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Analysis of the Segmentation in the Profile of Alpine Talus Slopes

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ABSTRACT

A method for analysing the segmentation in the profile of talus slopes is used in an Alpine periglacial environment. Two populations of talus slope profiles are examined according to the development of their headwalls. Beneath massive rockwalls the profile appears bi-segmented: a break point situated at a constant angle (33–34 degrees) divides an extensive proximal segment with a shallow curvature from a shorter and more concave distal segment. When the headwall disappears, the segmentation is modified and a concavity extends throughout the profile. A new model for talus slope formation is proposed in which the rockfall mechanism and the removal processes are combined.

RESUME

Une méthode d'analyse de la segmentation du profil des éboulis est expérimentée dans les Alpes, en milieu périglaciaire, sur deux populations de talus d'éboulis se différenciant par le développement de leur paroi dominante. Avec une paroi massive, le profil apparaît bi-segmenté: un point de rupture (ψ) situé à une valeur de pente stable (33–34 degrés) sépare un segment proximal doté d'une concavité à grand rayon de courbure et comprenant en longueur plus de la moitié du profil d'un segment distal plus court et à concavité plus accentuée. Quand la paroi disparaît, la segmentation évolue et peut aboutir à l'extension d'une seule concavité à tout le profil. Des arguments sont avancés pour présenter un modèle nouveau pour les éboulis de gravité en matériel à faible cohésion, dans lequel le mécanisme de chute et les actions de remaniement sont combinés. Ce modèle concorde bien avec les résultats des études effectuées récemment sur ces formations de pente dans plusieurs milieux périglaciaires.

KEY WORDS: Talus   Slope evolution   French Alps   Headwall

INTRODUCTION

Numerous profiles have been measured of talus slopes in various climatic environments and for many lithological groups. The most systematic studies are those of Piwowar (1902), Rapp (1960a, 1960b), Andrews (1961), Melton (1965), Malaurie (1968), Howarth and Bones (1972), Young (1972), Chandler (1973), Carniel and Scheidegger (1974), Statham (1976), Church *et al.*, (1979), Albjar *et al.*, (1979), Caine (1983) and Hétu (1986). Because talus slopes have traditionally been considered as accumulations of granular material deposited by individual rockfalls, analyses of their angle distribution is of great interest for generating talus slope evolution models (e.g. Van Burkalow, 1945; Carrigy, 1970; Chandler, 1973; Kirkby and Statham, 1975; Statham, 1976; Carson, 1977).

In testing scree material in the laboratory to determine characteristic angles and to simulate

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rockfalls, two antagonistic models have been developed. The older one, proposed by Ward (1945) and more recently by Carson (1977), considers the talus slope to be at the repose angle of the material. This angle approaches 35 degrees, an angle generally found on natural talus slopes and thought to reflect the constant redistribution of material from the apex to the base by slow creep or dry avalanching processes. More recently, Kirkby and Statham (1975) state that slope inclination is controlled by a balance between the input energy of particles falling from the headwall and the energy lost by friction as the particles move down the talus surface. This dynamic friction angle concept implies that the slope angle is less than the repose angle (i.e. angle of residual shear), as measured in shear box tests, because the latter is achieved only when the rockwall is completely buried.

Relatively few studies have examined the talus slope geometry in a natural environment. In general, the majority of profiles include a straight slope in the upper part and a concave slope in the basal part (e.g. Andrews, 1961; Howarth and Bones, 1972; Young, 1972; Statham, 1976; Church *et al.*, 1979). Kirkby and Statham (1975) infer that the straight-concave pattern is due to an exponential distribution (Poisson law) of particle travel distance on the scree slope. For others, mainly working in snow environments, the basal concavity mainly depends on processes such as snow avalanches and debris flows (e.g. Rapp, 1960a, b; Church *et al.*, 1979; Hétu, 1986; Kotarba *et al.*, 1987). Caine (1969) provides the only coherent model for slush avalanching as the principal process, but subsequent studies have not confirmed its validity (e.g. Gray, 1973; Whitehouse and McSaveney, 1983; Luckman, 1988).

In our study of talus slopes we have assumed that the profile is segmented. This is based upon two field observations: (1) there is a general downslope displacement of particles on the upper part of the talus, and (2) there is extensive fall sorting along the profile. If most of the material falling down the cliff were to come to rest on the upper part of the talus and if this material were to be removed by gravity-induced processes which stop before the base, a 'break' would appear, theoretically, on the profile. By contrast, a constant inclination of this breakpoint would suggest that material has achieved an angle of stabilization. It can also be assumed that the pattern of profile segmentation changes according to the development of the headwall, because this controls (a) the quantity of material supplied to the talus and (b) the probability that certain particles will reach the basal section.

METHODS

Thirty-five talus slopes were examined on low-cohesion materials in the French Alps (Briançonnais, 45°00 N, 6°30 E) at elevations between 2500 m and 3000 m a.s.l. The underlying lithologies were predominantly granites, gneisses and quartzites. The 0 °C isotherm is located close to 2500 m a.s.l. At these altitudes snow covers the talus for at least seven months of the year. Profiles were measured in 10 m segments from the base to the top of each talus slope. Accuracy of the slope angle measurements was close to half a degree.

The slope profiles were divided into two groups according to the size and shape of the headwall, using two headwall parameters: (1) relative height, defined as being the height of the talus slope (H_o) divided by the height of the talus slope plus the height of the headwall (H_i), and (2) mean inclination (α_w). A first group consisted of 18 talus slopes with massive and steep headwalls. In this group $H_o/H_i < 0.5$ and $\alpha_w > 45$ degrees. A second group consisted of 17 talus slopes with indistinct or missing headwalls. In this group the H_o/H_i value varied between 0.5 and 1.0 and $\alpha_w < 45$ degrees. In total, 724 slope segments were identified, of which 369 were in the first group and 355 were in the second group.

A purely geometric data processing approach was adopted, based upon 'soft' modelization. Let P be the slope, let t be the fractional distance upslope on the scree and assume that each profile is roughly linear within each zone. Its derivative will be approximately a step function and its second derivative will be nearly zero, except in the neighbourhood of each point of rupture, where it will present a step. Cubic smoothing splines are frequently used by statisticians in order to represent a signal. A parameter, ρ, permits one to differentiate between the 'smoothing' and the 'interpolation' term (Wegman and Wright, 1983). The main point of this procedure, as applied to talus slope profiles, is to identify the coordinates of principal discontinuity points which are present throughout the profile. In the simplest case (the straight-concave pattern) only one break point (ψ) occurs and the profile is 'bi-segmented'. In more complex cases several breaks appear along the profile. Some of these are local and accidental, and may be neglected. Others, which are signalled by the second derivative, produce durable alterations in the profile. Two have been recorded in our analyses, noted as ψ_{i} and ψ_{ii} according to the decreasing value of the second derivative.

RESULTS

Group One

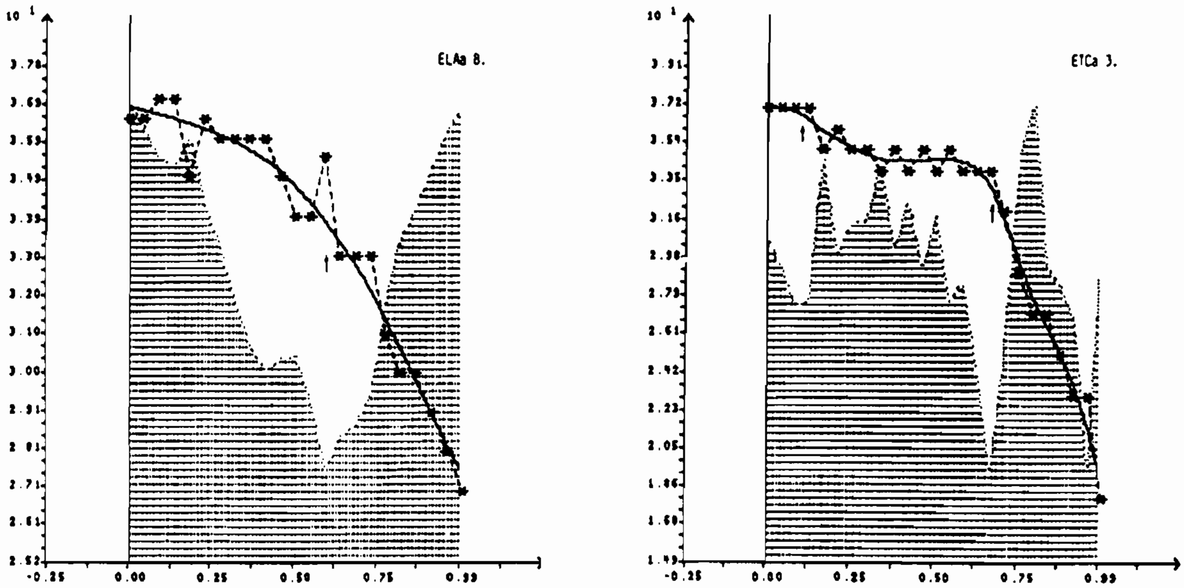
One can distinguish two general patterns: (1) an exponential curve presenting a clear and single break in the profile (Figure 1a, profile ELAa8), and (2) a more complex curve (higher value of ρ) with several breaks (Figure 1b, profile ETCa3). In both cases a proximal segment extends to 50–60% up the profile with a large shallow concavity. This segment precedes a shorter distal segment with a more pronounced concavity. The transition occurs at point ψ. Figure 2 plots the coordinates of selected break points and shows that ψ has a relatively uniform value for the majority of slopes: 33–34 degrees and 0.5–0.8 t. On the profiles with several break points it is possible to identify one well-marked break at 33–34 degrees and another may appear near the apex at 35–37 degrees. In this case, the second break point relates to the talus slope whose upper part has penetrated the rockwall by a chute.

Group Two

Three patterns are typical: (1) a tri-segmented pattern, including a straight slope followed by others which are more curved (Figure 3a, profile ELAw2), (2) a pattern which tends to fit with a straight line (Figure 3b, profile ELAa5) and (3) a profile with a straight and extensive proximal slope followed by a short and strongly concave distal slope (Figure 3c, profile EARal).

Synthesis

The data suggest that the segmentation of talus profile changes according to the size and inclination of the headwall. As shown in Figures 2 and 4, a high headwall (1) leads to a bi-segmented profile with a pronounced break point ψ whose position is quite stable. Stability involves angle value, always being close to 33 degrees. A small or



(a) (b)

Figure 1 Profiles of two talus slopes with massive rockwalls (Group One). (a) ELAa8 is a bi-segmented profile; (b) ETCa3 is a multi-segmented profile. Abscissa: fractional distance upslope, (t) (0.00, apex). Ordinate: angle value (x 0.1). Asterisk and dotted line: segment angle and linear interpolation. Solid line: cubic smoothing spline. Grey: second derivative of cubic smoothing spline. Arrows: break points.

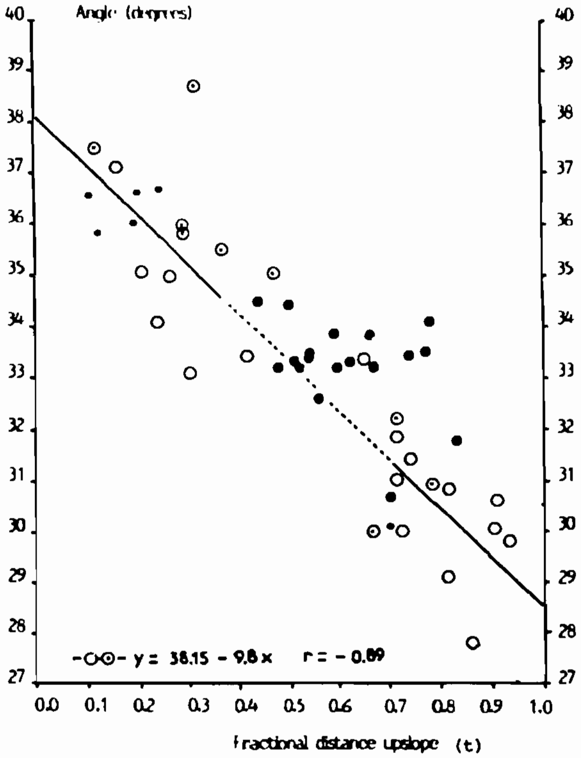


Figure 2 Plot of the coordinates of the break points identified on the profiles of the two talus slope groups. Solid circles, Group One: large circles, principal break points; small circles, second break points. Open circles, Group Two: empty circles, principal break points; circles with points inside, second break points. Regression line plotted for Group Two only.

low-angled headwall (2) generally gives a multi-segmented talus slope. The main break point (ψ_d) is located lower on the slope and at a gentler angle. On many talus slopes another break point (ψ_p) develops in the upper part at a steeper angle and the slope geometry tends towards an extensive concavity when headwall declines. This conflicts with the theoretical model of Kirkby and Statham (1975), which predicts a straight and steep slope in the final stages of evolution of the headwall-talus system.

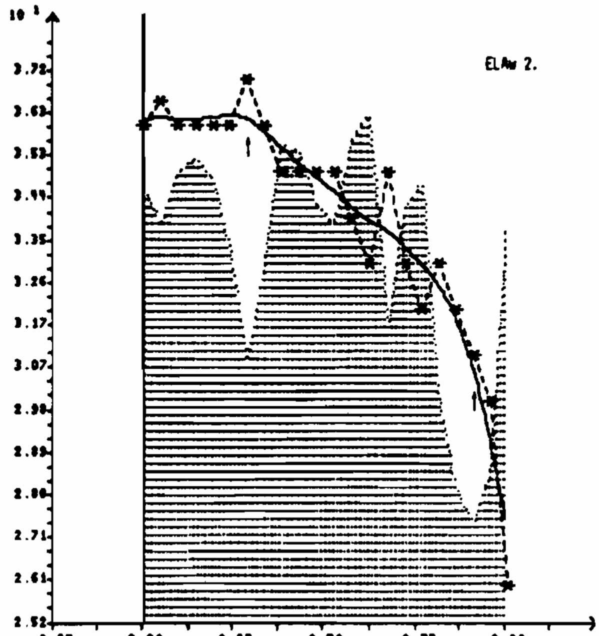
Frequency distribution analysis of the talus slope angle lends some support to this conclusion. Beneath massive rockwalls (Figure 5.1) scree slopes show a pronounced mode from 34 degrees to 36 degrees and few segments exceed 37 degrees. By contrast, where the rockwall is short or missing (Figure 5.2), the scree slope angle distribution has a higher kurtosis: while the modal value is the same at 35 degrees, 32-33 degree slopes are more common. At the same time, very steep (38-40 degrees) angles are also present and gentler ones (<21 degrees) are few in number. Although these differences are probably not statistically significant and testing has not been undertaken, such frequency distributions of the two groups does not support a model of low headwall talus slopes evolving towards a rectilinear profile.

TALUS SLOPE EVOLUTION

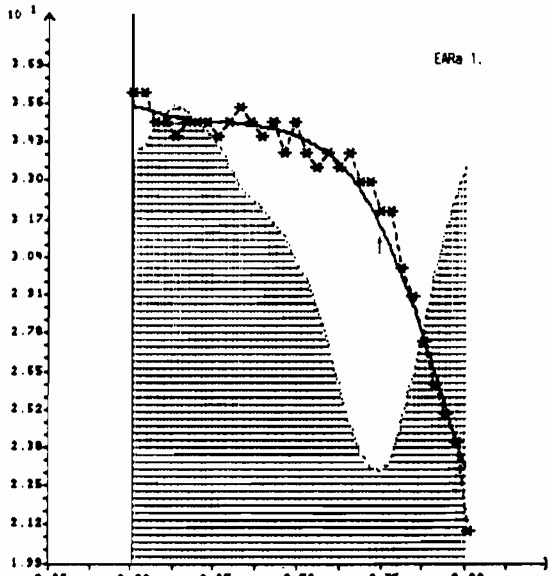
The evolution of the rockwall-talus slope system may be considered as a bi-phase model.

In the beginning, owing to the height of the headwall, detached blocks fall down the talus with great energy and are spread throughout the profile. One can assume that the probability of particle deposition decreases downslope, an assumption confirmed by several authors who have measured supply rates throughout the profile (e.g. Gardner, 1983; Pérez, 1985; Hétu, 1986; Luckman, 1988; Francou, in press). It is also well known that talus deposits, especially in the proximal zone, exhibit high mobility (e.g. Rapp, 1960b; Pissart, 1964; Gardner, 1979; Pancza, 1979; Hétu, 1986; Pérez, 1988). This type of non-cohesive material displacement has various origins. These include dry avalanches, impact energy transmitted by falling blocks, changes in the stability conditions due to matrix eluviation, and thermal variations around the freezing point. The sieve effect (Carniel and Scheidegger, 1974), generated by burying small particles under larger ones, maintains a constant instability, as pointed out by Church *et al.*, (1979). The constant occurrence of break point ψ at 33-34 degrees can be explained by the transition from a deposit-transport system in the proximal segment to a pure accumulation system in the distal segment (Figure 6). Break point ψ, therefore, represents a 'dynamic' break. This pattern is also reflected in sorting above and below the break point. The proportion of small-size particles (*a*-axis<10.0 cm) rapidly decreases downslope of this point (Francou, 1988).

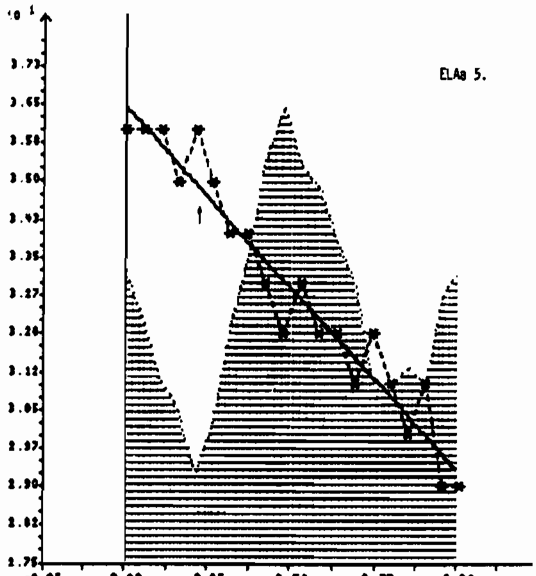
The second stage of evolution occurs when the rockwall tends to disappear. As the height of fall declines, chutes develop and large-size deliveries become less frequent. As a consequence, the movement of rockfall debris downslope tends to become shorter and accumulation zones are limited to the foot of the headwall. Oversteepening of the apical talus section continues to induce movement which is marked in some profiles by a break point



(a)



(c)



(b)

Figure 3 Profiles of three talus slopes with low or missing rockwalls in Group Two. (a) ELAw2, tri-segmented profile with rockwall; (b) ELAa5, profile tending towards one concave slope; (c) EARa1, profile tending towards straight slope with extinction of the headwall.

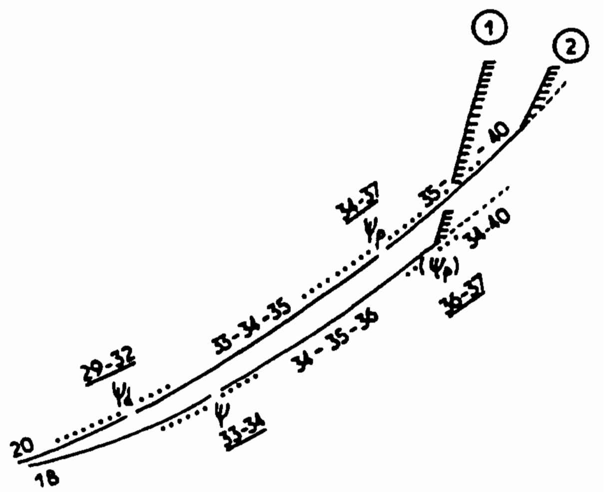


Figure 4 Types of talus profiles according to the development of the headwall. 1, Massive headwall; 2, Declining headwall. ψ, principal break point; ψ_p, break point in proximal position; ψ_d, break point in distal position. Numbers underlined indicate slope angles of break points. Numbers not underlined indicate slope angles of segments. The dotted lines indicate different possible positions of the break point in the profile.

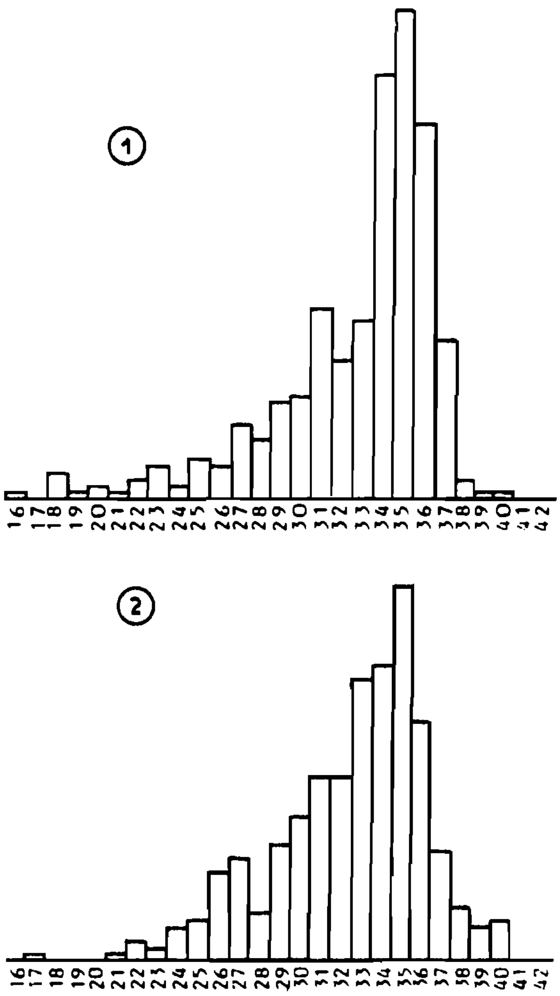


Figure 5 Frequency histograms of talus slope angles. 1, Group One, with massive headwalls; 2, Group Two, with declining headwalls.

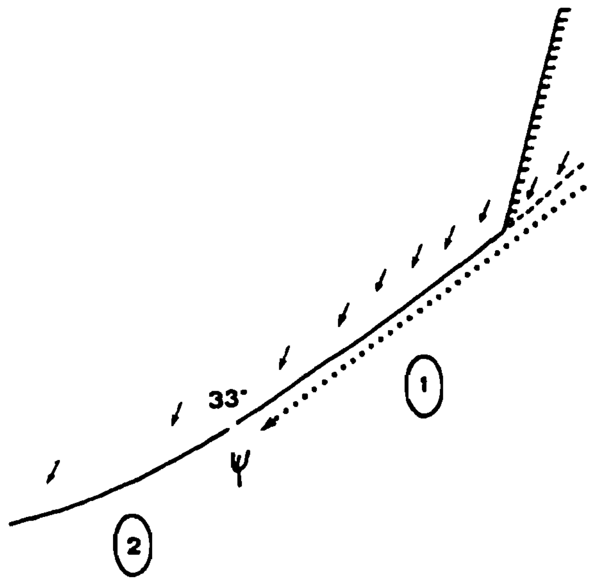


Figure 6 Bi-phase model for a scree slope with a massive rockwall. Small arrows indicate accumulation zone of rockfalls with the number of arrows proportional to rockfall frequency. Dotted line, transport after accumulation. ψ, principal break point, with the most probable angle. 1, Accumulation and transport phase; 2, pure accumulation phase.

(ψ_p, Figure 4). Its variable angle between 34 degrees and 37 degrees suggests that stability has not yet been achieved. At the same time, the previous break point occurs downslope at a gentler angle. Ultimately, in the final stage of rockwall retreat, we believe that talus slopes present a multi-segmented pattern. First, there is a straight and steep proximal segment which tends to approach the 35 degree angle of repose. If the rockwall declines and changes to a straight, uniform free face, the Richter slope (Bakker and Le Heux, 1952) prolongs the slope upwards. Second, there is a middle segment with a gentle concavity which corresponds with a declining angle of the repose slope to approximately 30 degrees. Third, there is a marked concave distal slope, nearly stabilized and with a low accumulation rate.

CONCLUSIONS

The principal inadequacy of the traditional scree-rockfall model of talus slope evolution is its inability to deduce slope evolution from the dynamic friction angle concept. Furthermore, it places the angle of repose at too high a value. Our analysis of the segmentation in the talus profile in the French Alps leads us to propose another concept of talus slope evolution. Talus is viewed as an assemblage of slopes which combine different dynamics and which work at different rates. As long as the rockwall is massive and active, the rockfall mechanism is the dominant process and talus slope development fits well with a bi-phase model. As the rockwall declines, removal activity becomes more important. In order to further refine this model, it is necessary to conduct studies upon the variability of granulometry and mobility of talus material. These may confirm the dynamic significance which we attach to the profile segmentation.

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