CHAPTER III:

FIELD METHODS OF SLOPE PROFILE MEASUREMENT, AND HILLSLOPE FORM IN THE STUDY AREA

3.1 INTRODUCTION

As was noted previously, studies of hillslope form and development have long occupied a central position in geomorphology, (Peel, 1967; Dury, 1972; Carter & Chorley, 1961; Twidale, 1958). However, there is still a need for the collection of a substantial body of accurate observations of slope form, (Young, 1971; Sparks, 1960, p.73), and the situation has developed in which the proliferation of theories and speculation has outstripped the gathering of the detailed measurements required to check them, so that preconceptions are common in slope studies, (Chorley, 1964). This is an unfortunate situation, since it is clear that before attempting explanations of slope development we must have an accurate knowledge of slope form; as White (1966, p.592) has pointed out "...the acceptability of any theory must rest on its ability to account for the geometry of real slopes".

Several reasons can be suggested for this lack of reliable observations of slope form. A fundamental consideration must be that slopes exist in a three-dimensional space, which makes it difficult to specify their form in a manageable way with any degree of completeness; the situation is confounded by the fact that slopes are essentially variable (for example, in terms of size, elevation, aspect, and so on) and complex features. For this reason, it has become accepted practice to only consider slope form in terms of two dimensions at any one time.[1] The most commonly adopted means of achieving this has been to survey, either in the field or from maps, "slope profiles", defined as the line of intersection of the groundsurface and a vertical plane, which are measured in the field by recording readings of slope length and angle along the steepest part of the slope, that is, normal to the contours, (Young, 1971). This method was originally applied by Tylor (1875), and subsequently by Lake (1928), Fair (1947, 1948a, 1948b), Savigear (1952), and others; since the pioneer work of Strahler (1950), such profiles have been used in conjunction with statistical analysis, for example by Hack

1. Troeh (1964, 1965) has attempted to describe landforms in three dimensions using simple mathematical equations, but this work remains largely undeveloped.

and Goodlett (1960), White (1966), Carter & Chorley (1961), Nieuwenhuis & van den Berg (1972), and others. Savigear (1967) has suggested that a surveyed slope profile remains the most accurate source of morphological data; however, even the consideration of a slope profile may be complex; some writers have therefore concentrated on particular parts of slope profiles; for example, on the upper convexity (Lawson, 1932), the lower concavity (Lake, 1928), or the middle straight segment (Strahler, 1950). In addition, a slope profile by itself is a poor representation of surface slope, since as Eyles (1965, p.133) has pointed out, slope is a vector quantity (possessing both a direction and a magnitude) and any complete analysis of ground slope must consider both characteristics; most studies using slope profiles neglect the directional characteristic. Several alternative ways of representing slope magnitude have been published (for example, see Raisz and Henry, 1937, and Miller & Summerson, 1960). A useful method is that of Chapman (1952) who has plotted "statistical slope orientation diagrams" which are similar to the Lambert projection used in the present study, (see section 3.5).

A complementary means of reducing slope form to two dimensions is to consider plan form, which in a manner similar to that used above, may be defined as the line of intersection of the groundsurface and a horizontal plane. Several possible varieties of plan form, in association with various profile forms, are shown in Figure 3.1. The significance of the plan form as an accessory to profile form was pointed out early in the development of slope profile studies by Aandahl (1948), who recognised that the total neglect of other aspects of slope form limited the usefulness of studies based entirely on "slope profiles", and who pointed out that, for example, the topography associated with a soil profile site cannot be described adequately just in terms of slope gradient. For this reason he distinguished "coves", "spurs" and "knobs" on the basis of their plan curvature (although identical "slope profiles" might be measured on each), and recommended that horizontal (that is, plan) curvature should be systematically measured, in addition to profile form. This recommendation has been almost completely ignored, although in recent years the idea has been revived (Walker, Hall & Protz, 1968; Pitty, 1966), and is being actively considered in some studies (for example, Waltz, 1970). Savigear (1967) has advocated simultaneous morphological mapping (as developed by Waters, 1958, and others) along the survey line, to provide information about the areal extent and significance of features identified along the profile.

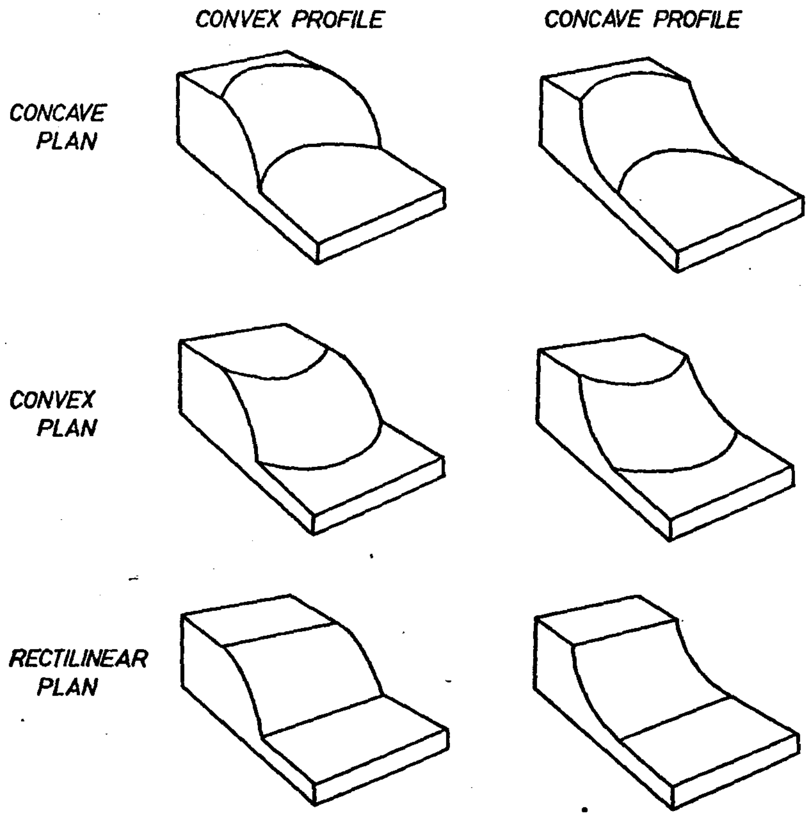


FIGURE 3.1

SOME COMBINATIONS OF PLAN AND PROFILE CURVATURE OF SLOPES

Partly after Troeh (1964)

Some geomorphologists have recognised the importance of plan form, but generally have evaded the issue by merely excluding from study any slopes which display significant plan curvature, and only measuring profiles where the contours were straight and parallel. Such a procedure has been followed, for example, by Strahler (1950) and by White (1966). (To the writer's knowledge no estimate has ever been made in such studies of the actual percentage of the groundsurface thereby excluded from study; it may be that in some topographic types the excluded area may amount to over 50% of the total area, so that the reliability of conclusions from such studies, meant to apply to the landscape as a whole, may be as minimal as the percentage of the area included in the study.)

Further reasons for the lack of reliable observations of slope form may also be suggested: once the form attribute to be measured has been defined and its significance understood, there arise the problems of sampling and measurement. Both of these are significant problems, and are discussed in the following section. In the remainder of the chapter will be described the method of slope form measurement used in the present study, the techniques used to analyse the measurements taken, and a discussion of the results of these analyses, as a means of describing the slope forms present in the study area.

3.2 THE MEASUREMENT OF SLOPE PROFILES IN THE FIELD

Whilst many studies of slope form have relied on information derived from topographic maps (for example, Tanner, 1956, and Eyles, 1965), most recent studies are based on the field measurement of slope form (for example, Young 1970; Nieuwenhuis & van den Berg, 1972; and Arnett, 1971). The increasing number of such studies has focused attention on the various methods of measuring slope form in the field. Interest in these matters has largely been generated by the work of Savigear (1952), and it has now become apparent that the making of the measurements is as important as any other stage of the research, the results obtained being partly dependent on the technique of measurement used. (Gerrard & Robinson, 1971).

Most studies in which slope angle along the profile is the quantity recorded (and these are the majority) rely on an Abney level (or clinometer) and measuring tape (for example, Arnett, 1971; Carson, 1970; Pallister, 1956; Young, 1970). The technique used to measure a slope profile with such equipment has been described by Savigear (1952, p.34; 1956). He measured slope profiles either up or down the maximum slope; the length of slope represented by each angle reading varied with the spacing of the ranging poles, which were placed at estimated breaks of slope. On slopes which appeared smoothly convex or concave, and no breaks of slope were apparent, the ranging poles were placed at fixed intervals, which were varied according to the radius of curvature of the slope; on long uniform slopes, the poles were placed 100 feet apart (the length of the measuring tape being used). Similar procedures are followed by others, for example Young (1970), Carson (1970), and Carson & Petley (1970).

This conventional procedure may be criticised on several grounds; such arguments have been presented by Pitty (1967). Pitty points out that subsequent statistical analyses on such measurements are made difficult for two reasons. First, each reading consists of numerical values of two quantities (length and angle), with no necessary connection between the two, and second, the results contain an uncontrolled subjective element.

Measurements of angle along unequal groundsurface lengths would mean, for example, that a frequency distribution in terms of angle would be difficult to interpret; thus there would be no way to identify "characteristic angles"

(Young, 1961), because the various angles would have different weightings depending on the actual ground length associated with each. This problem could be partially overcome by basing the frequency distribution on the total measured length corresponding to each angle, but reliable interpretation would still be difficult because of the inherant subjective element in the measurements. For example, profiles with low curvature might have been recorded in the field as being rectilinear; also, the magnitude of the recognised breaks in slope might have varied with the length of the slope, or its curvature, the vegetation cover, lighting conditions, or the direction of measurement (that is, upslope or downslope). With no control on such variables, the reliability of the measurements remains open to question (Pitty, 1967).

In the light of considerations such as the above, Pitty (1967) has therefore suggested that profile form should be measured by making a large number of angle measurements along short unit-lengths of slope. By this means the surveyor is freed of the necessity to make any decisions regarding breaks in slope, which are identified after the profile has been plotted. Various graphical or computerised procedures have been proposed for performing this operation (for example, Young, 1964, 1971; Ongley, 1970).

However, the use of a constant ground-surface length may introduce additional difficulties. If the unit used is too long, the observations may not represent adequately the slope angles which occur frequently on the slope; and by measuring at fixed intervals, a break in slope may occur within the unit, so that on plotting its position will be incorrectly shown (Gerrard & Robinson, 1971; Pitty, 1967). A range of possible unit lengths has been suggested by various workers; Pitty (1967) has suggested 1.52m; Fourneau (1960) 5m; Rapp (1967) 5m or 10m; de Bethune (1967) 10m; and Nieuwenhuis & van den Berg (1972), 10m. This variation in the unit-length used means that even studies based on this technique are not strictly comparable, since Gerrard & Robinson (1971) have shown that the form of frequency histograms of measurements along the same slope profile varies with the unit length used, although no difference in mean angle was obtained using lengths in the range 1.5 to 10m. However, it was found that the maximum angle recorded increased as the unit length decreased, and that in one case the modal angle in one frequency distribution was not represented at all in another distribution based on a different unit length.

The selection of sites for slope profile measurement represents a problem additional to those of the actual measurement, discussed above.

The problem of the plan form of slopes has already been referred to, and there exists the question of whether profiles should only be measured where the contours are straight and parallel, or whether all slopes should be sampled; in addition, contour patterns may be irregular, requiring that a profile line, to remain orthogonal, must be curved. It must be decided whether profiles at such sites should be included in a sample. Again, obstructions may require that a profile line be offset, and it must be decided whether such disturbed profiles are admissible (Pitty, 1966). Whilst random selection is usually advocated for purposes of areal sampling (King, 1969, p.62; Cole & King, 1968, p.114), considerations such as those mentioned above ensure that a large number of profile sites selected randomly will not be suitable for measurement. Pitty (1966) quotes the opinion of Fourneau (1960), based on extensive field experience, that the selection of slope profile sites must be subjective. However, Pitty (1966, p.457) suggests that this is not an acceptable alternative to "...the objectivity of strictly random slope selection". He suggests that sampling by the selection of random numbers to serve as grid references, through which orthogonal profiles are run, is not viable, since the profile sites selected are still subject to the problems outlined above; he therefore advocates a multi-stage sampling procedure. Young (1971, pp.145-146) has proposed a similarly complex stratified sampling scheme. The method used in the present study is described in the next section.

3.3 FIELD METHODS OF HILLSLOPE MEASUREMENTS USED IN THE PRESENT STUDY

Since the main part of the present study was concerned with slope angle (that is, the inclination of the ground-surface to the horizontal) and not slope form as a whole, it was determined that this quantity would be sampled by the measurement of slope profiles, as defined previously. No restriction whatsoever was placed on the allowable plan form of the slope surfaces sampled; the practice of Strahler (1950, p.675), White (1966), and others referred to previously, of excluding all but those sites where the contours were straight and parallel, appeared to lead to the neglect of perhaps two-thirds[1] of all slopes, and this was considered an unwarranted restriction. It was con-

1. In the present study the value was checked on completion of field measurement, and found to be 60% of all profiles measured.

sidered desirable to measure profiles without such bias, and to record for each site a qualitative observation on the plan curvature, and to investigate subsequently the effects that this may have had on the slope angle. It is possible that, on slopes having different plan forms (Figure 3.1), slope processes may operate differently (Troeh, 1964, Cline, 1961), and that soils may have different properties (Aandahl, 1948); this may make it impossible to compare slope profiles in terms of any other characteristic (including angle) if this factor is not controlled (Pitty, 1966). It was therefore decided to include consideration of plan curvature, albeit qualitatively, rather than to arbitrarily exclude a large number of slopes from the study.

The principal interest of the present study was in rectilinear slopes and sections of slopes. In a similar study, Carson (1971) selected slopes "...wherever straight sections appeared to be well developed". (Carson, 1971, p.35). No similar restriction was placed on the slopes measured in the present study, so that some idea of the proportion of slopes in the study area which displayed such features, and of the area to which the conclusions of the study therefore applied, could be determined.

Because of the inherant difficulties of random selection of slope profile sites, discussed previously, purposive sampling was employed. It may appear that this approach can be criticised on several grounds, as follows -

a) it could be argued that some inadvertent bias may have been introduced, for example by the exclusion of very steep slopes, and

b) that an uneven distribution of the chosen sites might have led to the underrepresentation of parts of the study area.

Both of these objections were borne in mind and, it is felt, overcome by the technique used. Firstly, as to the idea that inadvertent operator bias could have led to over- or under-representation of slopes with certain characteristics: this criticism becomes unwarranted in the present study when it is recalled that the items in the population being sampled are slopes, and not slope profile-lines. This point has been considered by Strahler (1950, p.678). If slope profiles are measured at closely spaced points along the contour, then statistical analyses are prohibited, since each statistical item (or slope) is sampled more than once. The spacing of profile sites must therefore bear a relation to the texture, or fineness of dissection, of the topography; if this consists of numerous small spurs and ridges, as in the study area, then only one profile should be sampled from each face, cove, and so on. This was the procedure in the present study, yielding 50 profiles from a map area of about 2.5 square miles, and this meant that most of the items of the population being studied were included in the sample.

If then it was to be argued that the profiles selected were atypical because of bias, it would be the suggestion that most slopes in the area were atypical, and this has no meaning.

The criticism of uneven distribution of measured sites is automatically denied by the above approach; in addition, the work was carried out from aerial photographs and the sites were located so as to give an even areal coverage of the study area.

Hence the complications of stratified and multi-stage sampling procedures were overcome by using a sufficiently dense spacing of measured profiles. This technique is simple, and frees the operator from all need to consult tables of random numbers, and so on. The only requirement is that the size of the area which can be studied must be governed by the number of profiles which can be measured. If the number is small, as in the present study, then the sample area must be kept small also. The actual relationship of number of profiles required to sample area size depends upon the "texture" of the topography. Profile measurements were made by taking numerous angle readings over a unit-length of slope of 1.5m. These were made with a specially-constructed device consisting of a baseboard (1.5m long) to which was attached a wooden protractor having a diameter of 30 cm, with a movable arm on which was mounted a level-bubble. The device was designed to allow vertical legs, 70 cm in length, to be attached to either end of the baseboard by steel brackets; this modification was used when measurements were required in thick scrub or long grass. The thin legs used could easily be pushed through such vegetation to contact the ground surface, hence reducing interference effects to a minimum. Where the ground surface was smooth, these legs were not used, and the baseboard was laid directly on the ground surface.

A further modification was to attach the protractor and level-bubble arm to the baseboard with simple sliding catches. In this way, when it was required to take more detailed measurements (for example, on backward-tilted slump blocks less than 1.5m across), the protractor could be instantly detached from the baseboard, and readings made using a unit length of 30cm. Multiples of five readings at this scale were always taken, so that if required they could be averaged to yield a reading for the entire 1.5m represented. The three methods of measurement used are illustrated in Figure 3.2.

The device constructed therefore has advantages possessed by no other which has been described in the literature: it can measure any angle (negative readings are taken simply by reversing the device), whereas for example, that of Riley (1969) is limited to those less than 50°, and of Blong (1971) to 63°[1]; also, it can be used to survey a profile to any required detail, depending on the needs of the study and the time available for slope survey. Using the present device and the accurate plotting method developed (section 3.4), all features on a profile down to a size of 30 cm (that is, including micro-relief) can be accurately measured and plotted. An unspecified amount of generalisation of surface form is present in all other survey techniques.

1. Angles of up to 68° were measured in the study area.

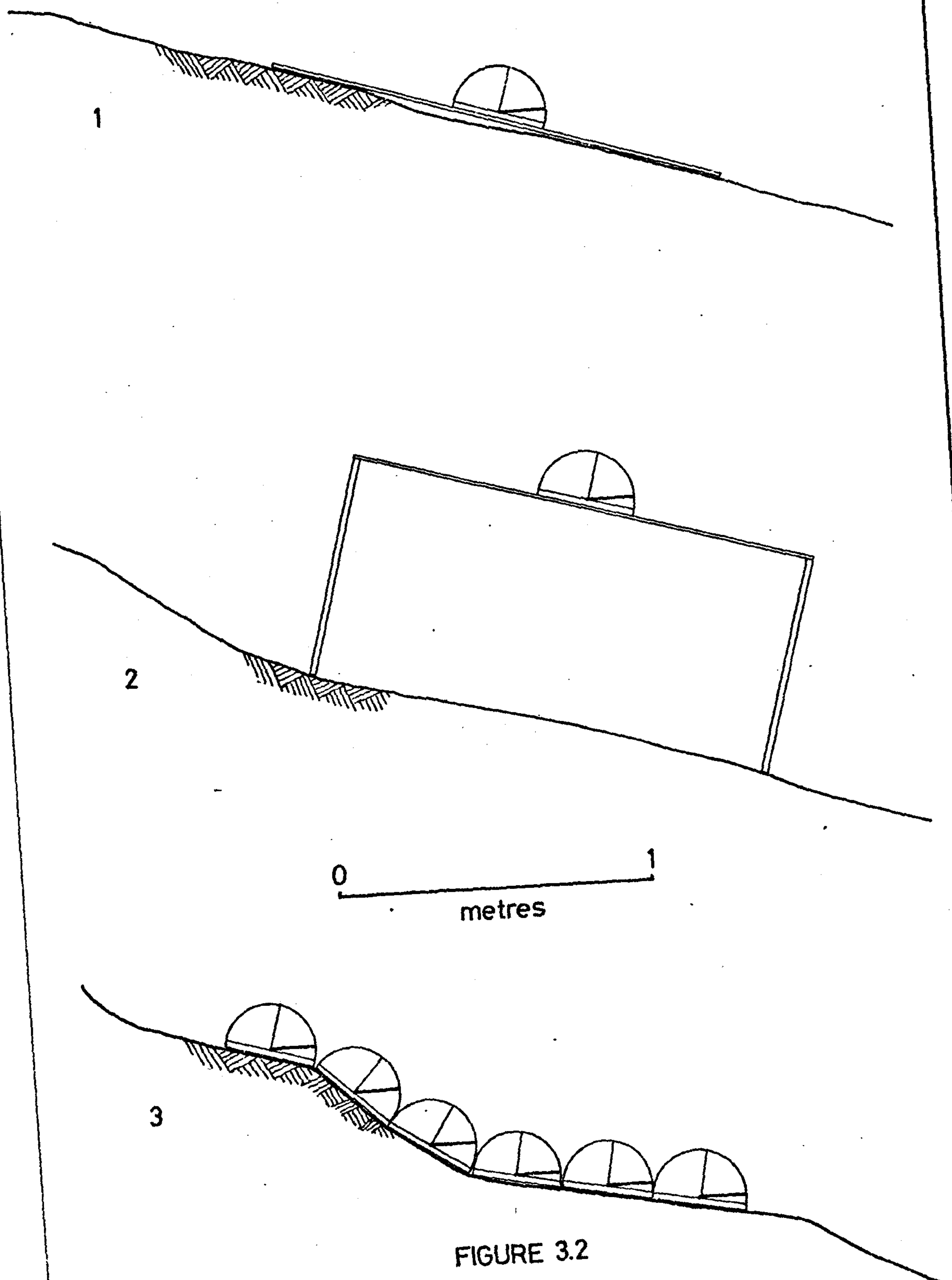


FIGURE 3.2

THE THREE METHODS OF SLOPE SURVEY

Further, it is a simple matter to change the unit length being used from 1.5m to 1m or to 30cm (or any desired length) simply by changing the baseboard, whereas in the cases mentioned above, and also that of Pitty (1968b), a completely separate instrument must be constructed. The device is also light and robust, and can be easily operated by one person.

The length of 1.5m was selected for the present study in relation to the profile lengths to be measured (100 - 200m). With profiles of this size, a length of 1.5m yields 100 - 150 readings of angle per profile, sufficient[1] to define "characteristic angles", if present; in addition, since the maximum error in recording and plotting a break of slope (referred to earlier) is half the measuring unit used, this gives a potential accuracy of ± 75cm as the most error on a slope of 100 to 200m length, and this was considered ample accuracy for the reliable determination of breaks in slope.

Measurements were taken either upslope or downslope, placing the measuring instrument end-to-end as successive readings were taken. The profile line was generally extended from the drainage line at the base of the slope to

1. According to Young (1961).

a point on the opposite site of the ridge crest, so that the position of the top of the profile could be reliably defined. A trial slope was measured in both directions, and the results were found to be the same.

Possible errors involved in this method of surveying include incorrect measurement of slope length, as a result of the repeated small steps involved (which was not checked but is likely to be a small fraction of the total profile length); errors resulting from failure to level the bubble correctly; effects of micro-relief on the instrument (Gerrard & Robinson[1971] found that when using a unit length of 1.5m, grass hummocks or boulders can cause variations in the measured angle of 1.5 - 2.0 degrees); and errors resulting from failure to survey orthogonal to the contours. Considering these sources it may be wise to regard all angle measurements as liable to an error of perhaps 2 degrees, (although care was taken to avoid such effects as interference from grass hummocks), and profile lengths to an error of about 1 metre.

3.4 METHODS OF ANALYSIS OF SLOPE PROFILE DATA

To analyse the data resulting from measurements along short unit-lengths of slope, the complete profile must be plotted, and breaks in slope identified. Because of the large number of readings involved in the present study, and because of the need for accuracy in plotting, it was decided that machine-plotting of the profiles was preferable to hand plotting with a protractor; hand plotting is slow and may be subject to sizeable cumulative errors because of the large number of short lines which must be constructed.

For this purpose, a program was especially written for use on a Hewlett-Packard 9100B calculator and 9125B calculator-plotter, made available by the School of Mathematics and Physics (Macquarie University) so that the slope profiles could be plotted to a guaranteed accuracy of ± 0.03 in. This program (which is described in Appendix B) simultaneously calculates the Cartesian co-ordinates of each end of every unit-length along the survey line. Totals for the x- and y- coordinates are available on completion of the profile, giving the length and height of the slope in metres.

In addition, in an attempt to find an automatic procedure for delineating the rectilinear sections of each profile (which was the principal interest of the present study), a sub-routine was included in the plotting program which calculated a progressive mean of all angles as they were entered; when an angle was entered which differed by more than a specified number (say 3) of degrees from the running mean, the machine marked this position as a break in slope. Various numerical values were used as the criterion; the results are given in the next section.

The program also allowed selection of any scale of plotting, and the use of any desired vertical exaggeration; change of unit-length (for example from 1.5m to 30cm) in mid-profile was possible without interrupting the program. Output included mean angle of the entire profile, of each section between breaks of slope, and the number of breaks in slope identified.

In addition to the plotting program, a computer program was especially written for the analysis of the profile data. This program (which is described in Appendix C) was used to convert all angle readings along every profile to values of equivalent vertical fall and horizontal distance in metres, which were required for certain analyses; for the calculation of slope gradient over each 1.5m unit length; for the production of frequency distributions in 2 degree angle classes for each profile; for the calculation of mean angle, and standard deviation, skewness, and kurtosis of all frequency distributions, and to calculate slope curvature for each 1.5m length as well as the average curvature of the entire profile.

Before analysing the data by computer, the 50 profiles were each plotted in their entirety; the crest and base of each profile was then identified, and only readings lying between these two points were used in subsequent analyses. The additional readings made merely to define the crest of each profile were thereafter not required. The slope data summarised in Appendix E includes only the readings along the slope profile defined in this way.

3.5 RESULTS OF ANALYSES OF SLOPE PROFILE DATA: HILLSLOPE FORM

3.5.1 Location of Slope Profiles

The distribution of the 50 surveyed profiles is shown in Figure 3.3. It is evident that a good areal coverage of the study area has been obtained. To investigate any

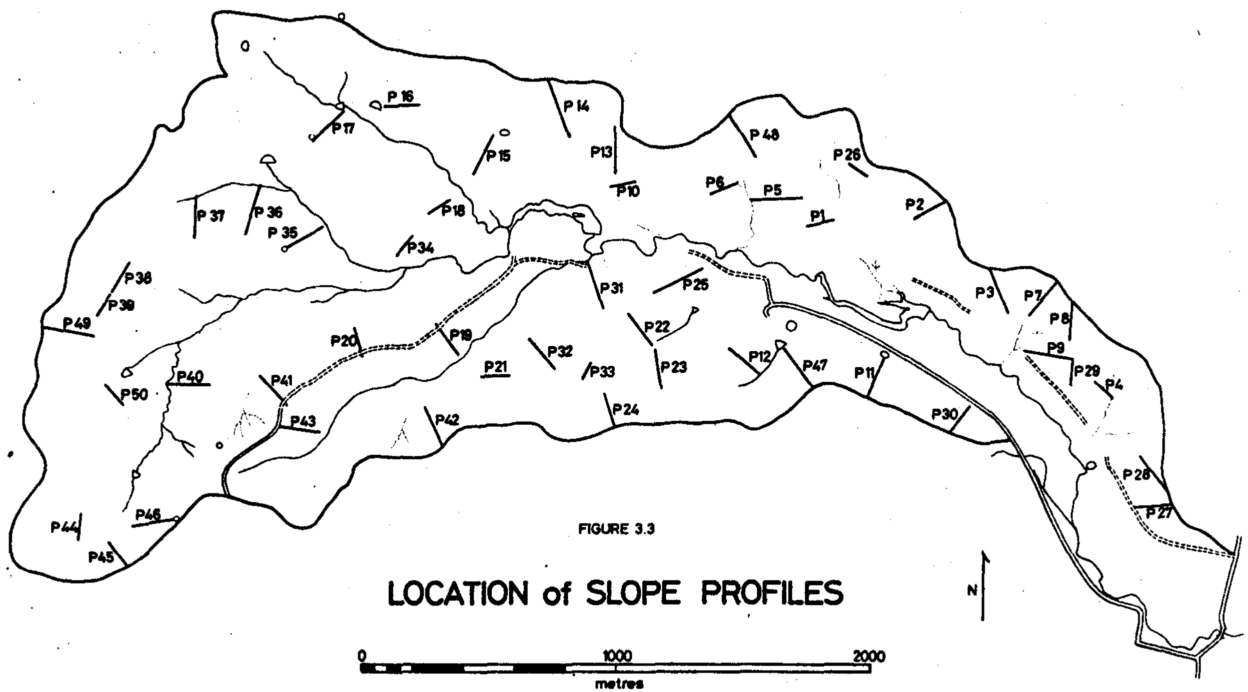


FIGURE 3.3

LOCATION of SLOPE PROFILES

D. Dunkerley 1972

directional preference which might be present, the aspect of each profile and the angle of the mid-slope segment of that profile (see Table 3.1) were plotted as a Lambert projection. This diagram is shown in Figure 3.4. The slope profiles are seen to almost completely encircle the stereographic net, indicating the lack of any directional preference. The exception to this is the small concentration of profiles running at about 250° and dipping at about 20 degrees, and the absence of profiles in the immediate vicinity of this concentration. This feature may be a consequence of the small sample size; however, this seems unlikely since the concentration reaches the maximum density (7 profiles per unit area of net) obtained, and is bounded by areas of zero profile density. Rather it seems that this feature is a reflection of some uninvestigated trend of the slopes in the study area.

3.5.2 Analysis of Profile Form

The criterion tested as a basis for the automatic delineation of rectilinear segments on the slope profiles was not successful. It produced a large number of breaks in slope along the profile, often every few metres; this is

Table 3.1

Details of Slope Profile Segments

Profile Number	Face	Inclination of basal segment degrees	Inclination of mid-slope segment, degrees	Inclination of crestal segment, degrees	Plan form of slope
1	071	-	21	-	rectilinear
2	252	-	17	-	convex
3	156	13	18	11	concave
4	128	-	14	-	rectilinear
5	255	12	21	13	convex
6	079	-	18	-	rectilinear
7	191	8	13	-	concave
8	170	-	16	-	convex
9	255	-	13	-	convex
10	245	17	31	18	convex
11	020	8	17	-	rectilinear
12	110	14	19	-	convex
13	165	11	20	-	concave
14	170	7	18	-	concave
15	185	12	24	16	convex
16	237	12	23	7	rectilinear
17	043	-	27	-	rectilinear
18	055	7	25	-	convex
19	125	10	23	-	rectilinear
20	310	-	25	-	rectilinear
21	260	-	22	-	rectilinear
22	127	12	35	24	rectilinear

Table 3.1 (continued)

Profile number	Face	Inclination of basal segment degrees	Inclination of mid-slope segment, degrees	Inclination of crestal segment, degrees	Plan form of slope
23	330	13	27	23	convex
24	335	13	29	-	rectilinear
25	050	-	13	-	convex
26	310	-	22	-	rectilinear
27	250	-	22	-	rectilinear
28	294	11	16	-	concave
29	172	-	17	26	convex
30	014	12	30	-	concave
31	336	-	12	-	convex
32	314	13	25	-	convex
33	020	-	27	-	rectilinear
34	201	-	22	-	convex
35	063	12	29	-	rectilinear
36	015	-	25	-	convex
37	351	-	28	-	rectilinear
38	022	-	35	-	concave
39	182	-	28	-	rectilinear
40	258	-	17	32	convex
41	297	-	17	27	convex
42	300	-	24	-	concave
43	066	13	27	-	convex
44	002	10	26	-	rectilinear
45	320	-	30	18	concave

Table 3.1 (continued)

Profile number	Face	Inclination of basal segment degrees	Inclination of mid-slope segment, degrees	Inclination of crestal segment, degrees	Plan form of slope
46	255	-	25	15	rectilinear
47	308	-	16	-	rectilinear
48	140	11	33	20	concave
49	095	12	23	-	convex
50	315	12	24	-	convex
Number		24	50	13	
Mean		11.45	22.58	19.23	
Standard deviation		2.3	5.8	7.0	

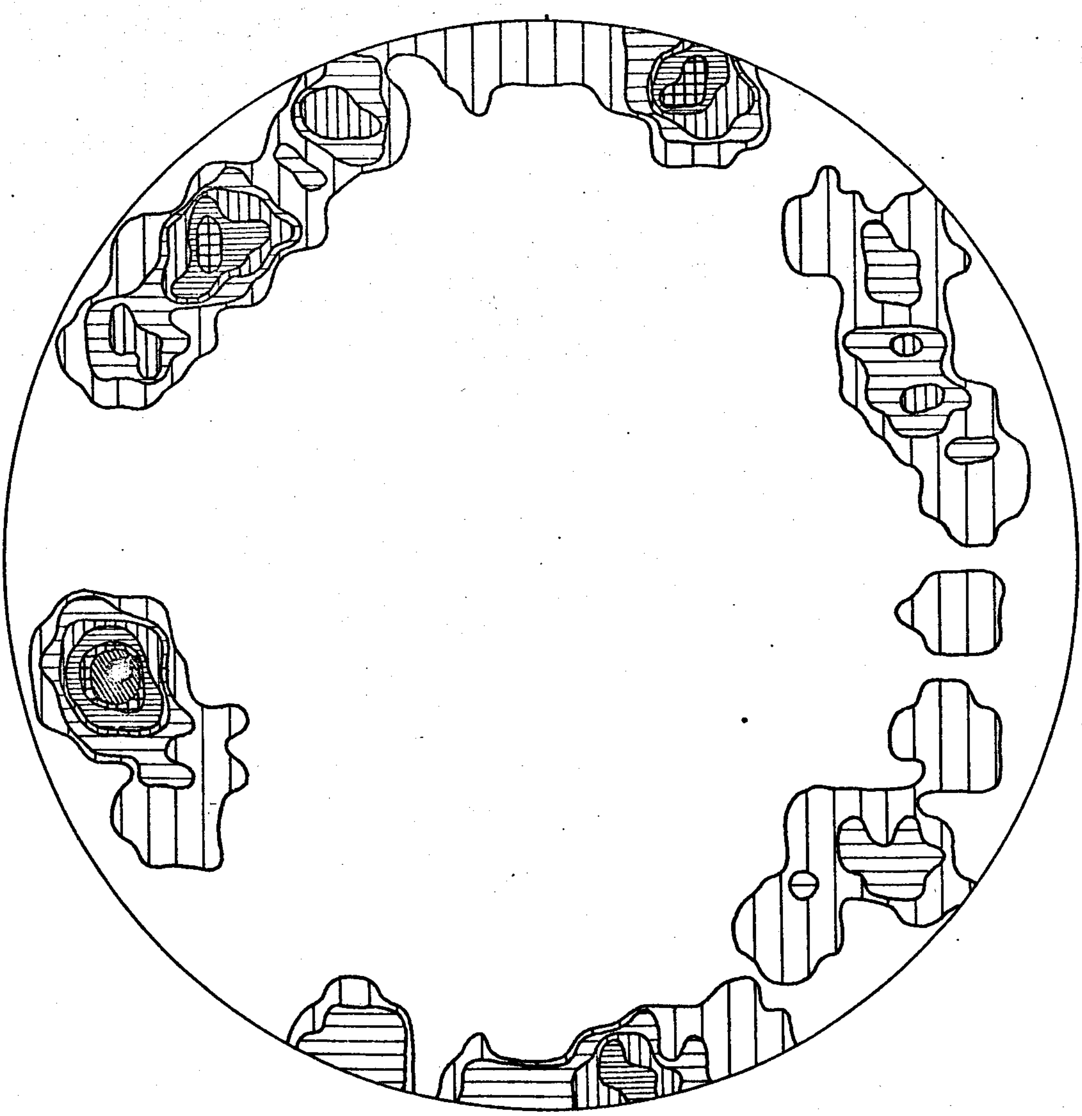
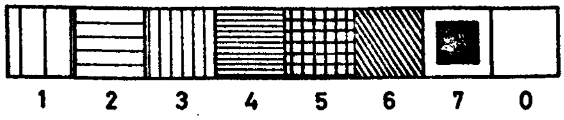


FIGURE 3.4

LAMBERT PROJECTION OF MID-SLOPE RECTILINEAR SEGMENTS



clearly the result of the method of profile measurement, in which large differences in angle are recorded between the short ground-surface lengths used. For example, a typical sequence of readings (from P5) is 18°, 23.5°, 25°, 18°, 26.5°, 18°, 19.5°, 20°, 19°. These rapid changes in angle, whilst being associated with such a small fraction of the profile that they do not interfere with the general rectilinearity, are sufficiently great to disrupt any mathematical computations based on such readings. An example of the analysis of a profile using the procedure attempted is shown in Figure 3.5. In an attempt to overcome this effect, the allowable angular variation within a rectilinear segment was increased, up to ± 10 degrees. This however was unsuccessful, since because of their gradual increase or decrease of angle, long convexities and concavities would be accepted by the program as being rectilinear.

Therefore the automatic procedure was abandoned. It appears that the rapid fluctuations in angle resulting from the detailed technique of measurement used prohibit any mathematical delineation of rectilinear segments, without employing some smoothing procedure, which would in any case defeat the purpose of the detailed measurement.

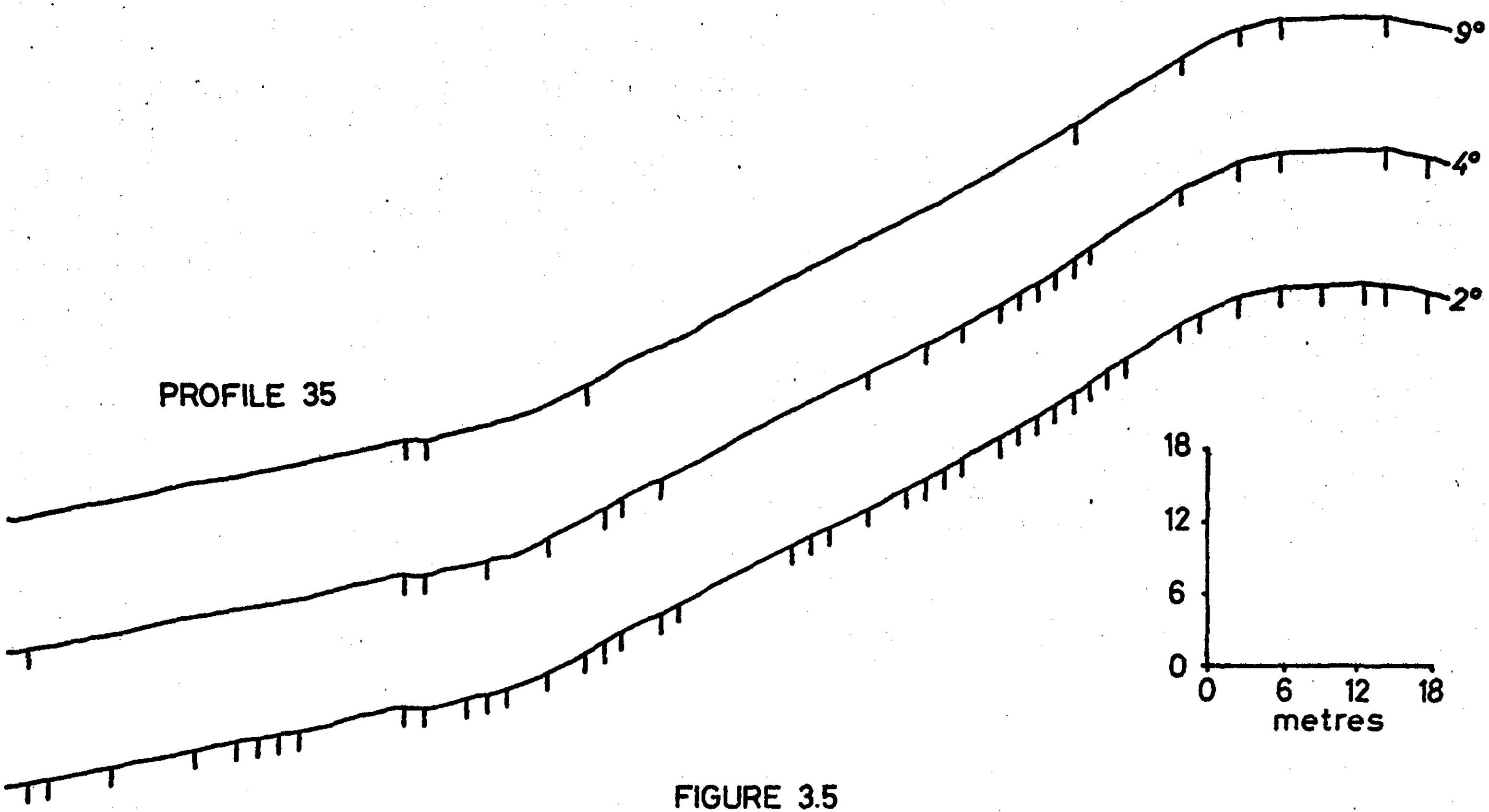


FIGURE 3.5
EXAMPLES OF AUTOMATIC PROFILE ANALYSIS
THE SHORT VERTICAL LINES MARK THE ENDS OF RECTILINEAR SEGMENTS DEFINED USING THE SPECIFIED LIMIT OF ANGULAR VARIATION FROM THE MEAN

It was therefore decided to identify breaks in slope by lying a straight-edge along the plotted profiles[1] and marking major discontinuities between essentially rectilinear segments. However, as a check on this procedure, the same profiles were analysed in two further ways - by plotting profiles on double-logarithmic scales (as used by Hack & Goodlett, 1960), and by plotting the relationship between slope gradient and horizontal distance from the ridge-crest. For this, the horizontal and vertical equivalents of each 1.5m length, and cumulative values for each, are required for the first analysis, and the gradient of each 1.5m length for the second. These data were obtained from the computer analysis referred to earlier. (This process alone involved some 35,000 computations and emphasises the need for computer analysis of data resulting from the survey method used.)

The Hack & Goodlett (1960) method of analysis involves the plotting of the slope profile on double-logarithmic graph paper. In this way convexities and concavities are generally found to plot as straight lines; inflexion points between these straight lines are much more readily apparent than breaks in slope between, for example, a convexity and a rectilinear segment on a conventional profile plotted on double arithmetic paper. Hack &

1. drawn at a scale of approx. 1:500.

Goodlett (1960) used such double-logarithmic graphs to express numerically the form of profile convexities; however, in the present study they have been used merely as a check on the consistency of the method used to delimit rectilinear segments of slope profiles.

An example of a slope profile plotted on logarithmic scales is shown in Figure 3.6; the breaks in slope interpreted from this graph are also shown, and have been marked in on the normal profile graph, shown in Figure 3.7, along with those determined by eye. As can be seen from the diagrams, this method of analysis delineates approximately the same breaks in slope as picked by eye.

In the method proposed by White (1966), the change in slope gradient with slope length is graphed. The principle employed is that if convex, rectilinear, and concave slope segments are present, then the gradient should increase over the convexity, remain essentially constant along the rectilinear portion, and decrease over the concavity. Breaks in the slope profile are inferred where the slope of the gradient curve (plotted on arithmetic or logarithmic scales) changes significantly. An example of a gradient-length graph is shown in Figure 3.8; the

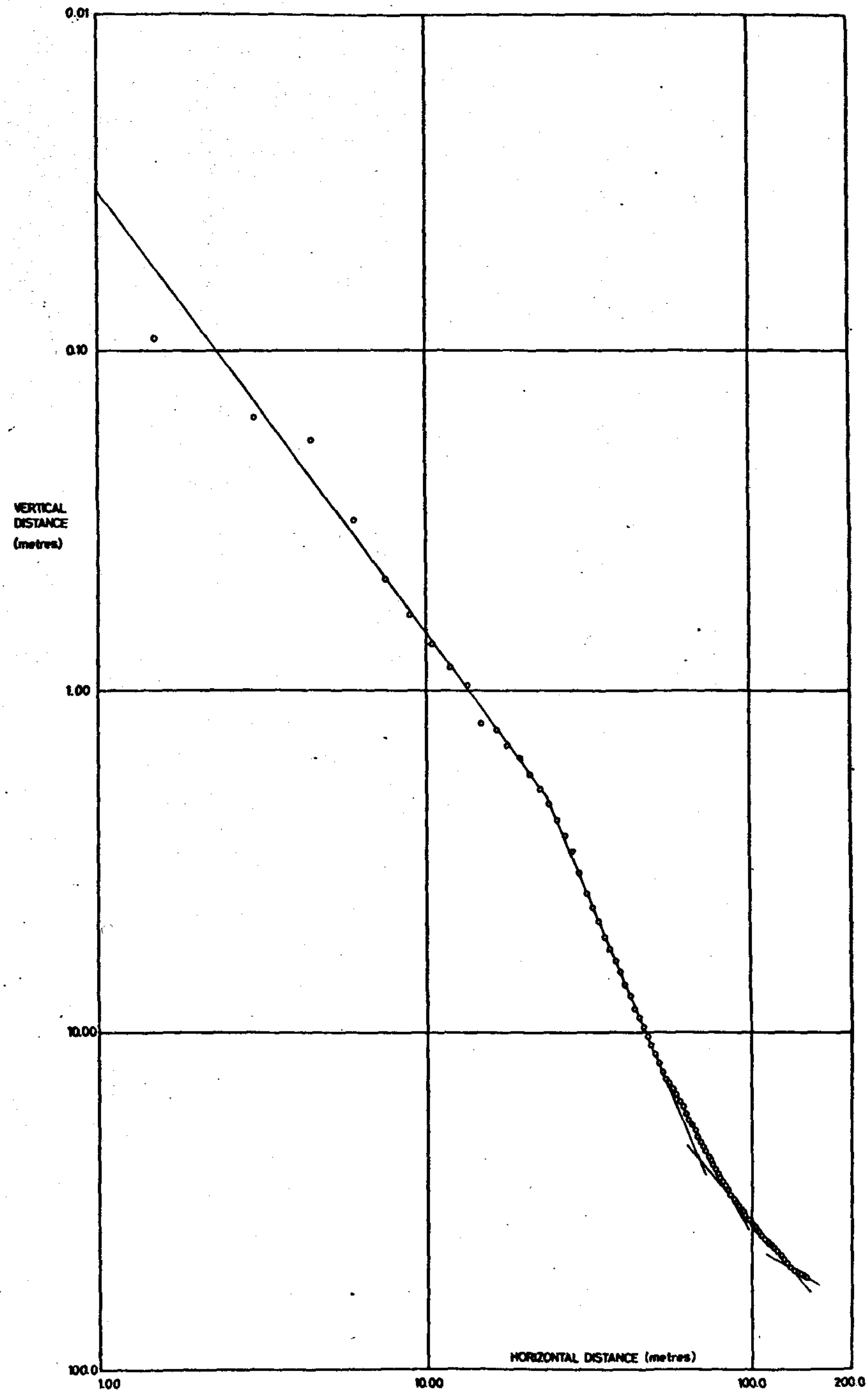

0.01
0.10
1.00
10.00
100.0
VERTICAL DISTANCE (metres)
HORIZONTAL DISTANCE (metres)
1.00
10.00
100.0
200.0

FIGURE 3.6

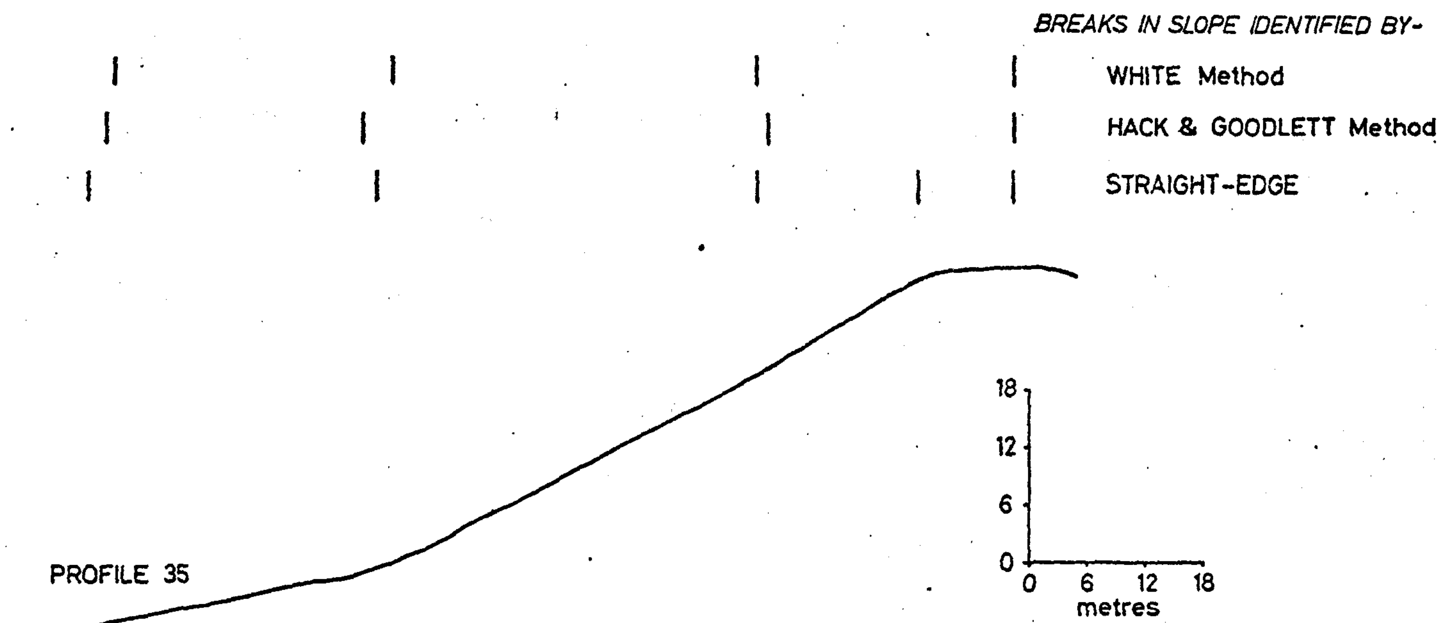


FIGURE 3.7
ANALYSIS OF A SLOPE PROFILE

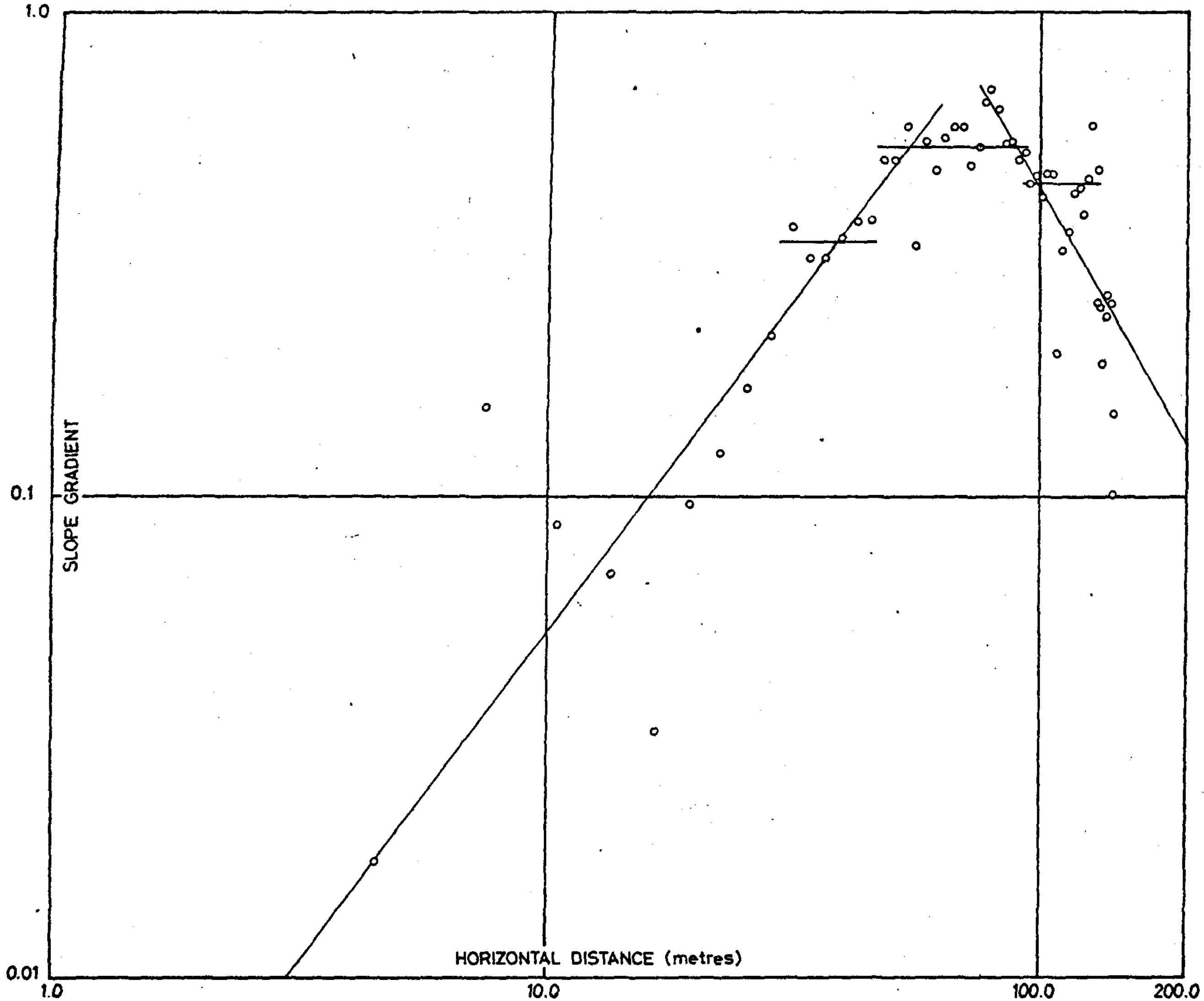

1.0
0.1
0.01
SLOPE GRADIENT
HORIZONTAL DISTANCE (metres)
1.0
10.0
100.0
200.0

FIGURE 3.8

breaks in slope interpreted from this graph are also shown, and have been indicated on the normal profile graph, shown in Figure 3.7. Again, approximately the same breaks in slope are identified, although because of the rapid fluctuations in gradient in the data, this method was found to be more difficult to use than that of Hack & Goodlett (1960).

However, the general conclusion may be reached from the above analyses that the method of identifying breaks in slope by eye is a valid method in that the results obtained agree with those obtained by two entirely separate methods.

3.5.3 Slope Profile Form

The slope profiles were not found to correspond in general to any of the classic schemes of the form of hillslopes in humid temperate areas. Six slope profiles were identified as being of the classical convex-rectilinear-concave type (P4, P17, P21, P27, P33, and P44; see Figure 3.9), although in all cases the rectilinear segment occupied the bulk of the profile (generally about 80%), and only a very small percentage of the total

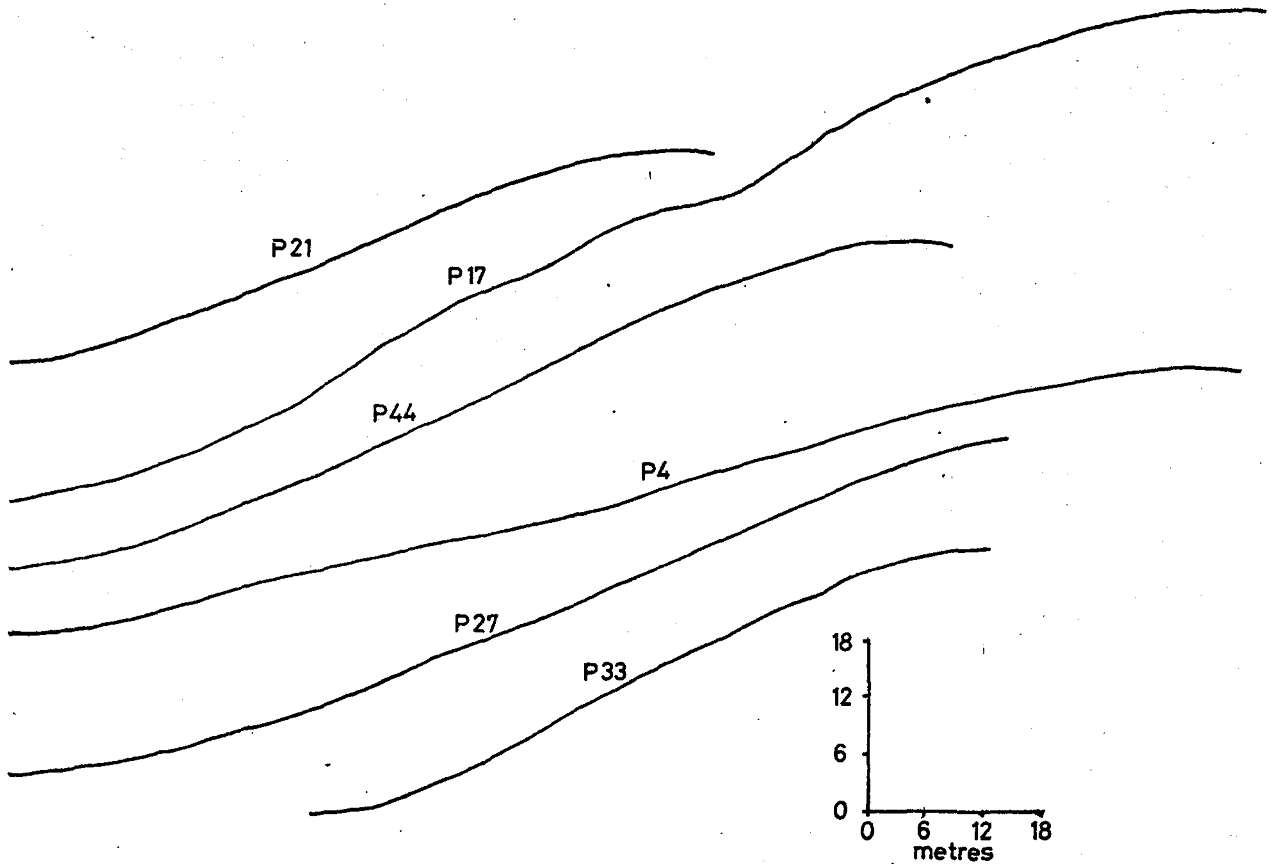


FIGURE 3.9
CONVEX - RECTILINEAR - CONCAVE SLOPE PROFILES
' - Unit of measurement

length was occupied by the convexity and concavity. Actual percentages are given in Table 3.2. It is felt that it would be more realistic to disregard the classical notion of profile form and regard these profiles as being essentially rectilinear, since this is their dominant characteristic, and to regard the convexity and concavity as relatively minor modifications of this basic form. Certainly no profile was recorded which in any way resembled the classical convex-concave hillslope envisaged by W.M. Davis.

Indeed the most striking characteristic of all the profiles is their composition, apart from the rounded crests, of one or more rectilinear sections which meet in sharp breaks of slope. Examples are P5, P7, P10, P11, P15, P16, P18, P19, P22, P23, P24, P28, P32, P35, P40, P41, P43, P45, P46, P49, and P50. (Figure 3.10).

After a complete analysis it was found that all profiles measured could be divided into a maximum of three principal rectilinear segments which have been named (according to their position in the profile) the basal rectilinear segment, the mid-slope rectilinear segment, and the crestal rectilinear segment. All of the 50 profiles contained a well-defined mid-slope rectilinear segment; in addition 45

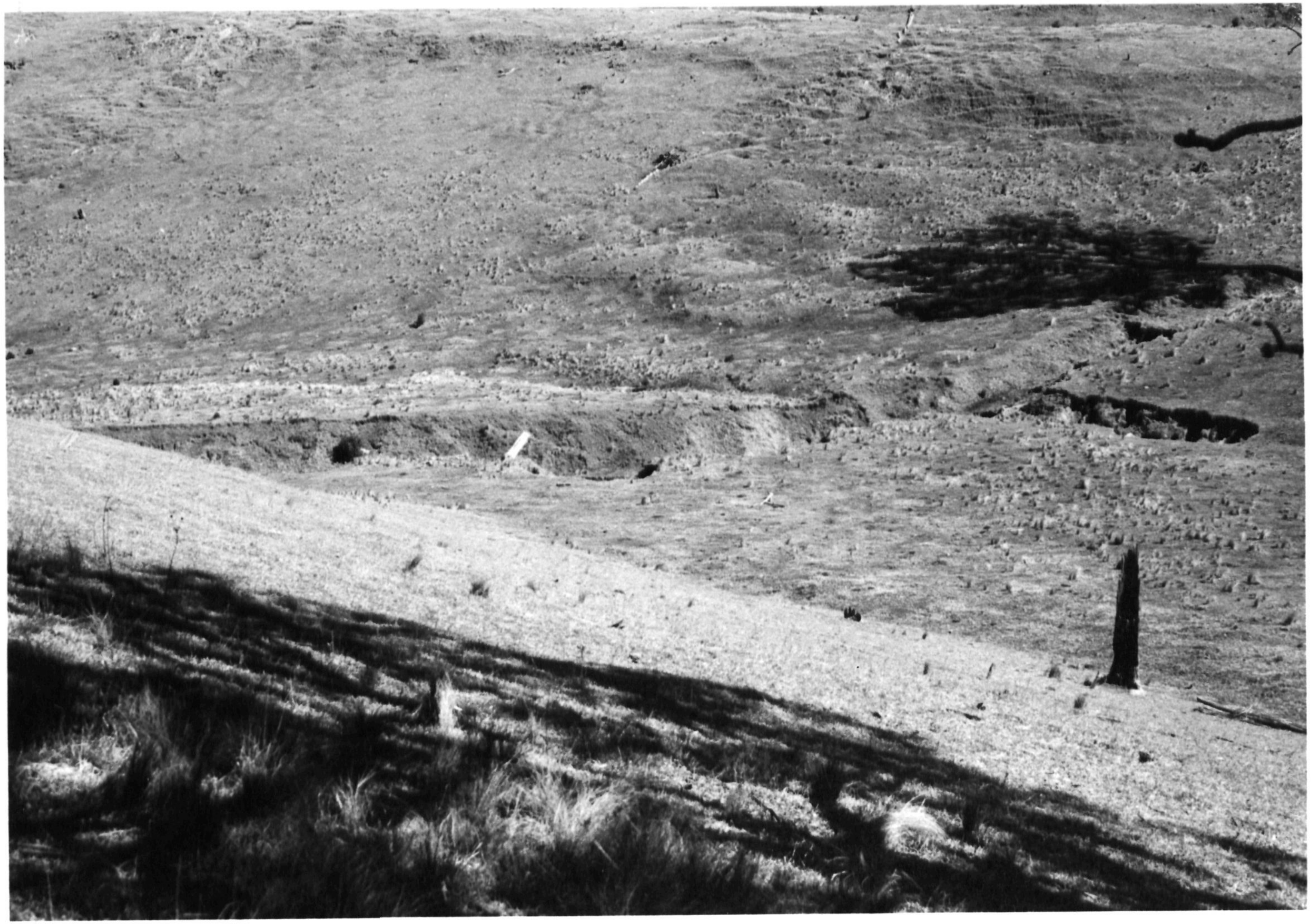


Plate 3.1 Example of a straight planar slope leading into fill material.

Table 3.2

Subdivision of each slope profile into segments

Profile Number	Length of Specified Slope Segment in Metres					Percentage of Profile Occupied by Specified Segment				
	Concavity	Basal	Midslope	Crestal	Convexity	Concavity	Basal	Midslope	Crestal	Convexity
1	21	-	148.5	-	22.5	11	-	77	-	12
2	4.5	-	66	-	10.5	6	-	81	-	13
3	-	75	60	51	-	-	40	32	27	-
4	10.5	-	102	-	6	9	-	86	-	5
5	-	16.5	87	69	16.5	-	9	46	37	9
6	3	-	60	-	7.5	4	-	85	-	11
7	-	49.5	55.5	-	37.5	-	35	39	-	26
8	-	-	-	-	-	-	-	-	-	-
9	-	-	151.5	-	-	-	-	100	-	-
10	-	33	25.5	22.5	-	-	41	31	28	-
11	-	43.5	102	-	3	-	29	69	-	2
12	9	40.5	60	-	12	7	33	49	-	10
13	-	39	18	124.5	9	-	20	9	65	5
14	-	-	-	-	-	-	-	-	-	-
15	-	42	51	72	-	-	25	31	44	-
16	-	33	51	31.5	-	-	29	44	27	-
17	28.5	-	72	-	33	21	-	54	-	25
18	-	22.5	66	-	15	-	22	64	-	14
19	-	22.5	64.5	-	-	-	26	74	-	-
20	13.5	-	79.5	-	-	15	-	85	-	-

Table 3.2 (continued)

Subdivision of each slope profile into segments

Profile Number	Length of Specified Slope Segment in Metres					Percentage of Profile Occupied by Specified Segment				
	Con-cavity	Basal	Mid-slope	Crestal	Con-vexity	Con-cavity	Basal	Mid-slope	Crestal	Con-vexity
21	18	-	36	-	13.5	27	-	53	-	20
22	-	78	19.5	30	7.5	-	58	14	22	6
23	-	81	28.5	34.5	22.5	-	49	17	21	14
24	-	42	51	-	18	-	38	46	-	16
25	-	-	175.5	-	-	-	-	100	-	-
26	1.5	-	90	-	19.5	1	-	81	-	18
27	30	-	103.5	-	-	22	-	78	-	-
28	-	52.5	82.5	-	3	-	38	60	-	2
29	-	85.5	27.5	-	7.5	-	74	19	-	6
30	27	61.5	19.5	16.5	9	20	46	15	12	7
31	-	33	82.5	37.5	-	-	22	54	25	-
32	-	49.5	45	-	66	-	31	28	-	41
33	15	-	42	-	15	21	-	58	-	21
34	34.5	-	46.5	-	10.5	38	-	51	-	11
35	-	34.5	60	-	9	-	33	58	-	9
36	51	-	76.5	-	28.5	33	-	49	-	18
37	33	-	69	-	15	28	-	59	-	13
38	45	-	51	-	6	44	-	50	-	6
39	10.5	-	78	-	10.5	11	-	79	-	11
40	-	64.5	24	-	22.5	-	58	22	-	20

Table 3.2 (continued)

Subdivision of each slope profile into segments

Profile Number	Length of Specified Slope Segment in Metres					Percentage of Profile Occupied by Specified Segment				
	Con-cavity	Basal	Mid-slope	Crestal	Con-vexity	Con-cavity	Basal	Mid-slope	Crestal	Con-vexity
41	24	36	60	-	24	17	25	42	-	17
42	-	-	91.5	-	-	-	-	100	-	-
43	-	12	79.5	22.5	24	-	9	58	16	17
44	-	10.5	63	-	17.5	-	11	68	-	21
45	42	-	42	40.5	22.5	29	-	29	28	15
46	7.5	-	52.5	24	7.5	8	-	57	26	8
47	70.5	-	88.5	-	33	37	-	46	-	17
48	-	142.5	16.5	27	6	-	74	9	14	3
49	-	13.5	106.5	-	-	-	11	89	-	-
50	-	21	40.5	-	19.5	-	26	50	-	24

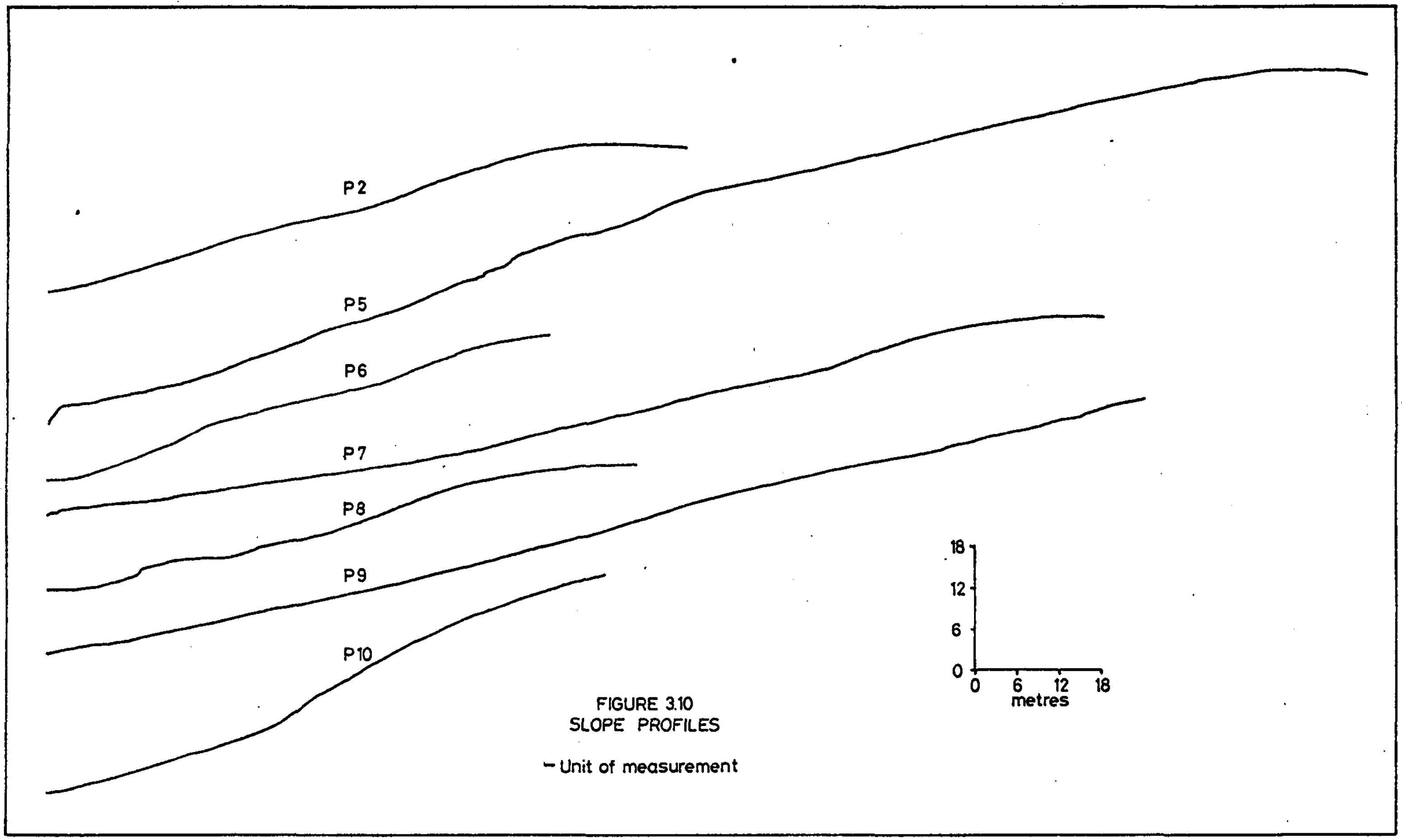


FIGURE 3.10
SLOPE PROFILES

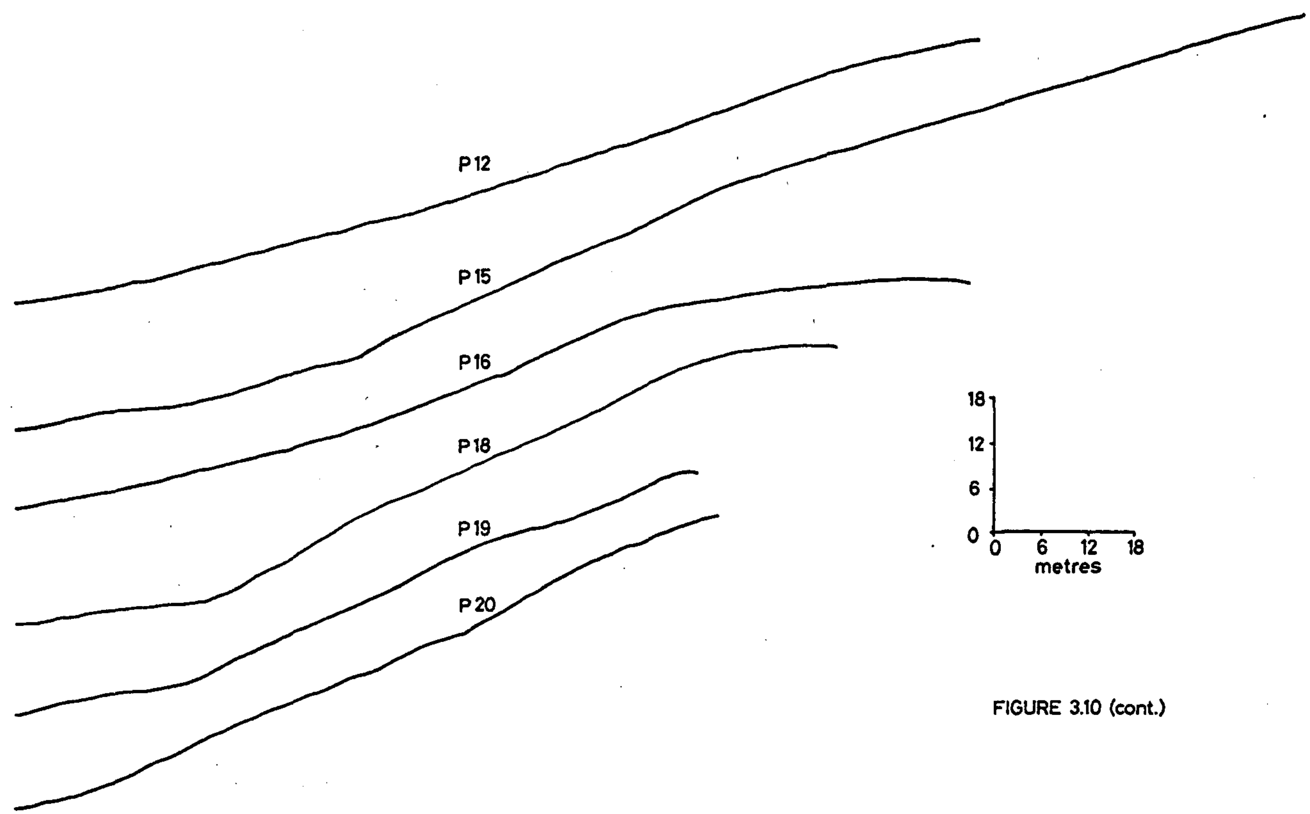


FIGURE 3.10 (cont.)

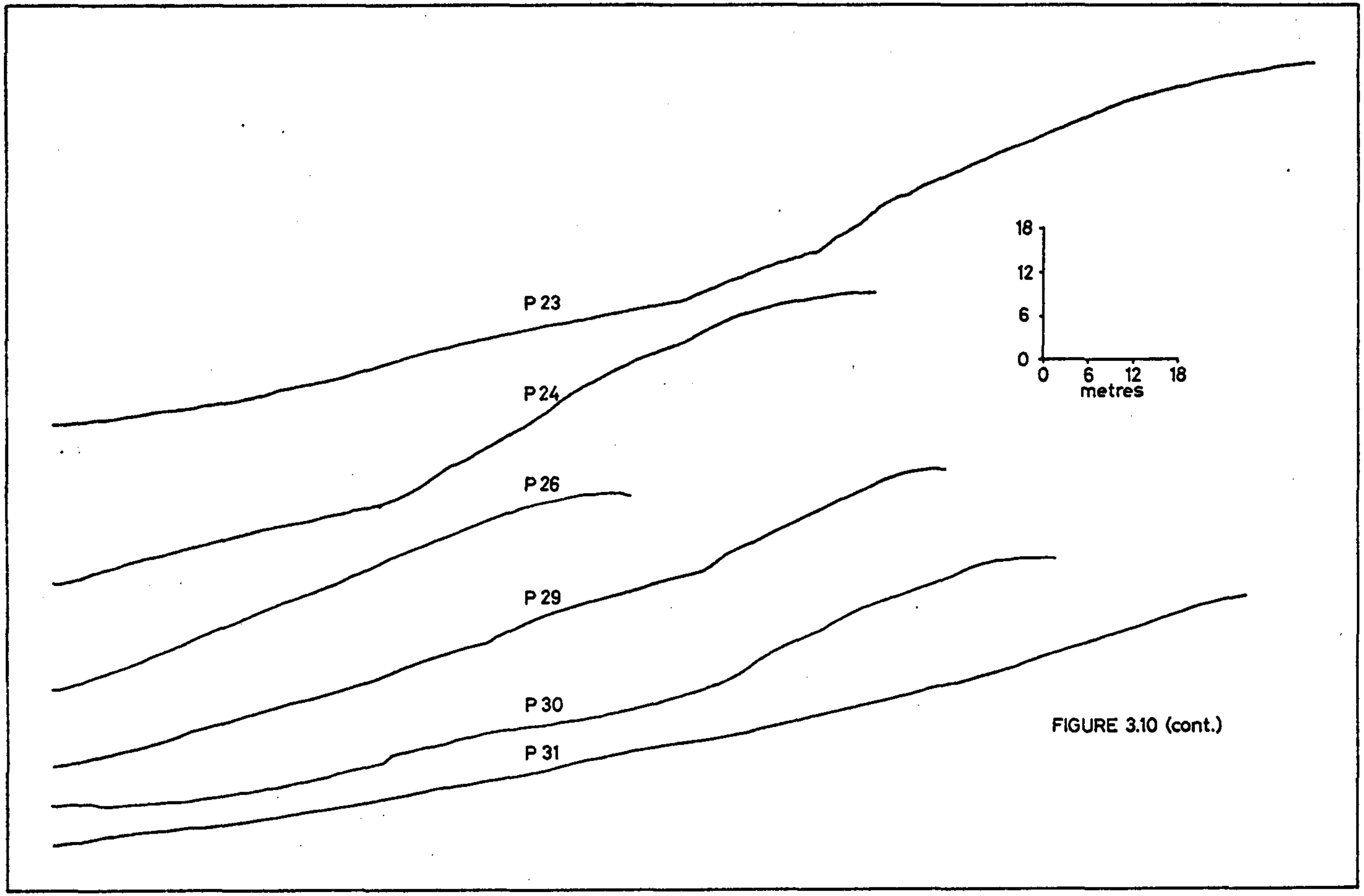


FIGURE 3.10 (cont.)

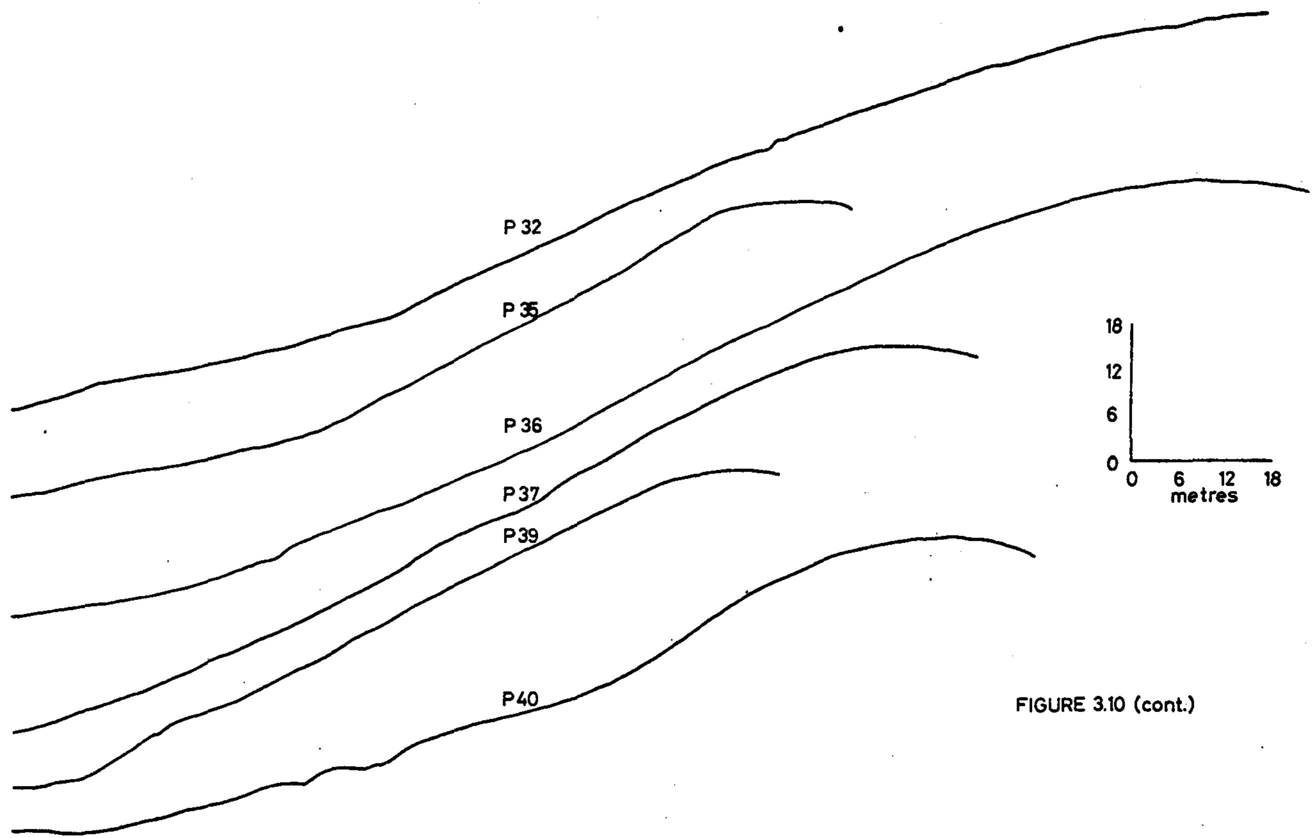


FIGURE 3.10 (cont.)

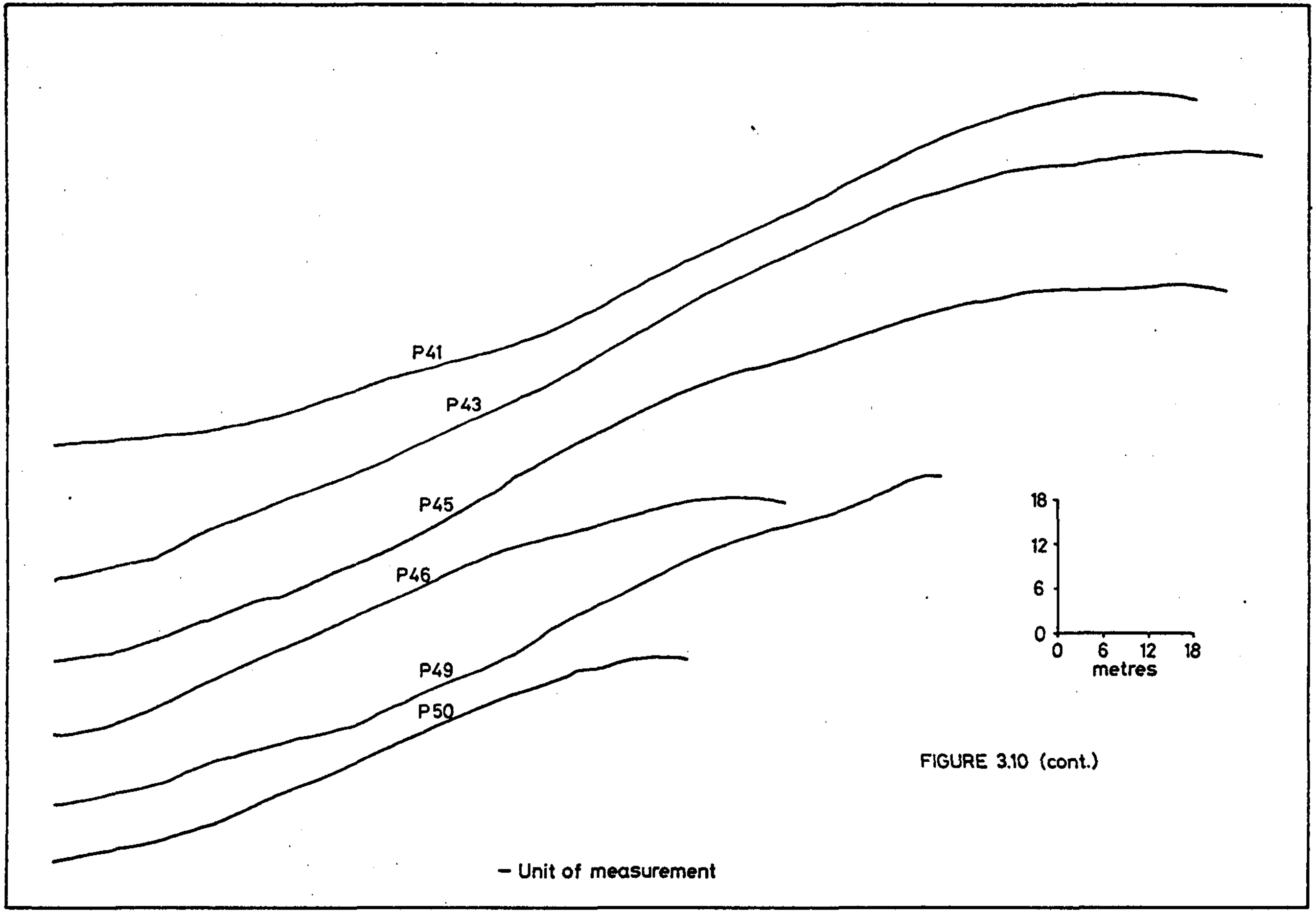


FIGURE 3.10 (cont.)

profiles displayed basal segments, and a further 13 displayed crestal segments; 9 profiles displayed all three divisions. The complete data are given in Table 3.2. The lengths of the basal segments in this table are to be regarded as minimum values. In the early stages of the surveying this part of the profile was often not completely surveyed as it was regarded as subsidiary to the principal steeper section of the slope above. Therefore many of the basal segments would be longer than is suggested by this table.

The most interesting feature of this pattern of slope form is the variance in angle within each of the varieties of rectilinear segments. As shown in Table 3.1, the inclinations of the crestal segments vary widely, from 7° to 32°. Considering the 13 crestal segments gives a mean of 19.2° and a standard deviation of 7.0° (Table 3.3). The mid-slope segments vary less widely, from 12° to 35°; considering the 50 segments yields a mean of 22.6° and a standard deviation of 5.8°. However, the remarkable feature is that the basal segments occur over only a small range of inclinations, from 7° to 17°; of the 24 basal segments, 16 (or two-thirds) lie within the range 11° - 13°; considering all of the 24 segments yields a mean of 11.5, and a standard deviation of only 2.3°.

Table 3.3

Frequency of slope segment types by angle

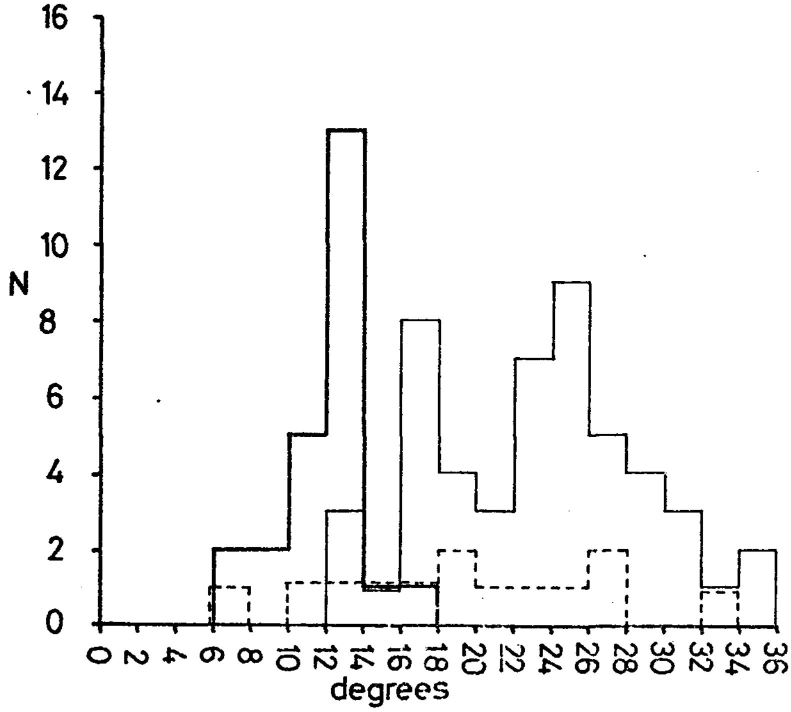
Angle class	Basal seg.	Mid-slope seg.	Crestal seg.
0 - 2			
2 - 4			
4 - 6			
6 - 8	2		1
8 - 10	2		
10 - 12	5		1
12 - 14	13	3	1
14 - 16	1	1	1
16 - 18	1	8	1
18 - 20		4	2
20 - 22		3	1
22 - 24		7	1
24 - 26		9	1
26 - 28		5	2
28 - 30		4	
30 - 32		3	
32 - 34		1	1
34 - 36		2	

Slope form in the study area may thus be summarised as follows: those slopes which lead directly into a drainage line are dominantly rectilinear, with minor crestal convexities; however, about 50% of the slopes are separated from drainage lines by an area of gently sloping ground which is also rectilinear in profile. The important point is that while the upper parts of all profiles may vary widely in inclination, the basal segments are invariably at an inclination of close to 11°. Further discussion of this matter will be given in Chapter 5.

The distributions of the three types of rectilinear segments in 2-degree angle classes is given in Figure 3.11. It is apparent that the inclination of the crestal segments varies over almost the entire range of the other two; however, the basal and mid-slope segments appear to form two separate distributions.

To investigate the significance of this apparent difference a t-test of the difference between the means of the two distributions was applied. In this test the standard formula

$$t = \frac{\bar{x} - \mu}{\frac{S}{\sqrt{n - 1}}}$$



—— BASAL SEGMENTS

—— MID-SLOPE SEGMENTS

------ CRESTAL SEGMENTS

FIGURE 3.11

FREQUENCY HISTOGRAMS OF SLOPE SEGMENT CLASSES for testing the value of a single mean from a known population is modified by taking

$$\bar{x} - \mu = (\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)$$

and

$$S = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}}$$

and

$$\sqrt{n - 1} = \sqrt{\frac{n_1 n_2}{n_1 + n_2}}$$

so that

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}}} \cdot \sqrt{\frac{n_1 n_2}{n_1 + n_2}}$$

(Yamane, 1968).

Assuming that there is no significant difference between the means, we obtain t = 8.95; with 72 degrees of freedom, values of t up to approximately 2 may be expected by chance; the calculated value greatly exceeds this and is significant at the 1% level. Hence we must conclude that the basal segments and mid-slope segments indeed form separate populations. The proposed explanation for this is given in Chapter 5.

3.5.3.1 The effect of Plan Curvature on Slope Inclination

Of the 50 profiles, 20 were subsequently found to be located at sites which were almost rectilinear in plan; 20 were at sites with convex plan curvature, and 10 were located at sites with concave plan curvature. The inclinations of the three slope segment classes according to plan form are given in Table 3.4. The means of each of the three subdivisions of each segment type (e.g. convex mid-slope, concave mid-slope, and rectilinear mid-slope,) have been subject to a t-test for significance of difference from the mean of rectilinear segments only, and in addition to the mean of all segments taken together, to investigate the effect of plan curvature on slope inclination as a whole, or on the inclination of particular segments. The results are summarised in Table 3.5 and Table 3.6. Insignificant values of t were obtained in all cases and this indicates that within the sample of slopes, differences in plan curvature have had no substantial effect either on the mean inclination of slopes or on the inclination of any of the varieties of rectilinear segments of slopes. The possible significance of this finding will be discussed in Chapter 5.

Table 3.4

Slope Data Subdivided on Basis of Plan Form

Mid-Slope Segments

Rectilinear	Convex	Concave	Total
N = 20	N = 20	N = 10	50
$\bar{x}$ = 23.85	$\bar{x}$ = 20.75	$\bar{x}$ = 23.70	22.58
σ = 5.12	σ = 5.35	σ = 7.79	5.8

Basal Slope Segments

N = 7	N = 10	N = 7	24
$\bar{x}$ = 11.00	$\bar{x}$ = 12.50	$\bar{x}$ = 10.43	11.45
σ = 1.73	σ = 2.46	σ = 2.15	2.3

Crestal Slope Segments

N = 3	N = 7	N = 3	13
$\bar{x}$ = 15.33	$\bar{x}$ = 22.14	$\bar{x}$ = 16.33	19.23
σ = 8.51	σ = 6.77	σ = 4.73	7.0

Table 3.5

	N	$\bar{x}$	σ	t	d.f.	Result
1. Mid Slope Segs						
All included	50	22.58	5.8	-	-	Assumed population
Rectil only	20	23.85	5.12	0.83	68	Not signif.
Convex only	20	20.75	5.35	1.21	68	Not "
Concave only	10	23.70	5.8	0.72	58	Not "

	N	$\bar{x}$	σ	t	d.f.	Result
2. Basal Slope Segs						
All included	24	11.45	2.3	-	-	Assumed population
Rectil only	7	11.00	1.73	0.46	29	Not signif.
Convex only	10	12.50	2.46	-1.14	32	Not "
Concave only	7	10.43	2.15	1.02	29	Not "

	N	$\bar{x}$	σ	t	d.f.	Result
3. Crestal Slope Segs						
All included	13	19.23	7.0	-	-	Assumed population
Rectil only	3	15.33	8.51	0.78	14	Not signif.
Convex only	7	22.14	6.77	-0.85	18	Not "
Concave only	3	16.33	4.73	-0.64	14	Not "

Table 3.6

(t-test of effect of plan form on mean slope angle)

Population	N	$\bar{x}$	σ	t	d.f.	Result
Rect. plan slopes	20	18.46	3.48	-	-	Assumed population
Convex plan slopes	20	16.84	2.82	1.57	38	Not signif.
Concave plan slopes	10	16.61	4.91			Not "

3.5.3.2 The Effect of Geology on Slope Form

It is known from field observations made during the year that on some slopes the presence of a sandstone bed produces a break in slope. Examples are shown in Figures 3.12 and 3.13. However, it was important for the remainder of this project to know whether the marked division of profiles into rectilinear segments, described in section 6.5.3 above, was a consequence of the presence of several sandstone beds on the slope, or of the action of the slope-forming processes.

To investigate this, the map showing locations of slope profiles was superimposed on the geological map, and the number of sandstone beds crossed by each profile line recorded. (This could be noted in the field in only a few cases, owing to the limited outcrop). As can be seen from the data (Table 3.7), there is no relationship between the division of the profile into one, two, or three rectilinear segments and the number of sandstone beds present. For example, on some profiles (e.g. P16), three segments are present, but no sandstone beds. Whilst the geologic map is only approximate, it is considered reasonable to conclude from this relationship that in many cases at least the division of the slope profile into rectilinear segments

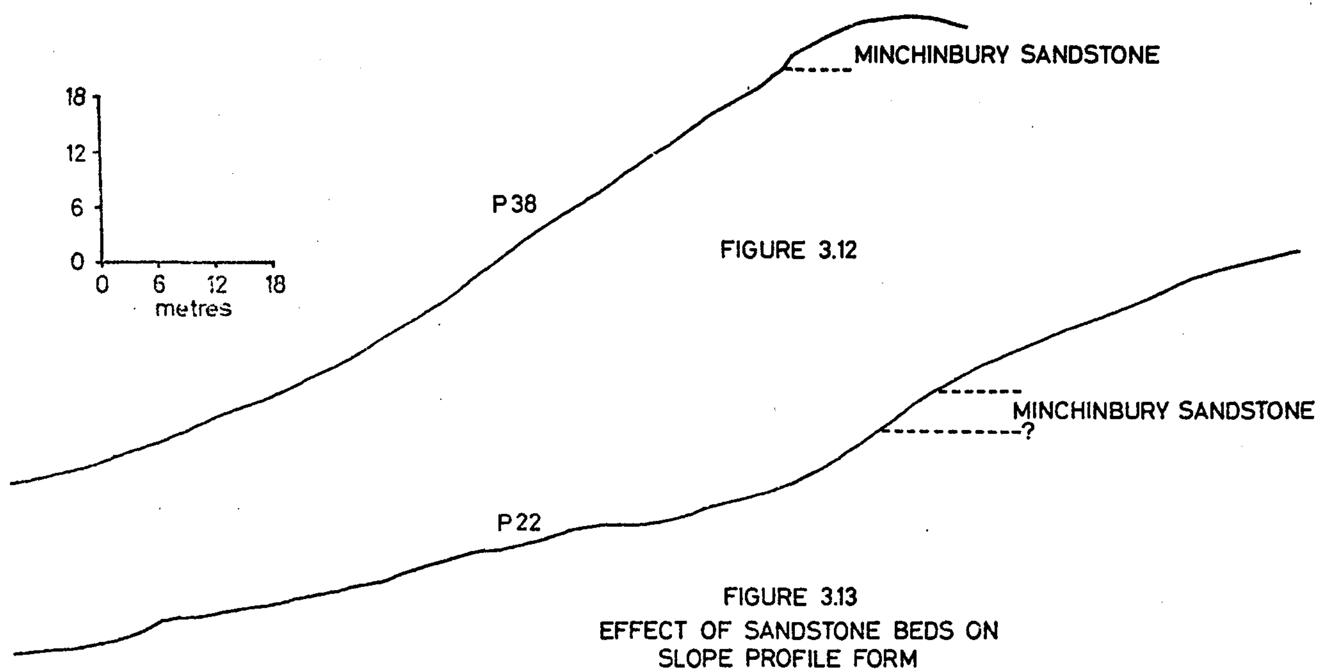


FIGURE 3.12

FIGURE 3.13

EFFECT OF SANDSTONE BEDS ON
SLOPE PROFILE FORM

Table 3.7

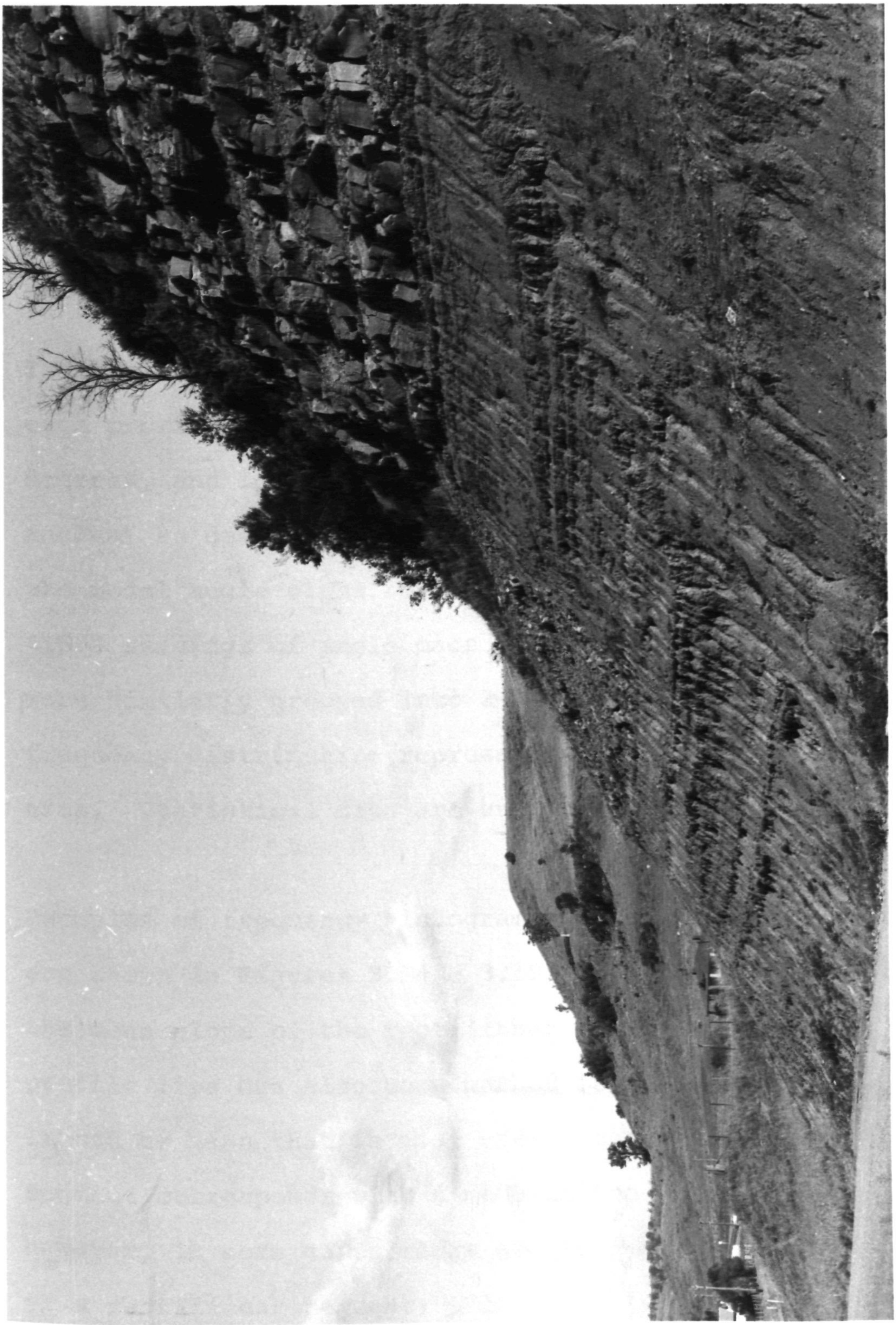
Relationships of presence of sandstone beds to the segmentation of some slope profiles

Profile number	Number of sandstone beds	Number of slope segments
P 1	1	1
P 2	1	1
P 3	2	3
P 4	1	1
P 5	1	3
P 6	2	1
P 7	2	2
P 8	1	-
P 9	2	1
P10	1	3
P11	1	2
P12	1	2
P13	2	3
P14	2	-
P15	1	3
P16	0	3
P17	1	1
P18	0	2

Plate 3.2

The effect of geology on slope form.

In the road cutting is visible the Razorback sandstone, overlain and underlain by shales. The topography related to this geological sequence can be seen on the hillslope in the background, where the sandstone forms a bench beneath which earthflows have occurred.



is not geologically controlled, and must therefore be a consequence of the operation of slope processes. The possible explanation for this is the subject of Chapter 5.

3.5.4 Angle Frequencies in the Study Area

For later purposes, the angle readings obtained along each profile were grouped into classes of width two degrees, and inspected for the presence of "characteristic angles" as defined by Young (1961), and also to determine the modal angle class for each profile. In addition, the 4,500 readings of angle made along all of the 50 profiles were similarly grouped into 2-degree classes to form a frequency distribution representing the entire study area. Statistical data are summarised in Table 3.8.

Examples of frequency histograms for six slope profiles are shown in Figures 3.14 - 3.19. The classes in which the mean slope of the rectilinear segments on each profile lies has also been marked on these diagrams. It can be seen that in most cases each rectilinear segment corresponds with a mode in the distribution; however, in some cases there are no modes corresponding to a rectilinear segment; this occurs when the segment

Table 3.8

Statistical data for slope profiles

PROFILE NO.	NO.OF READ-INGS	% OF PROFILE REP. BY 1.5M	MEAN CURVAT-URE, DEG.PER 100M	MEAN SLOPE	σ	β_1	β_2	LENGTH OF PROFILE METRES	HEIGHT OF PROFILE METRES
1	72	1.39	5.09	17.6	7.15	-0.16	3.33	102	32
2	54	1.85	12.35	14.2	5.23	-1.26	4.40	78	20
3	131	0.76	0.00	13.7	4.32	0.79	3.20	190	46
4	79	1.27	2.53	12.4	4.15	-0.83	3.59	115	25
5	126	0.79	27.51	16.5	10.15	2.40	11.34	179	53
6	47	2.13	-1.42	16.2	6.63	0.21	2.76	67	20
7	95	1.05	5.61	10.6	4.46	0.00	2.96	140	26
8	55	1.82	-3.03	12.3	9.28	1.49	7.58	80	17
9	101	0.99	-2.97	13.0	2.75	0.56	3.01	147	34
10	54	1.85	-4.94	21.4	7.90	1.10	4.00	75	29
11	99	1.01	5.72	13.5	4.27	-0.60	3.06	144	35
12	82	1.22	0.81	15.0	4.36	-0.39	2.90	118	32
13	126	0.79	6.35	18.3	9.62	0.50	3.13	177	59
14	167	0.60	6.19	14.3	10.40	0.23	2.73	239	61
15	110	0.91	-3.33	17.5	5.96	0.01	2.99	156	49
16	77	1.30	9.96	14.1	6.99	0.13	2.47	111	28
17	88	1.14	0.00	21.5	9.90	-0.10	2.60	121	48
18	69	1.45	3.38	19.3	9.51	-0.44	2.07	96	34
19	58	1.72	-2.30	19.9	6.97	-0.25	2.41	81	29
20	62	1.61	-6.99	22.6	7.00	0.05	2.16	85	35
21	45	2.22	6.67	17.9	5.95	-0.90	3.14	64	21
22	90	1.11	-3.33	17.3	9.04	0.44	2.76	127	40
23	111	0.90	-2.40	16.1	8.15	1.27	5.49	158	46
24	74	1.35	5.41	19.5	9.96	0.22	2.40	103	37
25	117	0.85	2.56	13.0	4.51	0.64	3.41	170	39
26	74	1.35	-6.31	19.5	6.08	-0.52	5.25	104	37
27	69	1.45	-5.31	18.8	5.92	-0.76	2.51	97	33
28	92	1.09	3.26	13.9	3.47	-0.08	2.76	134	33
29	79	1.27	7.17	18.6	6.45	0.52	3.54	112	37
30	85	1.18	-1.96	14.3	8.93	0.64	2.90	122	31
31	102	0.98	-2.94	11.8	4.08	0.67	3.91	149	31
32	107	0.93	5.30	17.2	7.04	0.07	2.74	152	47
33	48	2.08	-2.78	20.9	8.39	-0.80	2.72	67	25
34	61	1.64	-1.64	18.1	6.32	-0.82	2.84	86	28
35	69	1.45	4.83	20.3	9.84	-0.24	2.11	96	35

PROFILE NO.	NO.OF READ-INGS	% OF PROFILE REP.BY 1.5M	MEAN CURVAT-URE, DEG.PER 100M	MEAN SLOPE	σ	β_1	β_2	LENGTH OF PROFILE METRES	HEIGHT OF PROFILE METRES
36	104	0.96	0.32	20.0	8.15	-0.19	-	145	53
37	78	1.28	8.97	23.7	7.23	-0.73	4.18	106	47
38	68	1.47	5.39	27.7	10.06	-0.09	2.99	89	47
39	66	1.52	2.53	23.2	9.84	-0.70	3.36	90	38
40	82	1.22	-0.41	17.0	11.54	-0.05	2.36	115	35
41	96	1.04	4.51	17.8	9.19	0.07	2.72	135	44
42	61	1.64	-10.38	20.7	6.32	1.00	7.52	85	32
43	103	0.97	1.29	20.3	8.76	-0.63	2.25	143	53
44	62	1.61	6.45	20.2	6.75	-1.03	3.27	87	32
45	98	1.02	-1.36	18.7	9.25	-0.27	2.84	137	47
46	61	1.64	3.28	18.6	7.32	-0.79	2.82	86	29
47	128	0.78	0.78	11.4	6.05	0.53	3.38	187	38
48	133	0.75	0.50	13.9	8.92	0.62	3.22	191	47
49	80	1.25	5.83	19.8	7.50	0.14	2.45	112	40
50	54	1.85	7.41	17.8	6.55	-0.61	2.32	77	25

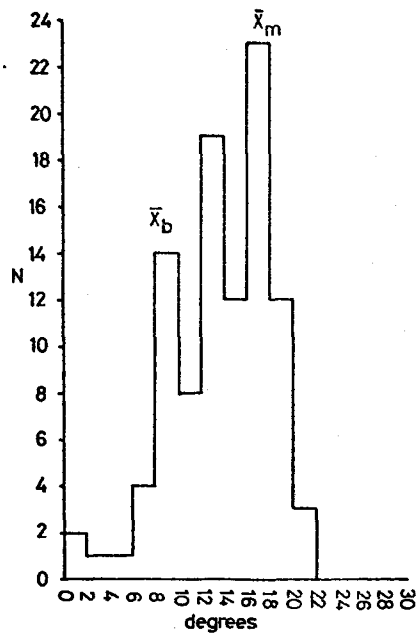


FIGURE 3.14

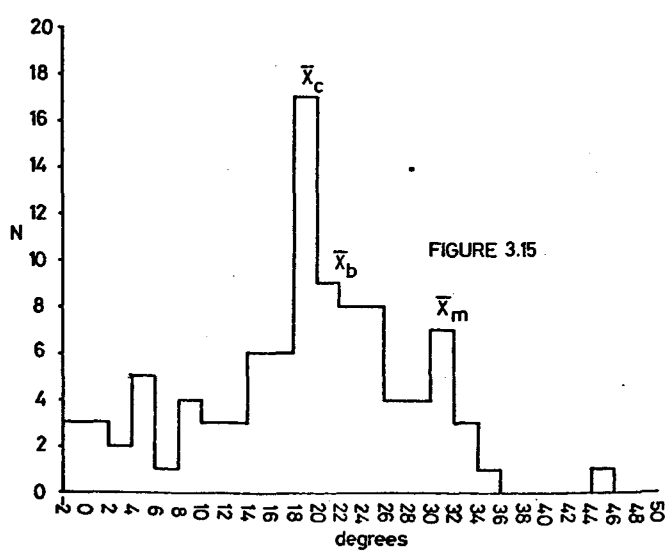


FIGURE 3.15

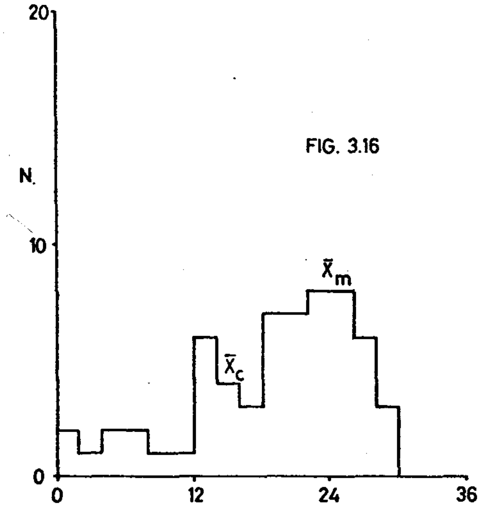


FIG. 3.16

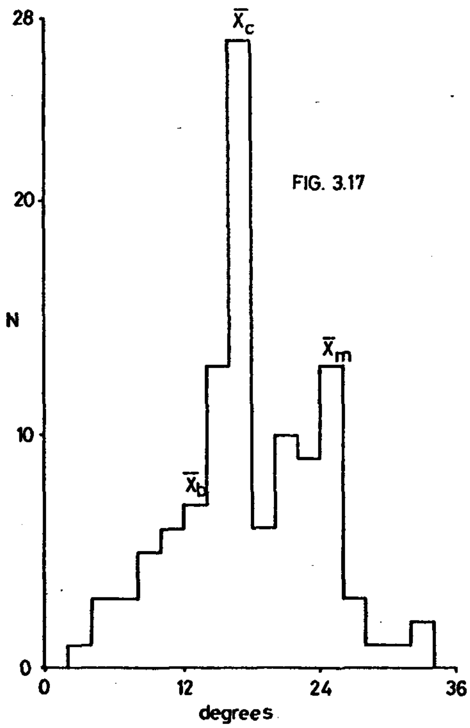


FIG. 3.17

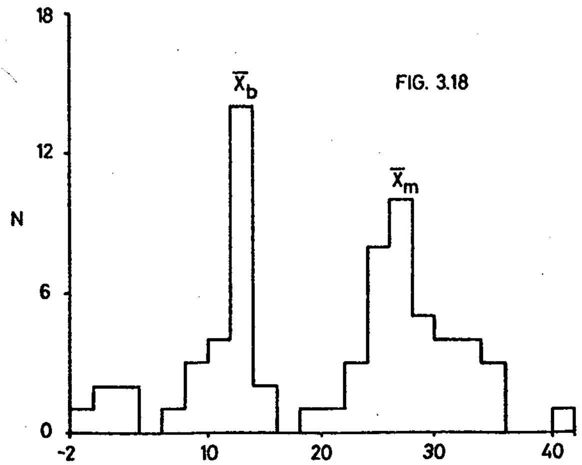


FIG. 3.18

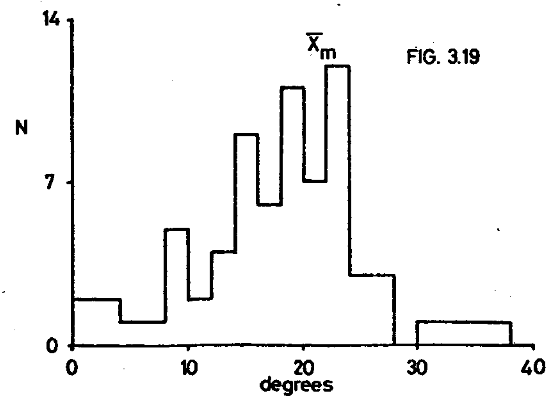


FIG. 3.19

is short. An example is the basal segment of Profile 45 (Figure 3.15). In other cases there are modes to which no rectilinear segment corresponds. An example is the mode in the class $12^\circ - 14^\circ$ on P11 (Figure 3.14). Hence in general interpretation of modes in the frequency distributions in terms of "characteristic angles" is realistic in terms of actual slope form; however, it is considered that using "characteristic angles" defined in this way is a doubtful method when applied to studies of slope form and development, because of the discrepancies referred to above. For this reason the interpretation of slope profile frequency distributions was not used as the basis for the latter part of this thesis.

However, it was considered that by taking a very large sample of slope angle readings from all over the study area (rather than a relatively small sample from a given profile), an accurate idea of the actual frequency of occurrence of particular angles could be obtained. The mode or modes of such a distribution should reliably reflect angles which occur most frequently in the study area and are thus "characteristic" of it.

For this purpose, 4,241 angle readings from the 50 slope profiles were grouped into 2-degree classes and a frequency histogram constructed. Three separate histograms were plotted, using successively more of the data. The first curve (Figure 3.20), based on 1,661 readings, showed two equal modes at $12^{\circ} - 14^{\circ}$ and $22^{\circ} - 24^{\circ}$; the second (Figure 3.21), based on 2,580 readings showed the same modal classes, but that at $22^{\circ} - 24^{\circ}$ was relatively subdued and possessed only half the frequency of that at $12^{\circ} - 14^{\circ}$; the final curve, based on 4,241 readings was essentially the same as the previous one. The final frequency distribution is shown in Figure 3.22. The curve is slightly asymmetric, with a suggestion of bimodality; the principal modal class is $12^{\circ} - 14^{\circ}$, and the secondary modal class $22^{\circ} - 24^{\circ}$. The explanation of these modes is the subject of Chapter 5. An interesting point is that probably about 2,000 readings were required to obtain a reasonable approximation to the final distribution; this is far more than is generally used in studies of "characteristic angles" (for example, Young, 1964). The conclusions of such studies may thus not be based on sufficient data.

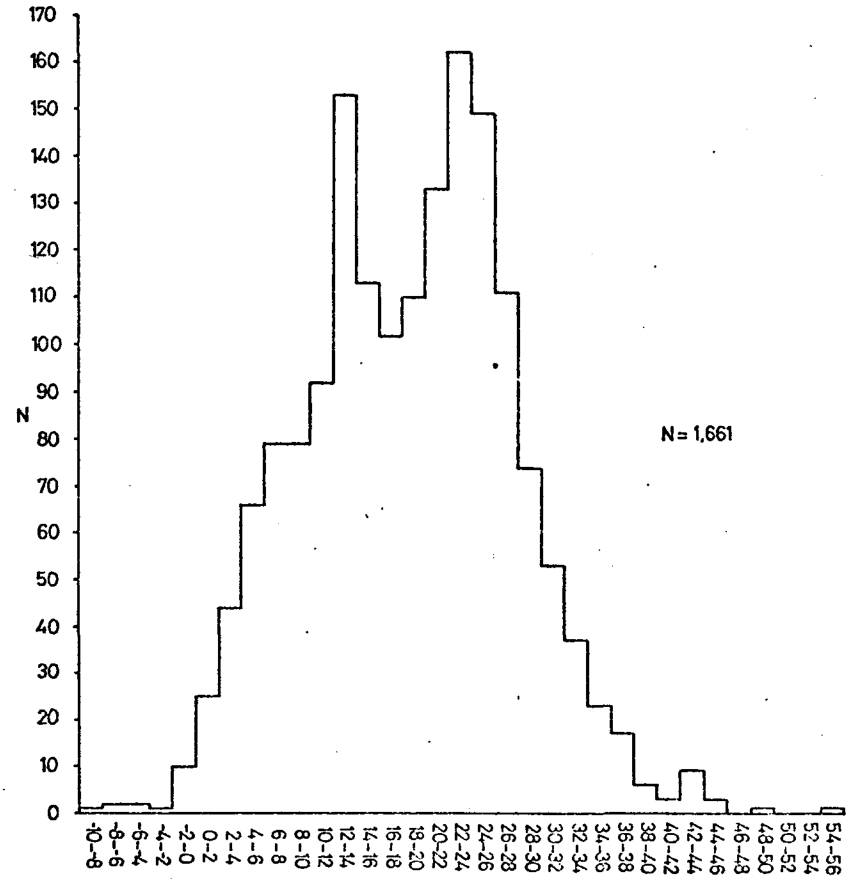


FIGURE 3.20

SLOPE ANGLE FREQUENCY DISTRIBUTION

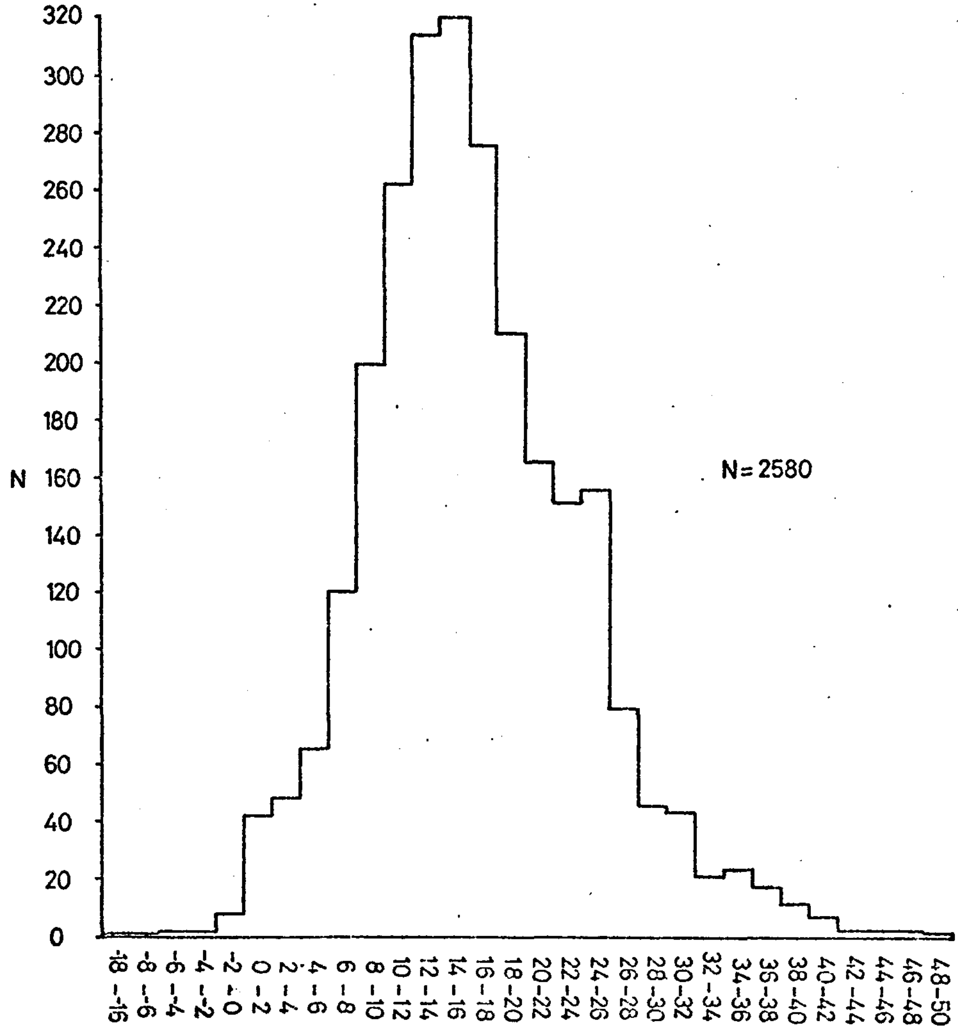


FIGURE 3.21
SLOPE ANGLE FREQUENCY DISTRIBUTION

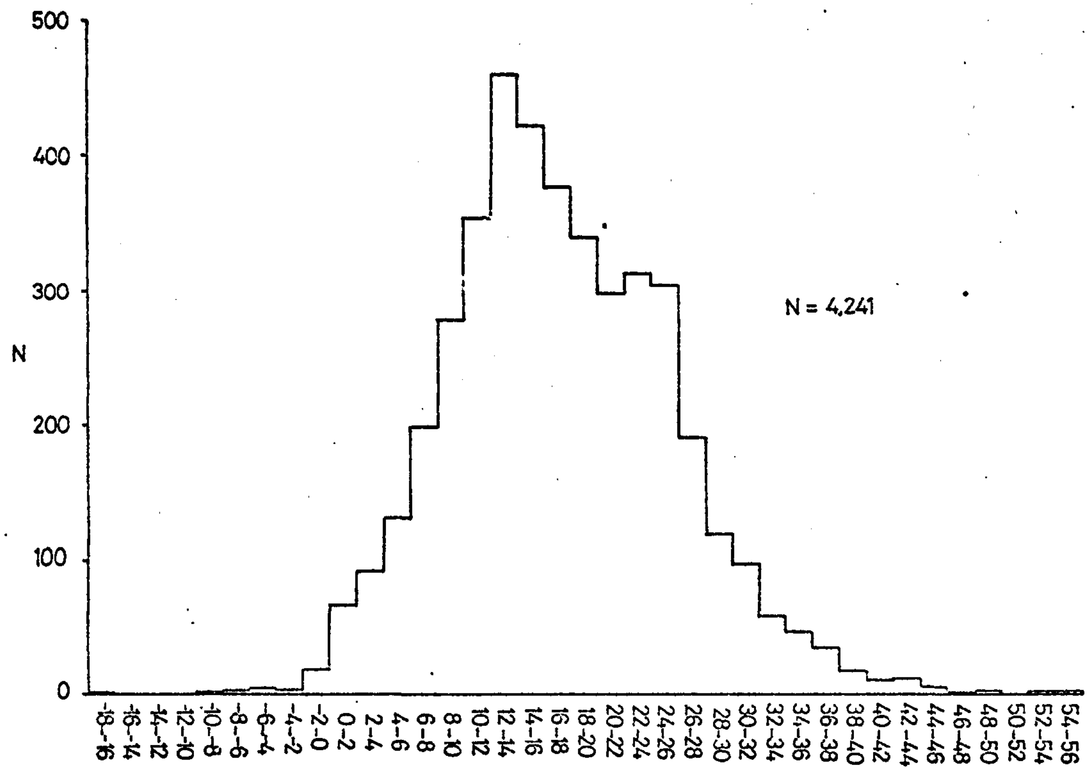


FIGURE 3.22

SLOPE ANGLE FREQUENCY DISTRIBUTION