[AMERICAN JOURNAL OF SCIENCE, VOL. 254, NOVEMBER 1956, P. 693-706]

# THE ROLE OF CREEP AND RAINWASH ON THE RETREAT OF BADLAND SLOPES

STANLEY A. SCHUMM

ABSTRACT. In badlands near Wall, South Dakota, two distinct types of topography have developed. The broadly rounded interfluves on the Chadron formation are interpreted as due largely to creep, whereas the steep, straight slopes formed on the overlying Brule formation are attributed to dominance of rainwash erosion.

Measurements of erosion depth along stake profiles on badland slopes reveal that erosion is rapid, ranging from 0.8 to 1.5 inches under 32 inches of rainfall during a $25\frac{1}{2}$-month period. Erosion depth increases with slope angle on Brule slopes controlled by rainwash, but is a maximum on the convex divides of the highly permeable Chadron slopes. Pediments adjacent to the badland slopes were lowered 0.9 inch during the same period.

The topographic differences appear to resemble those existing between characteristic humid and arid topographic types, or between the ideal forms postulated by Davis and Penck in their respective cycles of slope retreat. It is suggested that the dominance of creep over rainwash erosion causes the development of broadly rounded divides and convex slopes, whereas predominant rainwash maintains steep, straight, parallel-retreating slopes heading in narrow divides. The contrasting forms observed may be viewed as end members of a continuous series.

## INTRODUCTION

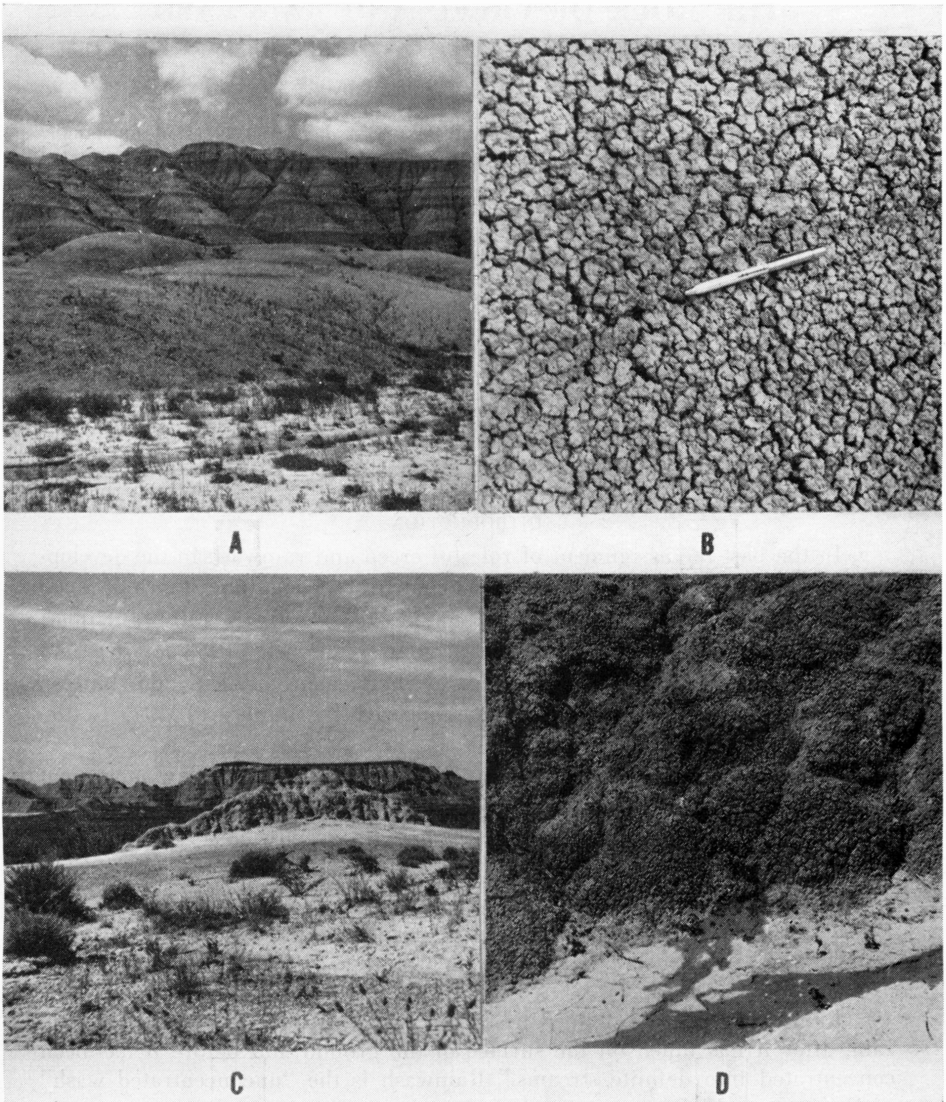
In the past the assignment of roles of creep and rainwash in the development of landforms has occasioned some controversy. The importance of creep in forming convex hilltops has been emphasized by Davis (1892), Gilbert (1909), Baulig (1940), Birot (1949, p. 23), and Penck (1953, p. 78), and the importance of rainwash stressed by Fenneman (1908) and Lawson (1932). Both concepts have been summarized by Baulig (1940), Cotton (1952), and Van Burkalow (1945).

Creep has been defined by Bryan (1922, p. 87) as "the slow movement of soil and rock waste down the slope from which these materials have been derived by weathering. Creep is due primarily to gravity but is facilitated by the presence of water, alternate wetting and drying, freezing and thawing, growth and decay of roots, and the work of burrowing animals." Gilbert (1909) generalized the mechanism of creep in the statement that "whatever disturbs the arrangement of particles permitting any motion among them promotes flow or creep."

Rainwash has been defined by Bryan (1922, p. 89) as "the water from rain, after it has fallen on the surface of the ground and before it has been concentrated into definite streams." Rainwash is the "unconcentrated wash" of Fenneman (1908).

During investigations of slopes and drainage systems of badlands in South Dakota, Arizona, and New Jersey (Schumm, 1956), examples were found which may illustrate the contrasting action of creep and rainwash. In Badlands National Monument, South Dakota, two distinct types of topography have developed. Steep, sharp-crested slopes, on which the mean of a sample of maximum slope angles measured 44°, have formed on the Brule formation, whereas the topography developed on the underlying Chadron formation, where exposed by the retreat of the overlying Brule, is composed of broadly rounded interfluves with a mean maximum slope angle of only 33° (pl. 1-A).

PLATE 1




Topography and slope surfaces at Badlands National Monument, South Dakota.

A. Typical topography of the Brule and Chadron formations. Contact between the two formations, just above the center of the photograph, separates the steep slopes developed on the Brule formation from the gentle, rolling topography developed on the Chadron formation.

B. Closeup of loose mosaic of aggregates forming the surface of slopes developed on the Chadron formation.

C. Small residual of the Brule formation showing straight steep slopes despite short slope length. Note pediment surface rising to make a sharp junction with the residual slope.

D. Water poured onto the surface of the Chadron formation follows subsurface channels to the base of the slope where it reappears on the pediment surface, sapping back the base of the slope.

The surface appearance of the slopes developed on each of the two formations is markedly different. In the dry state the Brule surface is hard; rill channels testify to copious runoff, although desiccation cracks are numerous. The dry Chadron surface, on the other hand, is composed of a loose mass of clay aggregates (pl. 1-B) which may be scooped up by hand.

The rapidity of breakdown of the Chadron clay and the looseness of its surface might suggest rapid erosion, and yet the harder, seemingly more resistant Brule has retreated far back from the margin of the Chadron (pl. 1-A). The Chadron thus appears to act as a more resistant rock. An explanation was apparent when a canteen was emptied on both types of slopes. Runoff occurred almost immediately on the Brule slope; whereas the water was completely absorbed by the loose Chadron aggregates. This suggested that the Brule slopes retreat more rapidly under the action of surface runoff, or rainwash, while the Chadron slopes with high infiltration rates are modified more slowly by the action of creep. To check these conclusions a 5-gallon hand pump was used to spray water on the slopes. On slopes developed on the Brule formation runoff usually occurred almost immediately and in all cases before 1 gallon of water was sprayed on an area of about 6 square feet. The water was quickly concentrated into rill channels and flowed away. In contrast 4½ gallons were sprayed onto about 6 square feet of Chadron slope before runoff began. By then the Chadron surface had become a sticky mud on which each aggregate had softened and slumped down until it came in contact with the next lower aggregate on the slope. From plate 1-B it is possible to visualize how the aggregates would move, sliding on the underlying fine-grained surface which apparently becomes sealed when wet.

## EROSION MEASURED ON BADLAND SLOPES

Erosion was measured on badland slopes developed in a clay-sand fill at Perth Amboy, New Jersey (Schumm, 1956) by driving wooden stakes into the slopes along profile lines orthogonal to the contours of the slope. The stakes were oriented normal to the surface and driven flush with the slope surface. Erosion depth was measured by the length of stake exposed after each storm. Using similar techniques, stake profiles were established on some slopes in the South Dakota badlands in July 1953. The stakes were 18-inch segments of concrete reinforcing rods, ⅜ inch in diameter.

After the installation of the profiles the areas were revisited 15 months (October 1954) and 25½ months (August 1955) later. Between July 1953 and October 1954 precipitation was about 20 inches but only 12 inches during the second period. The total was thus about 32 inches of rainfall between July 1953 and August 1955 at Badlands National Monument Headquarters (J. H. Fraser, personal communication).

Stake profiles are plotted in figures 1 and 2 with the measured erosion for the two periods indicated above each stake. Profiles A and B on figure 1 are from small residuals developed on the Chadron formation. Profiles A and B of figure 2 are on a larger residual composed of both the Brule and Chadron formations. Stake 4 of profile A (fig. 2) is on the contact between the two

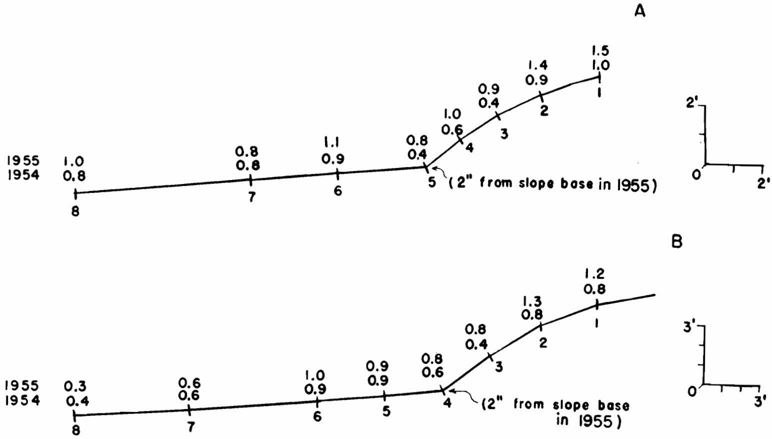



Fig. 1. Profiles showing slopes and pediments developed on two small badland residuals composed of the Chadron formation. Ticks on profiles show position of stakes; numbers above profiles indicate depth of erosion in inches measured in 1954 and 1955. The number assigned to each stake is listed below the profile. During the period of study the slopes of the two profiles have retreated 2 inches from the stakes driven at the junction of pediment and slope (stake 5, profile A; stake 4, profile B).

formations. The last vestige of Brule shale has been removed above profile B (fig. 2) which represents a slope composed entirely of the Chadron formation.

No stake profiles were established wholly on the relatively resistant Brule formation residuals with low infiltration rates, but profiles established on the fill at Perth Amboy illustrate erosion on slopes of similar appearance under the action of rainwash. At Perth Amboy the steep, straight slopes whose mean maximum angle is 49° intersect in narrow-crested interfluves very similar in appearance to those of the Brule. Among the many slope profiles measured at Perth Amboy that were straight from crest to base were several with convex summits. In these cases the parallel-retreating straight slopes had not entirely planed away remnants of the original upland surface. The break in slope profile between the upland and bordering straight slope was rounded by rainwash passing over the break in slope. The three Perth Amboy slope profiles selected for comparison with the Chadron profiles have convex summits and are illustrated in profiles A, B, and C of figure 3. The rainwash erosion on the relatively impermeable, convex Perth Amboy slopes may then be compared with the action of creep on the permeable, convex Chadron slopes.

Comparison of the profiles reveals differences in erosion rates between slopes here attributed predominantly to creep (profiles A and B, fig. 1; profile B, fig. 2) and those on which rainwash is assumed to be dominant (fig. 3 and possibly the combination slope fig. 2-A). On the Perth Amboy profiles (fig. 3) erosion at any point appears to be related to slope inclination. On the steep, straight portions of the slope, erosion is at a maximum and decreases on the convex summit areas. Compared to erosion on the summits, erosion on the straight portions of the slope is essentially uniform. Differences in erosion depth exist on the straight portions, but for the most part are due, as

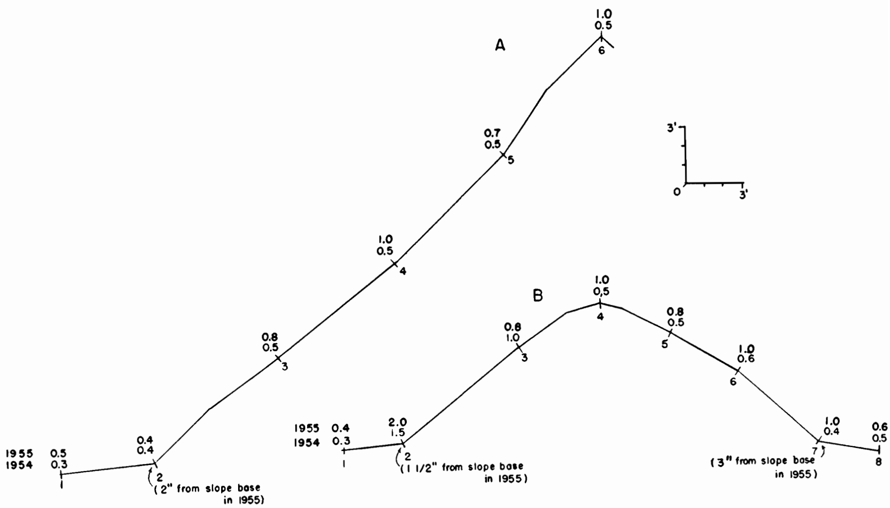



Fig. 2. A. Profile of slope composed of both the Brule and Chadron formations. Stake 4 is driven into the slope at the contact between the two formations. Stake numbers are given below each profile; erosion depth in inches above each profile.

B. Profile across same residual as in A above. Brule formation has been eroded off leaving slopes composed entirely of Chadron formation.

at stake 9, figure 3-B, to a slight concavity or in other cases to a convexity on the slope surface. A statistical comparison of erosion on 16 slopes during the 10-week period and of slope angles measured at the same points in 1949 and 1952 at Perth Amboy cast no doubt upon the hypothesis that the steep, straight portions are retreating parallel under the action of rainwash (Schumm, 1956).

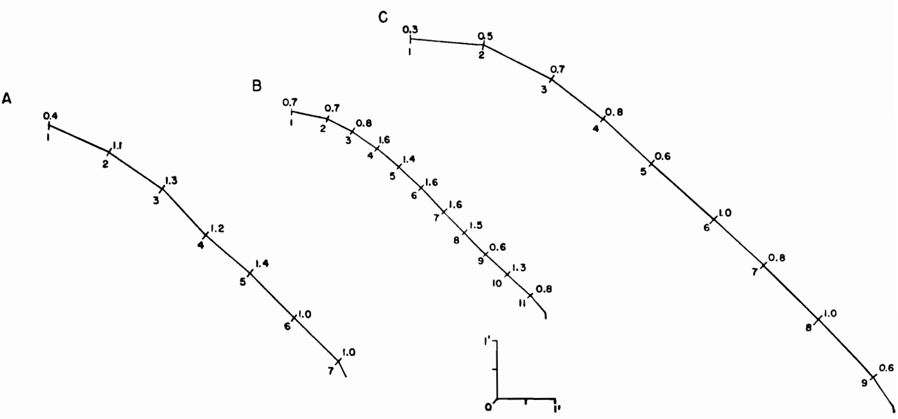



Fig. 3. Perth Amboy, New Jersey, badland slope profiles. Numbers above each profile give measured depth of erosion for a 10-week period in 1952. Ticks on profiles indicate position of stakes.

Erosion on the Chadron residuals of figure 1 shows an opposite relationship. Total erosion depths measured after 15 and 25½ months are greatest on slopes of least inclination. On profile B, figure 2, no systematic relationship is apparent between slope angle and erosion depth, yet a convexity is apparently developing. Note that stake 3 on profile B showed no erosion for the latter 10½-month period, but rather deposition of 0.2 inch. The lack of stakes on the lower steeper parts of this profile precludes the acquisition of data critical for the understanding of mass removal on the slope.

On profile A, figure 2, erosion was uniform over the length of the slope during the first period of erosion and is essentially uniform for the 25½-month period despite the fact that the mean slope below the contact between the Brule and Chadron formations (stake 4) is 39° and that above on the Brule formation is 44°.

The opposite relations as to erosion depths displayed by Chadron profiles in comparison with those of the Perth Amboy badlands (fig. 3) are considered most important to this discussion. Reversed relationships of slope steepness to erosion depth in these two areas can perhaps be reconciled by appealing to dominance of two different geomorphic processes: creep and rainwash.

Runoff or rainwash where observed on badland slopes occurs as surge or subdivided flow (Horton, 1945; Schumm, 1956). Minute obstacles check and deflect the runoff in its downslope course; the movement of the eroded material is therefore not continuous. The runoff neither constantly accelerates nor becomes overloaded toward the slope base on straight slopes in the cases observed. Erosion measured on straight badland slopes is essentially uniform over the length of that slope, although during any one storm the mean erosion depth for the slope as a whole may not be reached or may be exceeded on any part of the slope.

If the slope has a convex summit, due in this case to rounding of the junction between the valley-side slope and original upland slope by runoff, erosion will be less on the gentler slopes, and the steeper portion of the slope will encroach on this convexity until two straight slopes unite to form a sharp crest. In other words, when rainwash acts on a slope any particles A, B, C,

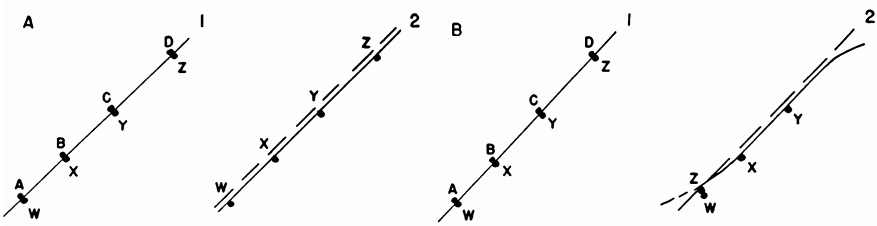



Fig. 4. A. Erosion of particles A, B, C, and D from a slope surface under the action of rainwash. The grains are not necessarily removed in sequence, but each layer of grains is removed before erosion of the next can begin.

B. Removal of particles A, B, C, and D from a slope surface by creep. The grains were removed in sequence, followed by particle Z, causing maximum erosion on the crest of the slope.

and D (fig. 4-A) spaced equally along the slope may be removed from the slope during any one storm or during several storms, but in any case before the underlying particles W, X, Y, and Z are removed. Rainwash is thus an eroding mechanism tending to remove a uniform thickness of material from a straight slope during a storm. It does this because as an eroding agent it attacks the steepest part of the slope with the greatest energy. Thus, when particle A (fig. 4-A) is removed from the slope, in effect, the base level for the particles above is lowered and they are quickly removed. If by chance particle D is removed first, a slight concavity results and erosion is less there until the lower particles on the slope have been removed. This type of action has been documented by repeated measurements along the stake profiles at Perth Amboy (Schumm, 1956).

Creep has been proposed as the dominant process active on the Chadron residuals. The individual aggregates move downslope by swelling from wetting, shrinking from drying and filling of the desiccation cracks from the uphill side, and possibly by rainbeat and sliding and slumping on the sealed, underlying, finer-grained surface. Unlike the action of rainwash, in which a sheet of material moves on the entire slope surface, a particle D (fig. 4-B) engaged in creep will not be removed from the slope at the same time or before a particle A but must traverse the entire slope length behind the particle downslope from it. Thus, the aggregates will be removed from the slope in the order A, B, C, D, Z. Since the movement of the creeping material should be greatest on the steepest slopes, it would seem that erosion would logically be greatest on these slopes. However, it may be that these slopes are principally slopes of transportation. The creeping material from upslope moves over these slopes, protecting the bedrock from rapid erosion.

Perhaps the above explains the partial burial of stake 3 on profile B of figure 2. Furthermore, a stake profile established on a badland slope in Sioux County, Nebraska also illustrates the partial burial of the stakes on steeper slopes (fig. 5). The slope illustrated in figure 5 is steep, bordered at its base by an ephemeral stream, and its surface is composed of highly permeable aggregates derived by weathering of the Chadron formation. After 1 year the upper two stakes of the profile were exposed by the action of creep. Of the

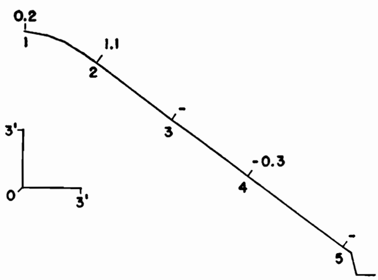



Fig. 5. Profile of badland slope developed in the Chadron formation (Sioux Co., Nebraska). Erosion is greatest at the upper two stakes, while the lower three were buried by downward creeping material from the slope crest. Erosion depth in inches is given above the profile.

lower three stakes on the steepest part of the slope, only stake 4 was found, buried 0.3 inch. Stakes 3 and 5 are assumed to have been buried as well.

If, as observed on slopes modified by creep, wasting is most rapid on the gentler slopes near the summit of a hill, the convexity will broaden and encroach on the less rapidly eroding side slopes, as illustrated by the lowering of the Chadron residuals. A lune-shaped wedge of material is thus removed from the slope as indicated by Lawson (1932) but not, as he thought, by rainwash. Perhaps, also, the supply of material from the flatter summit slopes and the ease of movement on these slopes is increased by the greater amount of rain falling per unit area as compared with the steeper side slopes

## EROSION ON MINIATURE PEDIMENTS

Stake profiles were extended across the miniature pediments bordering the badland residuals in figure 1-A and B. In each case the pediment was lowered, presumably by rainwash. Similar reduction of miniature pediment surfaces has been described by Bradley (1940) and Smith (in press).

In this area Smith recognized that while some pediments were being dissected and lowered others were being raised by aggradation. He concludes that the sheet wash is not a major erosional agent but is chiefly one of transportation. He expects slow lowering of the pediment, however, when it is graded to a "slowly falling base level stream."

In profile the pediments are slightly concave-up. Both pediments are graded to a small ephemeral stream. McGee (1897) and Davis (1938) agree that under such conditions the pediment probably will be degrading and probably concave in longitudinal profile.

The hypothesis favored here is that although modified by rainwash the pediment is not formed by it. Both Paige (1912) and Davis (1938) considered that formation of the pediment is by retreat of a steeper slope leaving the pediment behind as a surface of transportation to the nearest drainage channel or interior basin. In the South Dakota badlands the miniature pediments lie at the bases of retreating badland slopes. Slope retreat is accelerated by undercutting of the upper slope which differs on the two lithologic units. Greater runoff on the Brule shale slopes and "the spreading of sheetwash at rill channel mouths undercuts the escarpments" (Smith, in press). On pediments formed at the base of Chadron residuals the slope retreat is aided by basal sapping of the slope by the appearance of subsurface flow at the junction of slope and pediment surface (pl. 1-D).

During 25½ months the bases of the residual slopes retreated on an average of 2.0 inches from the stake originally placed at the junction of pediment and badland slope (figs. 1 and 2). The pediments were lowered on an average of 0.7 inch during the first 15-month period but only 0.2 inch more during the second period for a mean of 0.9 inch for the 25½ months. During the second period deposition occurred at the lower stake of profile B, figure 1. It may be that the greater total rainfall of the first period, including one storm which totaled 3.46 inches during 24 hours, produced much greater runoff which lowered the pediments by sweeping depositional material from the pediment surface.

## EROSION IN ARID AND HUMID CLIMATES

The differences observed between the two types of badland topography in Badlands National Monument have been interpreted as due to the different processes acting on the slopes: creep and rainwash. Because the topographic differences appear to resemble those existing between characteristic landforms of humid and arid climates, the explanation of the differences in the badlands may be projected to include differences in humid and arid topographic forms. Figure 6 shows the writer's concept of slope development on the highly permeable Chadron formation contrasted with that on the impermeable Brule formation. The differences are perhaps also illustrative of the distinctions between the classical slope retreat concepts of W. M. Davis and W. Penck. Under the action of rainwash (fig. 6-A) the initial slopes retreat at an essentially constant angle, leaving a pediment at their base adjusted to the angle required to allow removal of the debris brought to the slope base, thereby

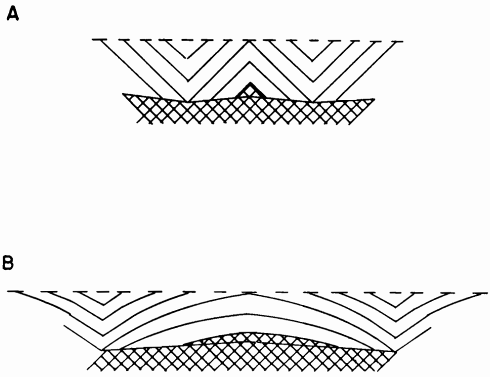



Fig. 6. A. The cycle of slope development on the Brule formation.
B. The cycle of slope development on the Chadron formation.

perpetuating the maintenance of the straight slope. The slopes remain constant until only a small residual remains surrounded by a pediment surface (pl. 1-C).

Slope angles measured on Brule residuals of all sizes are essentially constant in comparison to those measured on Chadron residuals, substantiating parallel slope retreat in this type of landform evolution (Schumm, 1956). Some reduction of slope angle with erosion of the Brule shale slopes may occur, however, due to the alternation of resistant and less resistant layers. The slopes capped by or composed of several resistant layers are somewhat steeper than those where the resistant layers have been removed by a shortening of the slope. Smith (in press) has shown a slight but significant lowering of slope angles on slopes ranging in length from 45 to 3 feet. He attributes this decrease in angle to a lessening of the undercutting of the slope base as it becomes shorter. causing a declining slope retreat even on the Brule formation residuals. This is not substantiated by the basal slope retreat measured on the profiles of figures 1 and 2, which is about 2 inches for all the slopes.

In the development of slopes controlled by creep (fig. 6-B), rounding of the upper slopes occurs early in the cycle, and the radius of curvature increases through much of the later slope development. In this example (fig. 6-B), however, illustrating the development of the Chadron residuals, a pediment also forms at the base of the steeper lower slope. In this area the pediment is apparently formed by basal sapping of the slope by the appearance of subsurface flow at the slope base (pl. 1-D). If this basal sapping did not occur transport would be slowed at the base of the steep slope, and deposition there would probably aid the formation of a concave lower slope analogous to the concave basal slopes of humid climates.

In an effort to obtain some information on the progress of the erosion cycle on the Brule and Chadron formations, a series of slope profiles was measured on remnant buttes exemplifying the results of erosion on slopes of each type.

In figure 7 three profiles were measured across the divide on a residual composed of the Brule formation. The mean slopes of each profile are not markedly different; a small decrease in mean angle is the result of the removal of a nodular layer which causes the convex appearance of the right slope of profile 1. Areas of more impermeable Brule maintain even steeper slopes until late in the cycle (pl. 1-C).

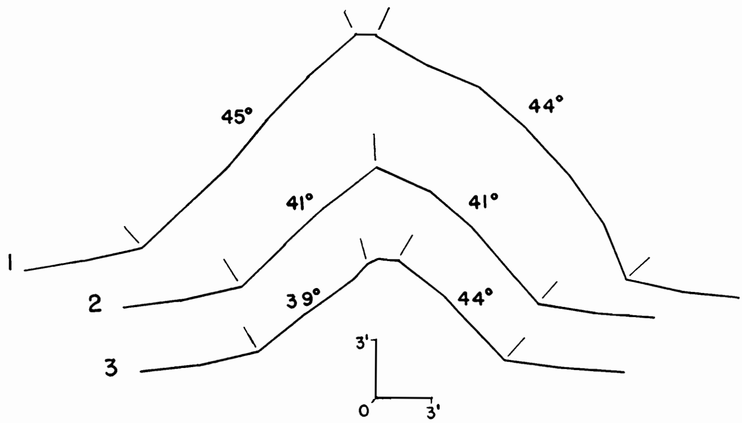



Fig. 7. A series of slope profiles measured on a residual of the Brule formation. Mean slope angles change only slightly with shortening of the slope on this relatively impermeable material.

Figure 8 shows the profiles of figure 2 with two additional profiles added to show the decline of the mean slope angle after the removal of the overlying Brule shale. Profile 1 (fig. 8) is a slope composed of both the Brule and Chadron formations. The dashed line indicates the contact between the overlying Brule and the stratigraphically lower Chadron. With the removal of the Brule from the upper part of the slopes, profiles 2, 3, and 4 show a progressive decline in mean slope angle.

Figure 9 shows a series of profiles across a residual of highly permeable Chadron clay. The texture of the topography in this area is relatively coarse for badlands, as would be expected in areas of permeable soils. The profiles show the marked reduction in slope angle as the erosion of the residual progresses.

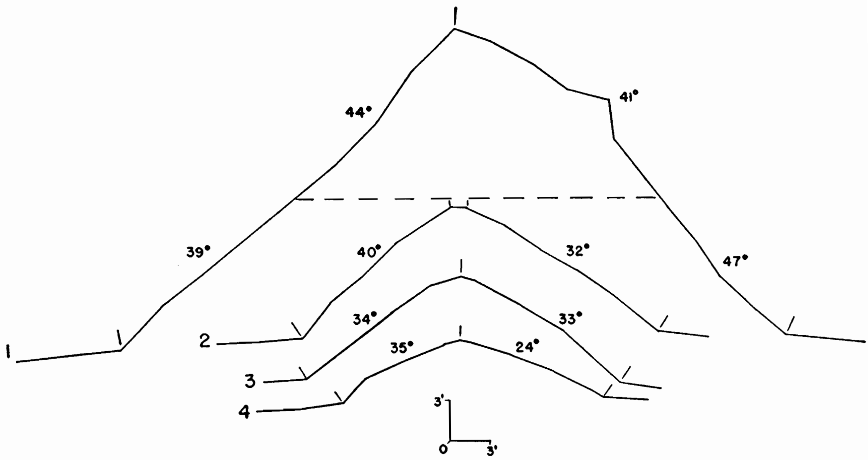



Fig. 8. Series of slope profiles on the residual where the stake profiles of figure 2 are located. The lower three (Chadron) profiles have moderate infiltration rates in comparison to the low rate of figure 7 profiles and the high rate of figure 9 profiles. Dashed line (profile 1) indicates contact between the overlying Brule and the Chadron formation.

The differences between erosion on the Brule and Chadron formations may be more clearly illustrated by comparing the rate of lowering of the residual divides with that of the reduction in width of the residual. In the three profiles of figure 7 (Brule) between profile 1 and 3 the width of the residual was reduced by 50 percent and the height by 56 percent. On the Chadron profiles of figure 8 between profile 2 and 4 the width was reduced only 56 percent while the height was lowered by 72 percent. On figure 9 (Chadron) between profiles 1 and 3 the width was reduced by 63 percent and the height by 81 percent. Therefore, in spite of variations in slope angles caused by lithologic units of differing resistance, the height of the Brule formation residual was lowered only 6 percent more than the width, indicating a small decrease in slope angle, whereas the height of the Chadron residuals is decreased by 28 percent and 18 percent over the width, causing a marked decrease in slope angle. These series of slope profiles seem to substantiate the hypothetical cycle illustrated in figure 6 and indicate that in this badland area the topographic differences are most reasonably explained by the difference in infiltration rates of the slope surfaces.

A further distinction between landforms fashioned by creep and those eroded by rainwash is suggested by a comparison of the rates of erosion on the Perth Amboy, New Jersey badlands and Chadron slopes in Badlands National Monument. The contrasts in mean slope angles and texture may be considered analogous to differences between any two areas of high relative relief fashioned by the two processes. Also, the comparison is justified on the

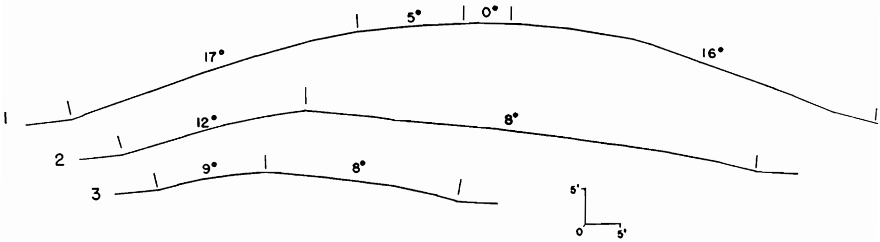



Fig. 9. Series of slope profiles on a badland residual located in a highly permeable area of the Chadron formation.

assumption that the clay-sand fill at Perth Amboy is probably about as easily eroded as any relatively impermeable material, while the Chadron is a rapidly eroding area in which permeability is high.

On the Chadron slopes 32 inches of rain fell, while a mean depth of 1.1 inches of material was removed. At Perth Amboy the mean depth of erosion was 0.9 inch in a period in which about 15 inches of rain fell (U. S. Weather Bureau, 1952).

Comparing directly, the Perth Amboy slopes were reduced an average of 0.2 inch less than the Chadron but with 17 inches less rainfall. With equivalent rainfall over the two areas (32 inches) the Perth Amboy slopes would, at the same ratio, be eroded to an average depth of about 2.0 inches as compared to the 1.1 inches on the Chadron. In other words, slope reduction would proceed at a rate about twice as rapidly by rainwash as by creep.

Influencing the reliability of this estimate are many factors of which the most important is probably the precipitation intensities involved. It is, however, reasonable to suppose that in areas otherwise comparable, rainwash erosion will proceed at rates nearly double that by creep. The hills of Chadron formation lying in front of the retreating Brule escarpment in the South Dakota badlands seem to support, at least qualitatively, the above estimate.

This concept may be of importance in attempting to extend the relationships between the geomorphic and hydrologic characteristics of drainage basins in semiarid regions to more humid areas and also as a partial explanation of the high rates of erosion in semiarid regions.

## CONCLUSION

In humid regions rapid rock disintegration produces thick soil horizons protected by good vegetation cover. As Davis (1930) has suggested, creep is probably dominant there. Abundant evidence (Sharpe, 1938) has been cited of its importance. In arid regions with poor vegetation cover and thin soils, rainwash is probably the dominant process. Undoubtedly, both occur in each climatic region, but in humid areas rainwash erosion probably occurs only in exceptional storms; whereas in arid regions creep is important probably only after several consecutive rains have saturated the soil. It may be that rainwash erosion and parallel slope retreat are dominant in the early stages of the erosion cycle in humid regions, when relief is great and slopes are steep

(Birot, 1949, p. 23), but that with the development of thick soil cover and grading of the slopes the action of creep and declining slope retreat become the characteristic process and form.

It is possible that the areas in which creep dominates over rainwash. or vice versa, are end members of a continuous series ranging through all proportions of both processes depending on prevailing vegetation, soils, and climate. Holmes (1955) has suggested that the classic examples of the arid and humid geomorphic cycles, as contrasted in the Penck and Davis concepts of slope retreat. are end members of such a series. This concept appears to be supported by the badland studies.

If creep is responsible for convex interfluves in the mature and later stages of erosion (after any initial surface of low relief is completely consumed), there is no need to resort to Penck's explanation that the recent diastrophic history of a region controls the slope profiles. In Penck's system the straight slopes of the Brule formation residuals would indicate uniform uplift (gleichformige Entwicklung) whereas the convex slopes of the Chadron residuals would indicate increasing rates of uplift (aufsteigende Entwicklung). Both diastrophic histories cannot be true within the same small area. Penck claims that such local exceptions do not invalidate his concepts. Perhaps this is true, but by the same token the diastrophic control is merely an unnecessary complication whose introduction is unjustified in many areas.

## ACKNOWLEDGMENTS

This study is part of a quantitative investigation of erosional landforms sponsored by the Geography Branch of the Office of Naval Research as Project No. NR 389-042, under Contract N6 ONR 271, Task Order 30 with Columbia University. The writer wishes to acknowledge the suggestions made by Professor A. N. Strahler of Columbia University and Messrs. M. G Wolman and L. B. Leopold of the U. S. Geological Survey for improvement of the manuscript.

## REFERENCES

Baulig, Henri, 1940, Le profil d'équilibre des versants: Annales de géographie, v. 49, p. 81-97. (Reprinted in Essais de Géomorphologie, 1950: Paris, Soc. Edition, Les Belles Lettres.)

Birot, Pierre, 1949, Essai sur quelques problèmes de morphologie générale: Lisbon, Instituto para a Alta Cultura, Centro de Estudos Geograficos.

Bradley, W. H., 1940, Pediments and pedestals in miniature: Jour. Geomorphology, v. 3, p. 244-254.

Bryan, Kirk, 1922, Erosion and sedimentation in the Papago country, Arizona: U. S. Geol. Survey Bull. 730, p. 19-90.

Cotton, C. A., 1952, The erosional grading of convex and concave slopes: Geog. Jour., v. 118, p. 197-204.

Davis, W. M., 1892, The convex profile of badland divides: Science, v. 20, p. 245.

———, 1930, Rock floors in arid and humid regions: Jour. Geology, v. 38, p. 1-27; 136-158.

———, 1938, Sheetfloods and streamfloods: Geol. Soc. America Bull., v. 49, p. 1337-1416.

Fenneman, N. M., 1908, Some features of erosion by unconcentrated wash: Jour. Geology, v. 16, p. 746-754.

Gilbert, G. K., 1909, The convexity of hilltops: Jour. Geology, v. 17, p. 344-350.

Holmes, C. D., 1955, Geomorphic development in humid and arid regions: A synthesis: Am. Jour. Sci., v. 253, p. 377-390.

Horton, R. E., 1945, Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology: Geol. Soc. America Bull., v. 56, p. 275-370.

Lawson, A. C., 1932, Rain-wash erosion in humid regions: Geol. Soc. America Bull., v. 43, p. 703-724.

McGee, W. J., 1897, Sheetflood erosion: Geol. Soc. America Bull., v. 8, p. 87-112.

Paige, Sidney, 1912, Rock-cut surfaces in the desert ranges: Jour. Geology, v. 20, p. 442-450.

Penck, Walther, 1953, Morphological analysis of landforms: New York, St. Martin's Press. (Translated by Hella Czech and K. C. Boswell.)

Schumm, S. A., 1956, Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey: Geol. Soc. America Bull., v. 67, p. 597-646.

Smith, K. G., Erosional processes and landforms in Badlands National Monument, South Dakota: Geol. Soc. America Bull., in press.

Sharpe, C. F. S., 1938, Landslides and related phenomena; a study of mass-movements of soil and rock: New York, Columbia Univ. Press.

Van Burkalow, Anastasia, 1945, Angle of repose and angle of sliding friction, an experimental study: Geol. Soc. America Bull., v. 56, p. 669-707.

Building 25
Federal Center
Denver, Colorado