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The Relationship Between Lithology and Slope Morphology in the Tucson Mountains, Arizona

A Relação entre Litogia e Morfologia das Encostas das Montanhas Tucson, Arizona

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Resumo

A relação entre a litologia e a morfologia das vertentes foi investigada em oito locais com substrato constituído por rochas graníticas, andesíticas e sedimentares, nas Montanhas de Tucson, Arizona. Vários métodos foram usados no estudo. Foram, ainda, construídos perfis topográficos. Os índices de obliqüidade, o comprimento do declive, e os ângulos de declive das diferentes vertentes foram calculados e comparados entre si. A análise granulométrica permitiu, para alguns perfis, a determinação das junções vertente/sopé. A natureza e características estruturais do substrato rochoso determinam a morfologia das vertentes nesta região semi-árida. De fato, há variações nos perfis com o mesmo substrato mas com diferente exposição. Estudos morfológicos mais precisos foram, também, efetuados comparando pares de litologias. Eles permitiram mostrar algumas semelhanças nas formas. Os declives de granito-andesito e os declives andesito-rocha sedimentar são as que mostram melhor relação entre a litologia e a morfologia do declive. A relação do declive entre granito-rocha sedimentar é mostrada nas concavidades da vertente, na região frontal da montanha e nos ângulos de declive do sopé.
Palavras-chaves : litologia; forma de perfis; vertente; sopé

Abstract

The relationship between lithology and slope morphology is investigated at eight sites on granitic, andesitic, and sedimentary hillslopes in the Tucson Mountains, Arizona. Several methods are used in the study. Topographic profiles are constructed. Skewness indices, slope length, and mean slope angles of the different slope profiles are computed and compared with each other. Debris size analysis has permitted for some profiles, the determination of hillfront/piedmont junctions. The nature and structural characteristics of the bedrock are the ones that determine the hillslope morphology in this semi-arid region. There are, as a matter of fact, variations in profiles on the same bedrock nature but differently exposed. More precise morphologic studies have been also done in comparing the different lithologic pairs. They have permitted to show some similarities in shapes. The granitic-andesitic slopes and andesiic-sedimentary slopes are the best comparisons which show the relationship between lithology and slope morphology. The granitic-sedimentary slope relationship is shown in the hillfront concavities, mountain front and piedmont mean slope angles.
Keywords: lithology; form of profiles; hillfront; piedmont; pediment

1 Introduction

Many studies have been done about the relationship between lithology and slope morphology (slope form and angle); however, these studies did not reach the same conclusions. In some investigations, rock type was found to be associated with slope morphology, while in others an opposite conclusion was reached, suggesting that slope morphology is not significantly related to lithology, but rather to other factors, such as tectonic activity and climate (Cooke, 1970; Abrahams *et al*., 1985).

The study area, represented by the Tucson Mountains, Arizona are located in particular climatic conditions, defined by a semi-arid zone, where it appears that these conditions were determinant in showing the influence of lithology on hillslope development. This study is undertaken to determine the relationship between lithology and slope form and angle in the Tucson Mountains. Their hillslopes, which present piedmonts at the toe of the mountain slopes, are developed on three different lithologies: Amole Granite, Shorts Ranch Andesite, and Amole Arkose as a sedimentary formation. This study area was selected because of the presence of a variety of slopes from hillfronts to piedmont surfaces and the occurrence of different lithologies. Slope profiles were drawn on the selected lithologies, and these profiles were then submitted to computations and morphometric analysis of the following parameters: profile skewness, slope lengths, and slope angles. In addition, field measurements were made of the debris size distribution on the selected hillslopes.

The sloping surface that connects the mountain to the level of adjacent plain is called the piedmont. It extends from the hillfront to the alluvial plain. Standing at the toe of the hillfronts are erosional surfaces called pediments, slope at less or equal to 11°.

2 Geographic and Geologic Setting

The variety of geological and climatic conditions in the Tucson Range give rise to a number of different morphological units; for practical reasons only the Tucson Mountains could be investigated. The Tucson Mountains lie within the Basin and Range Province of the United States, about one kilometer of Tucson. These mountains occupy latitude 32°00' to

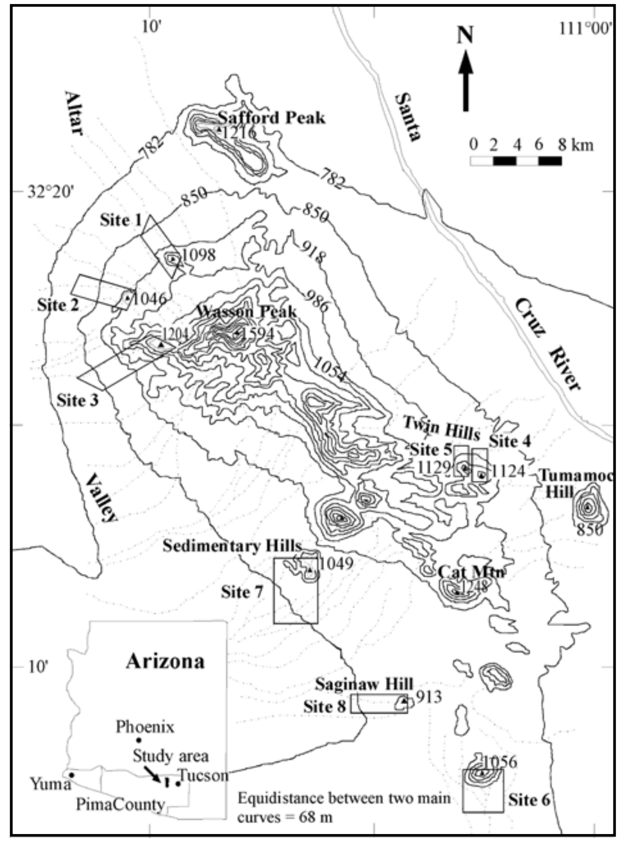

Figure 1 Location map of the study sites in the Tucson Mountains, Arizona.

32°30' North and longitude 111°00' to 111°15' West (Figure 1). The range trends about north-northwest and is bordered on the eastern side by Santa Cruz valley and on the west by a smaller Valley locally called the Altar Valley. Wassen Peak, which reaches 1594 m, is considered the highest hill of the Tucson Mountains. The hills armed by sedimentary rocks are the lowest ones where they do not generally exceed 1050m in height.

2.1 Climate and vegetation

The climate of the study area is semi-arid with wide daily temperature ranges and low rainfall. The temperature is characterized by a long hot season from April to October and daily temperatures above 32°C are present from May through September. The mean annual temperature is about 20°C at the Tucson Airport, with a mean daily maximum temperature of 37°C as the hottest month and a mean daily minimum temperature of 3°C in January as the coldest month

(U.S. Weather Bureau and the National Weather Service, 2002). The mean annual precipitation is 277 mm with the highest average monthly precipitation of 64 mm in July and 51 mm in August.

The distribution of precipitation through the year is such that 50 percent of the annual amount falls between July and September and usually from thunderstorm showers originating in moist air that flows into Arizona from the Gulf of Mexico. A secondary maximum precipitation of gentle and widespread rainshowers is from December through March when pacific storms move far enough south in their journey across the country to affect Arizona, and thus providing over 20 percent of the yearly precipitation. The mean annual precipitation is 280 mm at the Tucson Airport Station, with the highest average monthly precipitation of 64 mm in July and 51 mm in August. The lowest averages of monthly precipitation occur in April, May, and June with 7.9, 3.8 and 6.1mm, respectively.

The region of Arizona and especially the pediments have undergone since the late Cretaceous until Pliocene a dry climate by accumulating gypsy and salty deposits. The climate was for instance not able to develop a drainage network for relief planation. The humid and cold periods of the Plio-quaternary are however the ones that have permitted the birth of stream networks.

If the region has been submitted in Quaternary to climatic variations such as precipitations, it seems, that glaciations, cold and probably humid periods, had little direct influence in Arizona. The early Holocene (-11000 to -8000 yr), was rather cooler than today and may have been the wettest period. During this period, a strengthened summer monsoon brought in more moisture from the eastern Pacific Ocean and the Gulf of Mexico (Weng & Jackson, 1999). Then, the climate returned to its dryness, interrupted by some cooler periods.

Vegetation is characteristic of the semi-arid regions of the southwest of U.S.A. The common trees and shrubs in the Tucson Mountains are the mesquite, shrubs, palo verde, catsclaw, ocotillo (fouquiera splendens), and palo fierro. These plants grow mainly on the piedmont slopes and along the banks of the dry channels. In addition, there occur a large variety of the cacti, saguaro, prickly pear, and the cholla (opuntia imbricata), particularly on granitic and sedimentary slopes. Grass is scarce in the range.

The general vegetation on the sedimentary slopes resembles the one on the granitic and andesitic slopes. Among the most common plants are the cacti and saguaro, which thrive on the lower slopes. Prickly pear and related types are also common. Cholla are abundant on the sedimentary Hill surfaces and occotilo are sparse. Palo verde and mesquite are common especially along drainages. The mesquite is very rare on the Sedimentary Saginaw Hill (Figure 1), but creosote bush is abundant. The shrubs are distributed everywhere and the grass is very limited.

2.2 General Geology

The Tucson Mountains are tilted fault blocks and contain a mixture of rocks of different types and age (Lipman & Fridrich, 1990; Kring, 2002). The Cretaceous sediments are seen along the western slopes of the Tucson Mountains (Figure 2). The sediments include the Amole Arkose, seen in the central and southern parts of the range, and the Recreation Red Beds (red siltstones, sandstones, and minor conglomerate) found in the western side of the range. Besides these sedimentary rocks, there are volcanic rocks of the same age (Mayo, 1968).

The Amole Arkose sedimentary rocks are found in the Sedimentary Hill (site 7) and the Saginaw Hill (site 8). These rocks are of Cretaceous age and contain largely siltstones with frequent beds of arkose, arkosic sandstones, and less frequent beds of shale and limestones (Bennett, 1957; Risley, 1983). The Amole Arkose and older Mesozoic sediments and volcanics in the north-central part of the range are intruded by latite dykes (Amole Latite).

The Amole Granite (sites 1 and 3) occupies a broad area in the range (Figure 2). Along its eastern and southern borders, the granite is in contact with the granite porphyry and quartz monzonite. The western limit of the granite is bordered by the alluvium of the Altar Valley fill. This granitic exposure is of Lamaride age, which was a time of great disturbance in the Tucson Mountains between the early Cretaceous and Tertiary (74 m.y.). This granite has a medium to coarse grained texture and is composed mainly of quartz, biotite, and feldspar crystals.

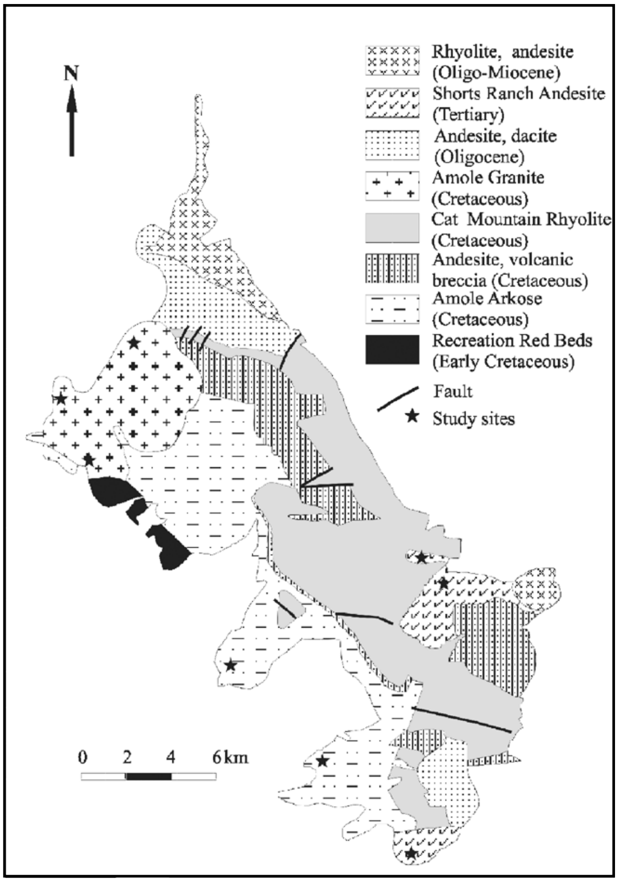

Figure 2 Geologic map of the Tucson Mountains, Arizona.

Rising in the eastern and southern parts of the Tucson Mountains are faulted and tilted series of different named rhyolite to andesite flows. One of the andesites named Shorts Ranch Andesite in sites 4 and 6 is a massive andesitic flow and is the uppermost unit of the Tertiary volcanic sequence dated at approximately 57 m.y. (Kinnison, 1958). Structurally, some of the Shorts Ranch Andesites are faulted at the Twin Hill (site 5) where it is in contact with the rhyolite, and at the extreme southern outcrop (site 6) where it is in contact with the lithologies of rhyolite and other andesite flows.

The northern and eastern sides of the range near Safford Peak and Tumamoc Hill consist of a sequence of faulted and younger rhyolite tuffs and andesites. These volcanic rocks indicate a late Oligocene-early Miocene age.

The Tucson Mountains are distinguished by broad deposits. The colluvium of different debris sorting covers to variable depths the hillfront and the pediments. It is thicker in andesitic and sedimentary slopes, in which it becomes more difficult to detect the pediment substratum. The origin of the colluvial mantle is the result of outcrop weathering, weathering in situ, and running water as an erosional and transporting agent. In contact with the above loose material are the alluvium sediments. They form the alluvial plains of the Santa Cruz and Altar rivers and are composed mainly of silt and clay.

3 Methodology

The main sources of data for this study were topographic maps, a geologic map, and field observations and measurements. The topographic maps at 1:24,000 each, of the Tucson Mountains, Arizona, Pima County are published by the U.S. Geological Survey (U.S.G.S, 1968). The topographic maps are: the Cat Mountain, Brown Mountain, Avra, and San Xavier Mission quadrangles. In addition, a more recent geologic map of the Tucson Mountains, at 1:62,500, was used in this study (U.S.G.S, 1993). This work has been completed by a field survey of the debris size across hillfronts and piedmonts.

3.1 Topographic Profile Construction

Topographic profiles were constructed by first establishing randomly distributed points on the different selected rock exposure, and then drawing a line running up and down from these points perpendicular to the contour lines and without crossing any washes and channels. The upper limit of each line was drawn to the maximum elevation and slope angle of the hill, before joining the crest slope. The lower limit was drawn to a fixed distance in the alluvium, taking into consideration that the lengths of the alluvium deposits from the bedrock pediments are more or less equal. However, some of the andesitic base profiles were ended at natural obstacles, such as channels or structural contacts, and these profiles include only minor alluvium surfaces.

Using a magnifying comparator, horizontal distances were measured in millimeters between every two contour lines crossing the profile line, going from the top to the base slope. Then, these map distances were converted into ground distances and then cumulative distances. The inclination of each segment of each profile line was computed by the following formula:

Tangent θ = contour interval (m) / horizontal distance (m)

3.2 Skewness and Other Parametric Analysis

To determine the slope form of a slope profile, profile skewness analysis was used to show the degree to which either rectilinearity or concavity dominates the total profile and hillfront/piedmont profile. The Y axis (vertical distance or contour interval) and the X axis (horizontal distance) of each slope profile was converted into cumulative percentages from 0 to 100 (Figure 3) and these converted profiles were then used in the profile skewness analysis.

The slope profiles were divided into hillfronts and piedmont profiles to examine their respective slope morphology. The division was determined by finding a subjective point of inflexion separating the hillfront from piedmont slope of each profile. The inflexion point was found by first delimiting a segment of the profile where the hillfront/piedmont junction was expected to occur. This junction is thus determined by the maximum break of slope between two adjacent segments. The formula used to estimate the slope form is:

$$PSK = \frac{(Vp90 + Vp10) - 2*(100 - Vp50)}{Vp90 - Vp10},$$

Where Vp is the vertical percentile and PSK is the profile skewness index. Thus, a slope profile which is essentially concave will have a negative skewness index and a rectilinear one will approach the zero (Pitty, 1970).

Values of elevation and distance of each profile, represented respectively in the vertical and horizontal axis, are converted in percentiles of 10% interval (Figure 3). Elevation percentiles are then reversed into decreasing order (100 to 0%). In order to better analyze the slope morphology, the subdivision of the profiles in two distinct parts: hillfronts and piedmonts has to be done. The junction between these two elements is represented thus by the maximal slope rupture between two adjacent segments.

In case the rupture of slope (knick point) is not apparent, the point of inflexion is subjectively determined. The method requires taking segment falls of 7 meters and for each segment, the difference between slope segments is computed, especially where the breaking of slope is expected to occur. Then, the biggest difference of slope segments is taken and it is between these two slopes that the point of inflexion is placed.

As shown in Pitty formula, the concavity index is calculated using only three percentiles values. To verify the adequacy of this index in the interpretation of the results, a second formula is used; it is the concentration index. Taken from the curve of concentration of Gini (Combrouze, 1993), the index is defined graphically as the ratio of the dashed area to the area of the triangle (ABC). More the concentration index is high, more will be the concavity of the profile (Figure 3). Thereafter, an analysis of regression between the concavity and concentration indexes is made for each rock sample and that to check the accuracy of the concavity index.

Besides, the skewness analysis, slope length and slope angle were used in this study. The purpose

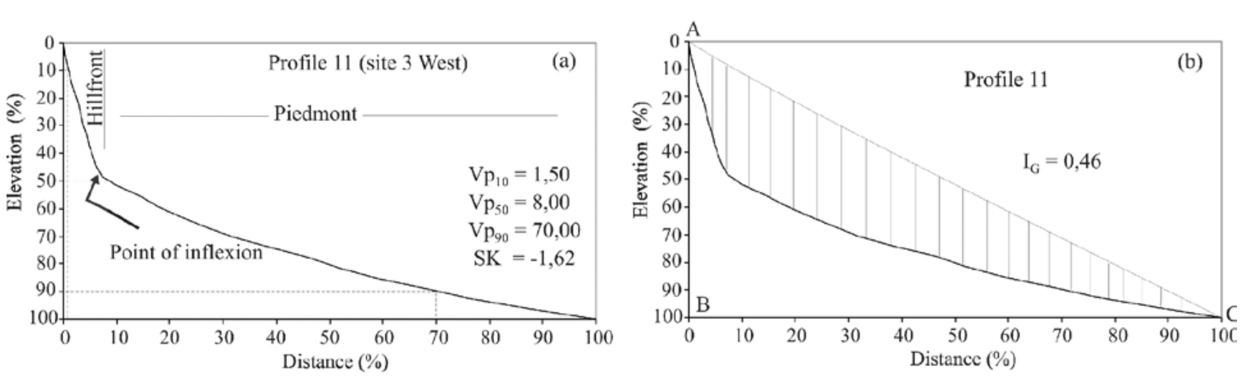

Figure 3 Model Diagrams of the study indexes. (a) skewness index, (b) concentration index.

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of these parameters is to provide additional details about the relationship between lithology and slope morphology.

3.3 Debris size analysis

Field investigation was done to determine the distribution of debris size from the upper slopes to the base slopes and to provide physiographic information on the study sites. The primary purpose of this investigation was to detect more accurately the hillfront/piedmont junctions.

Debris size distribution was done with the use of a 100 feet steel tape, a compass, and a vernier caliper. Starting from near the top of each site and ending at the base, slope inclination was determined. The tape was spread horizontally on the surface, and at one foot interval, the debris particle under the tape was measured at its b axis in millimeters by the vernier caliper. At least three measurements were made at the same slope angle, and 25-50 debris particles were collected from each measurement line. The debris was measured at selected intervals determined by the change of the debris size distribution.

A total of 3203 particles were recorded from the studied sites; 1003 were from the three granitic sites, 768 were from the two sedimentary sites, and 1432 were taken from the last three andesitic sites. Then, to show the degree of sorting, the first and third quartiles (Q_1 and Q_3) were taken at each selected slope angle. The degree of sorting, which equals Q_3-Q_1 and slope angles were plotted on graphs, on which increasing steepness of the graphic slope indicates less sorting. Decreased sorting means that the hillfront/piedmont junction is less apparent. In order to test rather than to assert this proposition, it is desirable to establish relations slope angle and debris size. Moreover, a regression analysis has been introduced in this study to examine more precisely the relationship between slope angle and debris size sorting.

3.4 Statistical testing of the parameters

Descriptive statistical testing was applied to profile skewness indices, slope lengths, and slope angles in order to test hypotheses about the relationship between each of the parameters and pairs of lithological populations. Significance testing using the difference between two sample means was employed (Hammond & Mc Cullagh, 1978). The testing computation is as follows:

a- Compute the standard error of each parameter:

$$\sigma xi = Si / \sqrt{ni-1}$$

where Si is the sample standard deviation of a parametric column ; σxi is the standard error, and ni is the sample size.

b- Compute the estimated standard error:

$$\sigma x_1 - x_2 = \sqrt{\sigma x_1 + \sigma x_2}$$

c- Perform the significance test using the significance ratio:

$$S.R. = (\overline{X_1} - \overline{X_2}) / (\sigma x_1 - x_2)$$

where $\overline{X_1}$ and $\overline{X_2}$ are the means

d- State the significance level at 1% and in some cases at 5 %, and:

- Obtain the degrees of freedom, which are $n_1 + n_2 - 2$.
- Identify the critical value of t (t*) from the t distribution table.

e- State the null hypothesis (Ho) that there is no difference between each of the parameters at the pairs of the lithological populations, in case where S.R. is less than t*. The null hypothesis is rejected when S.R. is greater than t*.

4 Description of the Sites
4.1 Granitic Slopes

The granitic outcrops do not differ fundamentally from the other types of rocks. They are not more resistant than the surrounding sedimentary and andesitic rocks. Most of the granitic slopes are represented by a poorly developed dendritic drainage pattern and low stream density and often scored by shallow intermittent channels. They are characterized by an abrupt break of slope which divides the slopes into hillfronts and piedmont surfaces. The hillfronts are steep and irregular slopes ranging mostly from

26° and 52° (Figure 4). The granitic hillfronts consist of apparent jointed bedrock and boulders standing either in isolation, in groups, or in clusters of residuals. These boulders are certainly the most widely distributed of the surfaces developed on granite. They range in diameter from about 25 cm to 4 m or more, and they vary in shape from spherical to ellipsoidal forms (Strahler, 1981); the former shape is related to the process active at or near the land surface as granular disintegration, which changes the fresh rock mass from angular to rounded. The upper hillfront slopes of sites 1 and 2, which take the form of cliffs and whose morphology reflects the influence of variable joint spacing, are mainly occupied by boulders and blocks exceeding 2 meters in diameter. The roughness of the hillfront slopes vary from low to moderate due to the different distribution of the channels eroded by running water.

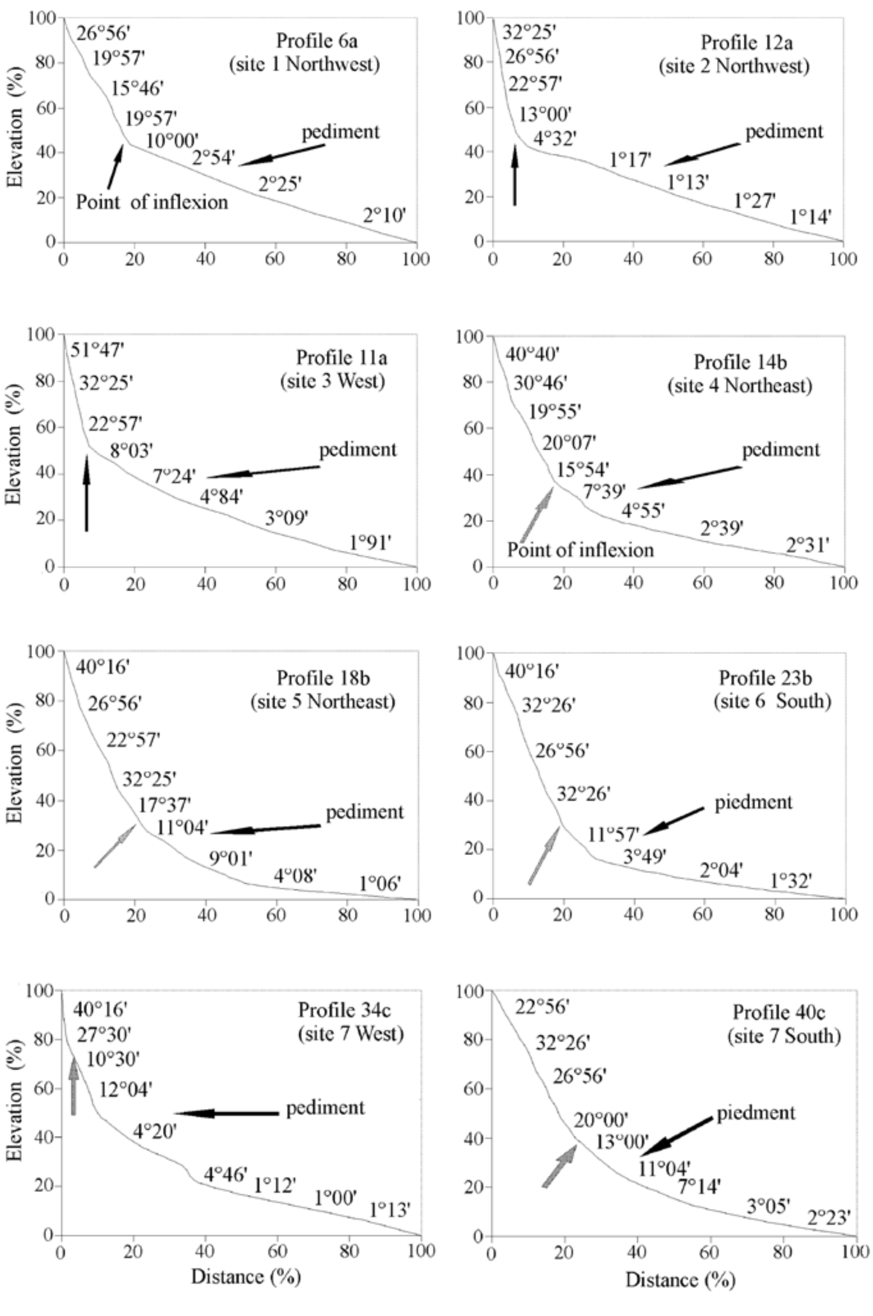

Figure 4 Selected studied hillslopes.

(a) granitic hillslopes,
(b) andesitic hillslopes,
(c) sedimentary hillslopes.

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The piedmont surfaces are characterized by broad and gentle surface slopes, forming an abrupt break of slope where they meet the hillfront (Figure 4). Some of these piedmonts are gently concave upward and others are almost rectilinear. Between the long streams that downcut the piedmonts, the slopes are smooth and more regular. The upper slopes vary from 4° to 11° and the lower slopes from 1°09' to 2°10'. The upper piedmont surfaces adjacent to the hillfronts, defined by pediments, are veneered by sandy debris transported away from the upslopes by rainwash and ephemeral streams (unknown soil thickness).

4.2 Andesitic Slopes

There are two types of the andesitic slopes, one type is short and limited by the convergence of other andesitic hills as at the Golf Course Hill, site 4, or by different lithological contacts as at Twin Hills, site 5. The other type is characterized by open slope surfaces as at site 6. The different lithological slopes do not show any apparent hilfront/piedmont junctions, but only continuous concave slopes (Figure 4). The maximum inclinations on these surfaces range from 26° to 52° and the minimum inclinations are from 1°09' to 4°02'. The steep slopes are characterized by an uneven debris size distribution of debris exceeding 100 mm and smaller ones, consisting of fractured bedrock outcrops. The debris is found loose on the surface or bedded on soil and may be covered by lichen. Going further downslope at angles inferior to 10 degrees, the bedrock outcrops and large debris decrease in their exposure. They are replaced by smaller debris generally from 6 to 20 mm (using median size) at inclinations of 5 degrees and less except in the Twin Hill area. The later do not show any debris size variation and the cobbles are thus the ones that dominate on the piedmont slopes, called stony piedmonts (Mabutt, 1977). Usually, this loose material is partially buried in soil and is enveloped by a desert varnish. Moreover, the debris on the Golf Course Hill and Twin Hill slopes is sub-rounded to rounded especially at slope angles between 25 and 10 degrees (even below 10 degrees at Twin Hills).

The gradual erosion of the andesitic hillslopes has given the birth of pediments which unfortunately do not show an apparent knick at the toe of the hillfronts. For this reason, a subjective method has been adopted to subdivide the profiles into hillfront and pediments. However, this method has revealed that these pediments were not always in contact with the hillfronts. There are 46% of piedmonts (sites 5 and 6) where the pediments are connected to colluvial foot slopes. The length of these foot slopes exceeds often 110 m and their upper slopes vary from 12° to 14°. The pediments of site 5, are occupied by large boulders derived essentially from debris slopes; they may be called stony pediments (Mabutt, 1977).

Furthermore, the drainage pattern on the andesitic surfaces is dendritic and is characterized by few intermittent streams cutting through these slopes. Sites 5 and 6 are primarily incised by shallow channels, but site 4 and its surrounding slopes are scored by deeper intermittent channels.

4.3 Sedimentary slopes

The sedimentary slopes are characterized by a dendritic drainage pattern. Site 8 is scored principally by shallow channels and the western part of site 7 is highly dissected by deep intermittent channels. The southeastern part of these hills is moderately incised, and stands as topographic highs in the weak and unresistant siltstones and argillites.

The slope shapes of the sedimentary rocks resemble those of the andesitic rocks. They are mostly concave without clearly marked hillfront/piedmont junctions; however, they do show more open and longer slope surfaces. The sedimentary slopes are generally moderate to fairly steep ranging from 17° to 32° at the upper slopes and 0°56' to 4° at the base slopes (Figure 4). Covered by a thick mantle of debris, the piedmont slopes do not show any structural irregularities. The debris size distributions on slopes of 5° or steeper are much less sorted. The gentle slopes of 5° and less are characterized by smaller debris ranging from 8 to 15 mm in median. The loose material covering these slopes is mainly angular to sub-angular arkose, sandstone, siltstone and some calcareous elements. Most of the piedmonts in sites 7 and 8 with west exposure, have pediments directly related to hillfronts. The ones exposed south show for instance slopes characterized by colluvial foot slope-pediment surfaces. The length of these colluvial foot slopes range between 90 and 140 m.

5 Analysis of slope profiles

The subdivision of the slope profiles into hillfronts and piedmonts was sometimes difficult since in some cases the knick point has been defined according to debris size sorting along the profiles. The test of significance between each pairs of rock types was introduced to permit comparisons between lithology and morphology of slopes.

5.1 Debris Size Sorting

This analysis was determined for the three lithologic slopes. The graphs in figure 5 show only the general trend of the debris sorting along the slopes and consequently points out of the segments alignment have been neglected. It is in the regression analysis that the totality of elements is taken in consideration and that to provide more information on debris distribution along the study hillslopes.

On the granitic slopes, the steep slopes are characterized by large sized debris which was brought from the higher slopes or was derived from in situ weathering. The debris size decreases downslope, occurring where piedmont slopes are inclined less than 5 or 10 degrees. Between this unit and the hillfront toes of 12 to 15 degrees, there is an abrupt increase of size elements where they almost tripled in diameter (Figure 5). This change is often observed by a break of slope at 10 to 11 degrees; it is the knick point. The debris elements in the piedmont slopes continue to decrease until reaching 9 mm on slopes less than 11 degrees. This type of size distribution has given excellent associations (r = - 0.94) between slope and debris sorting (Figure 6). Indeed, the graphs have shown that the change in debris size coincide perfectly with the estimated point of inflexion (Figure 5).

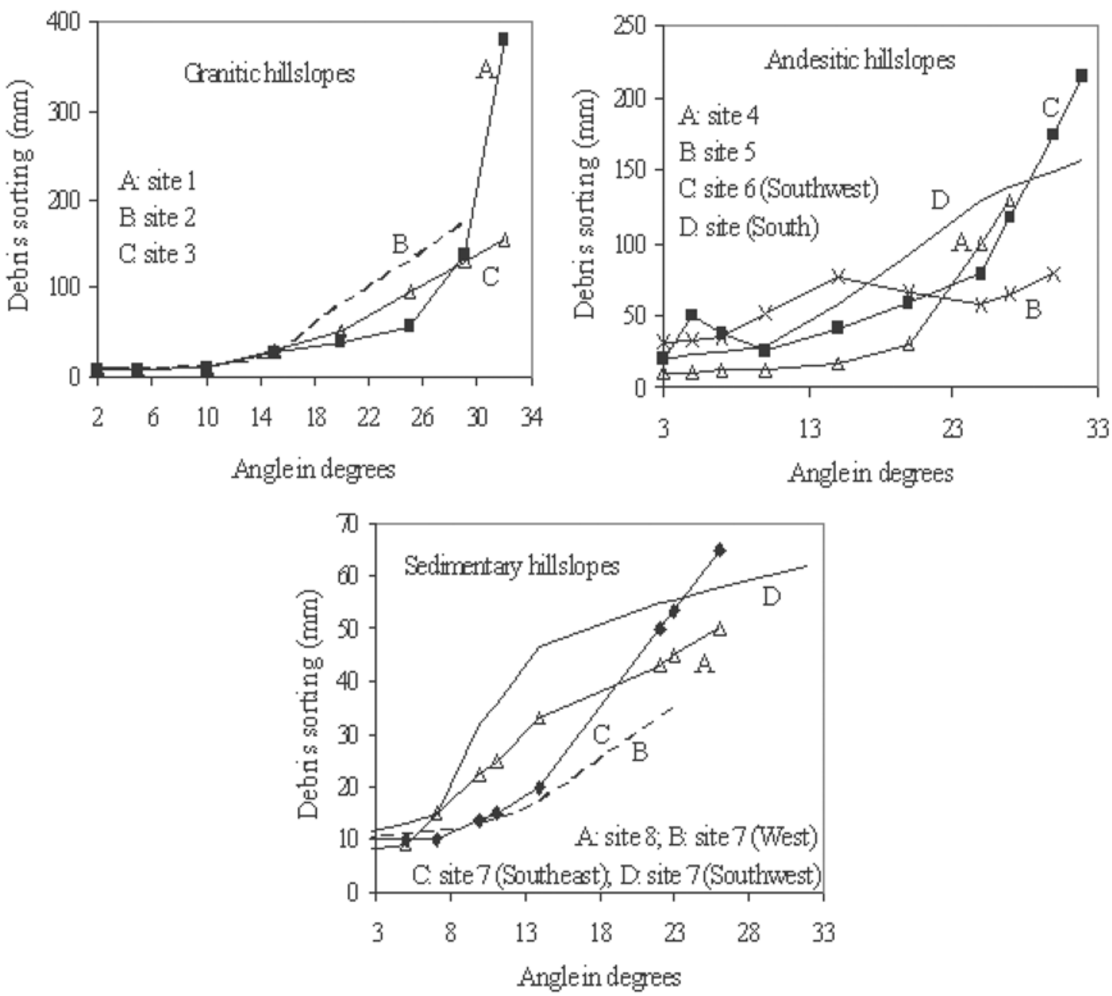

Figure 5 Debris size distribution in fonction of slope on the studied hillslopes.

On the other hand, the debris sorting analysis done on andesitic slopes has been of less interest, where three sites out of four show a low debris sorting from almost 5 degrees and up. The larger elements, including boulders of 70 mm in diameter, are found not only on steep slopes, but also on moderate and gentle slopes, especially at the Twin Hills (site 5) and hills of site 6. Contrary to site 6 (r = - 0.80), profiles of site 5 show a moderate relationship between debris size sorting and slope (r = - 0.72) with an important scattering of points around the line of regression (Figure 6). In fact, the analysis has shown that a decrease of slope is not automatically followed by a reduction of debris size. The only well sorted slope is at the Golf Course Hill (site 4), where the larger particles are confined to the steep slopes (greater than 12 degrees). On lower slopes the decrease in debris size is more significant, so that the selection of the hillfront/piedmont junction at that slope angle coincides well with the subjective inflexion point. Moreover, the coefficient of correlation (r = - 0.92) shows a good relationship between the two variables (Figure 6). On slopes below 12 degrees, where is located the less marked break of slope, the debris size remains generally unchanged (mean size of 11 mm).

The sedimentary slopes show larger particles (14 to 35 mm) on slopes between 6 and 11 degrees (Figure 5) at Saginaw Hill (site 8) and at one third of the sedimentary Hills (site 7). On these hills, the remaining 2/3 of the hillslopes present a progressive decrease of the size of elements (median value of 12 mm) on slopes less or equal to 10 degrees. The regression analysis of slope and particle size has revealed that these variables are strongly related with coefficients of correlation ranging from – 0.87 to – 0.92 (Figure 6). Although, these analyses have given good relations; they did not mark really the part of the slope in the large particle size decrease, and thus a difficulty is found in the determination of the hillfront/ piedmont junction. Even though, the point of inflexion remains the most useful criteria, the debris size analysis has sometimes helped to locate this point.

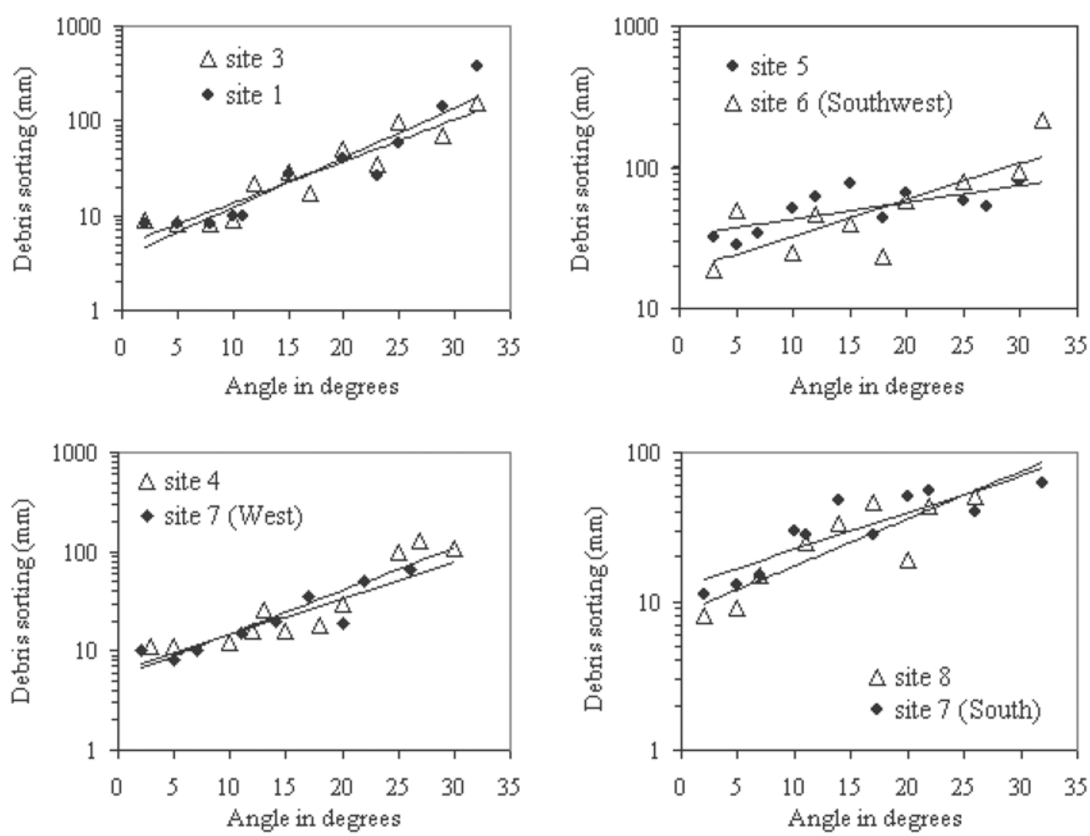

Figure 6 Relationship of particle size versus slope angle in selected traverses.

5.2 Form and length of slopes

Results of the regression analysis on profiles and piedmonts have revealed strong relationships between concavity and concentration indices (r > 0.92). Therefore, it is quite possible to introduce without major risks the concavity index in the determination of the profile forms. Comparisons between each couple of profiles on granite-andesite on one hand, and granite-sedimentary rocks on the other hand, have given some unexpected results. We expected that the granitic slopes would be more concave, but the computed concavity index has shown that the concavity on andesitic and sedimentary slopes is more pronounced (Figure 7). The tests have indeed given higher values of the significance ratios than the critical t (t*), and thus the hypothesis of concave similarity is rejected at 99% (Table 1). On the other hand, the comparison between andesite and sedimentary profiles did not show any difference in their concavity form.

The granitic piedmont slopes show the least concave profiles (PSK between – 0.01 and – 0.68). They are slightly concave to nearly rectilinear, whereas, piedmonts on andesite and sedimentary piedmont slopes are distinctly different but quite similar between themselves. Their concave indices vary indeed between – 0.43 and – 1.92 (Figure 7). Using statistical tests, the lithologic couples granite-andesite and granite-sedimentary rocks do not show similarity in their concavities (Table 1). The slope form similarity in the couple andesite and sedimentary piedmonts is due primarily to the lithological heterogeneity and texture of the sedimentary formation, and also to the shortness of some andesitic piedmont surfaces, which do not provide a representative picture of the complete andesitic slope forms.

Piedmont slopes present differences in their lengths. Slopes on andesite which range from 412 to 1006 m, are the least short. Piedmont lengths on granite and sedimentary rocks are similar, of which offer more extended pediment and alluvium surfaces. They range from 749 to 2096 m on granitic slopes and 725 to 1298 m on sedimentary slopes.

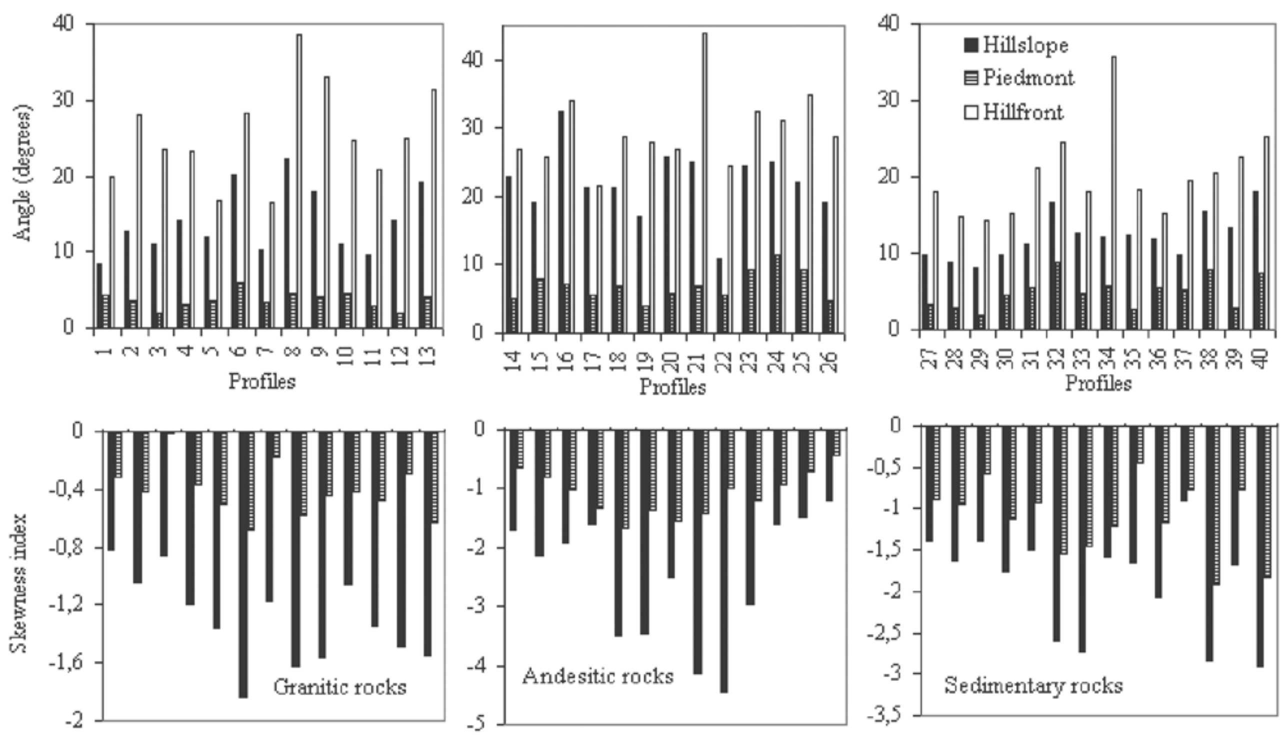

Figure 7 Slope angles and skewness indexes of the studied profiles.

5.3 Slope angles

Profile analysis has revealed that the similarity in mean slope angle is only valid for the couple granite-sedimentary hillslopes. The rest of couples show significance ratios greater than 3.5 and thus their slope angles are practically different (Table 1).

The forty study hillfronts show slopes developed on granite possess a mean slope angle of 31°57' and a range of 16°24' to 38°28' (Figure 7). The andesitic and sedimentary slopes are characterized respectively by mean slopes of 29°44' and 21°49', and by ranges of 21°27' to 43°52', and 14°18' to 35°49' (Figure 7). From comparisons done on these profiles, one can conclude that the couples, except the one on andesite-sedimentary rocks, present a similarity in their mean slope angles (Table 1). In this case, it is probably that the heterogeneity of slope angles in this couple reflects the role of lithology in the determination of the hillfront slope (Cooke, 1970).

Granitic piedmonts and those on sedimentary rocks show that their slopes are not significantly associated to lithology. The former piedmonts, ranging between 1°57' and 6°00' (Figure 7), have a low mean slope of 3°42'. The sedimentary piedmonts are generally characterized by slightly low slopes with a mean value of 5°16' and slope angles varying from 1°50' to 8°53'.

The andesitic piedmont slope analysis has provided a net difference from those slopes of the other rock types. This means that the relationship between slope angle and lithology is significant (Table 1). Given the importance of this relationship, it is worth considering in more detail the steepness of the upper andesitic piedmonts, which range between 11°57' and 14°15' in 46% of the study slopes.

6 Conclusion

As a result of the study in the Tucson Mountains, it can be concluded that profiles on granite and sedimentary rocks cover extended areas; however, the former profiles are less concave than the two other lithological formations alike in their shape.

The subdivision of the profiles into hillfronts and piedmonts and the determination of their point of inflexion, have been possible by using the method of a subjective choice and the debris size analysis in the study hillslopes. It is for instance on granitic slopes and at a least degree on sedimentary slopes that the junction is apparent and the good sorting coincide perfectly with the break of slope between the two physiographic units. Concerning the andesitic slopes, the junction has been determined by the point of inflexion, the larger debris distribution is continuous along the hillslopes.

1- Hillslopes

	1	2	3	S.R. 1 - 2	S.R. 1 - 3	S.R. 2 - 3	Decisions 1 - 2	Decisions 1 - 3	Decisions 2 - 3
Skewness index mean	- 1.30	- 2.50	- 1.91	0.68	0.18	1.69	S.R. < t*	S.R. < t*	S.R. < t*
Mean slope angle (θ°)	13°38'	21°08'	11°07'	3.81	1.62	7.63	S.R. > t*		S.R. > t*

2- Piedmont slopes

	1	2	3	S.R. 1 - 2	S.R. 1 - 3	S.R. 2 - 3	Decisions 1 - 2	Decisions 1 - 3	Decisions 2 - 3
Skewness index mean	- 0.40	- 1.08	- 1.15	6.18	5.81	0.45	S.R. > t*	S.R. > t*	S.R. < t*
Mean slope length (m)	1699.80	672.53	1546.30	6.70	0.85	6.10		S.R. < t*	S.R. > t*
Mean slope angle (θ°)	3°44'	6°46'	4°25'	4.70	1.46	2.70			

Table 1 Comparison of the three selected lithologic slopes.
Note: For granite (1), andesite (2) : degrees of freedom = 24, t* = 2.492
For granite (1), sedimentary rocks (3) and (2), (3): degrees of freedom = 25, t* = 2.485
Significance level (ν) = 1%; S.R. < t* : accept Ho; S.R. > t* : reject Ho

The relationship between lithology and slope angle in the chosen hillfronts is significant. The high values of slopes angles in the granitic and andesitic slopes and the moderate values in the sedimentary rocks reflect the importance of the lithological nature in the evolution of every landform. The morphology of granitic and sedimentary piedmonts whose slopes are low and the moderate andesitic slopes allow the appearance of a strong relationship between lithology and slope morphology, particularly in the form and slope angle of piedmonts. Thus it is possible to extract from this study the existence of a knick point in granitic hillfront/piedmont junction and the extension of slightly concave to rectilinear piedmont surfaces. More concave piedmont slopes are noticeable in both andesitic and sedimentary rocks with a subjective point of inflexion designation.

A set of such results can be suspected that both the hillslope morphology at hillfront/piedmont junction and the degree of concavity are in part functions of the types of weathering products of the different rock types. Granitic rocks weather to grus , which tends to be washed off the hills and is transported with relative ease across the piedmont. Rock types such as andesite and sedimentary rocks that result in blocky detritus would tend to be associated with thicker and wider colluvial wedges and more concave piedmonts.

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