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Stratification Mechanisms in Slope Deposits in High Subequatorial Mountains

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ABSTRACT

An analysis of the processes active in the frost environment of high subequatorial mountains makes it possible to propose a model for the stratification of slope deposits. Bedding is generated by solifluction sheets which move at the speed of a few cm y^{-1}. Solifluction involves needle ice, frost creep and gelifluction, and the ground thickness concerned is less than 20 cm. Sorting takes place by frost heaving. Coarse particles are concentrated at the front of the sheets, where matrix materials tend to be washed away, and are then buried by the advancing fine layer. Sedimentary characteristics allow recognition of several diagnostic features which can be used to indicate the origin of bedding in relic slope deposits situated in mid-latitudes. This model offers an alternative to earlier concepts of the stratification of slope deposits, but further studies are required, since other processes may also generate similar bedding features.

KEY WORDS: Stratified slope deposits High mountains Equatorial Andes Frost action

RÉSUMÉ

Sur la base d'une analyse des processus et des mécanismes actifs dans le milieu cryonival de la haute montagne subéquatoriale, on propose un modèle de mise en place de la stratification dans les formations de pente. Le litage est produit par des coulées de solifluxion qui descendent à une vitesse annuelle de quelques centimétres. La solifluxion est engendrée par les actions de la glace d'exsudation, de la cryoreptation et de la gélifluxion. L'épaisseur de sol concernée est inférieure à 20 cm. La sélection des particules s'opère au cours de la descente par cryo-expulsion de la phase grossière. Cette dernière se concentre sur le front de la coulée où la matrice tend à être lavée par les eaux de ruissellement, puis elle est ensevelie sous l'effet de l'avancée de la semelle fine. En analysant en parallèle la nature du sédiment, on parvient à mettre en évidence quelques marqueurs du mécanisme de litage. Ainsi, on peut utiliser ces derniers pour diagnostiquer l'origine de la stratification des formations de pente fossiles des latitudes moyennes. Des arguments existent pour suggérer que ce modèle peut constituer une alternative aux hypothèses classiques; mais d'autres études s'avèrent nécessaires, car il existe toute une gamme de processus pouvant être á l'origine de la stratification.

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INTRODUCTION

The term 'stratified slope deposit' refers to detrital materials which present an alternation of beds arranged by distinct grain size sorting (Dewolf, 1988). Beds maintain the same granulometric properties for at least several metres; thus, contact between two consecutive layers is clear and sharp. Four types of beds have been recognized by authors according to the proportion of matrix—i.e. the fraction with particle diameter <2 mm present in the material (Wasson, 1979; Coltorti *et al.*, 1983): (1) openwork beds, (2) partially openwork beds, (3) clast-supported beds, (4) matrix-supported beds. For the sake of convenience, we have termed the open type *openwork beds* and the fine enriched layers *matrix-rich beds.*

Bedding is present in a wide range of slope deposits. Using physiognomic and genetic criteria, one can distinguish (Dewolf, 1988; Francou and Hétu, 1989):

Stratified Screes

These are distinguished by a slope gradient >30°, a marked heterogeneity of material and the possible intervention of gravity-induced mechanisms (rockfall and grain flow) as factors producing the bedding.

Deposits of Grèzes-litées Type

These have a gentler slope gradient (from 28-30° to less than 5°), a greater homogeneity in the granule and sand fraction, and bedding development unrelated to individual falls and dry avalanches.

Bedded slope deposits have been reported from a range of cold environments, including the margins of zones which have been glaciated during the Pleistocene in Europe: Mediterranean borders (Tricart, 1956; Raynal, 1960; Andriès, 1980; Coltorti *et al.*, 1983; Van Steijn *et al.*, 1984); Atlantic margins (Guillien, 1951; Watson, 1965; Journaux, 1976; Boardman, 1978); and Central Europe (Dylik, 1960).

More recent studies have been conducted in high mountain environments of mid- and low latitudes, such as the Mediterranean mountains (Raynal, 1970; Soutadé, 1980; Vergès, 1982), the Tibeto-Himalayan area (Wasson, 1979; Francou *et al.*, 1990) and Andean Cordillera from subtropical (Lliboutry, 1961) to subequatorial zones (Francou, 1988a). Active examples have also been reported from temperate forest zones where cold winters and thick snow cover occur, as in Gaspésie (Hétu, 1986), and a few cases exist in Alpine high mountains (Francou, 1988b). In high latitudes, stratified deposits seem to be poorly represented. Nevertheless, some grèzes litées or bedded screes have been described from Svalbard (Jahn, 1960; Dutkiewicz, 1967), Western Greenland (Malaurie, 1968) and Southern Banks Island (French, 1976). The distribution of these deposits in cold environments tends to point to the role of frequent freeze-thaw cycles as a major process in the occurrence of stratification. Moreover, many oscillations of temperature around the freezing point are essential to allow efficient frost shattering and to produce a granulometric fraction as fine as that observed in the martrix (Lautridou, 1984). Logically, it seems likely that frequent frost plays a role in the development of rhythmic layering.

Many theories have been proposed to explain the origin of stratification, but very few have embodied field or laboratory experimentation (French, 1976; Washburn, 1979; Francou, 1988b). To simplify, two types of hypotheses are available, according to whether it is considered that the differentiation of consecutive beds is interdependent or not.

One group of explanations claims that deposition of openwork and matrix-rich beds are distinct both in time and in the processes involved. Matrix-rich units are attributed to solifluction *sensu lato* or to fast debris flows, whereas open-type layers are due to one process, or a complex combination of various processes, such as rockfalls gliding along a regular plane formed by snow cover or ice-cemented talus surfaces (Tricart and Cailleux, 1967; Andriès, 1980; Van Steijn *et al.*, 1984) or dry avalanches involving a grain flow mechanism (Wasson, 1979). The rhythm of such alternations would follow, more or less, a seasonal trend. The two major criticisms of these hypotheses are: (1) that they neglect mechanical conditions of movement of matrix-free particles, especially on slope gradients below 30°; (2) they demand for each prevailing process distinct and alternating periods whose length of time is unknown.

The second set of concepts considers bedding as the result of a progressive differentiation of granulometric fractions during transit along the slope, but various authors differ on the prevailing processes involved in the sorting of debris. Guillien (1951, 1964) invokes running water carrying selectively coarse and fine particles, while Journaux (1976) suggests only the washing out of the fine fraction. A complex combination of gelifluction, slope wash, slow creep of matrix-free particles and cryocomminution working at depth is proposed by Malaurie (1968) and Soutadé (1980). In these processes, matrix and coarse particles separate and move independently downwards (Vergès, 1982).

This paper presents the analysis of an active stratification process. Research was conducted at three levels: (1) identification of processes active on the ground, (2) reconstitution of stratification mechanisms and measurement of the bedding rate, (3) investigation of the sedimentological character of bedding. The study focuses on active deposits present in the subequatorial environment of the high Andes, but the extension of conclusions to other zones is also discussed.

STUDY AREA AND DATA COLLECTION

Field research was conducted in both the Andes of Peru at 12 °S and the Andes of Bolivia at 16 °S (Figure 1). At these latitudes, the Andes present the typical characteristics of high mountains near the Equator (Dollfus, 1965; Troll, 1968; Francou, 1988b). Mean temperature is almost constant through the year, with a small seasonal range, but diurnal thermal contrasts are strong. Snow cover is ephemeral, especially on sunny northeast-facing slopes, and annual precipitation is 600-800 mm. The periglacial zone is poorly developed at altitude, since the 0 °C isotherm is set at 4900-5000 m a.s.l. and the firn line is close to 4900-5300 m a.s.l., according to aspect. Slope processes are especially active at 4600-4800 m altitude, where freeze-thaw cycles occur every day at ground level. Stratification occurs only in frost-susceptible rocks which yield small clasts and an abundant fine fraction. Andesites, dacites, rhyolites, ignimbrites, schists and limestones are the principal lithologies concerned, although other rock types are frost-susceptible, owing to shattering by seismotectonic events and alteration by hydrothermal events. Data were collected in three ways: (1) by continuous measurement of temperatures in air, soil and rock from sites at altitudes between 4700 m and 5500 m (Francou, 1988b, 1989); (2) by measurement of displacement of material on slopes for 1-5 years (Francou, 1988b; Francou and Bourgeat, 1988); (3) by sedimentological and micromorphological analysis of sections in active and inactive stratified deposits.

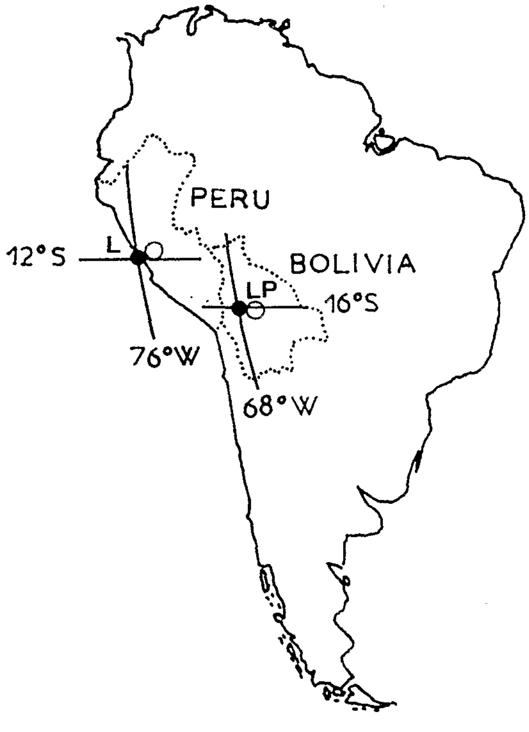

Figure 1 Study area (open symbols) near Lima (Huamapr) and La Paz (Chacaltaya).

SOIL MOVEMENT PROCESSES AND DIURNAL FREEZE-THAW CYCLES

The Freeze-Thaw Cycle in Subequatorial High Mountains

Measurements in Peru support investigations conducted in the low-latitude Andes (Troll, 1958; Graf, 1971; Hastenrath, 1977; Schubert, 1979; Pérez, 1984). At 5000 m a.s.l., on the northeast-facing slope of Huampar (Francou, 1988b), minimum air and soil temperatures were measured every day during the wet and dry seasons (Table 1). Temperatures rose every day to positive values on all probes, so freeze-thaw cycle frequency between the soil surface and 5 cm depth is 100 % throughout the year. Owing to an average precipitation occurrence of 170 days y^{-1} (Francou, 1983), the efficiency of cycles is assured on at least 200 days y^{-1} close to the soil surface. However, the freezing plane penetrates down to 10 cm on fewer than 3 days out of 10, and fewer than 2 days when moisture is present. Thus, under present conditions, the frost layer cannot exceed 15-20 cm in depth (Francou, 1989) although at the same altitude, on south-facing

Table 1 Range of minimum shade and soil temperatures measured at Huampar site. Soil consists of gravel with sandy matrix.

Site of measurement slope gradient: 10°	Minimum average in 1982 (wet/dry season)	Minimum absolute in 1982
Air	−3 °C/−5 °C	−6 °C
Soil surface	−6 °C/−12 °C	?
Soil − 5 cm	−1 °C/−5 °C	−6 °C
Soil − 10 cm	1 °C/−1 °C	−1 °C
Soil − 50 cm	3 °C/ 5 °C	1 °C

slopes, soil can freeze continuously for periods of about a week (Francou, 1988b).

Moisture and Runoff

Snow or 'granizo' (soft hail) cover the ground surface with an average frequency of close to 60% from December to March. However, snow thickness does not exceed 15-20 cm and melting usually occurs after 3-5 h, with snow melt and thawing of segregation ice formed near the surface combining to supply an important and repeated water discharge. This moisture allows needle ice to develop. Part of the meltwater runs off along the slope and washes away fine particles. With a maximun runoff rate of 2 mm h^{-1} (estimates for complete melting in 3 h), discharge cannot initiate rills or gullies on the slope. Thus, except for rare debris flows triggered by rainstorms, the ground surface only displays wash-induced patterns.

Ice Segregation in soil

In this kind of frost environment, needle ice activity has long been recognized by authors as the most important agent of soil disturbance (Lliboutry, 1961; Lawler, 1988). Indeed, pipkrake activity is evident in the ground surface, especially during the wet season. According to measurements made on a 5-10° fine-grained slope from 1982 to 1985 (Francou, 1988b), pipkrakes have moved 5-10 cm (*a*-axis) pacticles downslope by 3-35 cm y^{-1} (median: 6 cm y^{-1}). On a 28° slope, displacements for 1982-1983 were in a range of 20-70 cm y^{-1} (median: 32 cm y^{-1}). Pipkrakes play an important role, in combination with slopewash, in forming small sorted stripes which are common patterns in this type of periglacial environment.

Evidence of small ice lens structures near the ground surface triggering slow frost creep has been seen, a process which has not been mentioned before in cold environments near the Equator. Typical frost creep fabrics were detected by analysis of soil microstructures, which turn to gelifluction when water content increases and approaches saturation (Van Vliet-Lanoë and Francou, 1988). On the same marked plots of 10° angle slope, downslope movement for 10-30 cm particles controlled only by frost creep was in the range 1-3 cm y^{-1} from 1982 to 1985. During the wettest periods, the upward movement of meltwater to the freezing plane is very important. Instead of isolated needle growth, a 'frost crust' develops in coarse sand and gravel, with a few fine particles cemented by ice and forming a 3-5 cm thick crust lying at the soil surface or a few centimetres beneath.

Evidence of Slopewash Action

Measurements of direct removal by slopewash action are not available but the efficiency of this process is deduced from patterns resulting from removal of the fine fraction (sand and <50 μm particles). Two principal patterns were observed on slope surfaces:

(i) Sorted stripes (Figure 2): small stripes are the most common, but large stripes also occur behind isolated blocks. Pebbles and blocks are sorted by frost, while the openwork texture of the coarse stripes is due to slopewash.
(ii) Stone banks (Figures 2 and 3): in places openwork girdles result, in part, from wash action.

These patterns indicate that the slightest modification in water drainage along slopes, such as an obstacle or a local steepening of the gradient, is sufficient to increase small-size particle eluviation. Once formed, the open coarse surfaces move at a lower rate than do matrix-rich surfaces.

MECHANISMS OF SEGREGATION IN MATRIX-COARSE FRACTIONS AND BEDDING DEVELOPMENT

Clast Supply and Origin of Matrix

Temperature measurements on rock faces at 5150 m a.s.l. conducted in Huampar area (Peru)

Figure 2 Segregation of granulometric fractions just beneath the free face in a talus slope: fine-grained sheets with small sorted stripes on the surface; isolated blocks with stone stripes above and fine stripes below; openwork stone banks with imbricated clasts. Slope gradient: 20°. Chacaltaya (5000 m).

(Francou, 1988c) have identified the low intensity and surficial character of frost penetration. The lowest temperatures did not exceed −5 °C and freezing temperatures did not occur below 20–25 cm in depth. Therefore, only surface rocks weakened by alteration and microfractures are removed by frost shattering. Laboratory tests conducted in the Centre de Géomorphologie, Caen, on various rocks from the studied zones have shown that, with fast freezing and a minimum temperature of −3 °C, as at 5000 m a.s.l. in Peru, only rocks which exceed 10% porosity are frost-susceptible after 1000 cycles (Francou, unpublished data). Such rock faces are common in the studied zones and directly yield small fragments and matrix-size materials, as shown in Figure 4. On the other hand, the supply of blocks which form the coarse talus slopes suggests more severe climatic conditions in the past. A patina of dark iron and manganese formed by weathering on walls and large detached clasts indicate the past activity of frost-shattering in less porous rock types (Francou, 1989).

Segregation of Coarse Particles and Matrix

Once released from the rock face, debris becomes sorted and organized into stone-banked sheets or lobes (Figures 4 and 5). The principal agent producing the segregation of coarse particles is frost heaving, as observed in the field by Lliboutry (1961) and experimentally by Corte (1963). Transport by needle ice and frost creep continues for coarse particles on sloping surfaces. They finally concentrate in a girdle at the downslope end of a slope segment (Figures 3 and 5). The coarse bank is washed by runoff and takes on an openwork fabric. At depth, the fine layer ends in the coarse bank and generally presents a bevelled pattern (see Figure 6). Stone banks often exhibit a double sorting, with the largest particles situated at the front of the lobe and with stone size decreasing with depth. The first sorting occurs because coarse particles are supported by an inner fine layer and are carried forward by frost-induced processes. Once at the front, the smallest particles are sieved progressively and vertical sorting appears.

Advance of the Stone-banked Sheet and Development of Bedding (Figure 6)

The debris mass is differentiated at the front of the sheet, with an upper openwork layer and a lower matrix-rich layer. Front advance progressively buries the openwork coarse particles beneath the matrix-rich layer (Figure 6) and coarse particles, previously heaved towards the surface and concentrated at the front of the banks, are found beneath the matrix-rich layer and form a lower openwork bed. At the same time, while some of the matrix material serves for the advance of the sheet, some is washed out and moves forward. Therefore, movement of the front depends on the supply of matrix material and the dynamics of ice segregation inside the sheet. If both factors decrease, matrix eluviation increases in the stone bank and the front stops. Another front could then develop and pass over the former.

From painting marks on blocks on the sheet front, attempts have been made to measure the movement and rate of bedding development

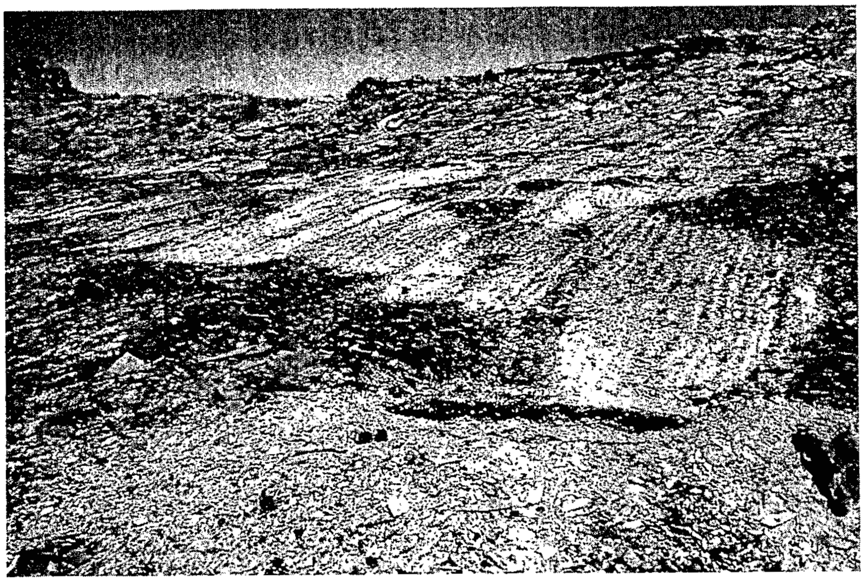

Figure 3 Section in the frontal stone bank showing stratified structure. Note the wavy pattern at the base of the matrix-rich layer. Thickness: 5-10 cm. Same site as Figure 2.

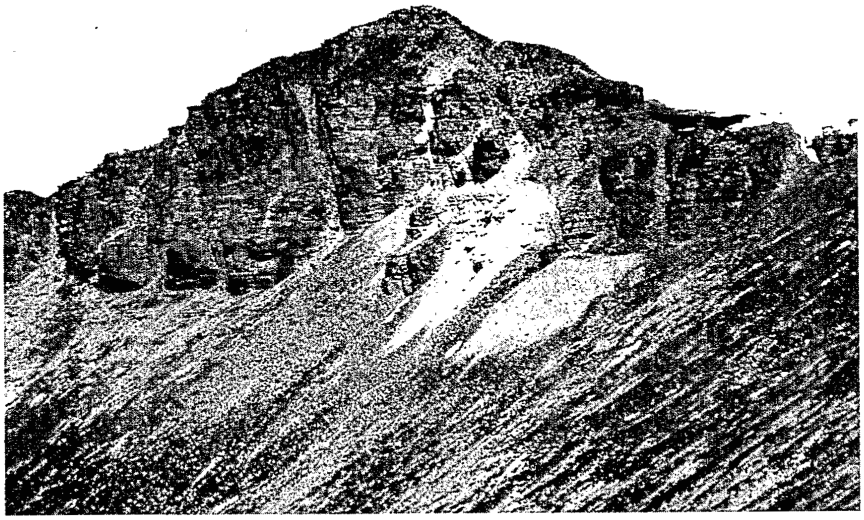

Figure 4 Development of a fine-grained sheet from matrix-size materials directly released by headwall (altered Silurian lutites).

(Francou, 1988b; Francou and Bourgeat, 1988). Table 2 presents the results from three plots close to 5000 m a.s.l. in Peru. If the rate remains constant over a long time scale, these velocities suggest that complete bedding development from one sheet on a 200 m long slope would require about 1000 years. However, sedimentation rates of stratified slope deposits may be faster, since stone-banked sheets are often grouped in convoy, as shown in Figure 7.

Figure 5 Stone-banked lobe at Huampar (4860 m) Height of stone bank: 80 cm. Thickness of surficial matrix-rich layer: 10 cm. Movement measured at front: 1-3 cm y^{-1} (1985-1987).

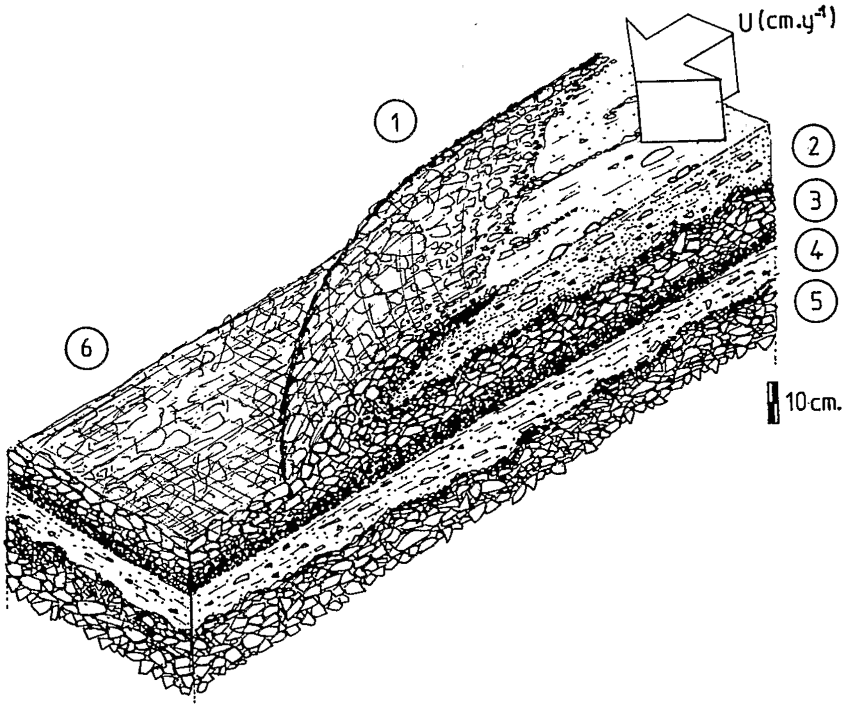

Figure 6 Section in the front of a bedded stone-banked sheet. (1) Stone bank with an openwork fabric and longitudinal sorting. (2) Fine-grained sheet with surficial moving blocks and sorted stripes. (3) Superposition of the coarse fraction of the front and the surficial blocks of the former sheet. A new openwork bed with double vertical sorting. (4) Matrix-rich bed of the former sheet. (5) The lower openwork bed with normal sorting. (6) Former coarse and non-active sheet which forms a 'threefold unit' (5 + 4 + part of 3). Arrow: displacement of the upper sheet (velocity: a few cm y^{-1}).

Table 2 Average displacements measured on three stone banks at Huampar site.

Form	Altitude and aspect	Slope gradient	Years	Average displacement (cm y^{-1})
Scree	5200 m a.s.l., N	35°	1983–1985	5–10
Stone-banked sheet	4900 m a.s.l., WSW	20°	1982–1987	10
Stone-banked lobe	4860 m a.s.l.	6°	1985–1987	1–3

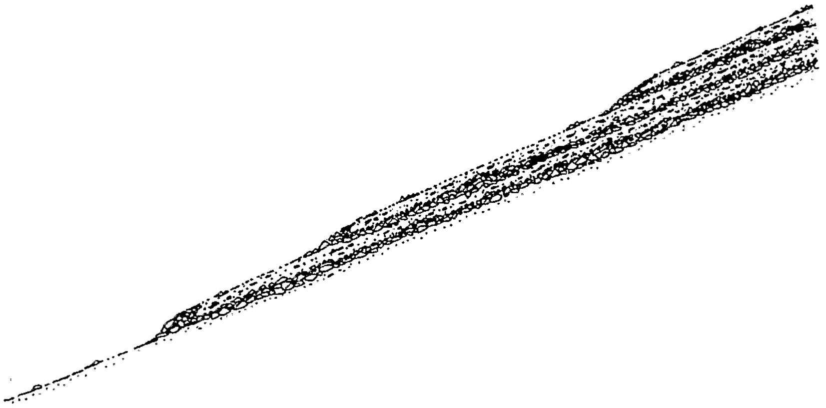

Figure 7 Regular bedding structure developed from a set of fine-grained sheets.

Where Do Stratification Mechanisms Occur?

Bedded structures form from various types of debris accumulations, namely:

(i) Talus slopes: proximal small-size materials usually initiate the creep movement and develop a fine-grained sheet (Figure 4). However talus can give coarse-grained sheets with an openwork fabric on the surface and a fine layer beneath (Figure 8). Where Richter slopes develop as free faces, they yield fine-grained sheets organized in convoys (Figure 3).
(ii) Old glacier moraines.
(iii) Gentle debris slopes with gradients as low as 5° (Figure 5): the front of most sheets may occur as a regular bench between 10–100 m wide, but others have a sharp lobate pattern (Figure 5).

Generally, the formation and displacement of sheets of block-size material depend on severe climatic conditions. First, frost is required to shatter fractured rockwalls to yield block-size material. Second, in order for ice to form in the matrix, the freezing plane must penetrate at least 10–20 cm of openwork material. This is possible only if frost penetration occurs for several days, as observed in Chacaltaya (Bolivia) at 5200 m a.s.l., where coarse-grained sheets are active.

SEDIMENTOLOGICAL CHARACTERISTICS OF THE BEDDING

Bed Granulometry

(i) Matrix-rich beds: the thickness range of matrix-rich beds is generally 5–15 cm, with a median close to 10 cm. This is equivalent to the soil thickness penetrated by diurnal freeze–thaw cycles. Fabrics are matrix-supported or clast-supported. Patterns related to frost creep, such as stratified ice lens microstructures, are visible to the naked eye. The proportion of <2 mm fraction is higher than 40–50 % and

Figure 8 Coarse-grained sheet on a talus slope. The frontal girdle is emphasized by melting snow. Slope gradient: 27°. Viuda zone, Central Peru.

this matrix usually contains 40–60 % of fines less than 50 μm. Coarser particles may be ejected by frost, so the average pebble size in most cases is smaller than in the openwork layers (Figure 9) but isolated blocks may be present. Matrix-rich beds often have the upper part covered by finer materials resulting from illuviation of silt and clay fractions.

(ii) Open-type layers are usually thicker than layers in the matrix-rich beds. Fabrics are openwork or partially openwork, and clast populations may be heterogeneous, with a size range from gravel to blocks of several decimetres. Frequent vertical sorting occurs, including two variations as follows (Figures 6 and 10): (1) A normal sorting with small particles overlying larger particles. Such sorting is produced in the openwork layer of the stone bank. During movement, small particles fill the voids between coarser particles and are the first to be buried by fines. The coarser fraction is then carried forward in the outer part of the front and buried. As a result, clast size decreases downwards to just under the lower limit of the matrix-rich bed. (2) A reverse sorting with coarse particles over fine. If the sheet has an openwork layer at the surface, due to constant removal of material, small particles progressively in-fill at depth.

When a sheet formed by coarse material at the surface is buried by another with fine material at the surface, the addition of coarse openwork layers produces a single open-type bed sorted both upwards and downwards, with size decreasing in both directions (see Figure 6). Double sorting occurs, with size increasing both upwards and downwards. This phenomenon results from the complete washing out of the matrix layer in a sheet formed initially by coarse materials at the surface. Nevertheless, the absence of sorting in the openwork level is frequent, particularly in very active sheets where the matrix is still present in the outer part of the bank. This situation makes it difficult for the selection mechanism to operate in the coarse fraction.

Nature of Boundaries between Beds

The upper and lower boundaries of the matrix-rich beds exhibit quite different patterns.

(i) Upper boundaries are sharp and straight, and appear to be real unconformities (Figures 9 and 10). These tabular planes have a double origin: first, the matrix is compacted by repeated frost action (aggregation and layering by ice lens microstructures) and desiccation; second, the

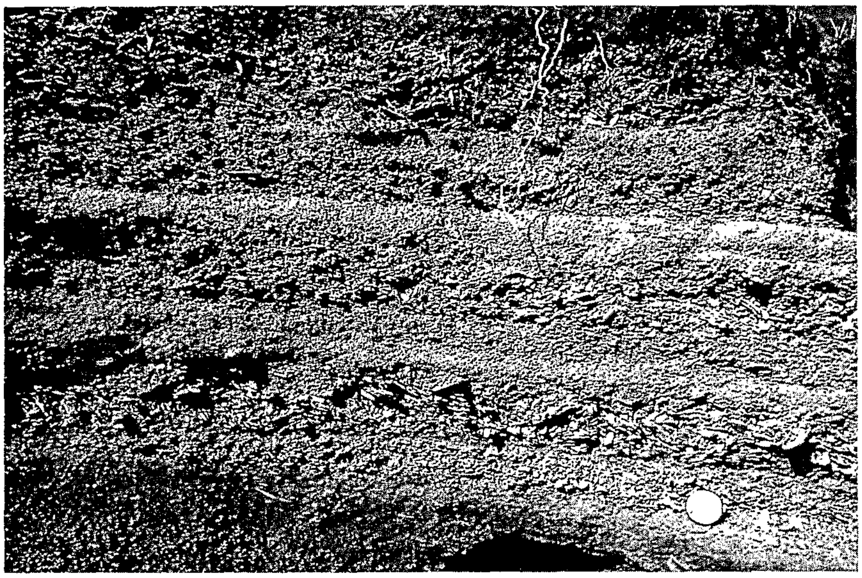

Figure 9 Longitudinal section in a non-active slope deposit at Milluni (4600 m), Chacaltaya zone.

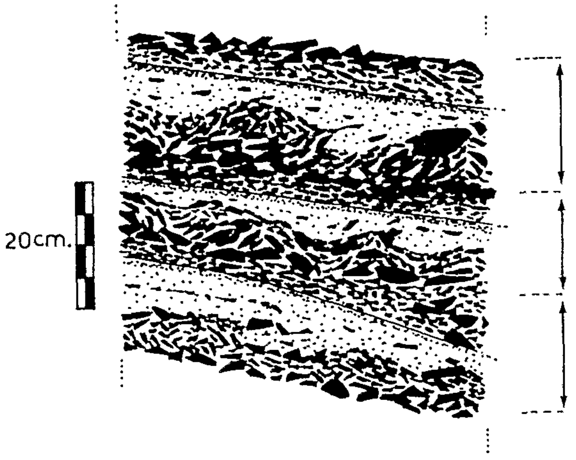

Figure 10 Nature of bed boundaries, sorting and clast fabric in a stratified structure at Chacaltaya, Bolivia. The distinct dynamic units are indicated.

upper part of the matrix-rich beds receives fine illuviation products and serves as a water drainage layer. Thus, irregularities tend to be smoothed and a plane surface develops.

(ii) Lower boundaries have a different pattern, with contacts not so sharp and showing an undulating trend (Figure 4). Moreover, the upper clasts of the lower openwork beds are cemented by the fine particles of the matrix-rich beds (Figure 9). Two hypotheses are proposed to explain these field observations. First, during thawing, the matrix-rich layer may move forward and behave, more or less, as a plastic body. Free particles are buried and cemented after desiccation. Because fine materials do not fill voids of the openwork layer, the boundary remains distinct. Second, the matrix-rich layer and coarse bank may not move regularly, but intermittently. Thus, advance may be faster during the wettest periods, when gelifluction, and even minor mudflows, occur at the sheet front. In this case, matrix materials pour outward from the stone bank and the bed tends to thicken. On the other hand, during drier periods, only heaving and frost creep operate. Thus, the stone bank is built up and the matrix-rich bed becomes thinner. Alternation of such periods leads to the wavy pattern of the base of the matrix-rich beds. The length between two 'waves', if detectable, is rarely regular and may vary from 15 cm to 30 cm, or more. On transverse sections, similar features may be observed (Figures 3 and 6). The upper boundary of the matrix-rich beds is tabular. This surface often supports surficial sorted stripes. The lower boundary is wavy and these irregularities originate from the presence of sorted stripes. Moreover, the width of 'waves' and stripes is the same. Water drains via the stone stripes and eluviation of fines makes the bed thinner near the front. Fine-grained stripes move by frost-induced processes and coincide with a thickening of the fines. Subsequently, illuviation makes the upper part tabular, whereas the lower remains wavy.

Clast Fabric in the Beds

In general, the fabric of the matrix-rich beds is anisotropic, with a strong majority of clasts having their *a*-axes oriented with the slope and dipping in that direction, as indicated by the Schmidt diagram (Figure 11). These characteristics show the effect of frost creep (Williams, 1959; Benedict, 1970; Washburn, 1979), as does the stratified structure of the matrix. Sometimes, however flow structure and clast imbrication occur, which suggest plastic deformation with high water content, such as gelifluction (Van Vliet-Lanoë, 1988).

Openwork beds have a more isotropic fabric. As plotted on a Schmidt net, orientation and dip values appear to be more randomly distributed

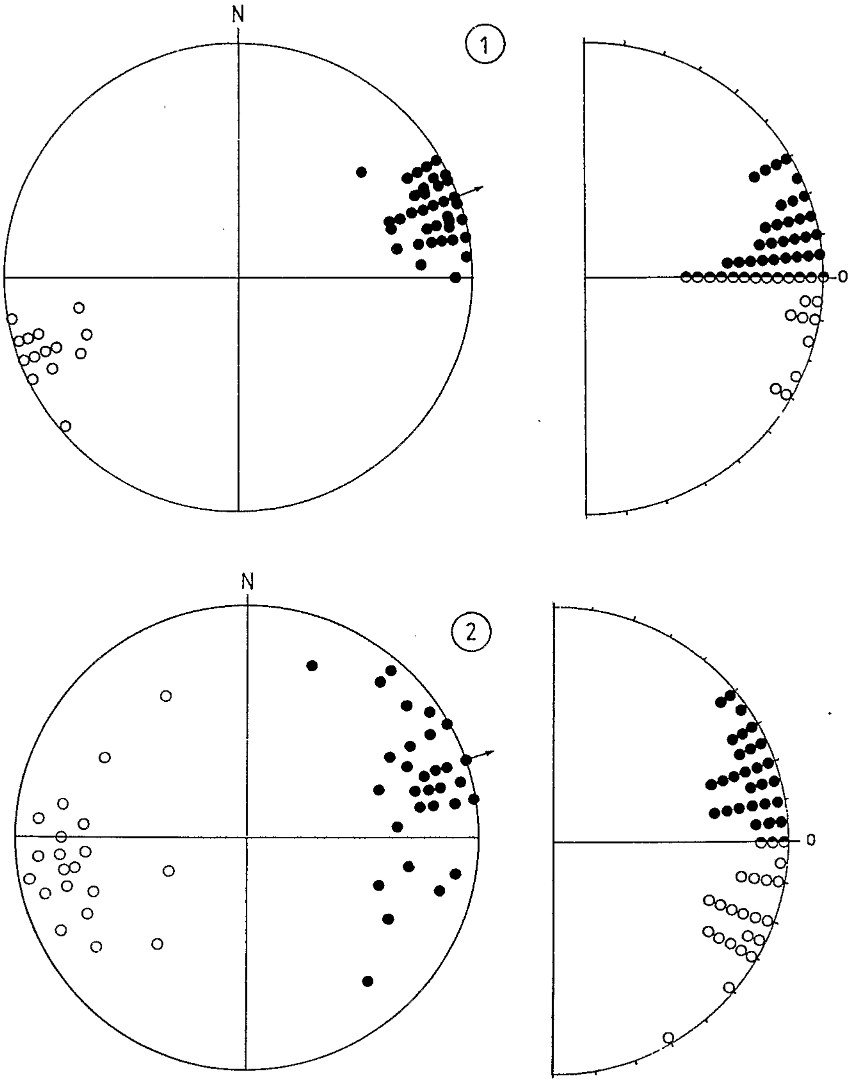

Figure 11 Fabric data represented on equal-area Schmidt nets (left) and dip diagrams (right) in a bedded slope near Chacaltaya, Bolivia: (1) Matrix-rich bed; (2) Openwork bed. Closed symbol: clasts dipping less than the bed angle. Open symbol: Clasts plunging more than the bed angle. Arrow: direction of the bed angle. Each diagram based on 50 particles.

(Figure 11). In fact, it should be noted that in the upper part of the openwork bed in contact with the matrix-rich bed, clasts dip in conformity with the wavy pattern mentioned before (Figure 9). Such a festooned pattern was also observed in transverse sections. These features indicate that matrix beds and the upper part of underlying openwork beds are closely and genetically linked and, thus, deposited at the same time.

The Dynamic Units

Openwork beds and matrix-rich beds form a binary system. This has been termed a 'cyclothème' by Guillien (1964). However, determination of the main boundaries in the system, at the top of either the matrix-rich beds (Guillien, 1964) or the openwork beds (Journaux, 1976), is a major problem. The use of the 'cyclothème' concept in the present model is therefore inappropriate. Instead, it is preferable to use the term 'dynamic units', because the layers are deposited by a moving sheet.

Thus, depending on materials, two types of dynamic units can be distinguished:

(i) 'Binary units': units made up of an openwork layer and an upper matrix-rich one. These derive from sheets having fine-grained materials at the surface and a stone bank at their front (Figure 12).
(ii) 'Threefold units': units in which the matrix-rich layer is placed between two open-type layers (Figure 12). In this case, the original sheet has a coarse-grained surface.

As pointed out before, the boundary between two units may be situated inside the openwork layer, as this occurs when a sheet advances on a former unit which presents openwork material at its surface (Figure 12). Thus, boundaries can sometimes be detected on the basis of clast fabric and sorting. However, the matrix might be completely washed out; thus, only graded small pebbles and gravel remain instead of a matrix-rich layer. In these cases, open-type beds are thick and may present double vertical sorting.

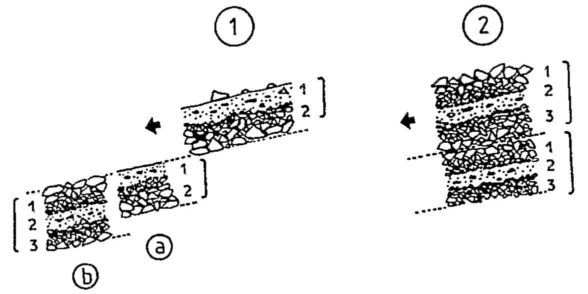

Figure 12 Types of dynamic units found in stratified slope deposits. (1) Binary unit which overlies former units—i.e.: (a) Another binary unit; (b) A threefold unit. (2) Coarse sheet forming a threefold unit which overlies another unit of the same type. Superposition of 3 (up) and 1 (down) forms an openwork bed with two types of sorting.

APPLICATION OF THE MODEL TO RELIC STRATIFIED SLOPE DEPOSITS OF MID-LATITUDES

Among the processes involved in the stratification mechanism, frequent freeze–thaw cycles are the most important. Thus, equatorial and tropical high mountain environments represent optimal conditions. On the other hand, wet high mountains of mid-latitudes and arctic regions are unfavourable, owing to the seasonal trend and duration of snow cover. In these areas, the annual freeze–thaw cycle occurs, flanked by a few surficial frosts. Moreover, deep frost penetration during winter, followed by rapid thawing and saturated conditions, allows cryoturbation phenomena and gelifluction to occur. Such disturbances prevent the formation of bedding. Thus, the rare occurrence of stratified slope deposits in those environments, as stressed by some authors (French, 1976; Dewolf, 1988), may be explained.

By contrast, dry high mountains of mid-latitudes are favourable environments for these processes (Raynal, 1970). For example, active stratified stone-banked sheet systems were observed in Western Kunlun by Francou *et al.* (1990) and in the Ladakh-Zanskar range by Fort (1981).

In European Pleistocene deposits, other concepts have been elaborated to explain the origin of stratification, including runoff action, washing, solifluction and rockfall. Debris flows as stratification processes have been suggested by Hétu (1986) and Van Steijn (1988), but these rapid flows create specific features: cruder stratification, lenticular structure, less clear sorting and a more isotropic fabric in matrix-rich layers.

In stratified screes, the same sedimentological features as were noted in the Andes are often present (Francou, unpublished observations). The frequent absence of headwalls at the top and slope gradients gentler than modal values obtained on rockfall talus slopes (Francou, 1988b) are other arguments which exclude falls and grain flows as stratification mechanisms. In typical grèzes litées. as shown in a recent study by Bertran *et al.* (1990), the stratification model presented here can provide an alternative to the classical interpretations which are always under discussion. The author believes that the principal sedimentological features pointed out in the Andes can be observed in Charente, France. However, other studies are needed on Pleistocene and active deposits to test the possible extension of the stratification model in different palaeo-environments. These might be done by analysing precisely the bedding features and by improving knowledge of the sedimentological signature of other possible processes involved in bedding development. Indeed, for many deposits, it is probable that bedding could result from a combination of various processes. Thus, a suitable interpretation of bedded deposits depends on the relationship that could be set up between the stratification processes as observed and measured in the field (and by experimentation) and the bedding characteristics as revealed by extensive sedimentological analyses.

CONCLUSION

Bedding is generated by solifluction sheets which move downslope at the speed of a few centimetres per year. Solifluction involves needle-ice, frost creep and gelifluction, and affects only the upper 20 cm of the ground. Sorting of coarse particles occurs in the debris mass (1) vertically, by frost heaving, and (2) horizontally, by slope washing after they have been concentrated on the front part of the sheet. Bedding results from the burial of the coarse openwork bank by the advancing fine layer.

Analysis of the stratification mechanism, together with the sedimentological characteristics, allow recognition of diagnostic features. The main features present in the sediment are the following:

(i) Clear and continuous alternations of matrix-rich and openwork beds.
(ii) Sharp boundaries between beds which are straight and tabular at the top of the matrix-rich bed, and wavy with upper openwork clasts cemented within the matrix at the base of the matrix-rich bed.
(iii) Frequent vertical sorting in the openwork beds: normal sorting in the upper part and reverse sorting in the lower part are most common. In the matrix-rich beds, a finer layer (silt and clay) always occurs at the top.
(iv) The development of microstructures in matrix materials due to frost action, the most common being platy structures related to ice lensing and laminar flow, typical features of frost creep.
(v) A strong tendency for clasts to parallel the slope gradient in both dip or orientation in the matrix-rich beds, but with more apparent isotropy in the openwork beds and their upper clasts conforming with wavy features of the adjacent matrix-rich beds.
(vi) When ending downslope, matrix-rich beds are generally laminated by wash and show a bevelled pattern.
(vii) Matrix-rich bed thicknesses are often less than those of open types, with a 10 cm median, but if matrix supply is abundant, matrix-rich beds may be the thickest.
(viii) In transverse section, many beds end in lobate features; festoons at the base of matrix-rich beds, repeated conformably by the lower openwork material fabric, attest to the activity of sorted stripes.

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