys. At every survey, SUP and BETA parameters were noted, as they may change with time. Over every period, monthly values of the following variables were computed: (a) *mean* and *median* of cumulated rates; (b) *standard deviation* (STD) and *coefficient of variability* (STD/mean), as parameters of dispersion; (c) *skewness* and *kurtosis* for testing the normality of the distribution, with $p < 0.05$ (Jones, 1969; Pérez, 1993). The number of painted stones found was noted for every survey to record the lost markers.

Rates were processed as cumulative values. Three considerations justify this option: (1) periods of measurement are irregular, varying from 6–13 months, and this irregularity may induce a rate dispersion which does not exist over long periods; (2) cumulative processing eliminates variability, due to random factors, as to the position of individual clasts and accidental movements; (3) many markers may be temporarily lost for a period, but may reappear in a subsequent period, and cumulative data minimize the effects of population variation. However, the cumulative approach stabilizes the rates over time and reduces the seasonal/annual variability.

Velocity rates were correlated with measured variables. Only those giving the best correlation coefficients were considered. A multiple regression makes it possible to estimate the maximum variance explained by the variables taken together. Considering the difference between the surveyed sectors, *sheets*, *stone banks* and *outer surfaces* data were processed as separate populations. As a cumulative approach tends to strengthen the relation with the selected factors in the multivariate analysis, tests were made on single periods to verify their stability with time.

The movement of the matrix-rich substratum has not been systematically analysed for these sites, but two 25 cm deep columns of coloured fine-grained sediment were placed in a sheet. This method was used before by Pérez (1985) in a similar environment – a paramo of the Venezuelan Andes – to measure fine material displacement with depth. These columns were composed of red sandy silts from the Altiplano's Cretaceous rocks. Movement was measured in a longitudinal section opened in the columns after 36 months. The microstructure of the sediments was studied in a marked sheet. On the other hand, three blocks of sediments were sampled from the upper 20 cm in the up-, mid-, and downslope parts of the sheet. Thin sections were prepared from the blocks after impregnation by a synthetic resin, and studied under an optical microscope.

STUDY AREA AND CLIMATE

Close to the Cerro Chacaltaya (5390 m ASL), the plots are accessible all year round (Figure 2). Debris comes from Palaeozoic sedimentary formations dominated by lutites and quartzites. A dense network of cracks due to tectonics and

Table 1 Periodicity of the surveys on the three plots, CH1, CH2ab and CH2c. The wet season (WS) is centred on December–April, the dry season (DS) on May–November. Month periods are cumulative.

Period/site	CH1	CH2ab	CH2c
Installation	18/12/1990	21/09/1992	12/05/1993
Final survey	02/12/1995	02/12/1995	02/12/1995
Cumulated periodicity of surveys	5.5 (WS)	8 (WS)	7 (DS)
(months) including	14 (+DS + WS)	14 (+DS)	18 (+WS + DS)
DS (dry season)	21 (+DS)	25 (WS + DS)	31 (+WS + DS)
WS (wet season)	29 (+WS)	38 (WS + DS)	
	35.5 (+DS)		
	46.5 (+WS + DS)		
	59.5 (+WS + DS)		
Total survey period (year + months)	5 years − 1 month	3 years + 2 months	2 years + 7 months

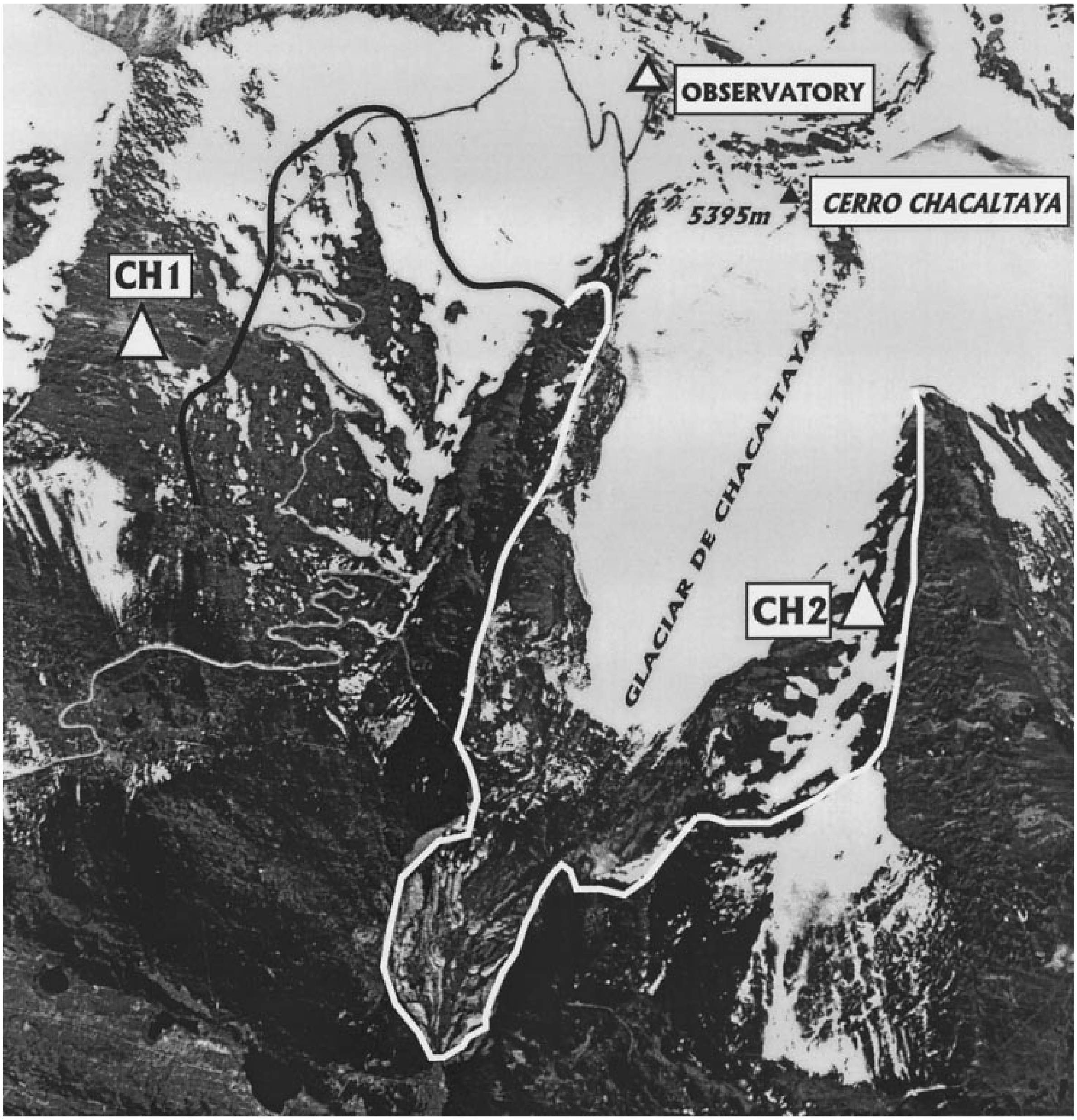

Figure 2 Chacaltaya (Bolivia): location of the two plots, CH1 and CH2. The Little Ice Age moraine contour is noted.

hydrothermal alteration make the rocks particularly frost-susceptible. The altitude of the sites (5200 m ASL) is close to the ELA of local glaciers (Francou *et al.*, 1998). The Chacaltaya Observatory's station (5230 m ASL) provided temperature and precipitation records for the last 40 years. Maximum and minimum average annual temperatures are +1.9 °C and −4.3 °C, while precipitation averages 600 mm ±200 mm a^{-1}. Precipitation occurs as snow and the wet season lasts from December to April, i.e. during the austral summer. The period from May to November, with scarce snowfalls, can be considered as a dry and cold season. A ground thermograph with eight probes from 1 cm–100 cm depth provided limited data over a three-year period. Extrapolated data indicate a minimum of 200 freeze–thaw cycles a year. The number of cycles decreases exponentially with depth, and the freezing temperature rarely occurs below 20 cm depth. The ground surface dries out rapidly owing to the high solar energy input to the ground surface – a minimum average of 300 W m^{-2} day^{-1} in clear-weather summer conditions, with maximum instantaneous values close to 1400 W m^{-2} (Berton *et al*., 1997). Snow cover rarely lasted for more than one month on the plots. This, together with the rapid drying of the ground, constitutes the principal limiting factors for freeze–thaw cycle efficiency.

The site characteristics are shown in Table 2. The plots differ in slope gradient and aspect. CH1 is assumed to be a more active sheet owing to a steeper slope and a south-west aspect: conditions are colder and wetter during the summer, but warmer during the winter. The sheet is 50 m long and fine-grained sediment is dominant on the surface. The coarse clasts are generally scattered, but in some places stone stripes form. The stone bank is poorly developed. CH2ab, a 30 m long sheet, appears to be less active for opposite reasons: the slope is 10° lower and the aspect is north. CH2c is a short (10 m) sheet, with markers only on the stone bank. CH2 sheets are bounded by more developed stone banks than CH1. Coloured columns and sampling for micromorphology were concentrated on CH2 sheets. On both sides, the sheet has a sandy silt matrix. There is strong evidence, based on Little Ice Age moraine location, that SBS formation is recent: the two plots were covered by glaciers until the second half of the last century (Francou *et al*., 1998).

VELOCITY ON THE SHEETS, STONE BANKS AND OUTER BANK SLOPES

Data shown in Tables 3 and 4 (plot CH1), 5, 6 and 7 (plot CH2ab), and 8 (plot CH2c) are computed by month. In the text, for convenience and in accordance with the literature, rates are quoted as annual values.

These results suggest the following remarks:

(1) Rates are high in the sheets, often close to 100 cm a^{-1}, with peaks as high as 200 cm a^{-1}. They are lower on the stone banks, with values close to 30 cm a^{-1} (CH1). On other plots, rates fall to 15 cm a^{-1} (CH2ab), and even to 6 cm a^{-1} (CH2c) on the stone banks. We observe that the best developed banks have the lowest rates (CH2c). Downslope, on the outer stone pavement, rates are weaker than on the stone banks (CH2ab).

Table 2 CH1 and CH2 plots: study site characteristics.

Sites	Size mean (SD) and median (cm)	Elongation mean a/b	Flatness mean $(a+b)/2c$	Slope gradient mean and range	Marker number and class of surveyed slopes
CH1	8.5 (6.6) 6.1	2.1	10.5	28° (35°–25°)	100 sheet + stone bank
CH2ab	7.4 (4.9) 6.1	1.5	11.0	19° (24°–14°)	150 sheet + stone bank + outer bank slopes
CH2c	11.0 (4.4) 10.9	1.5	11.2	28° (30°–19°)	25 stone bank

Table 3 CH1 plot, sheet: month rates are processed as cumulative values.

Cumulated period (months)	Mean (cm)	Median (cm)	SD (cm)	Coeff. of variability	Minimum (cm)	Maximum (cm)	Marker number
6	13.8	9.5	9.7	0.7	2.2	38.0	66
14	9.6	7.9	6.1	0.6	1.6	23.0	52
22	8.6	8.6	4.6	0.5	1.5	18.3	57
29	9.1	9.1	5.8	0.6	1.0	19.0	46
36	8.0	7.9	4.8	0.6	1.6	16.0	40
46	8.0	8.3	4.5	0.6	1.8	15.3	36
60	8.0	9.2	3.9	0.5	1.7	13.6	41

Table 4 CH1 plot, stone bank: month rates are processed as cumulative values.

Cumulated period (months)	Mean (cm)	Median (cm)	SD (cm)	Coeff. of variability	Minimum (cm)	Maximum (cm)	Marker number
6	3.6	3.2	1.6	0.4	1.7	6.8	20
14	2.6	2.4	1.2	0.5	1.1	4.9	21
22	2.3	1.9	1.2	0.5	0.9	5.8	21
29	2.4	2.0	1.3	0.5	1.0	6.0	20
36	2.0	1.8	0.9	0.5	0.9	3.7	19
46	2.5	1.7	2.2	0.9	1.0	8.4	17
60	2.3	1.6	1.7	0.7	0.9	6.8	18

Table 5 CH2ab plot, sheet: month rates are processed as cumulative values.

Cumulated period (months)	Mean (cm)	Median (cm)	SD (cm)	Coeff. of variability	Minimum (cm)	Maximum (cm)	Marker number
8	9.0	9.3	4.0	0.4	1.6	21.0	76
14	7.8	7.2	3.1	0.4	1.8	15.9	59
25	8.5	9.3	2.9	0.3	1.5	13.8	66
38	7.5	7.5	2.9	0.4	1.1	13.2	64

Table 6 CH2ab plot, stone bank: month rates are processed as cumulative values.

Cumulated period (months)	Mean (cm)	Median (cm)	SD (cm)	Coeff. of variability	Minimum (cm)	Maximum (cm)	Marker number
8	3.2	1.9	3.8	1.2	0.2	13.4	28
14	2.4	1.7	2.1	0.9	0.3	7.9	28
25	1.9	1.6	1.3	0.7	0.3	5.0	27
38	1.2	1.1	0.8	0.7	0.1	3.2	26

Table 7 CH2ab plot, outer bank slope: month rates are processed as cumulative values.

Cumulated period (months)	Mean (cm)	Median (cm)	SD (cm)	Coeff. of variability	Minimum (cm)	Maximum (cm)	Marker number
8	1.0	0.7	1.0	1.0	0.1	3.9	32
14	1.8	1.2	1.7	0.9	0.3	7.9	38
25	1.4	1.2	0.8	0.6	0.6	3.4	38
38	1.0	0.8	0.7	0.7	0.2	3.1	39

Table 8 CH2c plot, stone bank: month rates are processed as cumulative values.

Cumulated period (months)	Mean (cm)	Median (cm)	SD (cm)	Coeff. of variability	Minimum (cm)	Maximum (cm)	Marker number
7	0.6	0.3	0.7	1.2	0.0	2.9	18
18	0.7	0.4	0.7	1.0	0.0	2.2	17
31	0.5	0.5	0.4	0.8	0.1	1.3	15

Table 9 CH1, sheet and stone bank: mean rates (cm/month) are calculated on fractioned periods. Wet season (WS) is centred on December–April, dry season (DS) on May–November. Month numbers from 18 December 1990.

	Seasons and months						
	WS 0–6	DS + WS 6–14	DS 14–22	WS 22–29	DS 29–36	WS + DS 36–46	WS + DS 46–60
Sheet	13.5	5.9	8.6	12.5	5.1	11.3	12.0
Stone bank	3.6	2.0	1.6	2.8	1.9	5.5	2.1

(2) Rates tend to be higher during the wet season (austral summer). This is obvious if the values are calculated on fractioned periods (Table 9). During the wet season, snowfalls are frequent and melting occurs in a few hours. Therefore, moisture is abundant and freeze–thaw cycles occur every day. Rates may be two times higher than during the dry cold periods. This appears to be more evident on the sheets than on the stone banks. Statistical tests show that seasonal differences are significant in both cases ($p < 0.05$).

(3) Rates are always scattered, as indicated by high standard deviations and coefficients of variability and extreme ranges. We can observe that dispersion is generally greater on the stone banks, suggesting that the markers do not move *en masse* but individually. On the sheets, rates are normally distributed, while on the stone banks a clear positive skewness (asymmetry toward small rates) can be detected.

MULTIVARIATE APPROACH TO RATE VARIABILITY

Here, we focus on the variables which control rate variability. The cumulative total of measurements allows us to verify the stability of variables with time. The most significant variables are *size* (GM), *flatness* (FLAT), *substratum* (SUP) and *slope gradient* (BETA).

Plot CH1

The four variables are well related to velocity rates over three years, with a multiple correlation coefficient as high as 0.80 (Figure 3). Nevertheless, the differences observed between the total population (sheet + bank) and the sheet markers suggests a distinct behaviour between sheet and stone bank.

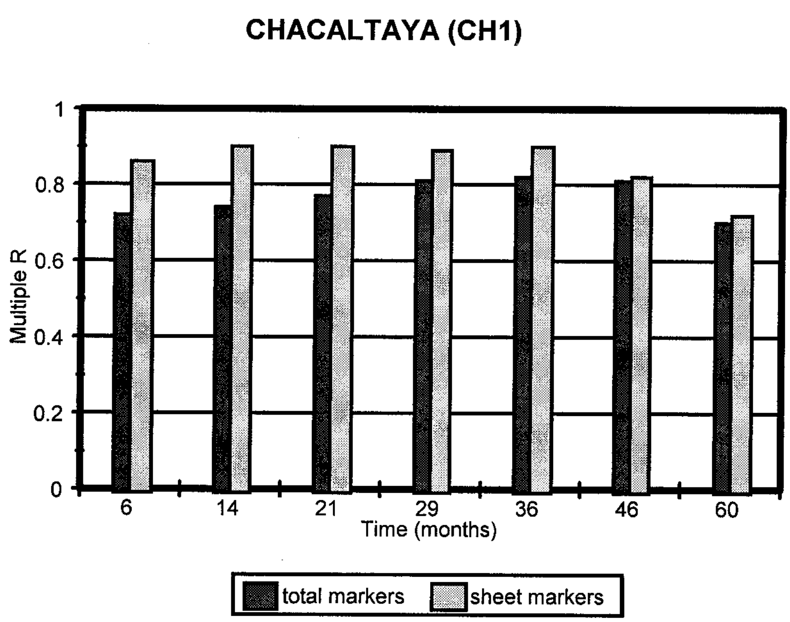

Figure 3 CH1: the multiple R coefficient calculated between velocity rates and the four variables GM, FLAT, SUP, BETA.

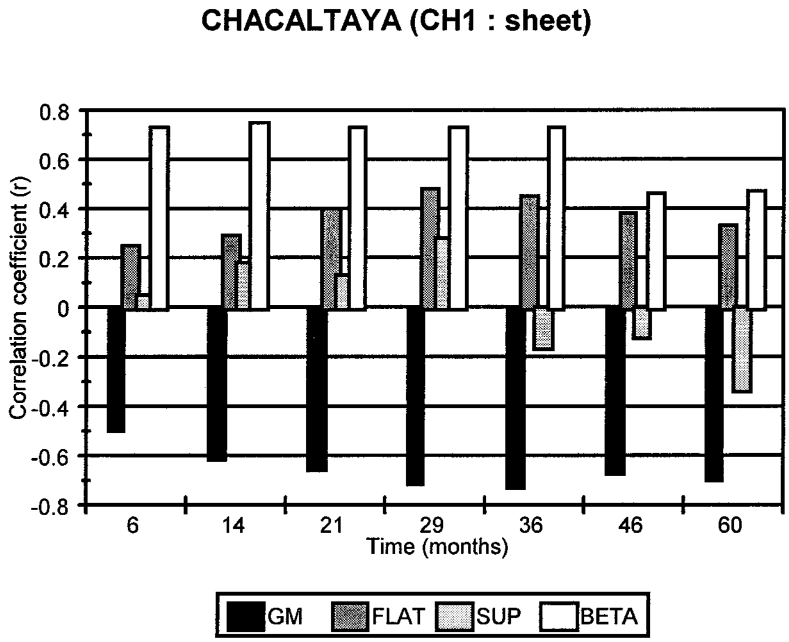

Figure 4 CH1: correlation coefficients between velocity rates and the four variables in the sheet.

In the *sheet* (Figure 4), computed correlation coefficients between velocity rates and each variable as a function of time show that slope gradient (BETA) and size (GM) are the most important variables ($r = 0.73$ and $r = -0.73$ respectively, over three years). Clast morphology (FLAT) remains significant, but correlation with substratum (SUP) is low, and negative after the first three years. This is because markers tend to change their substratum, either by concentrating on stone stripes, or by coming near to the stone bank where the texture becomes openwork. The best relation between velocity and the four variables after 36 months can be approached through the following equation:

$$\text{VELOCITY}_{\text{sheet}} = -9.834 - 0.278\text{GM} + 0.051\text{FLAT} + 0.126\text{SUP} + 0.705\text{BETA} \quad (1)$$

where multiple $R = 0.90$ (significant at 0.001 level), $n = 40$, $T = 36$ months.

On the *stone bank* (Figure 5), the low correlation coefficients with the four variables suggest a different behaviour. The smallest and flattest clasts tend to move rapidly, but BETA is negatively correlated. This can be explained by the morphology of the bank: on the steepest (external) part, clasts are imbricated and blocked in a quasi-static position (see Figure 1). The substratum has lost any influence, because the texture of the bank becomes openwork downslope.

Multiple regression equations were also calculated on each separate period from the same population ($n = 40$, excluding the markers lost during one interval) in order to verify the stability of the variables over time. Multiple R maintains high values (> 0.70) over 30 months, before a drop due to a decrease in SUP and BETA correlations.

Plot CH2ab

On the *sheets*, the best relation between rates and the four variables (Table 10) appears at the last survey (36 months), with a multiple R value of 0.83 (significant at 0.001 level; $n = 64$; $T = 36$ months). The multiple R is lower in this plot owing to the low correlation between clast size and rates ($r = -0.27$). The relative homogeneity of the debris (Table 2) could explain why size is not relevant here. As a consequence, slope gradient becomes the main factor. On the stone banks CH2ab and CH2c, the part of the variance explained by the four variables falls to 40%. None of the four variables significantly controls the velocity rates.

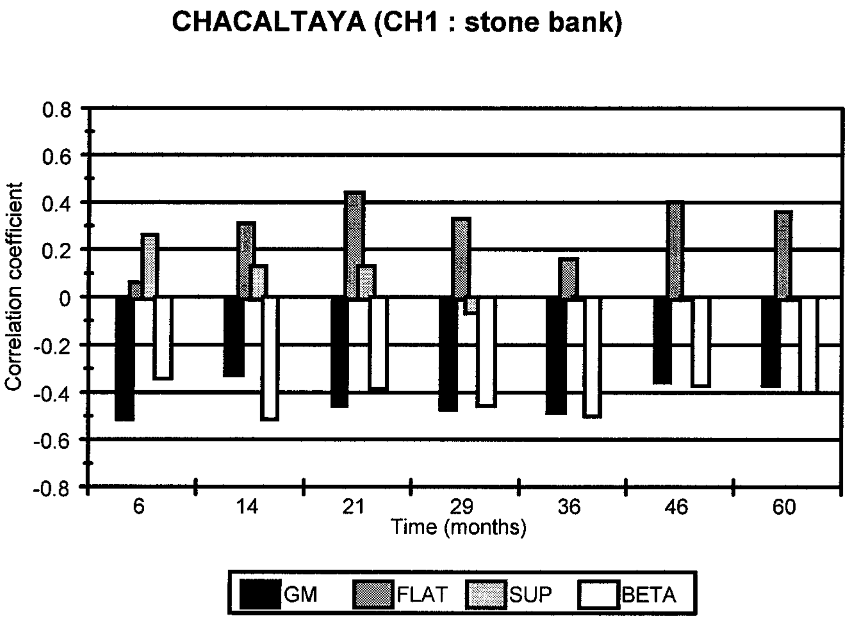

Figure 5 CH1: correlation coefficients between velocity rates and the four variables in the stone bank.

Table 10 CH2ab plot, sheet: correlation coefficients between velocity rates and the four variables.

Months	GM	FLAT	SUP	BETA
36	−0.27	0.37	0.26	0.74

MOVEMENT WITH DEPTH

At the surface, the coarse fraction of the coloured columns spread out downslope over 3 m. At depth, from 5 cm to 15 cm, columns have been broken into several pieces, all showing diffuse limits. Below 15–18 cm, only a slight deformation could be detected and contours were clear. These results are consistent with those obtained by Pérez (1985) in Venezuela. Two types of microstructures can be distinguished in thin sections: (1) in the upper 5 cm of the matrix-supported sandy silt sheet, porosity is composed of poorly interconnected elongated vesicles (Figure 6a and b); (2) below this unit, well developed platy aggregates are separated by smooth planar voids (Figure 6c). As for similar sheets and lobes investigated in this area (Bertran *et al.*, 1995a), the fine particle content of the sheet decreases toward the stone bank (clast support). The clasts are capped by, or embedded with, silt accumulations, whereas the interstitial matrix becomes dominantly sandy.

DISCUSSION

This analysis confirms the high clast velocity in Andean environments with a high frequency of freeze–thaw cycles. For similar slope gradient, the rates obtained in Chacaltaya's SBS rank among the most rapid that have been measured (for some comparative data, see Pérez, 1987, p. 49; and Francou, 1989). Slope gradient is an important factor, but clast size and morphology, as well as the nature of the substratum, also appear to be significant variables for clast mobility. This suggests that pipkrakes have a predominant role on clast displacement. In the case of a purely passive transport of clasts by solifluction of the matrix-rich substratum, the size and morphology of clasts would not have such an influence. On the other hand, for clasts >4 cm (*a* axis), measured rates are too high to be attributed to runoff, particularly in the absence of channels (Kirkby and Kirkby, 1974; Poersen, 1987). Moreover, the highest rates occur during the wet season, when

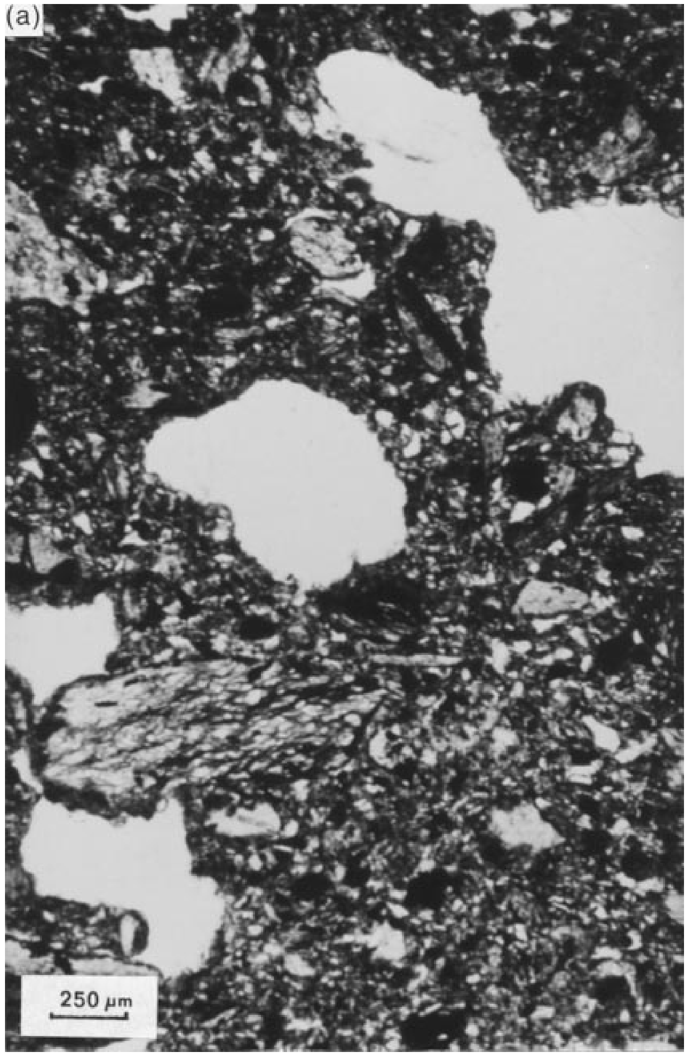

Figure 6a.

freezing remains close to the surface and favours needle ice activity.

Microscopic analysis clearly shows the role of ice lenses in the matrix-rich sheet, as indicated by platy microstructures. These probably form during winter when the frost layer can extend up to 10–15 cm deep. In the upper 5 cm of the sheet, the soil aggregates tend to collapse and give birth to vesicular voids. Because of the lack of rain at this high-altitude site, such a structure obviously reflects oversaturation following ice melting and the associated rapid soil deformation (gelifluction) (Harris *et al.*, 1993; 1995). This process is probably responsible for the minimum rates, close to 10–15 cm a^{-1}, that have been measured, particularly for boulder-size clasts. The grain size of the matrix-rich sheet progressively becomes sandier and less frost-susceptible toward the stone bank as a consequence of the washing out of fine particles. Velocity decreases and movement is mostly due to frost creep. On the stone banks, rates are variable, positively skewed and negatively correlated with slope gradient. This suggests individual displacements decreasing toward the external part of the bank where clasts are blocked and imbricated (Francou, 1990; Bertran *et al.*, 1995a). In the case of rapidly moving stone-banked sheets (type 1: CH1), the stone bank is poorly developed and moves on the slope with a velocity close to 30 cm a^{-1}. By contrast, type 2 sheets (CH2) have a thicker

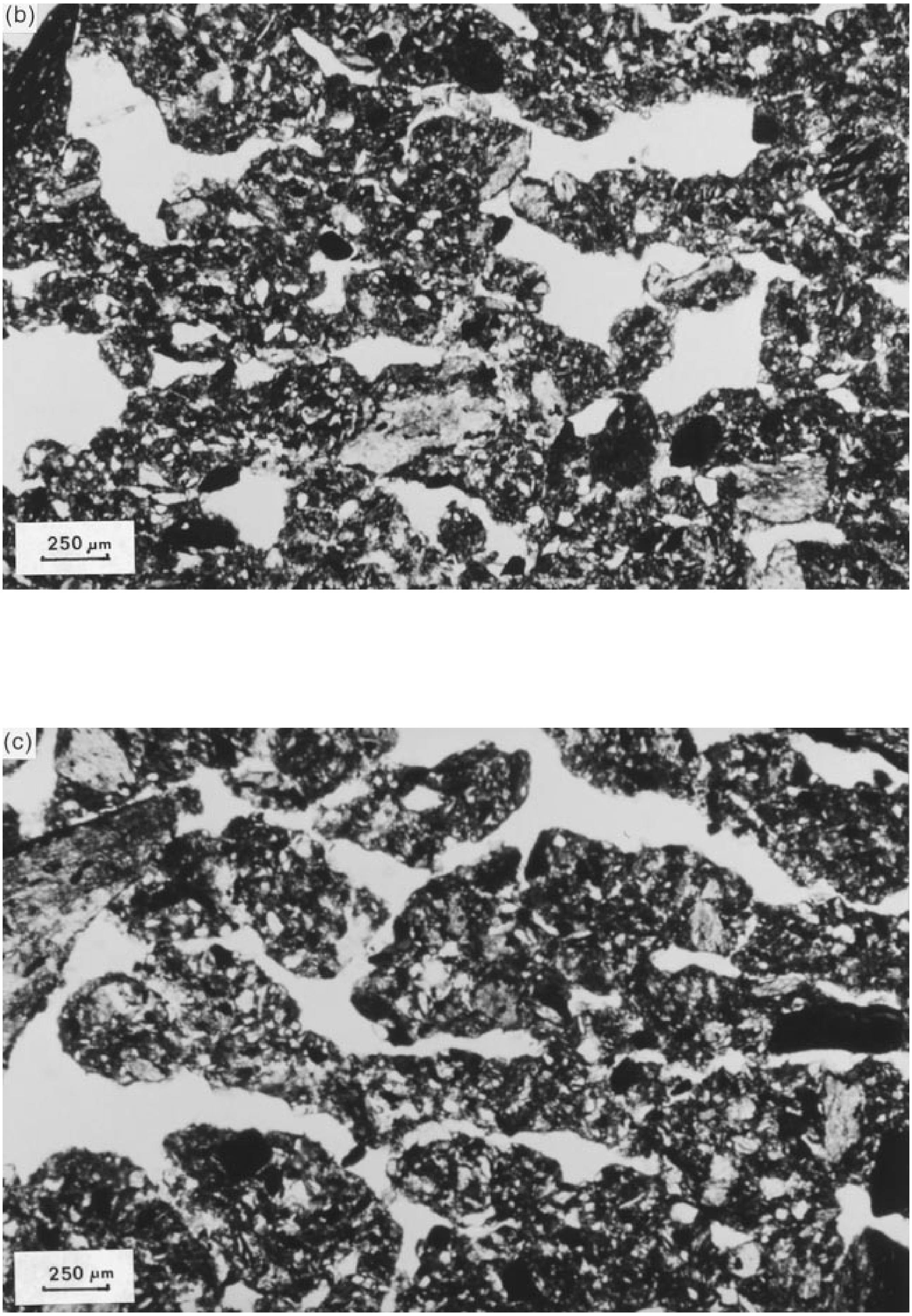

Figure 6b and c.

Figure 6a–c. Microstructures in the upper part of the sheet. Thin section, natural light. Depths: (a) 2 cm (b) 4 cm (c) 7 cm.

openwork front and rates as low as 10 cm a^{-1}. Similar measurements on type 2 stone banks at 5200 m ASL have also been made in the central cordillera of Peru (Francou, 1989). Since rates are comparable on type 1 and type 2 sheets, the differences in front velocities and development probably result from washing of fine-grained particles. Ahead of the stone bank, on the pavement slopes, rates range from 10–15 cm a^{-1}. Stone-banked sheets can be considered therefore as a morphodynamic system with the slower units located downslope. This explains the stratification process.

Assuming that past rates are similar to present rates, the calculated distance covered in 150 years (probable maximum age of these sheets) reaches 45 m for CH1 and 25 m for CH2ab. These values are consistent with the total length of the sheets, i.e. 50 m and 30 m respectively. These deposits are the first to overlie the till which forms the downslope pavement.

CONCLUSION

The analysis of displacement rates on the stone-banked sheets in the central Andes permits quantification of the mechanisms previously described by Francou (1988; 1989; 1990) and Bertran *et al.* (1995a). The deposition of openwork and matrix-rich layers results from the downslope displacement of stone-banked sheets with velocities ranging from 5–30 cm a^{-1}. Movement is mainly caused by pipkrakes, together with frost creep and gelifluction. Between 70% and 80% of the variance of movement is explained by four variables, which include clast size and slope gradient as principal factors. This overall simplicity is assumed to be due to the particularities of the tropical periglacial environment, i.e. a high frequency of surficial freeze–thaw cycles favouring needle-ice formation. Unlike mid–latitude alpine environments where runoff due to summer rainfall and cryoturbation associated with deep seasonal freezing usually interfere with solifluction, conditions are optimal for large stone-banked sheets to develop. This explains why stratified slope deposits are widespread in the low-latitude mountain regions.

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