Hillslope Processes in Southwestern Arizona

by

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Abstract

Longitudinal profiles of 17 hillslopes in southwestern Arizona were analyzed in order to elucidate arid hillslope processes. In addition, slope angles of the regolith and the bedrock, regolith thickness, and area of exposed bedrock were studied on numerous other slopes. All the slopes studied are developed on granitic bedrock. All but two slopes are less than 32 degrees, which is the angle of repose for large, loose detritus in arid areas. Since slopes range from 20 to 31 degrees, it appears that essentially parallel retreat of slopes is occurring in this part of Arizona.

Regression analysis indicates that the middle segments of the hillslopes are essentially straight. Minor irregularities in these straight segments are caused by bedrock ridges and scarps and by depressions that may be due to debris flows. Short upper and lower segments of the slope are convex to the sky and concave, respectively.

The straight-line portions of the hillslopes are believed to be due to weathering and local redistribution of the weathered detritus by creep and sheetwash. This redistribution removes slight topographic highs and fills in the lows with detritus, resulting in a straight profile. Local rapid movement of debris, probably due to debris flow, occurs on some slopes.

Weathering is, in general, proceeding at a more rapid rate than the redistribution of weathering products, provided the angle of repose is not exceeded. This is suggested by the lack of relationship found between particle size and position downslope, which indicates that distribution of size of large particles may be more closely related to joint spacing than to sorting.

In cases where the hillslope is approaching instability, large detritus is moved downslope rapidly. This is shown by blocks of detritus that lack desert varnish on their upper surfaces. On all of the lesser slopes, the coarse detritus has a well-developed and deep weathering rind and desert varnish.

Bedrock scarps that trend parallel to the hillslope contours may be transitory features. They are the foci of intense erosion that is manifested by the crumbling nature of the bedrock in the scarps and the general lack of desert varnish. These scarps die out laterally into regolith-covered slopes.

Introduction

Although pediments have been thoroughly studied, less attention has been paid to processes operating on hillslopes that flank pediments. Such studies are need to further our understanding of arid-region geomorphology.

The purpose of the present study is to understand the geomorphic processes that are operating on hillslopes in southwestern Arizona. Many slopes were studied in the field and some generalizations were formed. An advantage in the study area is that many slopes are developed on the same granitic rock type and under the same general climatic conditions. Thus, variations due to rock type and climate are minimal.

Slope profiles were measured to study slope geometry as a key to understanding which processes were responsible for a particular shape of a slope. These processes include sheetwash, creep, weathering, and gully erosion. The detritus found on the slope was studied to further delineate the important process or processes.

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Previous Studies

Previous geomorphic studies of hillslopes have centered around classification. Many workers (Ahnert, 1970a) have attempted to classify hillslopes according to overall or segmented geometry. Other studies have been made to mathematically model hillslope development (Ahnert, 1970b; Schumm, Bird, and Starkel, 1970). Presently, geomorphologists are beginning to study the slope in greater detail, observing the various aspects of the slope and then attempting to explain what process is responsible for the slope development (Cooke and Warren, 1973; Rahn, 1966; Melton, 1965).

A summary of the various works on hillslope processes and models is given by Leopold (1970). This work is fairly comprehensive and discusses the various hypotheses proposed over the years.

Location and Physiography

The study area is south of Buckeye, Arizona (lat 33°24' N., long 112°35' W.), which is 64 km west of Phoenix (Fig. 1). It is within the Basin and Range physiographic province (Fenneman, 1931).

Two mountain masses dominate the study area, Buckeye Hills and Maricopa Mountains. These masses extend about 500 m above the adjacent valley floors, and their summit areas are isolated, rugged peaks. The mountain drainage is by narrow, steepsided canyons, which debouch into through-flowing washes on the flanking pediments and alluvial fans.

Pediments are developed on bedrock and locally extend onto heavily caliched alluvium. The junction between fans and pediments is transitional.

Rainbow Valley separates the two mountain masses. It is filled with alluvial fans and is drained by intermittent streams, which eventually flow into Gila River. Gila River flows westerly, past Buckeye, and then turns southward past Buckeye Hills.

General Geology

The mountain masses in the study area were mapped by Wilson and others (1969). Buckeye Hills are composed of Precambrian and Cretaceous-Tertiary granite, quartz monzonite, granodiorite, quartz diorite, and gneiss. On the extreme western edge, Buckeye Hills are capped by a Tertiary basalt flow. Maricopa Mountains are composed of Precambrian granite, quartz monzonite, granodiorite, and quartz diorite. Both mountain masses are interlaced with quartz veins up to 1.5 m wide.

The valleys are filled with alluvium whose depth is over 213.4 m at one point in the center of Rainbow Valley (L. H. Lattman, 1974, oral comm.). The alluvium is extensively cemented by caliche.

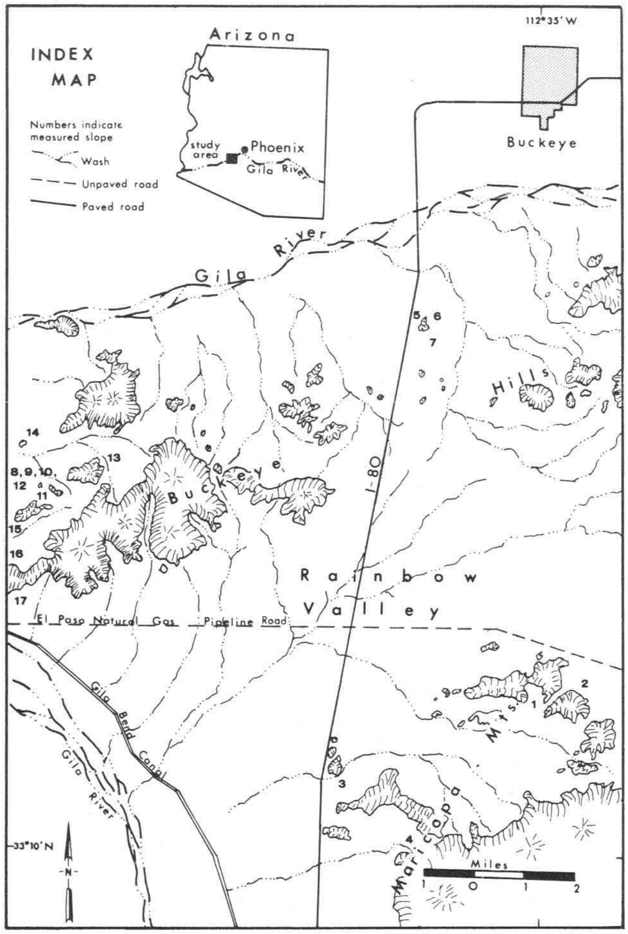


Fig. 1. Index map

Method of Investigation

Field Study

The field investigation consisted of a detailed study of the form and detritus of selected hillslopes. The hillslopes chosen were developed on a single type of bedrock throughout, are nearly the same height above sea level, and face into all quadrants of the compass.

The individual hillslopes were all studied in the same manner. Beginning at the top of the slope, a topographic profile perpendicular to the contours was made. Slope distance was measured with a ruled stick and vertical control was carried by hand level. Data and observations included slope angles, thickness of residual material, lengths of the three principal axes, and orientation in a horizontal plane of the long axis of sampled particles on the hillslope, and degree of development of desert varnish.

Slope Profiles

The location of the 17 slopes studied in detail is shown in Figure 1. Table 1 lists the significant data for each of these slopes. The hillslopes are developed on granite or quartz monzonite.

The 17 slopes measured exhibit an average slope angle ranging from 21 to 31 degrees (Table 1). The lower angles are usually found on the regolith, while the bedrock segments of the slope have a higher angle. Table 2 is a comparison of slope-angle differences between regolith-covered segments and bedrock segments.

The two highest slope angles, those of slopes 1 and 2 (31.6° and 30.1°, respectively), are hillslopes adjacent to high peaks; the remainder of the slopes are on outliers.

A Kruskal-Wallis one-way analysis of variance was used to test the concept that slope directions and slope angle were related. No significant relationship between slope direction and slope angle was found.

The results of regression analysis of the slope profiles are summarized in Table 3, which lists the percentage of variation of each profile explained by the various regression equations. For each profile an analysis of variance was performed for each equation to determine the lowest degree equation that would explain a significant amount of profile variation. In this way, the hillslope form could be determined and described by the simplest equation. A typical result is shown in Figure 2.

Regression analysis results show that for 14 of the 17 slopes, 99 percent of the profile variation is accounted for by a linear equation $y = mx + b$; this equation accounts for 97 percent of the variation of all the slopes studied (Table 3). Although visual inspection of these slopes in the field and the study of drawn profiles seem to reveal that the slopes are not linear, it must be noted that the convexities and concavities of the slope are at the beginning of the pediment and the top of the divide. These two segments are concave and convex, respectively. The major segments of the near straight-line slopes are the middle segments, which constitute more than 65 percent of the length of a slope. This is shown by the residual x values, which are computed by subtraction of the actual x coordinates from the predicted x coordinates. The predicted coordinates are computed by the regression equation. The greatest residuals (the greatest difference between actual and predicted values) usually occurred near the foot or the top of the slope. When a large residual value occurred in the middle segment of the slope, it usually could be explained by a bedrock outcrop, which will be discussed later. Deviations from a straight slope that occur at the top and bottom of hillslopes are minor in amount of concavity or convexity and in length of slope involved.

Slope Material

Gruss and finer material found on the full length of the hillslopes will be referred to collectively as regolith. The coarser fraction of the regolith, composed of fragments greater than 2.54 cm in longest axis and composed of more than two mineral grains, is considered float, regardless of its position in the regolith. Float may or may not be covered with desert varnish, and much of it is chemically weathered to some extent. There is no obvious preferred orientation to the float as determined by visual inspection. On slopes 6 and 7 the lengths of the longest measured axes of the float decreased downslope, but on the other slopes there was no systematic size variation with position.

Gruss is derived from the mechnical breakup of bedrock and float and is composed of single mineral grains. The longest axes of the grains range from sand size to 1.3 cm. The average size is 0.64 cm. Gruss is found throughout the entire slope profile and is usually well mixed with finer material.

Material finer than gruss is composed of particles smaller than sand-size. X-ray diffraction studies of the particles finer than 2 microns indicate smectite, kaolinite, and mica are present (Fig. 3). Quartz is also abundant.

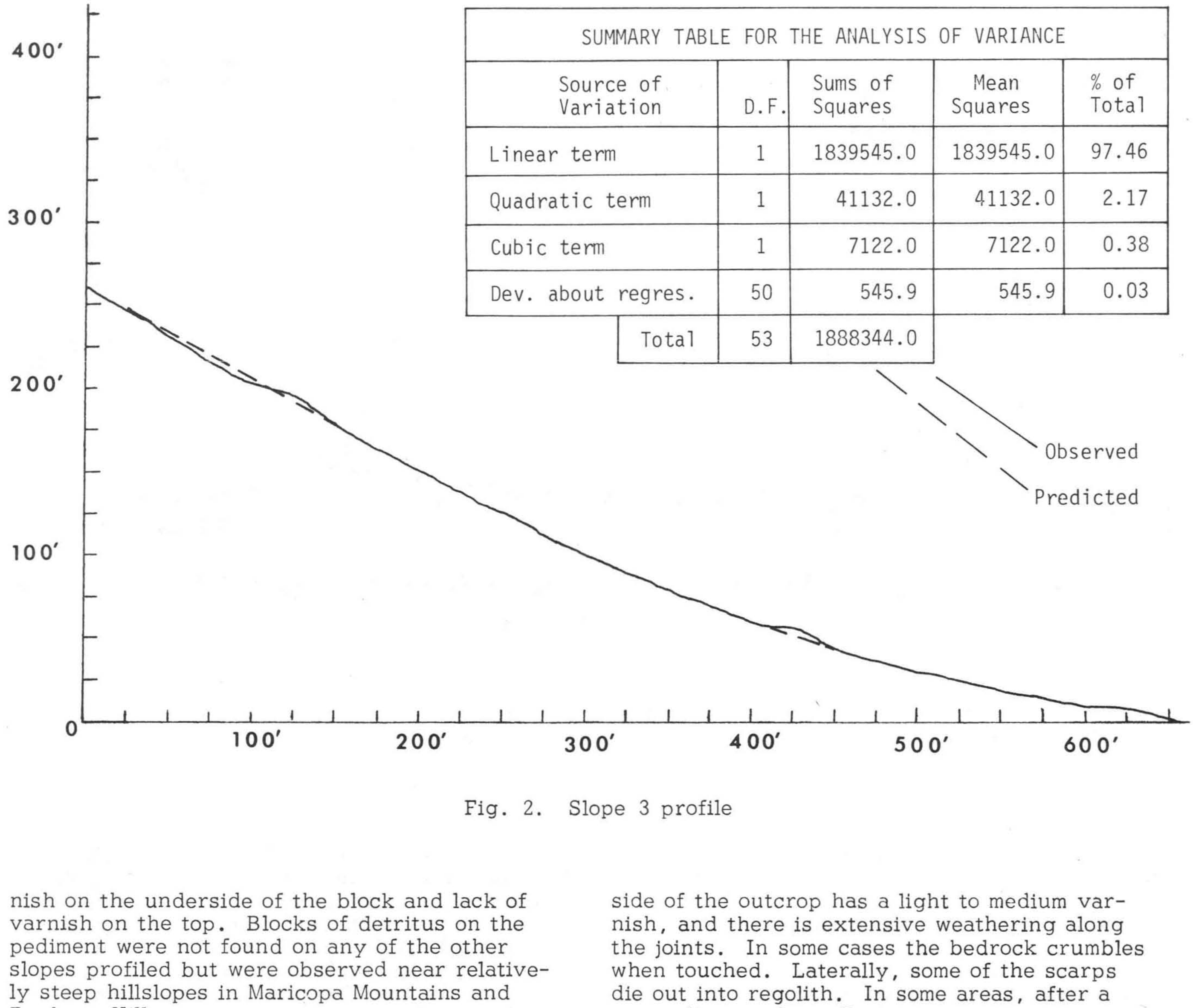
Since weathering is more active near the surface, the upper part of the regolith contains a larger proportion of gruss and finer material. At the surface, there is a concentration of gruss-sized material; this is because the material that is finer than gruss appears to have been winnowed by water and, perhaps, wind action.

The regolith thickens downslope from an average of 5.1 to 12.7 cm on the upper part of the hillslopes to greater than 17.8 cm near the bottom of the hillslopes. Near the foot of the hillslopes the contact between regolith and bedrock is transitional. Elsewhere on the slope the contact is sharp, but local gradational contacts are found. Leaching of finer material on the hillslopes is evident from slight color changes with depth, but it is difficult to differentiate soil horizons.

On hillslope 2, large blocks of detritus are found along the whole profile and onto the adjacent pediment. These blocks have been moved, as evidenced by the well-developed var-

Table 1. Summary of data from 17 slopes studied in detail

Slope No.	Location on USGS Topographic map	Compass Direction of Slope Face	Elevation, MSL, ft (m) Top of Slope	Elevation, MSL, ft (m) Bottom of Slope	Length along Slope ft (m)	Average Slope Angle Degrees
			Cotton Center Quadrangle, Arizona			
1	SE¼NE¼ sec. 32, R. 3 W., T. 2 S.	E	1,540 (469.4)	1,233 (372.8)	554 (168.9)	31.6
2	NW¼SE¼ sec. 33 R. 3 W., T. 2 S.	W	1,560 (475.5)	1,217 (370.9)	637 (194.2)	30.1
3	SW¼ sec. 2 R. 4 W., T. 3 S.	S	1,220 (371.9)	994 (287.7)	684 (208.5)	26.4
4	SW¼NE¼ sec. 29, R. 3 W., T. 3 S.	E	1,520 (463.3)	1,250 (381.0)	540 (164.6)	27.7
			Buckeye Quadrangle, Arizona			
5	SW¼ sec. 25 R. 3 W., T. 1 S.	N	1,115 (339.9)	1,011 (308.2)	242 (73.8)	23.9
6	SW¼ sec. 25, R. 3 W., T. 1 S.	W	1,020 (310.9)	942 (287.1)	161 (49.1)	27.8
7	SW¼ sec. 25 R. 3 W., T 1 S.	S	1,115 (339.9)	949 (289.3)	448 (136.6)	20.1
			Hassayampa Quadrangle, Arizona			
8	SE¼ sec. 10 R. 5 W., T. 2 S.	N	1,020 (310.9)	900 (274.3)	302 (92.4)	22.8
9	SE¼ sec. 10 R. 5 W., T. 2 S.	W	1,020 (310.9)	974 (296.9)	335 (102.1)	22.4
10	SE¼ sec. 10, R. 5 W., T. 2 S.	S	1,020 (310.9)	954 (296.9)	402 (122.5)	22.2
11	NW¼NW¼ sec. 14 R. 5 W., T. 2 S.	N	1,200 (365.8)	1,023 (311.8)	352 (105.7)	26.0
12	SE¼ sec. 10 R. 5 W., T. 2 S.	N	1,020 (310.9)	900 (274.3)	246 (75.0)	27.3
13	SW¼ sec. 11 R. 5 W., T. 2 S.	E	1,040 (317.0)	900 (274.3)	292 (89.0)	25.9
14	NE¼NE¼ sec. 10 R. 5 W., T. 2 S.	E	1,110 (338.3)	860 (262.1)	536 (163.4)	23.2
15	NW¼SE¼ sec. 15 R. 5 W., T. 2 S.	S	1,110 (338.3)	1,032 (314.6)	222 (67.6)	21.8
			Arlington Quadrangle, Arizona			
16	SW¼NE¼ sec. 18 R. 5 W., T. 2 S.	E	1,220 (371.9)	1,090 (332.2)	292 (89.0)	24.2
17	SE¼NW¼ sec. 15, R. 5 W., T. 2 S.	W	1,020 (310.9)	942 (287.1)	195 (59.4)	21.2



SUMMARY TABLE FOR THE ANALYSIS OF VARIANCE

Source of Variation	D.F.	Sums of Squares	Mean Squares	% of Total
Linear term	1	1839545.0	1839545.0	97.46
Quadratic term	1	41132.0	41132.0	2.17
Cubic term	1	7122.0	7122.0	0.38
Dev. about regres.	50	545.9	545.9	0.03
Total	53	1888344.0		

Fig. 2. Slope 3 profile

nish on the underside of the block and lack of varnish on the top. Blocks of detritus on the pediment were not found on any of the other slopes profiled but were observed near relatively steep hillslopes in Maricopa Mountains and Buckeye Hills.

The average hillslope had less than 30 percent bedrock exposure by visual inspection. Bedrock outcrops, where they do occur, are weathered and varnished to various degrees. Recent exposures of bedrock are lightly varnished and therefore lighter in color than adjoining areas of heavily varnished, older exposures.

Bedrock outcrops occur in three distinct ways: (1) as scarps that trend nearly parallel to contours, (2) as ridges that extend perpendicular to the contours, and (3) as relatively small, isolated, flat outcrops on the slope.

The bedrock scarps that trend parallel to contours are, on the average, 6 feet (2 m) high. There is an accumulation of regolith on the upslope side of the scarp. The downslope side of the outcrop has a light to medium varnish, and there is extensive weathering along the joints. In some cases the bedrock crumbles when touched. Laterally, some of the scarps die out into regolith. In some areas, after a scarp dies out laterally its apparent continuation is found further along the slope.

Bedrock ridges perpendicular to contours rarely extend the full length of the slope; none were observed that reached the pediment. The ridges are usually heavily varnished and weathering is extensively developed along the joints. The slopes of the crests of ridges are greater than those of the adjacent hillslopes (Table 2), and there is a fairly sharp break in slope between ridge sides and the adjacent hillslopes. Blocks that have apparently been broken from the ridges lie fairly close by and are varnished to a high degree, except on the underside. This indicates that the blocks were not transported away from the ridges recently.

The flat, smooth, isolated outcrops of bedrock are usually found on the middle or lower parts of the slopes. These outcrops are only

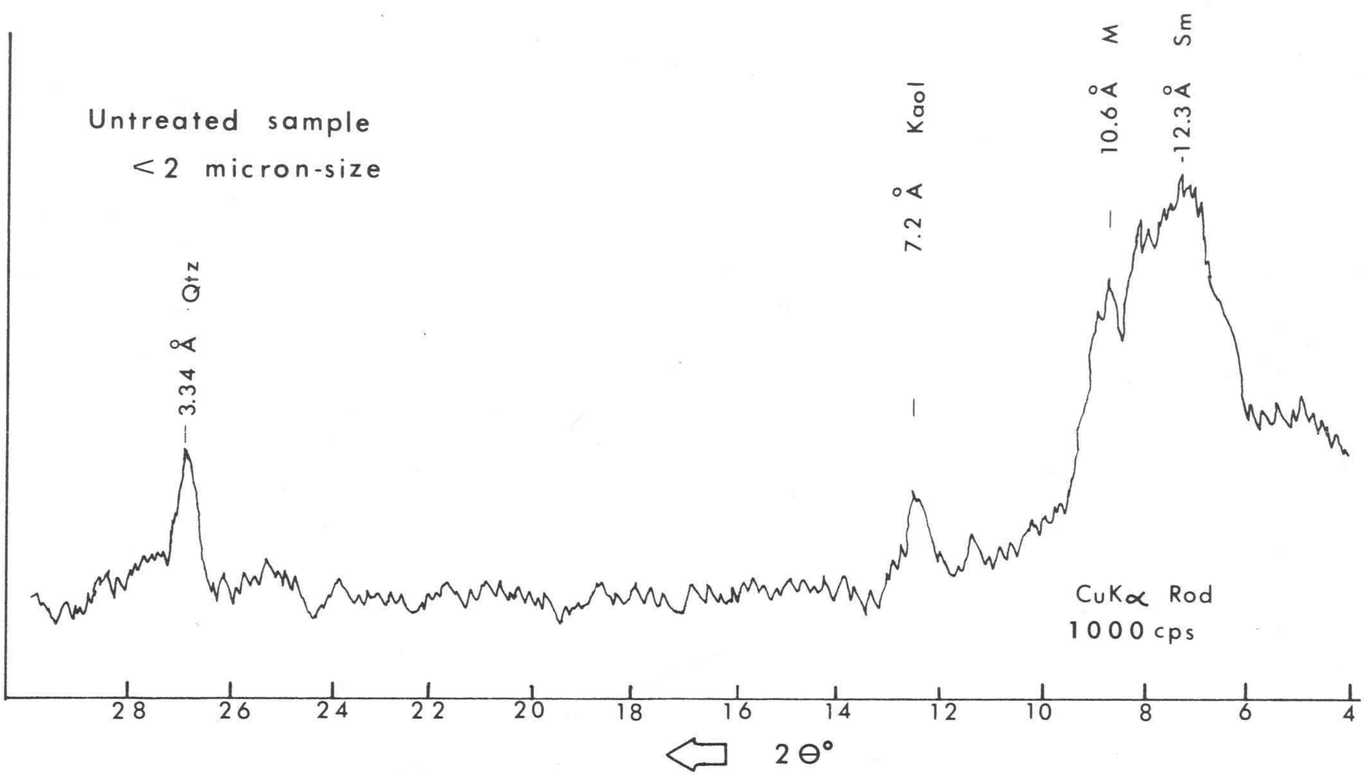


Fig. 3. Representative x-ray diffraction of the less than 2 micron-size material. This sample is from slope 3. Sm--smectite; M--mica; Kaol--kaolinite; Qtz--quartz.

a few square feet in area and have a slope angle that is fairly close to, or slightly less than, that of the adjacent hillsopes. The flat outcrops, in some instances, are free of regolith; in some cases, they show scattered overlying regolith. These outcrops are not very extensively varnished or weathered. A slight convex upward break in slopes has been observed on the upslope side of these outcrops.

At isolated places on the hillslopes there are local areas from which weathered debris has been removed, possibly by debris flow. Flows of different age occur, and relative age may be distinguished by degree of varnish on all sides of the boulders in the material moved.

A more recent flow, on slope 3, was studied in detail. It is a lobate tongue of large blocks and smaller, more rounded boulders. These smaller boulders are weathered to a greater extent than the blocks. The maximum size of the largest block within the lobate tongue is 30 inches (76.2 cm). The average size of the blocks and smaller boulders was not determined. The two parallel, lateral edges and the front of the flow are 1.5 feet (0.5 m) higher than the adjacent hillslope and are 3 feet (1 m) higher than the center of the flow. The center of the flow is a bedrock surface. This surface is planar, very smooth, and there is a sharp convex upward break in slope bounding the upslope part of the surface. Fine material is absent from the lateral edges of the flow but is found as small wedges downslope from the end of the flow.

Pediment Surfaces

The pediments are developed on bedrock or on heavily caliched alluvium, and they may be veneered with patches of regolith. The loose detritus measured on the pediment of profile 3 decreased in maximum size away from the hillslope. The largest block near the hillslope measures 10 x 10 x 8 inches (25.4 x 25.4 x 20.3 cm), and the size of the largest detritus at last station, near the toe of the pediment, is 6 x 3 x 1 inches (12.7 x 7.6 x 2.5 cm). The size of the loose detritus was not measured across all of the pediments.

The pediments are commonly free of gullies. The few gullies that traverse the pediments head about a third of the way up the flanking hillslopes.

Table 2. Difference of slope angle on bedrock slopes and regolith slopes

Bedrock Slope, length over 6 ft (2 m)		Regolith Slope, length over 6 ft (2 m)	
Angle	Comment	Angle	Comment
21°		19°	
27	Ridge perpendicular to contours	17	
20	Flat outcrop	15	
23		20	
24	Lower segment of slope	20	
27		19	
27	Ridge perpendicular to contours	20	
33		27	Upslope, behind boulder
26	Ridge perpendicular to contours	20	
24		18	
24		20	
27	Ridge perpendicular to contours	25	Top segment of slope
Ave. = 26°		Ave. = 20°	

The transition from hillslope to pediment is usually marked by a concave upward break in slope caused by a bedrock scarp. This break in slope between hillslope and pediment is generally not sharp. The few cases of a sharp junction between hillslope and pediment are along mountain fronts and not around outliers.

Origin of Hillslope Form

The straight segments that compose the major part of the hillslopes studied suggest a process of nearly uniform intensity. Creep and sheetwash, active on the hillslopes, are not capable of much direct erosion of the bedrock surface, as evidenced by the large areas of hillslope covered by regolith. Both of these processes move material already loosened by physical weathering and redistribute it.

As Gilbert (1877) noted long ago, weathering is more effective at the divides, and together with creep, it results in a convex upper slope. The material moved to the foot of the slope by sheetwash is deposited with a concave-upward surface.

The longest segments of the slopes in the study area are straight, suggesting uniform weathering on a single rock type. Regression analysis indicates the slopes' profiles are very close to straight lines and the deviations at the top and foot are minor. It is concluded that uniform weathering is the dominant process forming slopes in the study area and that sheetwash and creep play a minor, but significant, role in shaping the uppermost and lowermost parts of the slope. Uniform weathering and the minor role of sheetwash and creep are also suggested because many of the slopes show no systematic change in largest particle size downslope.

The straight segments are locally broken by bedrock scarps. The scarps are subject to intense weathering, as indicated by the depth of weathering and crumbly nature of the outcrop. Regolith above the scarp is thicker than average; therefore it may store moisture and aid in weathering of the scarp. Laterally, some of the present scarps die out as the regolith above moves down over the very low residual scarp. It is suggested that these scarps are transitory and are eventually removed (Fig.4).

Bedrock ridges that are perpendicular to

Table 3. Percentage of slope profile variation accounted for by linear, quadratic, and cubic equations

Slope No.	Equation			% Deviation about Regression
	Linear	Quadratic	Cubic	
1	99.356%	0.564%	0.055%	0.025
2	99.505	0.347	0.121	0.027
3	97.460	2.170	0.380	0.030
4	99.861	0.089	0.016	0.035
5	99.911	0.066	0.004	0.016
6	99.302	0.566	0.007	0.126
7	99.690	0.072	0.040	0.196
8	98.952	0.637	0.232	0.179
9	99.615	0.227	0.105	0.057
10	99.838	0.074	0.006	0.083
11	99.707	0.129	0.125	0.039
12	99.793	0.066	0.030	0.112
13	99.845	0.050	0.054	0.051
14	98.813	0.991	0.135	0.061
15	99.720	0.016	0.213	0.051
16	99.946	0.023	0.001	0.029
17	99.839	0.107	0.007	0.047

contours are apparently divides between areas of concentrated slope wash.

Relation of Slope Detritus to Slope Angle

The angles of the hillslopes profiled in this study are below the angle of repose for loose, large detritus. Melton (1965) suggested that the loose detritus on granitic hillslopes in southeastern Arizona becomes increasingly more unstable as the slope angle becomes greater than 28 degrees. He also indicated that 36 degrees is the upper limit for which any loose detritus will remain stationary. The slope angles in the present study are well below the 36-degree upper limit, and only two slopes, slopes 1 and 2, exceed 28 degrees (31.6° and 30.1°, respectively).

Blocks of detritus are found on the headward portion of the pediment of slope 2. These blocks have been moved relatively recently, as indicated by the high degree of varnish on the undersides of the blocks and the lack of varnish on the upper surfaces. Large blocks are found on hillslope 1, but no blocks are found on the adjacent pediment. This may be due to the shape of the drainage basin. The slope and pediment lie within a narrow, U-shaped drainage basin. The geometry of this drainage basin suggests increased runoff across the pediment, which would remove the large detritus.

If the hillslope is less than the angle of repose, the loose, large detritus will weather in situ. In-situ weathering is also indicated by blocks of detritus that have broken free from relatively steep ridges perpendicular to contours. These blocks are found adjacent to the ridges, and extensive desert varnish on these blocks suggests little movement.

Conclusions

The form of the hillslopes studied is determined by weathering and redistribution of the weathering products. Direct, active erosion of bedrock such as gullying or intense sheetwash is a very minor factor in shaping slopes. Average angles of the slopes were not significantly related to direction of exposure.

On the uppermost parts of the slopes, more

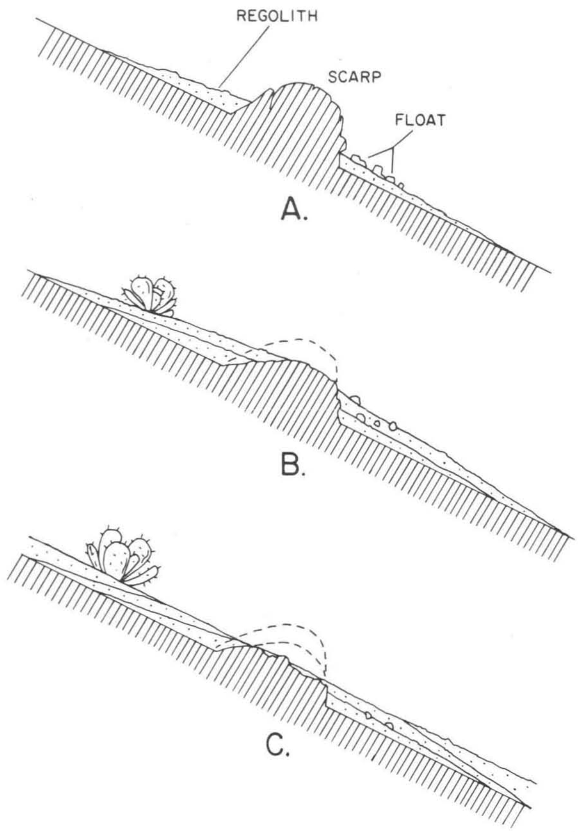


Fig. 4. Destruction of a bedrock scarp on the hillslope. The scarp is weathered, supplying detritus downslope, and material accumulation upslope of the scarp. Material upslope of the scarp may retain moisture that aids in the weathering of the scarp.

active weathering and creep result in a convex form of local extent. The lowermost parts of the slopes are concave due to deposition of weathering detritus by water flow (perhaps dominantly sheetflow). By far, the largest part of the hillslopes exhibits a straight profile, as determined by regression analysis. These segments are all developed on granitic rock. It is concluded that uniform weathering is the dominant slope-forming process here; removal of the products of weathering is also uniform and of lesser importance if the slope angle is less than the angle of repose of the weathered material.

Weathering is, in general, proceeding at a more rapid rate than the redistribution of the weathering products. That the distribution processes are weak if the angle of repose is not exceeded is suggested by the lack of relationship found between the large particle size and position downslope. This indicates that distribution of large particles is probably more closely related to weathering and joint spacing than to agents of transportation. In addition, the orientation of elongate large detritus showed no preferential direction.

In the single case studied where the slope exceeded 28 degrees, coarse detritus is being removed rapidly. This is shown by slope profile 2, which has an average of 30.1 degrees and on which the upper surfaces of large blocks have little desert varnish. On all the lesser slopes the coarse detritus has a well-developed deep weathering rind and desert varnish.

Locally, the slope profiles are broken by bedrock ridges, which may be parallel or perpendicular to the contours. Those parallel to the contours may be joint controlled, and those perpendicular to contours appear to be divides.

The scarps parallel to the contours are apparently transitory features and are destroyed because they may be the foci of intense weathering. This weathering is manifested by the crumbly nature of the bedrock in the scarps and may be due to moisture retention by the locally thick regolith lying at the upslope edge of the scarp. These scarps commonly die out laterally in the regolith-covered slope.

The ridges perpendicular to contours are, of course, being weathered today, and coarse material being removed from them is not transported far.

Locally, debris flows cause rapid movement of the products of weathering. The lobate remains of such flows are found scattered on the present slopes and adjacent pediments. An average of no more than 2 percent of a slope area exhibits these relict features today, and debris flows are not considered a significant mechanism forming the modern slopes.

The slopes range from 20 to 31 degrees. The lack of slopes of lower angles suggests that essentially parallel retreat of slopes is occurring.

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