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HILLSLOPE EVOLUTION ON THE PENNINGTON FORMATION, CENTRAL TENNESSEE: AN ILLUSTRATION OF DYNAMIC EQUILIBRIUM

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Abstract

Along the Cumberland Escarpment in central Tennessee, sandstone cap rocks are underlain by the predominantly shaly Pennington Formation. Slopes on this formation are covered with a mantle of coarse sandstone debris derived from the cap rock above and have an average inclination of 21°. Once the cap rock is removed, however, the texture of the debris mantle becomes finer and the slopes decline. A linear relation was found between the steepest slope angle on a hill and the vertical distance of the hill top below the base of its former cap rock. The latter variable also shows a high negative correlation with gravel and sand content of the debris mantle, and a high positive correlation with clay content. These findings are related to the concept of dynamic equilibrium and also are discussed in the context of a recent model of hillslope development.

Introduction

For many years geomorphologists argued over whether lowering of interfluves took place by decline of hillslopes (e.g., Davis, 1899) or by parallel retreat of hillslopes (e.g., Penck, 1924; King, 1953). Despite their differences, these earlier workers shared one belief: given that base level, rate of uplift, and climate remained constant, landscapes would show a progressive and inevitable change through time.

Against this background, Hack (1960) introduced the concept of dynamic equilibrium, which challenged this fundamental belief. According to Hack, as long as the abovementioned factors remain constant, and as long as similar rocks are exposed at the surface, the topography remains in a steady state and shows no progressive change through time. Erosion takes place, but all elements of the topography are mutually adjusted so that they downwaste at the same rate. Slopes and streams are adjusted to the caliber of rock waste they must transport. For example, hills composed of mica schist commonly have more gentle slopes than do hills of quartzite because the schist is comminuted by weathering to fine particles that can be easily removed on gentle slopes, whereas quartzite weathers into larger particles that can be transported only on steep slopes.

Change in the landscape occurs only when a change in one of the above factors takes place. A new equilibrium must then be achieved, so that the topography undergoes an evolution from one form to another. Hack (1960, 1966) has given a number of examples of topography in equilibrium, but topography that is undergoing a readjustment in order to achieve a new state of equilibrium is ephemeral and therefore rare. A situation in which such readjustment is taking place exists along the Cumberland Escarpment, where hills on shale that have recently been stripped of their sandstone cap rocks are undergoing a decline in slope. The purpose of this paper is to document this hillslope evolution.

Geologic and Topographic Setting

The area of study was the vicinity of the Cumberland Escarpment in central Tennessee, centered on eastern Putnam County. Here the Cumberland Plateau is held up by lower Pennsylvanian sandstones, especially the Sewanee Conglomerate and Warren Point Sandstone in the southern part of the region and their lateral equivalents, included in the Fentress Formation (Fig. 1), in the northern part. Underlying the Pennsylvanian sandstones is the Mississippian Pennington Formation (Fig. 1), consisting mainly of claystone but with beds of limestone, dolostone, and sandstone. It ranges in thickness from 35 m to 100 m, although in most places it is at least 60 m thick. Underlying the Pennington is the Bangor Limestone (Fig 1).

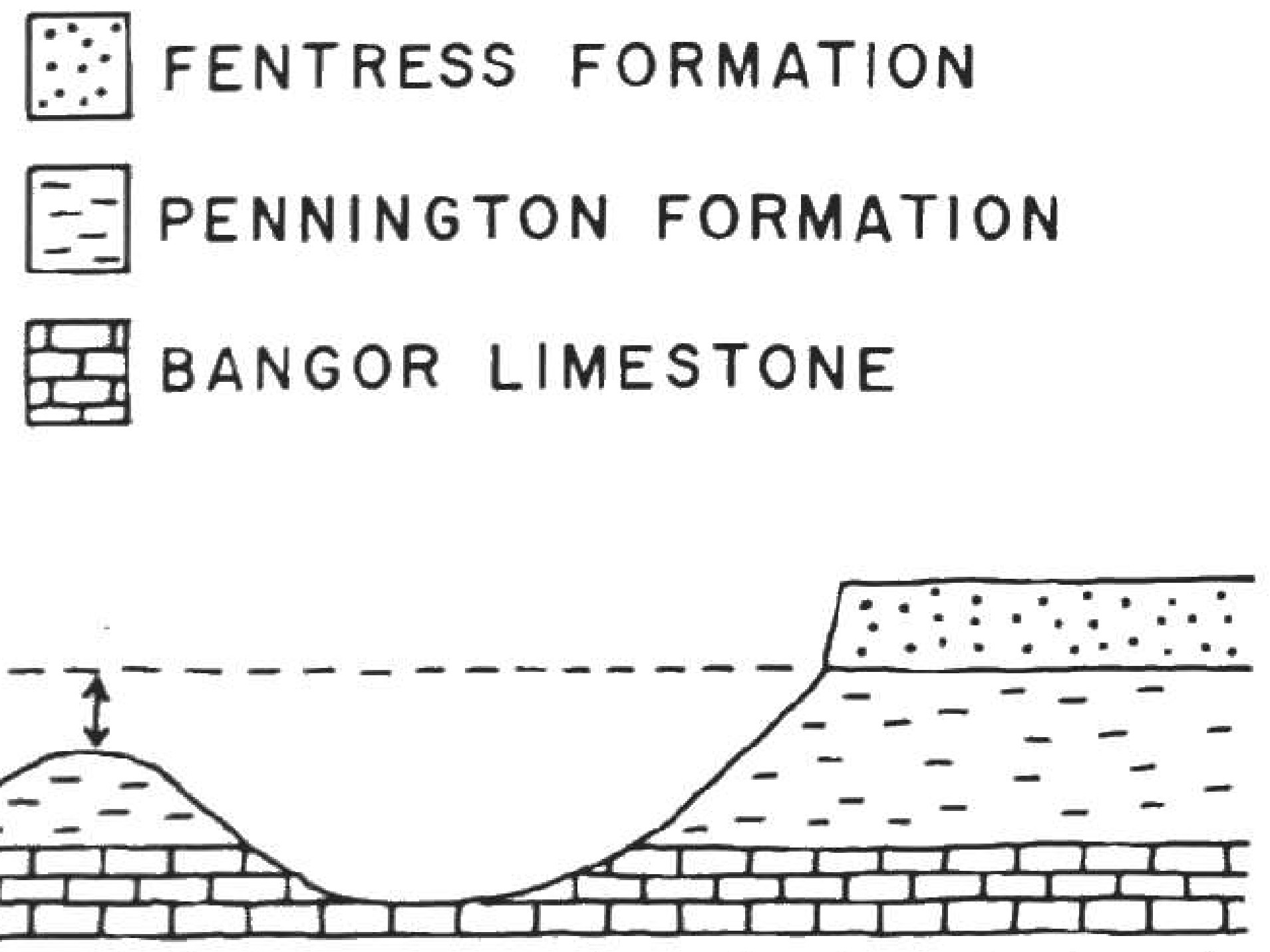

FIG. 1: *Geologic cross section showing stratigraphy of study area. Dashed line and arrow are explained in text.*

The margins of the Cumberland Plateau are deeply indented by flat-bottomed valleys known as coves. As two adjacent coves enlarge, a narrow ridge capped by Pennsylvanian sandstones develops between them. Eventually this ridge is breached in places, and becomes divided into a number of hills, each held up by a cap rock. In many cases these isolated cap-rock remnants assume a roughly circular form before their final disappearance, so that sandstone "nipples" cap the hill tops.

As long as the cap rock exists, slopes on the underlying Pennington Formation are covered with a surficial mantle containing much coarse sandstone debris supplied from above. The slopes are relatively steep, presumably adjusted to the large size of rock fragments that must be transported downhill. Once the cap rock vanishes, however, the amount of coarse material in the mantle decreases, and, in order to reestablish equilibrium, the slopes decline, as steep slopes are no longer required to transport the finer debris. This, of course, is not an unusual situation, but the simple geology of the area makes it possible to associate the amount of slope decline with the length of time since the cap rock was removed. The absolute time cannot be ascertained, but an index of relative time can be. This index is simply the thickness of Pennington strata that has been eroded since the removal of the cap rock. The manner in which this thickness can be determined is indicated in Figure 1. Because bedding in this area is almost horizontal it is possible to estimate the vertical distance between a hill top and the base of its former cap rock by extrapolating the elevation of the latter from the nearest hill retaining a cap rock to the hill top in question (dashed line on Figure 1). This procedure allows one to order hills in the Pennington Formation as to their relative ages. For example, if a hill top is 50 m below its former cap rock, the hill has had much more time to evolve than has a hill whose top is only 5 m below its former cap rock.

Previous Work

The above technique for assigning relative ages to hill tops is an example of what is sometimes called "substituting space for time." Such an approach is necessary because of the great interval of time required for landscape evolution, which makes it nearly impossible to actually observe the effect of time on landform change. Strahler (1950), in a study of stream-valley walls, compared slopes which were being actively undercut by streams with those which were protected by floodplains, and found the former to be somewhat steeper. Savigear (1952) compared the angles of sea cliffs currently being undercut by waves with those which had been protected from wave erosion for some time by spits, with similar results. One criticism of such work is that it is difficult to justify expanding the short time scales relevant to these studies to the much longer spans of geologic time (Carson and Kirkby, 1972). In the present study, however, this criticism is less applicable, as the time required to erode, say, 50 m of strata is probably significant even in terms of geologic time.

Hack (1966) discussed the Cumberland Escarpment in terms of dynamic equilibrium but said little of hillslope decline, aside from noting that once the sandstone cap disappears, hills along the Escarpment are rapidly eroded.

Procedure

A total of 54 hills capped by Pennington Formation were located on geological maps of the following 12 central Tennessee quadrangles: Bald Knob, Cassville, Cookeville East, Doyle, Dry Valley, Livingston, Monterey, Monterey Lake, Moodyville, Okalona, Sparta, Welchland. For each hill, the vertical distance between the hill top and the base of the former cap rock (for brevity, this distance will henceforth be referred to as depth below cap rock, or DBC) was estimated as described previously. It is thought that this estimate in most instances is likely to be within 20% of the true value, and, in any case, the error should be unbiased. In addition, on each hill, the steepest portion of the hillslope over a vertical distance of 18 m (60 ft, or 3 20-ft contour intervals) was found by inspection and the angle of this slope measured. For comparison, hillslope angles were also measured on 16 randomly selected Pennington slopes located below intact cap rocks.

At 11 sites on the Cookeville East, Monterey, and Monterey Lake quadrangles, field measurements of slope angles and mantle textures were made. Where possible, measurements were made 100 m (along slope) below the crest. At 3 sites, additional measurements were made 20 m below the crest. At seven sites, slope profiles were surveyed by means of tape and clinometer.

Mantle texture was measured by two methods. First, a tape marked at regular intervals was laid out across the slope. At 50 or 100 points along the tape, a thin metal rod was inserted 10 cm into the ground and the presence or absence of a stone recorded. It was found that stones 8 mm in diameter or larger generally could be detected by this technique, whereas smaller ones could not. Thus, this procedure allowed an estimate of the percent of clasts 8 mm or larger in the surface layer of the mantle, which provides an index of "stoniness." Particles 8 mm or larger will henceforth be referred to as "clasts" and smaller ones as "matrix." The second method involved the matrix material, and consisted of taking a composite sample of matrix from each site and then determining the percent sand, silt, and clay in the less-than-2 mm fraction by means of hydrometer analysis in the laboratory.

Results

Figure 2 shows the results of plotting the angle of steepest slope against the DBC. The regression line, based upon the 54 hills capped by Pennington Formation (solid circles), was obtained by the method of least squares. The open squares represent the 16 slopes below intact cap rocks. Note that the average of the latter group and the value of Y predicted by the regression equation when X=0 are both about 21°. Considering the many possible sources of variation in this relationship, a correlation coefficient of −.68 (significant at the 99% confidence level) is impressive.

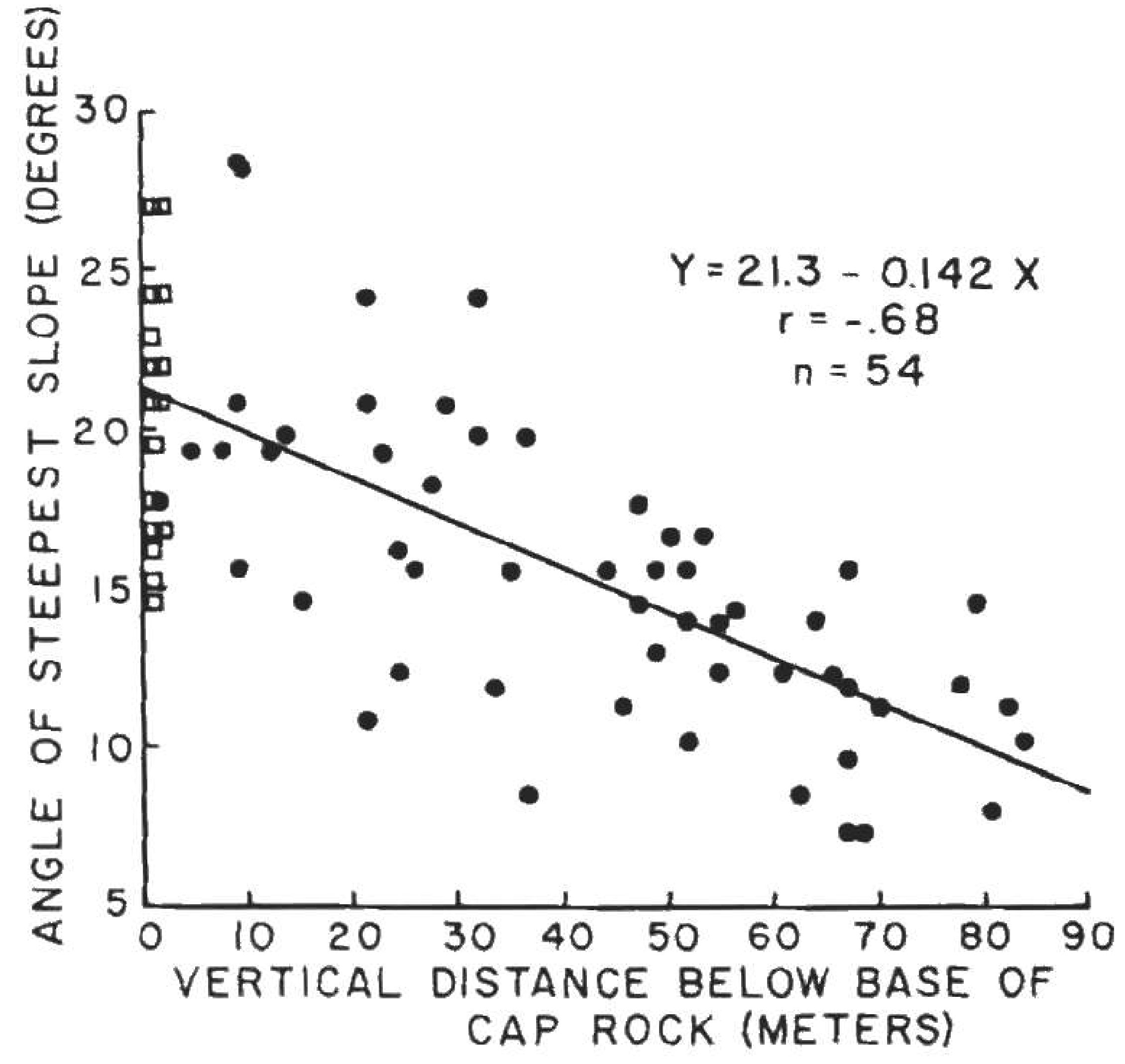

FIG. 2: *Angle of steepest slope plotted as function of the vertical distance between the hill top and the base of the former cap rock. Solid circles represent hills capped by Pennington Formation, and regression line is based on these points. Open squares represent steepest slopes measured on hills with intact cap rocks.*

Figure 3 presents vertically exaggerated profiles of seven hillslopes. These are based on measurements made at 10-meter intervals down the slope; the use of intervals of this size smooths out small irregularities but does not obscure benches formed by the thicker resistant beds in the Pennington Formation. Despite the effect of these beds on the profiles, however, the overall steepness is clearly related to the DBC. Profiles M2 and C4 were surveyed below extant cap rocks (DBC=0), M3 was surveyed where the DBC was only 1.5 m, and the remaining, somewhat more gentle, profiles were surveyed where the DBC was about 50 m.

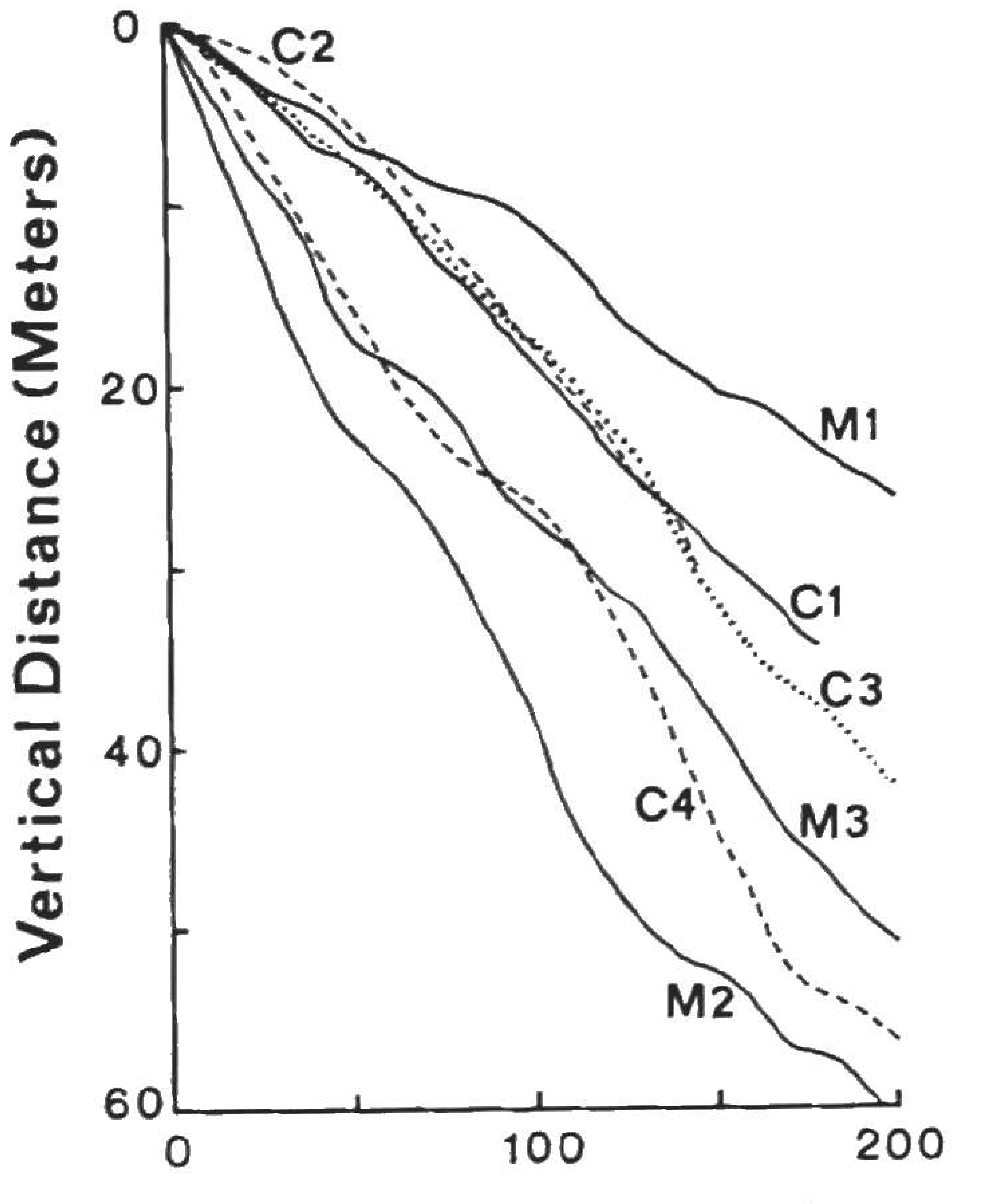

FIG. 3: *Profiles surveyed on seven representative hillslopes. Vertical exaggeration is 5 X. Profiles are discussed in text.*

Textural analysis showed that the percentage of clasts in the surface layer of the mantle ranged from 2% to 76%. Percent sand in the less-than-2 mm fraction ranged from 14% to 65%, percent silt from 29% to 66%, and percent clay from 5% to 41%. These textural indices showed significant correlations with each other and also with DBC and field-measured local slopes. Table 1 presents the correlation coefficients between each pair of variables (in this table, *n* varies from 10 to 14). Coefficients marked with an asterisk are significant at the 99% confidence level and the remainder are significant at the 95% level. This table shows that as DBC increases, slope declines, thus supporting the results obtained by map measurement of slope (Fig. 2). In addition, as DBC increases and slope declines, stoniness decreases, percent sand decreases, and percent clay increases. The highest correlation, —.89, was observed between DBC and percent clasts. This relationship is shown graphically in Figure 4.

TABLE 1. *Correlation Matrix of Hillslope Variables*

	Slope	% Clasts	% Sand	% Clay
DBC	—.70	—.89*	—.74	.78*
Slope		.78*	.78*	—.67
% Clasts			.85*	—.85*
% Sand				—.70*

Although texture may be controlled in part by DBC, slope also exerts an independent influence. This is shown by the three cases in which texture was measured both 20 m and 100 m below the crest. In all three cases, the upper site, where slope was steeper, possessed coarser textures.

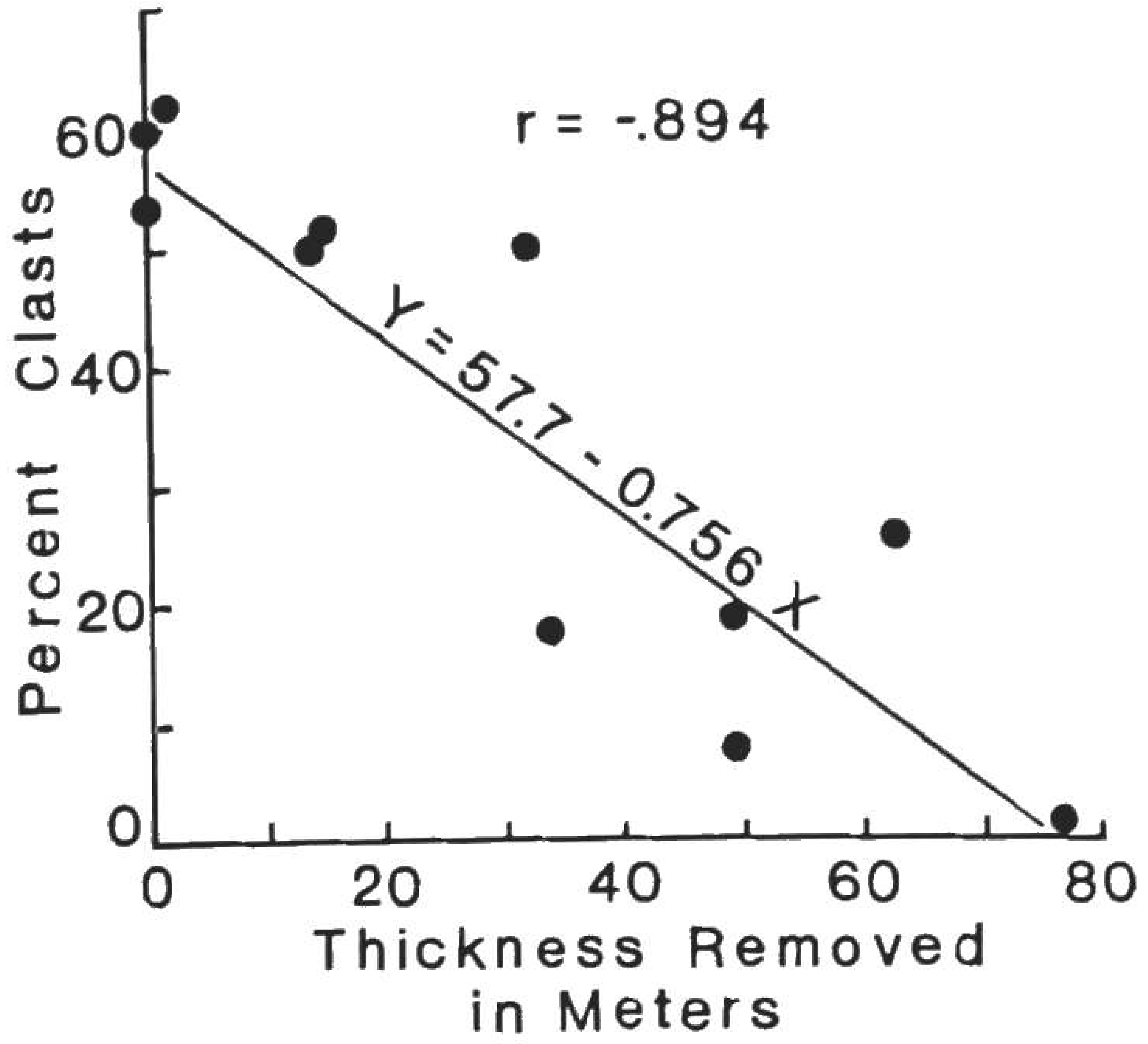

FIG. 4: *Percent clasts in surficial mantle plotted as function of total thickness of Pennington strata removed since stripping of the cap rock.*

DISCUSSION

The results show that the coarseness of the surficial debris on the Pennington slopes decreases as a linear function of the DBC, and that this decrease is accompanied by a similar decline in slope angle. These associations suggests, according to the concept of dynamic equilibrium, that the decrease in particle size (presumably caused by the loss of a source of coarse debris owing to removal of the cap rock) results in a decrease in slope angle, because slopes become graded to the size of debris they must transport. However, an alternative explanation may also be possible. Although the correlations suggest strongly that slope angle and mantle characteristics are linked, it may be that the former causes the latter, rather than the reverse as dynamic equilibrium would have it. One effect of decreasing slope, for example, would be to slow the rate of downhill transport of surficial debris, thereby allowing it to become more weathered in transit.

It will not be possible to decide between these two explanations until the relative importance of particular erosional processes on these slopes is known. In this regard the principle of dynamic equilibrium is rather like Le Chatelier's principle in chemistry: it allows prediction of the general tendency of the system, but leaves one ignorant of the mechanics. Only measurement of processes can provide information on the latter. As little data of this nature is available for this area, it is possible only to make a few speculations at present.

On hillslopes covered with dense forest, processes involving slope wash or raindrop impact would seem to be of little importance. It is true that some locations on Pennington claystones are bare and relatively free of vegetation, presumably because of high erosion rates. Here these two processes appear to be of importance. However, it may be that such locations are the product of disturbance by European settlement, and do not represent natural conditions. Creep is very likely an active process, although no measurements on rates are known for this area. Another possibility is slope failure. Although no evidence of recent failure was seen, it may be that this is, over geologic time, an important means of erosion. Failure probably could occur on these slopes only during very exceptional rainstorms, perhaps ones with several-hundred-year-recurrence intervals. Between such storms creep and slope wash would obscure the evidence for such movement.

If slope failure is indeed a major means by which slopes on the Pennington Formation are eroded, it may be possible to shed light on the question of whether mantle characteristics control slope angle or vice-versa. By measuring engineering properties of the surficial mantle and making certain assumptions about pore pressure conditions, it is possible to predict the steepest slope that this material can support. If these predictions agree with the steepest slopes actually measured in the field, it would suggest that mantle properties do determine slope angle.

Carson and Kirkby (1972) provide a model for such an analysis and show that hillslopes might be expected to decline as the mantle weathers. Their model assumes that the initial weathering product is talus at the base of a cliff. Because of the great permeability of talus, pore pressure can be ignored, so that the maximum hillslope angle would be equal to the angle of internal friction for this material, about 32°-38°. Subsequent weathering produces sufficient fines to fill the interstices of the talus; this material is referred to as taluvium. The angle of internal friction of taluvium (43°-45°) is actually higher than that of talus. However, the presence of fines means that pore pressure now becomes a significant factor. The authors assume that sooner or later the worst possible situation will arise: the water table will rise to the surface. Based on this assumption, and assuming that cohesion is minimal, the authors show (using the Coulomb failure criterion) that the tangent of the maximum angle of stability is roughly equal to one-half the tangent of the angle of internal friction. When the latter is 43°-45°, the former is thus 25°-27°.

With continued weathering taluvium becomes colluvium and the angle of internal friction, and therefore the angle of stability, decreases. A sandy colluvium often has a maximum angle of stability of 19°-21°, based upon the same assumptions as above. By the time the colluvium develops a high clay content, the angle may be only 8°-10° (although cohesion may be significant in this stage).

The data obtained in the present study suggest that this model may be appropriate for the Pennington slopes. At the Cumberland Escarpment, true talus (that is, blocky debris without interstitial fines) appears to be rare. Weathering apparently is rapid enough to produce taluvium from the initial stages. This observation is supported by the fact that no Pennington slopes steeper than 28° were measured, either on maps or in the field. More typically, where DBC is zero or close to zero, maximum slope angles are about 21°, an angle that Carson and Kirby (1972) associate with sandy colluvium. Where DBC is high, maximum slope angles are close to the 8°-10° range that these authors associate with clay-rich colluvium. An obvious line of further research is to determine angle of internal friction and cohesion for samples obtained from the Pennington slopes, use these data to predict maximum angles of stability, and then compare these predictions with measured slope angles. Carson (1971), for example, has carried out such a study.

In attempting to resolve the cause-and-effect question, another possibility that should be considered is that neither slope angle nor mantle character is the independent variable, but rather they may be interdependent, linked to one another as part of a positive feedback system. Suppose, for example, that there is an initial tendency for the mantle to become finer. This causes the slope to decline, which, in turn, because it results in a decrease in slope transport rate, allows greater weathering of the mantle material. The mantle thus becomes finer, thereby tending to cause the slope to decline, which in turn further decreases slope transport rate and promotes further weathering of the mantle, and so forth. In such a situation, the initial "cause" would be of less importance than the linkage of these two variables in this feedback system.

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