MATERIAL-FORM RELATIONSHIPS
ON TALUS SLOPES
IN SOUTHWESTERN BRITISH COLUMBIA

by

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We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
March, 1976

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ABSTRACT

Talus slopes were investigated in a process-material-response framework. The work was concerned with clarifying concepts and terminology concerning slopes of granular materials and interpreting talus slope angles in the light of this clarification; verifying this interpretation in a field investigation; and seeking statistical relationships between talus slope angle and material properties.

Field investigations were carried out in South West British Columbia. Slopes were investigated in the southern Coast Mountains and in the Similkameen Valley.

Theoretical concepts relating to slopes in granular material were discussed. Two angles of repose were distinguished; a peak angle of accumulation ($\alpha_c$) defined as the steepest angle attainable by a mass of granular material, and a lower angle, the angle of repose ($\alpha_r$) to which the material slides after failure. $\alpha_c$ and $\alpha_r$ were related to concepts of shear resistance and the angle of internal friction ($\phi$); $\alpha_c$ was linked to $\phi$ and $\alpha_r$ was thought to correspond to the residual angle of internal friction ($\phi_r$) for a given material. $\alpha_c$ and $\alpha_r$ were related through a regression equation of the form:

$$\alpha_c = -3.29 + 1.273(\alpha_r)$$

These concepts were examined with reference to talus slope form and some of the contradictions in the literature were presented. The characteristic and limiting slope angles noted in review were found to correspond to $\alpha_r$ and $\alpha_c$. 
respectively for talus material. This correspondence gave rise to the supply induced transformation hypothesis which appeared to provide a suitable transformation model for rockfall talus.

The relationship between material properties and slope angle was examined using parametric multivariate statistics. Significant correlations, at the 99% level, were obtained between segment angle and size (inverse) and segment angle and sorting (direct). At the 95% level significant correlations were found between segment angle and sphericity (inverse) and Zingg's Flatness Ratio (direct). In multiple regression analysis only 37.11% of the variation in slope angle was accounted for by material properties (sorting and the variance in Zingg's Elongation Ratio) at the 95% level of significance. Shape factors contribute very little to the explained variance whilst fabric related variables contribute nothing.

Implications of these results for talus slope development were discussed. Rockfall talus slopes subject to supply-induced transformation processes are thought to have a distinctive morphology which may be an explanation for the typical profile concavity noted on such slopes. Determinants on the frequency of talus slides were examined. The problem of the basal layer cannot be ignored in a consideration of talus slope development models.
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<th>Usage in this work</th>
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<td>( \tau )</td>
<td>Threshold shear strength required to resist failure (shear resistance)</td>
</tr>
<tr>
<td>( \tau_c )</td>
<td>Applied stress great enough to exceed ( \tau ).</td>
</tr>
<tr>
<td>limiting slope</td>
<td>Term taken from Young (1961). Modified for usage in this work and taken to be equal to the upper value of a slope angle on slopes affected by a particular denudation process</td>
</tr>
<tr>
<td>characteristic slope</td>
<td>Term taken from Young (1961). Modified for this work and used with reference to the angle which most frequently occurs on a particular landform e.g. talus slopes</td>
</tr>
<tr>
<td>threshold slope</td>
<td>Term taken from Carson and Petley (1970). Used in this work as a slope that exists in equilibrium with the strength characteristics of the materials composing it. May refer to a slope in equilibrium with peak or residual strength.</td>
</tr>
<tr>
<td>peak angle of accumulation (( \kappa_c ))</td>
<td>The maximum slope angle attainable by a granular mass for a given set of aggregate properties and depositional conditions</td>
</tr>
<tr>
<td>angle of repose, or rest (( \kappa_r ))</td>
<td>Angle assumed by a granular mass following failure resulting from an exceedance of ( \kappa_c )</td>
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<tr>
<td>angle of internal friction (( \phi ))</td>
<td>Representative of the frictional resistance of an aggregate of soil particles. Usage as in Terzaghi (1943)</td>
</tr>
<tr>
<td>( \phi_f )</td>
<td>The interparticulate friction component in ( \phi ) (Rowe, 1963)</td>
</tr>
<tr>
<td>( \phi_d )</td>
<td>Dilatancy component in ( \phi ) (Rowe, 1963)</td>
</tr>
<tr>
<td>( \phi_a )</td>
<td>The re-arranging effect component in ( \phi ) (Rowe, 1963)</td>
</tr>
<tr>
<td>residual angle of internal friction (( \phi_r ))</td>
<td>Residual or ultimate value of ( \phi )</td>
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$\phi_{cv}$

Angle of internal friction measured when volume change in the soil material as a result of shear reaches zero. (Lambe and Whitman, 1969)

imbrication angle

Term used after Rees (1968) and is the angle between the slope of deposition and the mean angle of dip of the particles deposited on that slope.
ACKNOWLEDGEMENTS

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CHAPTER ONE

INTRODUCTION

1.1 Terminology

Talus slopes appear to be a very common element of mountainous terrain where they are frequently found at the base of rock faces as an accumulation of rock debris. Talus slopes occur as a component in valley side slopes of the highest order streams as well as those of lower order and are also seen to constitute a component of many summit slope systems in the mountain environment. Such slopes are usually characterised by a slope angle intermediate between that of the rockwall above and the valley floor which they may adjoin, a looseness of coarse fragments which cover the slope, low density or complete absence of vegetation, and a straight or concave upward slope profile.

In North American the word "talus" is used both to describe a landform and the material that composes it. In this work "talus" will be used to describe the material that makes up a "talus slope", a distinct landform. Some refer to talus slopes as "talus slides", or to talus as "sliderock". The use of these words conveys a false impression as to the mode of accumulation of talus (cf. Sharpe, 1960). Further, material collecting in a debris slope beneath a gravel or silt face is often referred to as talus (e.g. Rahn, 1969), but the term should be restricted to that material beneath a rock face.

"Talus" and "scree" tend to be synonymous in most geomorphological circles although there is a strong preference for
the use of scree in the United Kingdom and for talus in North America.

1.2. **The Talus Slope System**

The talus slope system may be viewed as a sub-system within the mountain environment, the characteristics of which give the study of mountain processes a unique place in geomorphology. Some of these characteristics are (cf. Hewitt, 1972);

(a) The mountain environment is a high relative relief and a high energy process environment.

(b) The surface of a mountain landscape in large part consists of bare rock, rock debris, snow and ice.

(c) The great variability in status variables such as climate (due to elevational differences) and materials (lithological variations) makes it difficult to generalise about mountain processes.

(d) Processes and response surfaces are not always amenable to study due to the magnitude of events (e.g. large rockslides) and inaccessibility (mountain slopes).

The study of talus slopes in the mountain environment must be pursued with some of these characteristics in mind.

Various workers in discussing slopes, mountain slopes or otherwise, have found it both conceptually convenient and conceptually useful to use a model to illustrate the structure of a particular slope system (e.g. Carson, 1969; Chorley and Kennedy, 1971). In this work, it is the intention to discuss talus slopes as a sub-system of the mountain slope system in general. Such a
model will be similar to a process-material-response model (Krumbein and Graybill, 1965).

With reference to the talus system this writer in previous work (Evans, 1969) presented a qualitative process-material-response model for debris slopes in South Wales. Towler (1969) appears to have gone further and was successful in obtaining statistically significant correlations between some of the parameters within the model. In other work Howarth and Bones (1972), present a verification of a general process-response model for Arctic talus slopes on Devon Island, N.W.T.

The typical mountain slope system has three loci of failure; the mountain slope in general and its components, the rock wall and the talus slope. This work will concentrate on the talus slope and will be limited to a concern for process-material-response links on the talus slope itself. In considering these links, it is necessary to make a distinction between change resulting from a redistribution of material within the limits of the slope (e.g. creep, talus slides, slush avalanches), change resulting from a loss of material beyond the lower limit of the slope (erosion by sea, ice, rivers or transport by snow avalanches), and change achieved by gain of material through the upper limit of the slope which constitutes the depositional phase of rock wall transformation.

The processes involved in these types of change vary according to environment but two basic processes are seen to be common to all taluses, i.e. rockfall (deposition of talus) and talus slope failure or modification. Figure 1.1 illustrates the
Figure 1.1: Controls on transformation types within the talus system
factors which appear to determine the process of talus slope modification. These factors have been assembled from the literature and their mode of presentation is after Varnes (1957).

1.3 **Material Properties and Slope Form**

The relationship between material properties and slope form has been investigated in pioneer work on London clay slopes in South England, by Skempton and De Lory (1957), Skempton (1964) and Hutchinson (1967a) who demonstrated the relationships between the incidence of mass movement processes, material properties and observed slope angles on slopes in the Tertiary sediment. Other work along similar lines has been carried out by Chandler (1970 a,b) on Lias clay slopes in England, by Lohnes and Hardy (1968) on loess slopes in Iowa, and by Carson and Petley (1970) on debris covered hillslopes in two upland areas in Britain. Swanston (1970) conducted studies on glacial till slopes on Prince of Wales Island, Alaska whilst Carson (1972) looked at debris-covered hillslopes in the Laramie Mountains of Wyoming with a similar conceptual framework.

Until recently the material-form link had not been studied on talus slopes specifically and the work of Rouse (undated ms.) and Chandler (1973), working in South Wales and Spitzbergen respectively, represent the first work in that direction.

The importance of material properties and their effects on slope form is implicit in the statements of Strahler (1952) and Chorley (1966) who comment on the role of stress-strength
relations in process studies. Strahler (1952) noted that "all geomorphic processes that we observe... are basically the various forms of shear, or failure... of materials" (p. 924). Chorley (1966), stressed the importance of force-resistance ratios since they expressed "the effectiveness of the force in producing change in materials of a given strength attribute" (p. 283).

A geomorphic event, the sum of which over a period of time represents a geomorphic process, occurs when an applied stress ($\tau_c$) is greater than a threshold shear strength ($\tau$) required to resist failure.

Material properties should be related to slope form in the following ways:

(a) A threshold must exist for all slopes where $\tau_c > \tau$, i.e. a limiting value for strength, and this threshold must have a morphometric manifestation. This manifestation would correspond to the limiting slope.

(b) Equilibrium conditions, where $\tau = \tau_c$, i.e. a lower bound for the operation of a process, must exist for all slopes and this must have a morphometric manifestation. This manifestation would correspond to the threshold slope as defined by Carson and Petley (1970).

(c) Changes in form take place as a result of a process where $\tau_c > \tau$.

1.4 Statement of the Problem and Objective

Most workers in the past have been preoccupied with
petrologic aspects of talus accumulation (viz. size, shape, etc.) and have not related these properties to the mechanical properties of the talus or directly to slope form. A considerable gap exists in knowledge concerning the relationship between mechanical properties of talus, talus slope processes and slope form. Confusion also continues to be rampant (vide recent texts on slopes and slope processes) with respect to concepts of angle of repose, shear resistance, and their relation to values of threshold and limiting slopes.

The major objective of this work is to investigate relationships that exist between material properties and talus slope form on selected rockfall talus slopes in southwestern British Columbia. It will be met in two ways:

(a) By clarifying concepts and terminology concerning slopes of granular materials and interpreting talus slope angles in the light of this clarification,

(b) By seeking statistical relationships between talus slope angle and material properties of particles that make up the slope.

The work will be carried out in a way suggested in Figure 1.2.
Figure 1.2: Organisation of work: form-material relationships

Figure 1.2: Organisation of work: form-material relationships
CHAPTER TWO

REVIEW OF TALUS SLOPE FORM, STRUCTURE AND PROCESSES

2.1 Talus Slope Form

2.1.1 Gross Form; The distinction between various types of talus slopes has been noted in works by Rapp (1960 b) and Stock (1968) and the implications for process-form relationships have been examined by Howarth and Bones (1972).

Rapp (1960 b) distinguished three gross forms exhibited by talus slopes; the cone form as illustrated in Figure 2.1 which occurs at the outlet of a rock chute, mountain gully or couloir, the sheet form (Figure 2.2) which accumulates at the foot of a continuous rock face, and a compound slope which occurs where several cones coalesce as illustrated in Figure 2.3. Stock (1968) has much the same basis for his classification except that he distinguishes a fourth type, a debris slope, the common feature of which is the apparent thinness of the debris mantle over the bedrock beneath which controls profile characteristics (Figure 2.4).

2.1.2 Talus Slope Profile Form

(a) Slope Angle; In reviewing the literature, it was found that talus slope measurements have been presented, confusingly, in two forms i.e. on the profile scale which may represent either the mean angle of slope calculated from segment data or the overall angle of slope, and on the segment scale consisting of measurements on discrete parts of the profile. The length of
Figure 2.1  Talus cone at Lindeman Lake studied in this work
Figure 2.2 Example of sheet talus on Norwegian coastline south of Måløy

Figure 2.3 Example of coalescent cones forming a compound slope, south of Måløy, Norway
Figure 2.4 Example of debris slope on Norwegian coastline, south of Måløy
these segments may vary from scarcely 1 metre to over 100 metres. As a result of this differentiation the two sources of data have to be treated separately.

With regard to profile measurements, slope angles were obtained from existing works where slope angles were given and are illustrated in histogram form in Figure 2.5. Many other works give illustrations of profiles but do not give slope angle data. Details of the slopes on which Figure 2.5 was based are given in Table I. From an examination of Figure 2.5 the following points arise:

(i) Based on published sources the mean profile angle of talus slopes is $29.6^\circ$ with $n = 181$.

(ii) The data appear to be almost unimodal at $32.0^\circ$ (modal strength of 13.2%). A weak secondary mode is seen at $27.0^\circ$ (modal strength of 6.5%) but if data from Evans (1969) is excluded it would not be evident.

(iii) 35.9% of the observations occur between $32^\circ$ and $35^\circ$ inclusively.

(iv) The range of the data is $29^\circ$ i.e. between $11.0^\circ$ and $40.0^\circ$.

The implication of these observations will be discussed below. There have been indications that profile angle is related to the "dominant process" within a particular talus system. White (1968) recognises rockfall talus, avalanche talus and alluvial talus. He reports that their mean slope angles are, respectively,
Figure 2.5 Histogram of mean talus slope angles from published sources (n = 181)

1 - Reported as means
2 - Mean of means
3 - Calculated from mean of segments
Figure 2.6 Histogram of published segment angles measured on talus slopes (n = 207)
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<tr>
<th>Source</th>
<th>Location</th>
<th>Lithology</th>
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<td>Howarth &amp; Bones (1972)</td>
<td>Devon Island, N.W.T.</td>
<td>Limestone</td>
</tr>
<tr>
<td>Koons (1955)</td>
<td>Various Locations in Arizona, New Mexico</td>
<td>Basalts, Limestones, Sandstones</td>
</tr>
<tr>
<td>Stock (1968)</td>
<td>Baffin Island, N.W.T.</td>
<td>Schists, Granitic Gneiss</td>
</tr>
<tr>
<td>Gardner (1970)</td>
<td>Lake Louise, Rocky Mountains, Alberta</td>
<td>Quartzizites, Shales, Carbonates</td>
</tr>
<tr>
<td>Evans (1969)</td>
<td>Fforest Fawr, South Wales, U.K.</td>
<td>Quartzites</td>
</tr>
<tr>
<td>Caine (1969)</td>
<td>Southern Alps, New Zealand</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Caine (1967)</td>
<td>North East Tasmania</td>
<td>Dolerite</td>
</tr>
<tr>
<td>Rapp (1960 a)</td>
<td>Karkevagge, Sweden</td>
<td>Gneisses</td>
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<tr>
<td>Rapp (1960 b)</td>
<td>Spitsbergen</td>
<td>Chert, Limestones</td>
</tr>
<tr>
<td>Chandler (1973)</td>
<td>Spitsbergen</td>
<td>Schists, Limestones</td>
</tr>
<tr>
<td>Tinkler (1966)</td>
<td>Eglwysweg, North Wales, U.K.</td>
<td>Limestones</td>
</tr>
<tr>
<td>Frankfort (1968)</td>
<td>Central Connecticut</td>
<td>Basalt</td>
</tr>
<tr>
<td>Worobey (1972)</td>
<td>Similkameen Valley, British Columbia</td>
<td>Cherts, Lavas and Limestones</td>
</tr>
<tr>
<td>Thornes (1971)</td>
<td>Iceland</td>
<td>Massive Basalts</td>
</tr>
<tr>
<td>Fair (1948)</td>
<td>Karoo, Natal, S. Africa</td>
<td>Shale, Sandstone, Dolerite</td>
</tr>
</tbody>
</table>
within the ranges $37^\circ-40^\circ$, $35^\circ-38^\circ$ and $30^\circ-38^\circ$ ($30^\circ-35^\circ$ for lower portion, $35^\circ-38^\circ$ for upper portion). Howarth and Bones (1972) contend in similar fashion that rockfall talus profiles are steeper ($33.5^\circ-35.5^\circ$) than meltwater-affected slopes ($30.3^\circ-31.0^\circ$). As Howarth and Bones (1972) point out, "in most cases significant differences in geometrical form occur between slopes subjected to different dominant processes" (p. 151). Figure 2.5 must be viewed with this in mind.

Segment angles show substantially different characteristics, and the results from the literature review are seen in histogram form in Figure 2.6. Details of the slopes are found in Table I. The following comments can be made on the data;

(i) Based on published sources the mean segment angle on talus slopes is $30.9^\circ$ with $n = 207$.

(ii) The data appear to be strongly unimodal at $35^\circ$. The modal strength for this mode is 17.9%.

(iii) 50.7% of the observations occur between $33^\circ$ and $36.9^\circ$. 32.9% occur between $34^\circ$ and $35.9^\circ$.

(iv) The range for the data is $28.9^\circ$ (i.e. between $11.0^\circ$ and $39.9^\circ$).

According to Young's definitions the characteristic slope angle is that angle "which most frequently occurs either on all slopes under particular conditions of rock types or
of climate or in a local region" (p. 126). Limiting angles of slopes are "those that define the range within which particular types of ground surface occur, or particular denudational processes operate" (p. 127).

Viewing the data with Young's (Young, 1961) terminology in mind it can be concluded that on the basis of published data that the characteristic slope angle for talus slopes is 35° (cf. Chandler, 1973) whilst the limiting slope angle appears to be 40°.

(b) Profile Shape: Visual inspection of published talus slope profiles confirms that in general they tend to be concave upward. This pervasive characteristic of talus slopes has attracted the imagination of many geomorphologists several of whom have theorized on its possible origin (e.g. Penck, 1924; Kirkby in Carson and Kirkby, 1972; Scheidegger, 1970). Penck, among others, explained the concavity as being due to the size gradient downslope (i.e. fine at the top, coarse at the bottom). Kirkby has obtained a similar concavity in laboratory experiments designed to simulate talus slope development and contends that distance travelled by each rock in the rockfall process is the determining factor. Scheidegger thought that packing variations and their relationship to the angle of repose might account for the observed concavity.

A second impression derived from an examination of slope profiles is the existence of "mini-concavities" superimposed upon the general slope concavity. Andrews (1961) and Scheidegger (1970) have also noted their existence. It may be
noted that these are far more evident in the field than by visual examination of a published slope profile (cf. Morisawa, 1966).

As a result of this review of talus slope form certain general comments can be made;

(i) Other processes may be active on talus slopes apart from rockfall processes. These other processes have been shown to be effective in producing a characteristic response. (cf. King, 1966).

(ii) Whilst the characteristic slope angle for talus was found to be $35^\circ$ there is no basis for the generalisation put forward by such workers as Carson (1969) that talus slopes stand at $35^\circ$.

(iii) The limiting slope angle for talus slopes is considerably higher than $35^\circ$ i.e. $40^\circ$.

(iv) The talus profile is concave upward in general which gives rise to a considerable range of segment angles within the slope.

Finally, it may be noted that on some occasions where basal processes are active in eroding the base of the slope a convexity may result at the foot of the slope, (e.g. King, 1956). In instances where the top of the slope is under an extremely steep rockface talus slopes often show a slight upward convexity (Ryder, 1968) near the top of the slope.
2.2.5 Effects of Particle Characteristics on Talus Slope Form; Many workers have reported that large boulders are present at the base whilst smaller ones are found at the top of the slope. These workers include early geomorphologists and geologists such as Thoulet (1887) who believed that size was an important variable in the determination of slope angle. Behre (1933) believed that size was not only important but that talus slope angle varied directly with particle size. Behre's conclusions were severely criticized by Bryan (1934). Van Burkalow (1945) concluded that "it is doubtful that variation in slope angle is caused by the contrast in size of fragment" (p. 699) and cited such factors as shape, height of fall, density of the aggregate and surface roughness as the important controls. Fair (1948) commenting on talus in Natal reported "the angle of slope is in direct proportion to particle size", (p. 72). Andrews (1961) in the Lake District of England found an inverse relationship between slope angle and size whilst Frankfort (1968) found no relationship between slope angle and size. It is of interest to note that Rapp (1960 a,b), Caine (1969), Stock (1968), Gardner (1970 a,b), Luckman (1971), and Bones (1973) all infer by virtue of the shape of the talus slope profiles presented in their works (i.e. concave upwards) and the size gradients they note downslope, that slope angle varies inversely with the size of the talus material. Thornes (1971) reported work from Iceland to which the same inference applies. Worobey (1972) reporting results from a talus cone in southwest British Columbia concluded that some positive correlation between size and angle was implied in his data.
Although Ryder (1968) and Van Burkalow (1945) think that there are no simple relations between slope angles and material properties, workers such as Piwowar (1903) who contended that more angular particles seemed to support steeper slopes than rounded and Koons (1955), who reported from Southwestern USA that basalt talus slopes were less steep because of the more rounded nature of the blocks, conclude that particle shape is important. This is also noted by King (1966). Frankfurt (1968) found that "slope stability" tended to increase with particle angularity. Thornes (1971) in a rare attempt to examine other material characteristics and their possible effects, found no systematic variation in slope angle and the sorting, slope and orientation of particles (which Davison (1888) had contended to be an important factor). Caine (1967) found "little inter-relation, between the talus variables (shape, size and fabric)... and that the arrangement of the blocks in talus is (no) more than fortuitous" (p. 501).

In retrospect there has been a definite pre-occupation with the role of size of talus particles and not, as one would expect, in relation to slope angle per se, but with respect to position on slope. Material-response relationships in talus systems, appear to be contradictory and imperfectly understood.

2.3 Internal Structure

The slope evolution models of Lehmann (1933), Bakker and LeHeux (1946, 1947, 1950, 1952) and Scheidegger (1970) amongst others assume that talus slope materials at depth are similar to those found on the surface, i.e. loosely packed rock
fragments without a subsidiary matrix. Other workers, such as Wallace (1968) and Worobey (1972), have calculated volumes of talus cones on the assumption that the material is homogeneous throughout. Further, many definitions of talus slopes infer that a talus slope is a pile of rock rubble largely composed of rock fragments. A non-homogeneous structure would affect the calculated volumes of talus, not only compromising some of the theories of the mode of talus development, but also the rates of talus deposition calculated from field data.

Field observations by this writer and other workers give an impression that talus slopes in general appear to be heterogeneous in structure. The material beneath the surface is not rock rubble throughout its depth but a structure similar to that as illustrated in Figure 2.7. This observation is not only limited to low altitude mountain valleys but is also noted in sub-alpine or even alpine talus slopes.

The top layer (A), or mobile layer, is usually loose angular talus fragments which give a talus slope its typical external appearance. Layer (B) is an intermediate zone where pockets of fine material form a patchy matrix. The larger fragments still maintain inter-fragment contact. A third layer (C), is a basal layer where the fine grained matrix is predominant and encloses the larger talus fragments completely so that inter-fragment contact is minimal.

Previous workers have noted elements of this stratification. It may be pointed out that the intermediate layer does not always occur, or at least if it does occur it may be
Figure 2.7  Schematic illustration of talus slope structure
extremely thin. Von Moos (1953), in reporting materials encountered in a gallery driven into a talus slope in the Swiss Alps, noted an increase in the sand fraction toward the rock boundary and the lack of a fine matrix near the surface. Ritchie (1963) presents photographs showing the finer matrix of the intermediate and basal layer beneath the mobile layer which had been stripped off in the course of highway construction in Washington State, whilst Ball (1966) and Hutchinson (1967 b) show photographs of similar materials beneath the mobile and intermediate zones in Wales and Ireland. Breth (1967) describes what is apparently a landslide in the basal layer of a talus slope in the Austrian Tyrol whilst Branthoover (1972) encountered similar stratification to that in Figure 2.7 during an investigation of talus slopes near Lewiston, Pa. Morisawa (1966) in Colorado and Bailey (1971) in Wyoming note crude layering parallel to the surface of talus slopes whilst Gerber and Scheidegger (1974) mention the fact that loose talus material "forms only a relatively thin cover" (p. 26) on talus slopes in Austria. Examples of my own observations from the field area near Princeton, B.C. and the Ross Dam Area, Washington State, are given in Figures 2.7 and 2.9 respectively.

It is not intended to consider the origin of this stratification in detail, although the origin of the matrix in particular and the basal layer generally would aid in an assessment of their stability characteristics. The following alternatives appear to present themselves:

(a) A glacial origin: in which till from the final
Figure 2.8  Talus slope structure; location - Similkameen field area (N.B. Transition from open, loose mobile layer to basal layer, to left of Figure, exhibiting the finer matrix)
Figure 2.9 Talus slope structure; location Ross Dam area, Washington State (N.B. Mobile layer; basal layer evident just above road)
glaciation in all the areas mentioned above has mantled the bedrock slope and which has been mantled in turn by post glacial talus accumulation. If this is the case in British Columbia, for example, post glacial talus accumulation has been surprisingly little. The appearance and the density of the basal layer, however, would tend to support this hypothesis.

(b) **A weathering origin:** in which the material in the basal layer and in scattered pockets in the intermediate layers are the results of weathering and material breakdown of older talus accumulations. The lack of distinct boundaries in the talus and also the fact that the matrix gets more persistent with depth, i.e. a gradation change, would tend to support the idea of a weathering profile origin for the layering or zonation.

(c) **The sieving effect:** an origin proposed by Gerber and Scheidegger (1974) whereby the finer material such as fragments and dust filters through the talus to collect at the bottom, i.e. in the basal layer. The grain size distribution in vertical section would support this hypothesis but the volume and source of dust and small fragments required to form the widespread matrix is difficult to visualise.

Examples exist of glacial deposits such as glacio-lacustrine silts being found beneath the lower portions of the slopes (e.g. Kicking Horse Canyon, B.C.). Fluvial sand and gravel has also been found in the toe portions of talus (e.g. Worobey, 1972, Breth, 1967). Wahrhaftig (1958) also notes that till is sometimes found beneath talus in the Alaska Ranges and
Lewis (1969) notes a similar situation in the East Kootenays of British Columbia.

It is sufficient to note that although the stratification may be due to one or more of the processes noted above its presence seems to be common. It is, therefore, considered vital to acknowledge the existence of the stratification in a treatment of material-process links, talus slope stability, slope development and attendant transformation processes.

2.4 Transformation Processes on Talus Slopes

2.4.1 Transformation Agents: A variety of transformations can be operative on talus slopes. Rapp (1960 b) lists some of the more important ones which are reproduced with modification as follows:

(a) **Individual particle movement** reflecting thermal changes, creep, or movement caused by the impact of falling rock.

(b) **Talus slides** which are described as failures in the talus material itself.

(c) **Snow avalanches**, the effect of which has been noted by White (1967) and Luckman (1972).

(d) **Alpine mudflows** which may emanate from the gullies that feed many talus slopes (specifically talus cones), Rapp 1960 b, Behre, 1933, Fryxell and Horburg, 1943).

(e) **Overland flow**, (Howarth and Bones, 1972; Dingwall, 1972).
The relative importance of these various processes will vary necessarily with the environment in which the talus slope has developed. The main concern in this work will be talus slides and shear processes within the slope itself.

2.4.2 Shear Processes in the Talus System: A distinction will be made in this review discussion between failure in the mobile layer and failure in the basal layer although in Section 2.4.1 they are both referred to as talus slides. It is thought that the intermediate layer does not have a distinctive failure mode since it shares certain properties with both the mobile and the basal layers;

(a) Failures in the Mobile Layer:

Two scales of failure can be distinguished in the mobile layer, (i) the movement of individual particles and the occurrence of talus slides involving rock fragments in the mobile layer. The differentiation, however, may reflect the scale of observation and measurement rather than intrinsic differences in the scale of the process.

(i) Movement of individual particles:

Measurement of the movement of individual particles on talus slopes has been carried out by many workers. Results have been presented with very little accompanying rationale for the movements observed. Barnett (1966) found that movement was extremely erratic and concluded that it did
not vary in a systematic way. Stock (1968), on talus slopes on Baffin Island found similar behavior. Worobey (1972) working in the Similkameen Valley of British Columbia found no systematic behavior in the movement of particles, but noted that coarse debris moved more than fine debris. Rapp (1960.a) found that the movement of individual particles was irregular both in space and time. Gardner (1969) has concluded that the movement measured in the Alberta Rockies was "very erratic". He states that the erratic movement of small groups of particles or individual ones suggests that the forces producing the movement are isolated in certain parts of the slope. He did find, however, that the rate of movement of the particles was greater toward the top of talus slopes than toward the base, an observation which has considerable significance in the light of discussions in succeeding chapters.

As Gardner (1969) is right to point out, the forces producing movement may include such diverse processes as rockfall, snow avalanches or failures in the mobile layer.
(as described by Rapp, 1960 b). To this should be added thermal effects, settling, seismic forces or movements in the basal layer.

In fact, there is little reason to expect that measurements of the movement of individual particles should show a systematic variation since their movement appears to be related to many processes which may involve an aggregate of particles of which the measured particles are only a part. Studies of their movement would appear to remain inconclusive if other factors such as the incidence of talus slides or basal layer processes are not considered.

(ii) Talus Slides
A larger scale of failure than the above has been noted on talus slopes and is termed talus slide by Rapp (1960 b) and debris slide by Gerber and Scheidegger (1974). They occur as a movement of a mass of material on the surface of the slope and form a lobe or tongue-shaped deposit which, according to Gerber and Scheidegger, are observed "everywhere on talus slopes" (p. 34).
In his investigation of talus slopes in Spitzbergen, Rapp noted directly 12 such debris slides which occurred in "unstable talus". They occurred largely in the upper portions of the slope and came to rest not very far below their point of origin. This observation is also of importance in the light of subsequent discussion. Large boulders were invariably found near the front and the sides of the slide mass. Most slides were narrow in width, shallow in depth but varied in length. Rapp describes them as sliding down "in slow motion in which larger stones slid on top", (p. 61) and noted that they were similar in principle to tongue-like slides which often occur in gravel pits and mounds of tipped ore.

Worobey (1972) attributed the very marked striping of talus slopes in his field area to the operation of talus slides.

In Allen's opinion (Allen (1970 a)) such debris sliding, or as he terms it "avalanching", is the dominant process shaping many screes". (p. 348). Morisawa (1966) also
deems talus slides to be "the most important mechanism for shifting large amounts of material on talus slopes" (p. 113) at high altitudes in Colorado.

It will be noted in succeeding chapters that the process of talus sliding may be linked both to properties of material deposited on talus slopes and to the form of the slopes themselves.

(b) Failure in the Basal Layer

Direct observations of failures in the basal layer of a talus slope do not exist as such but movements in talus slopes referred to by Rapp (1963), Terzaghi and Peck (1967), Bjerrum and Jorstad (1968), and Branthoover (1972) are most certainly not in the mobile layer as defined earlier in this chapter. The presence of water played a large part in these failures and it is probable that the basal layer was involved since it is the only part of the slope where pore pressures could be expected to develop. Rapp (1963) documents the slides at Ulvådal following extremely heavy rains. Terzaghi and Peck (1967) note that such slides often occur during periods of snow melt when large quantities of free water are available, whilst Bjerrum and Jorstad (1968)
comment on the failure of a talus slope at Modalen, Norway, which was caused by a very large boulder falling onto the talus surface the impact of which caused liquefaction of the apparently saturated basal layer. The material in the Modalen slide was described as "stones and boulders with the pores between these fragments being filled with fine material" (p. 6). As Hutchinson (1967 b) notes, gradation curves of material that is very probably from the basal layer do not obviate the possibility of such material being prone to liquefaction especially under dynamic loading conditions such as seismic forces or the impact of a falling rock.

A notable example of a slide in the basal layer is given by Breth (1967). Although he terms the stratum in which the failure took place "moraine", the stratigraphic position of the material beneath the mobile layer and its properties as described by Breth make it very probable that the slide, caused by reservoir filling in the Kauner Valley, Austria, was a failure in the basal layer. A further example has been described recently by Azimi and Desvarreux (1974) in the French Alps.

Note must also be made of an "artificial" basal layer being effective in causing water promoted
failure in a zone above the actual basal layer. In areas of permafrost, the permafrost table could provide an impermeable layer sufficient to cause some displacement in the mobile layer (cf. Bones, 1972 and Chandler, 1973).

Movements caused by instability of the basal layer are of a very large scale compared to other forms of instability and very often go beyond the boundary of the talus slope in question and deposit material in areas of the valley floor, e.g. the Modalen Slide. Lack of direct observation, however, hinders a more detailed discussion of failure in the basal layer.
CHAPTER THREE

DISCUSSION OF FIELD PROCEDURES

3.1 Field Investigations

3.1.1 Initial Field Criteria; to meet the objectives outlined in Chapter 1 these were:

(a) that the talus slopes to be investigated should be dominated by rock fall processes,

(b) that the material forming the talus slopes should be of a constant lithology both within the free face above each slope and between individual slopes.

(c) that the talus slopes should be accessible andlogistically viable.

3.1.2 Description of Initial Field Areas; Talus slopes which appeared to satisfy the above criteria were studied in the Coast Mountains near Pemberton and Garibaldi, and in the Skagit Ranges at Lindeman Lake. All slopes were developed on granite or granodiorite. The slopes were at elevations where snowfall was thought to be low enough that snow avalanches would not assume dominance as a slope process. The locations of slopes selected are shown in Figure 3.1.

Six slopes were chosen in the Pemberton area because several colleagues were also involved in geomorphic investigation in the area (see Slaymaker, 1972; Gilbert, 1972, 1973; Ponton, 1972) and access was therefore facilitated. Two slopes in the Cheakamus Valley, south of Garibaldi, and one slope at Lindeman
Figure 3.1 Location of slopes studied in South West British Columbia
Lake were also selected. Brief descriptions of the slopes studied are as follows:

(a) **Sheet taluses:**

(i) **Lillooet Lake No. 2:** a sheet talus on the east shore of Lillooet Lake which terminated about 35 m. above water level. No observable processes were active at its toe. The slope was quite active in that the noise of falling rock was a constant companion in the field.

(ii) **Poole Creek:** two very short talus slopes developed at the foot of a rockface above Poole Creek Flats, 3.2 km. south of Birken. No fresh debris was observed on these slopes and in many places soil and organic matter filled the interfragmental voids.

(iii) **Spetch:** active talus slopes developed at Spetch on the north side of the Birkenhead River, 8 km. north of Mount Currie. Partly vegetated but active talus accumulation taking place. At Spetch No. 2 a recent rockslide had deposited fresh debris on the slope.

(iv) **Cheakamus Valley:** two active talus slopes developed just north of Brohm Lake on the east side of Highway 99.
(b) **Cone taluses:**

(i) **Lillooet Lake No. 1**; a cone talus on the west side of Lillooet Lake the foot of which terminated in the water of Lillooet Lake. Evidence of snow avalanche activity was found.

(ii) **Lindeman Lake**; a cone talus (see Figure 2.1), developed at the outlet of a couloir on the east side of Lindeman Lake. Evidence of snow avalanche activity observed but rockfall very intense.

3.1.3 **Additional Field Criteria:** After examining the results of the initial investigation it was thought that the quality of the results reflected amongst other factors the physiographic variation in the environments in which the talus slopes were located, e.g. variation in slope aspect, elevation, gross geometry, etc. The following field requirements were imposed on the selection of a further field area:

(a) that talus cones be excluded,

(b) that talus slope orientation be held as constant as possible,

(c) that talus slopes with little or no vegetation be selected,

(d) that talus slopes with comparable gross geometries be preferred,

(e) that the talus slopes be located in a low snowfall area to obviate the possibility of snow avalanche
<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Activity</th>
<th>Basal Conditions</th>
<th>Base Elevation</th>
<th>Height</th>
<th>Mean Angle</th>
<th>No. of Segments</th>
<th>Length of Segments</th>
<th>No. of Particle^Measured</th>
<th>Remarks</th>
<th>Orientation</th>
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</thead>
<tbody>
<tr>
<td>Lillooet Lake #2(5)</td>
<td>East side of Lillooet Lake</td>
<td>Active</td>
<td>Road along shore</td>
<td>245 m. asl</td>
<td>156 m.</td>
<td>35.5°</td>
<td>8</td>
<td>30 m.</td>
<td>80</td>
<td>Sheet talus</td>
<td>180°</td>
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<td>Poole Creek #1(3)</td>
<td>S.E. side of Poole Crk. Flats</td>
<td>Non-Active</td>
<td>Poole Crk. Flats</td>
<td>305 m. asl</td>
<td>24 m.</td>
<td>29.6°</td>
<td>7</td>
<td>6 m.</td>
<td>70</td>
<td>&quot;</td>
<td>290°</td>
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<td>Poole Creek #2(3)</td>
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<td>Non-Active</td>
<td>&quot;</td>
<td>305 m. asl</td>
<td>12 m.</td>
<td>27.2°</td>
<td>4</td>
<td>6 m.</td>
<td>40</td>
<td>&quot;</td>
<td>340°</td>
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<td>Spetch #1(2)</td>
<td>N.W. side of Birkenhead River</td>
<td>Active</td>
<td>Birkenhead River</td>
<td>335 m. asl</td>
<td>125 m.</td>
<td>32.1°</td>
<td>5</td>
<td>4x30 m.</td>
<td>50</td>
<td>&quot;</td>
<td>120°</td>
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<td>Spetch #2(2)</td>
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<td>335 m. asl</td>
<td>85 m.</td>
<td>28.9°</td>
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<td>6x152 m.</td>
<td>70</td>
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<td>East side of Highway 99</td>
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<td>Road along bench</td>
<td>365 m. asl</td>
<td>94 m.</td>
<td>34.0°</td>
<td>5</td>
<td>30 m.</td>
<td>50</td>
<td>&quot;</td>
<td>250°</td>
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<td>Cheakamus #2(1)</td>
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<td>&quot;</td>
<td>365 m. asl</td>
<td>60 m.</td>
<td>34.1°</td>
<td>7</td>
<td>15 m.</td>
<td>70</td>
<td>&quot;</td>
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<td>Lillooet Lake #1(4)</td>
<td>West side of Lillooet Lake</td>
<td>Active</td>
<td>Lake</td>
<td>215 m. asl</td>
<td>200 m.</td>
<td>32.6°</td>
<td>9</td>
<td>5x30 m.</td>
<td>90</td>
<td>Cone talus</td>
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<td>Lindeman Lake (6)</td>
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<td>Active</td>
<td>Morainic ridge</td>
<td>855 m. asl</td>
<td>127 m.</td>
<td>34.8°</td>
<td>6</td>
<td>5x30 m.</td>
<td>60</td>
<td>&quot;</td>
<td>270°</td>
</tr>
</tbody>
</table>

Notes: 1: In some cases the survey was not taken to the top of the slope because of the fact that the loose talus terminated some way down from the top and because of the danger from falling rock near the top of some slopes.
2: Estimated from 1:50,000 topographic maps to the nearest 5 metres.
3: Total number of particles measured on each slope.
<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Activity</th>
<th>Basal Conditions</th>
<th>Base Elevation</th>
<th>Height</th>
<th>Mean Angle</th>
<th>No. of Segments</th>
<th>Length of Segments</th>
<th>No. of Particles Measured</th>
<th>Remarks</th>
<th>Orientation</th>
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<td>North Side of Similkameen Valley 13 m. east of Princeton</td>
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<td>No Process Active</td>
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<td>33.5°</td>
<td>4</td>
<td>4x30 m.</td>
<td>199</td>
<td>Sheet talus</td>
<td>185°</td>
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<td>&quot;</td>
<td>610 m. asl</td>
<td>67.2 m.</td>
<td>34.2°</td>
<td>4</td>
<td>4x30 m.</td>
<td>198</td>
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<td>175°</td>
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<td>34.6°</td>
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<td>199</td>
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<td>&quot;</td>
<td>&quot;</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>610 m. asl</td>
<td>62.4 m.</td>
<td>32.7°</td>
<td>4</td>
<td>4x30 m.</td>
<td>199</td>
<td>&quot;</td>
<td>167°</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>610 m. asl</td>
<td>62.4 m.</td>
<td>32.5°</td>
<td>4</td>
<td>4x30 m.</td>
<td>200</td>
<td>&quot;</td>
<td>179°</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>610 m. asl</td>
<td>65.4 m.</td>
<td>33.6°</td>
<td>4</td>
<td>4x30 m.</td>
<td>200</td>
<td>&quot;</td>
<td>190°</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>610 m. asl</td>
<td>112.2 m.</td>
<td>32.5°</td>
<td>7</td>
<td>7x30 m.</td>
<td>350</td>
<td>&quot;</td>
<td>184°</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>610 m. asl</td>
<td>*</td>
<td>27.3°</td>
<td>2</td>
<td>2x30 m.</td>
<td>99</td>
<td>&quot;</td>
<td>180°</td>
</tr>
<tr>
<td>Similkameen Pilot</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>610 m. asl</td>
<td>49.2 m.</td>
<td>33.0°</td>
<td>3</td>
<td>3x30 m.</td>
<td>149</td>
<td>&quot;</td>
<td>185°</td>
</tr>
</tbody>
</table>

Notes: 1: In some cases the survey was not taken to the top of the slope because of the fact that the loose talus terminated some way down from the top and because of the danger from falling rock near the top of some slopes.
2: Estimated from 1:50,000 topographic maps to the nearest 5 metres.
3: Total number of particles measured on each slope.
* Only lower portions investigated.
activity which had been observed on some initial slopes studied.

3.1.4 Description of a Further Field Area; A location which appeared to fit the above requirements for further testing of the hypotheses was found on the north side of the Similkameen Valley between Hayes Creek and Stevens Creek approximately 12.8 km. east of Princeton and 20 km. west of Hedley. Talus slopes have developed on the margins of the Thompson Plateau (Holland, 1964) where the Similkameen Valley has been incised into it (Figure 3.2). The slopes met the more stringent field requirements as follows:

(a) Talus slope development in the area has been of the continuous sheet variety and forms an apron along the Plateau edge. Talus cones were not in evidence (Figure 3.3).

(b) The talus slopes have developed with a southerly aspect and this results in an almost constant slope orientation (see details in Table II).

(c) Vegetation did exist on the slopes but was sparse and scattered.

(d) The slopes were of comparable geometries in that slope heights were not widely variable.

(e) The slopes in the Similkameen appear to be part of a similar process environment. There is no great elevational difference along this section of valley and further, no basal processes are active. Thus it could be assumed that the slopes are subject
Figure 3.2 Location map of Similkameen talus slopes. Shaded area indicates sheet talus developed on north side of Similkameen Valley, 13 km. east of Princeton. Slopes studied are marked A and B.
Figure 3.3 Photograph taken towards northwest, of sheet talus on north side of Similkameen Valley, 13 km. east of Princeton. Profiles were measured on slopes A, B, C. Note fresh debris on slopes.
to the same variety of processes. Rockfall processes were seen to be very active as was evidenced by the large number of fresh boulders present on the slopes.

(f) The area has low snowfall compared to locations in the Coast Mountains. Mean annual snowfall at Princeton and Hedley is 156 cm. and 75 cm. respectively. This compares with 282 cm. at Pemberton Meadows and 422 cm. at Garibaldi. Although there may be no direct correlation between mean annual snowfall and avalanche occurrence the talus slopes developed in the Similkameen probably have less likelihood of being subject to avalanche processes than the slopes investigated in the Coast Mountains.

3.2 Sampling Plan Formulation

The existence of differentiation in talus slopes with respect to material, form and process would suggest in turn that some stratification be essential in a plan to sample material properties and form elements. A preference exists, therefore, for a sampling unit, or stratum, smaller than the whole slope profile in order that intra-slope variations may be detected in the field investigations.

3.2.1 Alternative Sampling Plans; In reviewing sampling plans used in previous work it has become clear that the delimitation of a stratum is not always an objective exercise.
The following methods have been used to delimit sampling units or segment boundaries:

(a) on the arbitrary basis of where breaks in slopes have occurred (e.g. Bones, 1973),

(b) on the basis of "environmental conditions" (e.g. Thornes, 1971):

(c) a proportional sampling approach where segments on different slopes will be of different lengths but will be of the same proportionate length in relation to the total length of the slope (e.g. Evans, 1969; Garner, 1971),

(d) a systematic sampling method where on talus slopes of approximately similar dimensions a fixed length of segment is adopted.

Unfortunately, all four of these approaches have drawbacks. Breaks of slope are not always clearly defined on talus slopes and are difficult to detect in the field. Breaks of slope may also occur at too small a scale to be distinguishable. "Environmental conditions" are not always definable on talus slopes particularly when they are not in a state of high activity. The proportional sampling plan, although it has certain intuitive benefits has disadvantages in that sample size must be changed from slope to slope as the length of the segment and therefore the target population changes. It also requires a pre-survey to define the length of the proportional segments. On too long a segment important variations in slope angle and material properties may be missed. Finally, a systematic approach may suffer from the fact that the length of segment selected may not detect
meaningful changes in materials and slope angles.

A systematic approach to delimiting the boundaries of the strata may be the most beneficial, however. In terms of detecting changes in slope angle and material properties obviously the length of segment has to be tailored to the magnitude of change in these properties within a given set of slopes. This can be carried out in a pilot study which would examine the variability of these variables at differing spatial scales. The systematic approach therefore appears to be sympathetic to the variability of the parameters under examination in a way that the other three methods are not. It also lends itself to a rigid system of within-stratum sampling more readily than the others.

The field investigations were based on two different sampling plans. A rather loose proportional sampling plan was adopted initially. The method involved the estimation of the slope length by eye and the adoption of one quarter of this length as the segment length. However, it is very difficult to estimate slope length from the base of the slope and frequently the interval selected was much too short. Further, the proportional slope segments were so variable in length, because of the variable lengths of the talus slopes studied, (see Table II), that the fixed sample size adopted did not reflect the variability of the target population being sampled.

Based on this experience and the argument presented above a systematic sampling plan was subsequently adopted.

3.2.2 Delimiting Sample Points within the Strata or Segments; A transect sampling approach was adopted. Selection of sample
points by random numbers and by a fixed-interval method was considered. The random method, although desirable in many ways, has the following disadvantages; (a) time consumed in locating positions determined by the random numbers, (b) time wasted by several concurrent random numbers falling on a large boulder in blocky talus.

The fixed-interval method on the other hand, whilst not completely solving the difficulty of several points falling on the same boulder does ensure that the particles are measured over the whole length of the segment and is far more efficient.

3.2.3 Delimiting the Length of Segment; In defining the length of segment for the investigation three factors were considered:

(a) The length of the segment should be representative of a slope of deposition and thus should be mechanically meaningful.

(b) The length of segment should be long enough to include an ample number of boulders from which to draw a sample.

(c) The length of the segment should be such that given conditions (a) and (b) the variability of the particle properties should be kept at a minimum. This factor assumes importance because internal stratification in material properties exists and the variability of the sample would increase with an increase in segment length.
3.3 **Pilot Investigations for the Similkameen Talus**

A pilot investigation was carried out in the Similkameen to obtain data which would lead to a selection of optimum segment length and optimum sample size. A slope was selected that appeared to be of a constant angle over a large part of its length.

3.3.1 **Determination of Segment Boundaries**; The top and bottom of the talus were defined as the points where a matrix of vegetal debris and/or fine material obscured the interparticle contacts of the talus material. Using field techniques outlined in the following section a tape and Abney level were used to measure slope angles on differing lengths of segments. (Figure 3.4).

Four distance scales were used to measure slope angle. The general slope angle over 90 m. was 33°; three segments of 30 m. were all 33°; at the 15 m. scale the range was 32.0° to 34.5°; at the 7.5 m. scale the range increased to 4.0° (31.0° - 35.0°). Thus as the segment length decreased the range of measured segment angles increased (cf. inclination diagram in Figure 3.4).

The parameters of axial measurements and fabric data were measured on particles at 3 spatial scales. (The 7.5 m. scale was omitted because of insufficient boulders.) A sample size of 50 was used for the three scales, a figure which determined the sample point location in the systematic sampling plan discussed above. The variability was calculated using the coefficient of variation.(see Carson, 1967) for size and shape
Figure 3.4 Inclination diagram and slope profile for pilot slope on Similkameen talus
### TABLE III. VARIABILITY OF MATERIAL PROPERTIES

**AT THE THREE SPATIAL SCALES STUDIED**

<table>
<thead>
<tr>
<th>Length of Segment</th>
<th>Mean Size(^1)</th>
<th>Size c.v.(^2)</th>
<th>Mean Shape(^3)</th>
<th>Shape c.v.</th>
<th>Rotational Vector Strength(^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>-7.7130</td>
<td>81.8%</td>
<td>0.6310</td>
<td>15.0</td>
<td>70.0%</td>
</tr>
<tr>
<td>30</td>
<td>-7.7643</td>
<td>80.6%</td>
<td>0.6336</td>
<td>15.2</td>
<td>69.6%</td>
</tr>
<tr>
<td>90</td>
<td>-7.8180</td>
<td>82.6%</td>
<td>0.6330</td>
<td>13.3</td>
<td>73.0%</td>
</tr>
</tbody>
</table>

\(^1\)Mean of long axes measurements in Phi-units

\(^2\)c.v. = sample coefficient of variation (c.v. = S/\(\bar{X}\), where S is the sample standard deviation and \(\bar{X}\) is the sample mean)

\(^3\)Mean of Krumbein's Intercept Sphericity

\(^4\)Value of significant rotational vector strength
and for fabric, a comparison of significant vector strengths was considered a suitable index for variability. The results are seen in Table III and from them the following conclusions are made:

(a) The variability of size at the three linear scales is high whilst the magnitude of that variability is similar at the three scales,
(b) The variability in shape, by contrast, is low and the magnitude of the variability is similar at the three scales,
(c) The length of the segment does not affect the value of the vector strength which at all scales is high and significant at the .01 level,
(d) The length of the segment does not produce substantial differences in the variability of material properties under examination.

At this juncture it is perhaps instructive to compare the variability encountered in this study with the variability reported by other workers in the size parameters they obtained by using differing sampling plans and in differing process environments. The data are summarized in Table IV. Size data are highly variable except where point data has been collected (Caine, 1967; Thornes, 1971). Lateral sampling produces great variation in the case of Melton (1965) and Gardner (1970), whilst Griffiths (1959) using the same method finds a low coefficient of variability. Because of the different measures of size used in the investigations and the variety of process-environments they
<table>
<thead>
<tr>
<th>Author</th>
<th>Lithology</th>
<th>Measure of Size</th>
<th>Sample Size in each Strata</th>
<th>Sampling Method</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melton (1965)</td>
<td>Granitic</td>
<td>&quot;B&quot; Axis (ins.)</td>
<td>?</td>
<td>Steepest part of slope, randomly select point sample horizontally from this point</td>
<td>29.41%-90.24% (Mean 57.75%)</td>
</tr>
<tr>
<td>Gardner (1971)</td>
<td>Sandstones, Shales, Carbonates</td>
<td>&quot;Mean Nominal Diameter&quot;</td>
<td>25</td>
<td>Point (Proportion sampling), one at centre line, 12 either side, laterally, selected by random numbers</td>
<td>50.0%-120.0% (Mean 80.00%)</td>
</tr>
<tr>
<td>Caine (1967)</td>
<td>Dolerites</td>
<td>&quot;Phi-Measure&quot;</td>
<td>At a point (no word on sampling plan)</td>
<td></td>
<td>50.0%-9.3% (Mean 7.06%)</td>
</tr>
<tr>
<td>Thornes (1971)</td>
<td>Basalts</td>
<td>Mean Log &quot;A&quot;</td>
<td>50-120</td>
<td>Point-metre grid</td>
<td>5.42%-14.70% (Mean 13.2%)</td>
</tr>
<tr>
<td>Griffiths (1959)</td>
<td>Quartzite</td>
<td>Phi-&quot;B&quot; Axis</td>
<td>64-88</td>
<td>Laterally along line</td>
<td>7.64%-0.97% (Mean 8.80%)</td>
</tr>
<tr>
<td>Frankfort (1968)</td>
<td>Basalt</td>
<td>&quot;B&quot; Axis</td>
<td>25</td>
<td>20' grid</td>
<td>42.78%-101.53% (Mean 65.7%)</td>
</tr>
<tr>
<td>Carson (1967)</td>
<td>-</td>
<td>D&lt;sub&gt;50&lt;/sub&gt; by Volume</td>
<td>Within slope</td>
<td></td>
<td>34.00%</td>
</tr>
<tr>
<td>Evans (Pilot)</td>
<td>Granitic</td>
<td>Phi-&quot;A&quot; Axis</td>
<td>Line downslope</td>
<td></td>
<td>15 metre seg. 81.80% 30 metre seg. 80.63% Total slope 82.60%</td>
</tr>
<tr>
<td>Author</td>
<td>Lithology</td>
<td>Measure of Shape</td>
<td>Sample Size in each Strata</td>
<td>Sampling Method</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------</td>
<td>------------------</td>
<td>----------------------------</td>
<td>----------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Thornes (1971)</td>
<td>Basalts</td>
<td>Krum-bein's $\psi$</td>
<td>50-120</td>
<td>Point-metre grid</td>
<td>5.03%-18.45% (Mean 16.45%)</td>
</tr>
<tr>
<td>Evans (Pilot)</td>
<td>Granitic</td>
<td>Krum-bein's $\psi$</td>
<td>50</td>
<td>Line downslope</td>
<td>15 metre seg. 14.99%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 metre seg. 15.15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total slope 13.27%</td>
</tr>
</tbody>
</table>
encompass, very little interpretation can be placed on the data, but it does provide comparative information on the variability of the "size variable", however defined, used by other workers. In comparing the data in Table IV it is seen that one of the highest coefficients of variation in the size variable has been obtained for the Similkameen data, despite the use of the Phi-transformation which would reduce the value of the coefficient. This may be due to the fact that the sampling plan, i.e. downslope sampling, used in this study is its first reported use in talus slope investigations. A more variable sample is to be expected from such a plan since a much larger section of the slope is sampled compared to point, grid or transverse sampling plans. It is noted that sphericity measurements by Thornes (1971) exhibit a similar variation to the ones from the Similkameen Pilot Study.

In selecting the segment length it was felt that (a) at the 7.5 m. level the slope angle measurement reflected to a large extent the differences in fragment elevation above the general slope of deposition, particularly at the base of the slope in the vicinity of very large boulders. Further, at this scale there were often very few boulders from which to sample, and (b) at the 15.0 m. scale again the lack of availability of sufficient boulders near the base of the slope presented problems. Three factors had a bearing on the decision to adopt the 30 m. segment length;

(a) it appeared to represent a "general depositional surface" within the talus slope which was
considered important in view of intra-slope processes,
(b) it provided an ample accessible population,
(c) it provided a scale of measurement compatible with the geometries of most of the slopes in the area.

3.3.2 Determination of Sample Size within Segments; In determining the optimum sample size for particle measurement within a segment it is pointed out that three basic sets of data are obtained directly and indirectly, i.e. size, shape and fabric, each set having different degrees of variability, a fact which is already apparent in Table III. For a sampling program, therefore, the optimum sample size determined by the most variable parameter will be the operative sample size for each segment. In the case under consideration the most variable parameter is size, more specifically, the length of the long axis in Phi-units. Calculations for an operative sample size were carried out with respect to this parameter.

Indications from existing literature (e.g. Bones, 1973) were that an initial sample size of 50 particles would be sufficient to estimate size. With respect to the 30 m. segments the results of the pilot study indicate that there is a 95% probability that the sample mean differs from the population mean by an amount less than 2.3 cm., and a 99% probability that the sample mean differs from the population mean by an amount less than 9.7 cm. Given the accuracy of the measurement technique outlined in the following section, these errors are well within
those limits tolerable. A sample size of 50 particles within each segment was, therefore, considered statistically acceptable.

In summary, the sampling plan adopted as a result of the Pilot Investigation was as follows:

(a) 30 metre segments as the basic sampling unit within the slope as a whole,

(b) 50 particles were measured at 60 cm. intervals along a transect upslope within the basic sampling unit or slope segment.

3.4 Field Measurement Techniques

3.4.1 Measurement of Profile Properties; Profile measurement was carried out using Abney level and tape. At certain locations profile measurement was carried out using a rangefinder fitted with a clinometer. However, this method was not very reliable and checks on measured distances with a tape found the error in the operation of the rangefinder to be in the order of 10%.

In the Similkameen the sampling plan described above was adopted. The selection of a profile for measurement was based on ease of access and the absence of vegetation. Following the selection of a suitable profile its measurement was undertaken in the following manner:

(a) The base of the profile was marked with a stake (base stake) and flagging tape,

(b) A bearing was taken with a Brunton compass to the top of the profile,

(c) The field assistant proceeded to the 15 m. mark
where a slope angle reading was taken with a hand-held Abney level sighting onto a marked pole.

(d) The field assistant continued onto the 30 m. mark where the slope angle was again taken from the base stake. The field assistant flagged the 30 m. location.

(e) Particle characteristics were measured at 60 cm. intervals and at the 15 m. mark another slope angle was taken.

(f) This operation continued upslope with periodic readings being taken to control the direction of the movement up the slope. Once the top of the talus (as defined above), was reached a check was made on the quality of the profile's rectilinearity by aligning the flagged 30 m. stations with the base stake.

This method of slope angle measurement was adopted because the 15.0 m. check on the slope angles would point out any great discrepancy in the 30.0 m. reading. It would not be unreasonable to suggest that slope angles measured in this way were accurate to within ±1°.

A problem encountered on slopes where the boulders were very large was the coincidence of a measuring station with the top of a boulder that was much higher than the general slope surface. If measured according to the criteria outlined above the resultant reading would give an exaggerated value and in such cases the field assistant was directed to either side of the
massive boulder or just behind it.

3.4.2 Measurement of Boulder Properties: Within one 30 m. segment the tape was secured at both ends. Axial and fabric measurements were carried out on the boulder that was directly underneath the 60 cm. mark and in this way approximately 50 boulders were measured for every segment. In some cases the rock fragment was of such a size that it extended beyond the sampling point over two or three sampling stations. In these cases only one particle measurement was taken at that location.

The three principal axes of the rock fragments were measured by hand tape following procedures well established in sedimentary petrology (e.g. Krumbein, 1941). The "a" axis is the longest axis of the fragment, the "b" axis is the intermediate axis in the same plane as "a" but perpendicular to it, and "c" is the shortest axis perpendicular to the plane of "a" and "b". Obviously problems arise with equidimensional boulders and several efforts to discern the principal axes of these boulders may be necessary. Access to the large majority of fragments was comparatively easy since they tend to lie on the surface with all faces exposed.

A Suunto compass/clinometer was used to measure the orientation of the long axis ("a") and its dip relative to the horizontal (Figure 3.5). Measurement of the orientation of the long axis was made relative to north. Equidimensional boulders presented problems for reasons recounted above. Dip was measured by aligning the base of the compass with the approximate plane of the long axis. The Suunto compass provides an accuracy in
Figure 3.5 Measurement of particle dip on Profile D, Similkameen talus. Clinometer on Suunto instrument faces camera. Base of clinometer is 5 cm.
both orientation and dip in the order of ±5° since the gradation on both the compass and the clinometer is in 5° intervals. Although the measurements obtained with this instrument appear coarse the instrument has distinct advantages with regard to ease of manipulation, ruggedness, and efficiency in use. In comparison with other fabric measurements on talus slopes, Caine (1967) does not specify the methods he used, whilst Thornes (1971) using a similar instrument on Icelandic talus claims that the possible error is not more than ±3°. Gardner (1971) does not discuss error problems in his report on talus particle orientation in the Moraine Lake area, Alberta.
CHAPTER FOUR

THE INTERPRETATION OF TALUS SLOPE ANGLES

An essential part of material-response investigations in talus slopes is an examination of the uses of such concepts as angle of repose, angle of rest and angle of internal friction in the interpretation of talus slope form, specifically talus slope profiles. Relationships between these terms will be investigated and longstanding misconceptions concerning these relationships will be examined and hopefully corrected. Factors controlling the various parameters will be examined and the implications for the interpretation of talus slopes will be looked at.

A. THEORETICAL CONCEPTS AND TERMINOLOGY

4.1 Definitions of Angle of Rest, Angle of Repose and Peak Angle of Accumulation

Misconceptions have arisen from the use of "angle of rest" and "angle of repose" both in the geomorphological and the engineering literature. As Carrigy (1967) has pointed out, although the term "angle of rest" appears in many publications its use has been ambiguous (cf. Van Burkalow, 1945). The first source of confusion occurs where some workers have used the term to describe the angle of slope of an inclined plane at which a particle resting on it will begin to slide, whilst others have

\footnote{See Glossary of Terms}
used the term to express the angle at which a mass of loose granular material will stand when piled or dumped. It is apparently not realized that the differences between these angles are substantial since one describes particulate behavior whilst the other describes mass behavior and two different thresholds are therefore involved.

Usage of the angle of rest (or repose) in this work will be limited to that describing mass behavior but a second source of confusion is immediately encountered. Van Burkalow (1945), Sharpe (1960) and Carrigy (1967) have pointed out there are two "angles of repose" which are rarely distinguished; the steepest angle that can be achieved by the granular material when piled or dumped and a lower angle to which the material will slump when the steeper angle is exceeded and failure has taken place. These two angles can be readily appreciated by tipping a sugarbowl until the sugar contained therein moves and achieves, first the higher slope angle, then the lower one.

The two angles have been variously defined and interpreted. Bagnold (1941), The American Geological Institute (1957), The American Society for Testing Materials (1966), Metcalf (1966), Simons (undated ms.), Rahn (1969), to mention a few, refer to the higher angle as the "angle of repose". Carson and Kirkby (1972) on the other hand term the lower angle "the angle of repose" and the higher one "the angle of maximum slope". Both Van Burkalow (1945) and Carrigy (1967) refer to the higher angle as the "maximum angle of repose" whilst the lower angle has been defined as the "angle of rest after avalanching" (Carrigy (1967)), "the
angle of shear" (Bagnold, 1941), "the residual angle of shearing" (Allen, 1970 a,b,c) and the "minimum angle of repose" (Van Burkalo...1945).

Terzaghi (1943) defined the angle of repose as follows, "the material will slide... and not come to rest until the angle of inclination of the slope becomes equal to a certain angle which is called the angle of repose" (p. 4). The inference seems to exist (i.e. after sliding) that the angle of repose thus defined by Terzaghi is the lower angle of repose discussed above.

For the purposes of this work it is intended to adopt the following definitions and notations for the two different angles, which will be used in subsequent discussion:

(a) the peak angle of accumulation ($\alpha_c$); the steepest angle that a mass of granular material will stand at without shearing taking place,

(b) the angle of repose (or rest) ($\alpha_r$); the angle assumed by granular material after shearing has taken place following an exceedance of threshold conditions as defined by $\alpha_c$.

4.2 Factors Affecting the Peak Angle of Accumulation ($\alpha_c$)

Investigation of the factors affecting the peak angle of accumulation ($\alpha_c$) have largely been studied in the laboratory using model techniques and artificial conditions of accumulation. The emphasis has been on the effects of material on the values of $\alpha_c$ obtained, or material-response relationships.
Van Burkalow (1945) experimenting with a wide variety of materials found that $\alpha_C$ varied with material properties in the following manner:

(a) inversely with size of fragments in perfectly sorted materials but directly with those imperfectly sorted,

(b) inversely with density of fragments,

(c) directly with their angularity, roughness and degree of compaction,

(d) inversely with height of fall of materials onto accumulation surfaces.

Carrigy (1967) found that size and sorting had little or no effect, that $\alpha_C$ increased with increased particle angularity and surface roughness. He concluded that values of $\alpha_C$ are dependent mainly on shape.

Allen (1970 a,b,c) after looking at an ideal case of prolate spheroids both in theory and experiment, found that $\alpha_C$ increased with departure from the spherical form; increased with particle concentration (aggregate density); and decreased with parallelism of the long axes of particles with the direction of maximum slope of the deposits and surface. Allen found that the difference between $\alpha_C$ and $\alpha_r$, increased with aggregate density which he contended reflected the increase in the dilatant component of shear resistance of the materials considered.

Simons (undated ms.), in a comprehensive survey involving laboratory and field measurements, noted that $\alpha_C$ can be viewed as a function of size, shape, surface texture, mass density
and gradation. He concluded that the primary variables influencing \( \alpha \) seem to be shape, size and, probably, surface texture of the particles. Metcalf (1966) also found shape to be an important factor.

4.3 **Concepts of Shear Resistance and Angle of Internal Friction**

At this stage in the discussion some well known concepts of shear resistance are introduced since elements of shear resistance are presumably important in determining the behavior of slopes at the thresholds denoted by \( \alpha_c \) and \( \alpha_r \).

4.3.1 **Definitions of Components of Shear Resistance:** The shear resistance, or shear strength, of slope forming materials determines the behavior of that material under shear stresses. In its most basic form the shear resistance \( \tau \) of a material can be expressed by Coulomb's Law as follows:

\[
\tau = c + \sigma \tan \phi
\]  
(Eq. 4.1)

where \( c \) is the cohesion of the material, \( \phi \) is the angle of internal friction and \( \sigma \) is the normal pressure on the failure plane. Normally, however, interparticulate cohesion, which may exist in clays and silts, does not exist in granular materials and the law is simplified to;

\[
\tau = \sigma \tan \phi
\]  
(Eq. 4.2)

As will be seen below, however, granular material does not behave as a purely frictional material as implied in Equation 4.2. Further, at high normal pressures the failure envelope defined by Equation 4.2 departs from the linear form.
Workers such as Rowe (1963), Lee and Seed (1967) and Koerner (1970 a,b) have attempted to establish by experiment additional components in the shear resistance of granular materials beyond that of simple friction. The following components have been identified:

(a) strength due to interparticulate friction approximating to the angle of solid friction of one particle on another and which was the frictional component envisaged by Coulomb in Equation 4.2 denoted by $\phi_f$.

(b) strength due to dilatancy effects where energy has to be expended to create the volume increase necessary for one particle to pass over another in the shear process denoted by $\phi_d$.

(c) strength due to re-arranging effects (or crushing effects under high shear stresses) denoted by $\phi_a$.

The various components are illustrated in Figure 4.1 and $\phi$ can be expressed as follows;

$$\phi = \phi_f + \phi_d + \phi_a \quad \text{(Eq. 4.3)}$$

It should be noted that $\phi$, the angle of internal friction, corresponds to the peak angle of internal friction. During the shear process the dilatant component is "removed" and the value of the angle of internal friction falls to the so-called ultimate or residual value ($\phi_r$) (Lambe and Whitman, 1969). In the post shear state, therefore, the components in the residual shear resistance of a mass of granular material are as follows;

$$\phi_r = \phi_f + \phi_a \quad \text{(Eq. 4.4)}$$
Figure 4.1 Schematic illustration of the components of shear resistance in a granular material. (Adopted from Rowe, 1962)
In the residual condition the material is also in the critical state where the void ratio remains constant with further deformation (Lambe and Whitman, 1969, Bishop, 1971). It is to be noted that the magnitude of the dilatant component varies directly with the bulk density of the granular mass, since the denser the aggregate, the greater the expansion needed to shear it, and the greater the value of the angle of internal friction.

4.3.2 Factors Affecting the Angle of Internal Friction of Granular Materials: Most of the work on the measurement of shear resistance in granular materials, such as rockfill, has been done in connection with the design and construction of rockfill dams. Casagrande (1936) was one of the first workers in the field of soil mechanics to point out the effects of particle characteristics on the angle of internal friction of cohesionless materials.

Holtz and Gibbs (1956) and Vallerga et al. (1957) found the particle shape very important in accounting for variations in the angle of internal friction and found that it increased directly with angularity. Morris (1959) found similar relations with angularity and surface roughness of particles. Mackey (1964) found that shape affected the shear resistance of a granular mass in contrasting ways. He found more spherical particles could be compacted to a greater degree than angular ones thus increasing the value of $\phi$. Farouki and Winterkorn (1964) and Du Terte and Winterkorn (1966) found that $\phi$ varies directly with angularity and with dispersion on the Zingg shape diagram. Size was not considered important. Marsal (1967) and Fumagalli (1969) found
that shape is an important factor in accounting for strength variations at similar densities whilst Nichiprovich and Rasskazov (1967) found density an important control on shear resistance. Anagosti (1967) in a general report, stated that the shear strength of coarse cohesionless material likely depends on; mean and maximum grain size, gradation shape, mode of packing, strength of grains, normal strength, porosity, and effects of time (weathering, strain softening, etc.).

Al-Houssaini (1972), Mogami and Yoshikoshi (1971), Marachi et al. (1972), Pike (1973) and Bishop (1971) all believe shape to be very important. Indeed, Bishop goes so far as to say "particle shape which influences particle rolling plays an overriding part in the behavior of cohesionless soils" (p. 22). Leps (1970) in a review work concluded that $\phi$ varies inversely with normal stress and sphericity but directly with relative density and crushing strength of the constituent particles. Oda (1972) found that grain fabric affected mobilized strength and dilatancy relations.

In summary, therefore, the following factors are thought to control the value of the angle of internal friction ($\phi$) in cohesionless materials such as rockfill or talus;

(a) **Size:** The effect of size seems to be ambiguous. This fact may reflect the many different measures of size used in the investigations reviewed above. It may also reflect confusion over the role of the effective matrix and its relation to density and packing properties., (Figure 4.2).
(b) **Sorting (Gradation):** The effects of sorting also seem to be ambiguous. The majority of reports indicate an increase in the range of sizes existing in a given aggregate leads to an increase in $\phi$. This may be related to the higher densities that can be achieved with such a gradation or the increase in contact forces brought about by increased interparticle contact. Other reports indicate that an improvement in sorting (i.e. a decrease in gradation) leads to an increase in $\phi$ of an aggregate possibly reflecting the role of an effective matrix. (Figure 4.2).

(c) **Shape:** This variable is seen by most workers to be very important in determining the shear resistance of a granular mass. The angle of internal friction has invariably been observed to increase with angularity. Further, $\phi$ increases with variation in shape.

(d) **Surface Roughness:** Increased particle roughness seems to lead to an increased value of $\phi$.

(e) **Fabric:** Increased parallelism of the major particle axis with the direction of shear increases the value of $\phi$.

4.4 **Relationships between Peak Angle of Accumulation ($\alpha_c$), Angle of Repose ($\alpha_r$), Angle of Internal Friction ($\phi$) and Residual Angle of Internal Friction ($\phi_r$).**

The nature of the relationships among $\alpha_c$, $\phi$, $\alpha_r$ and
Case One: Well sorted cohesionless material. All particle contacts contribute to shear strength of material. Mean size of particles accurate indication of particles determining shear resistance.

Case Two: Poorly sorted cohesionless material. Large particles with a finer matrix. Contacts of larger fragments effective in controlling shear resistance. Matrix properties are subsidiary in their effect, and do not contribute to shear resistance. Mean size of particles not an accurate indication of particles determining shear resistance. May yield similar standard deviation of size measurements as Case Three.

Case Three: Poorly sorted cohesionless material. Large particles enclosed in a finer matrix. Contacts of larger particles do not contribute to shear strength of material which is controlled by matrix properties. Mean size of particles not an accurate indication of particles determining shear resistance.

Figure 4.2 Differing combinations of particle sizes illustrating the effective matrix problem (Modified after Marsal, 1965)
\( \phi \) assume critical importance in the understanding not only of shear processes on slopes consisting of granular materials but of the values of threshold slopes in such materials and the factors that control them.

4.4.1 Relationships between Peak Angle of Accumulation (\( \alpha_c \)) and Angle of Repose (\( \alpha_r \)): From the work of Allen (1970 a) and Carrigy (1967), and the data they present it is possible to obtain a statistical relationship between \( \alpha_c \) and \( \alpha_r \). Allen has illustrated the relationship thus;

\[
\alpha_c = \alpha_r + \Delta \alpha
\]  

(Eq. 4.5)

where \( \Delta \alpha \) is the dilatant component in \( \alpha_c \). If the data from Carrigy and Allen's work is plotted with \( \alpha_c \) as the ordinate and \( \alpha_r \) as the abcissa as in Figure 4.3 it appears that a relationship exists between the two variables. Contrary to Allen's curious contention that \( \alpha_c \) is invariant there appears to be wide range of values, i.e. between 25° and 40°.

Using the data from Carrigy (1967) a value of \( r^2 = 0.96 \) was obtained from the following equation;

\[
\alpha_c = -3.290 + 1.273 \alpha_r
\]  

(Eq. 4.6)

The importance of the dilatant component is seen at higher peak angles of accumulation.

Data from Butterfield and Andrawes (1972) have been added to Figure 4.3 due to the correspondence that is thought to exist between their "static and kinetic angles of friction", the values of \( \phi \) and \( \phi_r \), and \( \alpha_c \) and \( \alpha_r \). The suggestion is apparently confirmed by the location of their data points. Of additional
Equations for Lines:
LINE 1 (Carrigy's data only): $\alpha_c = -3.29 + 1.273 \alpha_r; r^2 = .962$
LINE 2 (Carrigy and Allen's data): $\alpha_c = 2.60 + 1.198 \alpha_r; r^2 = .786$
LINE 3 (All data on plot): $\alpha_c = 0.1320 + 1.290 \alpha_r; r^2 = .904$

Figure 4.3 Relationships between $\alpha_c$ and $\alpha_r$
interest is the location of the two peaks noted in studies by Melton (1965) and Rahn (1969).

4.4.2 **Relationship between Peak Angle of Accumulation ($\alpha_c$) and the Angle of Internal Friction ($\phi$);** A slope of cohesionless material standing at the peak angle of accumulation, as defined in Section 4.1, is standing at the steepest angle that can be formed without shearing taking place. This being the case, the slope is in a state of limiting equilibrium and $\alpha_c$ denotes the threshold slope for that material.

In a state of limiting equilibrium the shear forces acting on a slope are precisely balanced by available shear resistance, i.e. the ratio of strength to stress is unity. Following convention in soil mechanics this is expressed in a Factor of Safety ($F$) as follows:

$$F = \frac{\text{shear resistance}}{\text{shear stresses}} = \frac{\tan \phi}{\tan \alpha_c} = 1.00 \quad \text{(Eq. 4.7)}$$

According to this argument, therefore, the peak angle of accumulation is equal to the angle of internal friction, for those particular conditions of aggregate packing and density.

Workers have found contradictory relationships between $\alpha_c$ and the angle of internal friction. Metcalf (1966) using somewhat unconventional testing procedures, found that $\alpha_c$ was correlative with the angle of internal friction of the material in its densest state. Chandler (1973) found that $\alpha_c$ was equal to the angle of internal friction of the material in a loose state at constant volume ($\phi_{cv}$). It is thought by this writer, however, that both extremes are not generally applicable.
Rather, the relationship between $\phi$ and $\alpha_c$ is specifically related to the characteristics of the mass being examined (cf. Nandakumaran et al., 1974).

### 4.4.3 Relationships between Peak Angle of Accumulation ($\alpha_c$), Angle of Internal Friction ($\phi$), Angle of Repose ($\alpha_r$) and Residual Angle of Internal Friction ($\phi_r$)

When failure takes place at the threshold defined by Equation 4.7, the dilatant component of shear resistance is expended and the material comes to rest in its loosest state where shear strength is at a minimum or residual value (Equation 4.4). The angle assumed by this material corresponds to the angle of repose of the material ($\alpha_r$), i.e. the post shear angle. Thus $\alpha_r$ would appear to correspond with $\phi_r$ for those particular conditions of aggregate packing and density which are effective in controlling the dilatant component in $\alpha_c$ (or $\phi$).

The two angles $\alpha_c$ and $\alpha_r$ can therefore evidently be treated in much the same way as the peak and residual angle of internal friction respectively (cf. Bishop, 1971).

There is an exception to the above argument and this occurs where the depositional density of the granular material under consideration is very low and approaches the critical density. In this case $\alpha_c$ would be equal to $\alpha_r$ and $\phi$ would equal $\phi_r(\phi_{cv})$.

### B. TALUS SLOPE FORM

#### 4.5 Interpretation of Talus Slope Angles

#### 4.5.1 Previous Interpretations; Insufficient distinction has
been made in the literature between $\alpha_c$ and $\phi_r$, and between $\phi$ and $\phi_r$.

Many workers have asserted that the angle of a talus slope is equal to the "angle of repose" for the talus material. As has been pointed out elsewhere (e.g. Andrews, 1961) these investigations ignore the fact that talus slopes are not generally rectilinear in profile and that slope angles within the slope show considerable variation generally resulting in a concave upward profile. At the same time they rarely define which "angle of repose" (cf. Section 4.1) is being referred to. Workers who are specific as to which angle of repose they refer present contradictory impressions. For example, Gilully et al. (1959) observe that "talus slopes... (stand at) the angle of repose because it is the steepest slope on which the material will stand without rolling downward..." (p. 178). In this case the angle of repose is the peak angle of accumulation ($\alpha_c$). Carson and Kirkby (1972) on the other hand state that "talus and scree... stand at the angle of repose of the coarse material" (p. 333). The usage of the term "angle of repose" in their work indicates that in this case the angle of repose is $\phi_r$.

Workers have equated the angle of repose with the talus slope angle and have gone on to equate the angle of repose with the angle of internal friction. It is in this regard that problems created by not distinguishing between $\phi$ and $\phi_r$ (and incidentally $\alpha_c$ and $\phi_r$) become extremely important. Ward (1945), for example, inferred in his early work on slope stability, that the limiting slope for talus ($\alpha_c$) was determined by the angle of
internal friction of the material in a loose state. Carson (1969) on the other hand noted that the limiting slope ($\alpha_c$) was determined by $\phi$. In a later paper, Carson and Petley (1970) note that the angle of repose of bouldery rock fragments is equal to $\alpha_r$ but in the same paper indicate that slope angle, vis-à-vis the angle of repose is equal to $\phi$. The lack of distinction between residual shear strength values and values of shear strength above that threshold also detract from studies by Scheidegger (1970) and Carson (1971).

Problems have also arisen in attempts to interpret the value of the characteristic slope angle for talus, i.e. $35^\circ$. Obviously this interpretation is linked to the discussion above and frequently the three relationships are discussed together, viz. talus slopes stand at the angle of repose - the angle of repose is equal to the angle of internal friction - the slopes stand at $35^\circ$. Many workers have erroneously thought that $35^\circ$ represents the limiting slope for talus (e.g. Ward, 1945; Carson, 1969, 1971) which is clearly not the case. (Figure 2.5). The limiting slope is obviously higher than $35^\circ$ although Carson and Petley (1970) do suggest that $35^\circ$ affords an estimate of the ultimate angle of shear resistance ($\phi_r$) for bouldery rock fragments.

4.5.2 The Supply Induced Transformation Hypothesis; To resolve the obvious contradictions listed above it remains to determine the following which are central to the interpretation of talus slope angles;

(a) limiting slopes for talus materials corresponding to the peak angle of accumulation ($\alpha_c$),
(b) the reason for the fact that $35^\circ$ seems to be the characteristic slope angle for talus.

The limiting slope for talus materials is, as defined above, the peak angle of accumulation ($\alpha_c$) and in order to ascertain this value, a review of the values of $\alpha_c$ for various types of talus-like materials was carried out. The results are presented in Table V. Values for $\alpha_c$ were found to be between 40.8 and 42.0 on the basis of published information which corresponds quite well to $\phi$ for low confining pressures and low densities from the work of Leps (1970) and Nichiprovitch and Rass-kazov (1967). It also corresponds to the values of maximum talus angles published in the literature ($40^\circ$ - by Miner, 1934; Rapp, 1960 b; Howarth and Bones, 1972).

If it is assumed that the value for $\alpha_c$ for talus materials taken from Table V is $41^\circ$ it is possible to estimate the value of the angle of rest ($\alpha_r$), vis-à-vis the residual angle of internal friction ($\phi_r$) by the use of Equation 4.6. In Equation 4.6 with $\alpha_c = 41.0^\circ$, $\alpha_r$ is calculated to be $35.0^\circ$. This value is coincident with the characteristic talus slope angle noted above.

$35^\circ$ would, therefore, appear to represent the "characteristic" angle of repose ($\alpha_r$) for talus materials and would also correspond to the angle of internal friction of the same material in a loose state. It further corresponds with the residual angle of internal friction of coarse single mineral soils as reported by Kenney (1967).

The fact that $35^\circ$ is interpreted to be the general
angle of rest ($\alpha_r$) by its relationship to $\alpha_c$ through Equation 4.6 for talus materials has led this writer to formulate the **supply induced transformation hypothesis** which relates process material and form for the mobile layer in rockfall talus slopes. Under the terms of this hypothesis, supply of debris takes place from the rockwall above with deposition occurring near the top of the slope until the peak angle of accumulation is exceeded. Failure takes place and by downward movement the debris is deposited at a slope equivalent to $\alpha_r$ or $\phi_r$. The fact that a relationship was found to exist between $\alpha_c$ and $\alpha_r$ for talus materials is an interesting prima facie confirmation of the hypothesis (Figure 4.3).

The hypothesis has further supportive evidence. In Chapter 2 it was noted that observable movement on talus slopes both in terms of individual particles and the incidence of talus slides is concentrated in the upper portions of the slope, i.e. near the rockwall. This together with what is known about depositional patterns on talus slopes (Gardner, 1970; Caine, 1969) would indicate that the supply induced transformation hypothesis may have a basis in observed reality as well as in the relationships between the threshold slopes noted above.

Field evidence given by Rapp (1960 b) from Spitzbergen is of further note. Slopes which he considered as being dominated by talus slides stand at angles of 34.9°, 34.8°, and 34.2° respectively, angles which compare favorably with the value of $\alpha_r$ or $\phi_r$ obtained above (i.e. the angle assumed after failure has taken place).
Work by Allen (1972) reports the results of investigations into the intensity of deposition from debris slides in model experiments. He concluded that "the high intensities of deposition... correspond to degrees of packing... that are very nearly the loosest possible for natural materials" (p. 105). Applying this to talus slides it tends to suggest the idea that the material deposited by talus slides exists in a critical state, i.e. \( \phi_{CV} = \phi_r = \alpha_r \).

The characteristic slope angle and the limiting slopes for talus in general appear to correspond to \( \alpha_r \) and \( \alpha_c \) respectively. These values are related through Equation 4.6 which appears to be a suitable transformation model for rockfall talus and relates the three factors noted in Section 1.3. As far as this writer is aware the transformation process described above has not been satisfactorily explained before, and the observed distribution of talus slope angles seems to afford a confirmation of this process.

C. THE CASE OF THE SIMILKAMEEN TALUS

Under the terms of the supply induced transformation hypothesis, the characteristic slope angle exhibited by rockfall talus slopes can be assumed to be equal to the angle of repose \( (\alpha_r) \) for that material, thus affording an interpretation of rockfall talus angles.

The hypothesis was investigated with reference to the Similkameen talus slopes which, for reasons outlined in Chapter 3, were considered well suited for the purpose.
4.6 Evidence for the Operation of Supply Induced Transformation Processes

A necessary precursor to a discussion of slope angles is an examination of the evidence for the operation of supply induced transformation processes, i.e. talus slides. Since direct observations of talus slides were not carried out, inferences must be made based upon the interpretation of response elements such as slide debris, slope profiles and fabric patterns.

4.6.1 Aerial Photography and Slide Debris; Fresh deposits of debris can be seen on aerial photographs (Figure 4.4) on the talus slopes on the north side of the Similkameen Valley between Stevens Creek and Hayes Creek. These deposits give the characteristic striped pattern to the talus slopes similar to that observed by Worobey (1972) on talus slopes further east in the Similkameen Valley near Keremeos. Alternative origins for the deposits could be rock slide debris, the result of snow avalanches, debris avalanches or flows, as well as being products of talus slides. In the field the debris does not appear to be a result of rockslide deposition since the deposit is too narrow. Whilst the possibility of the deposits being the result of snow avalanche does exist this must be considered very unlikely in view of the light snowfall in the area.

4.6.2 Slope Irregularities; A distinct feature observed on the Similkameen slopes was the existence of "fronts" or localised steep sections of the slope profile. These tended to give the profile in some cases a stepped appearance evident in a series of mini-concavities. As can be seen in Appendix I and
Figure 4.4  Aerial photograph of slopes studied on north side of Similkameen Valley. Note lobate forms (arrowed) on sheet talus and lighter tone of fresh deposits. (From B.C. Air Photograph BC 4436-213; Scale 1 cm. = 150 m.)
and Figure 4.5 these fronts may vary in height from 1.5 m. to 3 m. The origin of these fronts may be explained by one of the following alternatives:

(i) it could represent the scar of a movement in the material downslope from it, as indicated in Figure 4.6,

(ii) it could represent the "front" of a mass of debris slide material that has slid on the slope as indicated in Figure 4.6.

Andrews (1961) noted a similar phenomenon in the scree slopes he studied in the Lake District. He suggested that they were the result of slope failure "producing localised movements of the scree material and resulting in a steep frontal slope and a more gentle back slope" (p. 223). He further noted that the failure plane was parallel to the slope and the steep foreslope was formed by the moving scree overriding the natural downslope. Gerber and Scheidegger (1974) also noted the existence of these "fronts" in the investigations in the Austrian Alps. They felt that the irregularities in the profile are the result of small rotational slips occurring in the mobile layer which "explains the observed overlapping tongue shaped structure of the deposits on scree slopes" (p. 34). From the evidence of shear phenomena in cohesionless materials, however, it is very unlikely that the failure would be rotational with a curved failure surface but more likely to be planar as Andrews (1961) speculates.

The location of these fronts, between a third and two thirds downslope (see for example Similkameen E or Spetch No. 1
Figure 4.5  Photograph of front on Similkameen talus
(A) The scar of a movement of material downslope from it

(B) Front of a mass of debris that has moved downslope from above

Figure 4.6 Alternative origins of the fronts observed on talus slope profiles
in Appendix I) tends to indicate that origin (ii) above would be more applicable particularly since, as noted in Chapter 2, movement of talus materials has generally been reported to have been concentrated in the upper portions of the slope.

4.6.3 Fabric Pattern; Note was made in Chapter 3 that very high vector strengths were obtained in the Similkameen talus that were also highly significant. This was in contrast to other workers who had been unsuccessful in obtaining such results (e.g. Caine, 1967, 1969; Thornes, 1971; Gardner, 1972) although earlier observations by Davison (1888), Hamelin (1958), Rapp (1960 a) and Andrews (1961) had reported, qualitatively, the existence of preferred orientations on talus slopes.

The lack of "success" encountered by the authors mentioned above is partly explained by their sampling design (two used grid sampling at a point and one measured orientations on a line transverse to the profile), and partly in the fact that they were dealing with talus slopes which may have been affected by such processes as intense snow avalanching, slush avalanching and mudflows that would tend to produce different fabric patterns.

Fabric measurements were taken as described in Section 3.4.2, and were analysed using the technique outlined by Mark (1971) as explained in Section 5.2. As noted in that section the vector strength and fabric data used here were the result of Rotational Vector Analysis.

The objective of a fabric investigation was to investigate whether the Similkameen slopes were dominated by supply induced transformation processes and exhibited fabrics similar
to those produced by analagous shear processes in dry slopes of sand. Work pioneered by Rees has led to the discovery that distinct fabric patterns result from shear processes in dry cohesionless materials, i.e. when $\phi_c$ is exceeded. The characteristics of these fabric patterns are as follows:

(a) a parallelism of particle long axes in the direction of shear, i.e. downslope,

(b) the long axes of the particles slope less steeply than the surface of deposition, or slope, and have a mean angle of imbrication relative to the plane of deposition, of $25^\circ$.

The production of these distinctive fabrics is apparently due to the effects of repeated intergranular collisions which occur when a concentrated dispersion of particles is sheared (Rees, 1966, 1968; Hamilton, Owens and Rees, 1968).

The results of the fabric analysis are found in Figure 4.7 and Figure 4.8. In Figure 4.7 the orientations of the mean vectors are given in relation to slope aspect. All vectors are significant at the .05 level and at the corrected level of significance given by Mark (1973). In order to ascertain whether or not a parallelism exists in the fabric pattern the Parallelism Index of Cailleux, as used by Caine (1969), was employed. The Index is the percentage of observations lying within $45^\circ$ of the slope direction. A value of 91.2% was obtained for the talus as a whole (i.e. the mean of the Index values for each segment). This value of the Parallelism Index is considered evidence to support the suggestion that parallelism exists in the Similkameen talus.
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(b) the long axes of the particles slope less steeply than the surface of deposition, or slope, and have a mean angle of imbrication relative to the plane of deposition, of 25°.

The production of these distinctive fabrics is apparently due to the effects of repeated intergranular collisions which occur when a concentrated dispersion of particles is sheared (Rees, 1966, 1968; Hamilton, Owens and Rees, 1968).

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Figure 4.7  Orientation of mean vectors on Similkameen talus in relation to slope orientation (given at base of slope line)
Figure 4.8 Dip of mean vector (in relation to horizontal), Similkameen talus
In Figure 4.8 the dip of the mean vectors is given in relation to the horizontal. In general the dip of the mean vectors is less steep than the slope surface. Negative angles of dip (Figure 4.8) occur at six locations and can be considered anomalous since they may represent boundaries of talus slides. If these negative angles of dip are excluded the mean angle of dip for vectors calculated for the Similkameen talus is $25.6^\circ$. If this value is subtracted from the mean slope angle of $33^\circ$, the mean angle of imbrication as used by Rees (1968) is $7.4^\circ$.

Although the existence of a parallelism in the fabric would indicate a correspondence with a sheared fabric as derived by Rees and his co-workers the mean imbrication angle is not as high as predicted. The high degree of parallelism would tend to indicate, however, a response to a mass downslope movement and the possibility exists that higher imbrication angles that may have been created by this movement have been decreased by the settling or creep of particles within the sheared mass. The fabric evidence, therefore, for the occurrence of shear processes on the Similkameen talus, whilst not totally conclusive, is suggestive of their operation.

4.7 Slope Angles on the Similkameen Talus

4.7.1 Characteristic and Limiting Slope Angles; In view of the evidence presented above for the operation of shear processes on the Similkameen talus it would be in order to interpret the characteristic slope angle in terms of the angle of repose ($\alpha_r$) of the material making up the slopes. A histogram was constructed
(Figure 4.9) and a mode is noted at 33° (modal strength = 28.8%). This value being the characteristic slope angle for the Similkameen slopes is therefore the angle of rest for the material making up those slopes under the terms of the supply induced transformation hypothesis.

To obtain the limiting angle ($\alpha_c$) for the talus in the Similkameen use is made of Equation 4.6 because of the evidence presented in Section 4.6. By inserting the value for $\alpha_r$ obtained above a peak angle of accumulation of 38.7° is obtained. In assessing the quality of this estimate it is significant that no slope angle over 37° was measured in the field.

An additional method of assessing the value of the $\alpha_c$ obtained is available in the work of Allen (1970 b) who developed relationships between the axial dimension, a and b, and values of $\alpha_c$ for various peaking arrangements of cohesionless prolate spheroids. Packing Case VI given by Allen (1970 b) was thought to apply approximately to the packing arrangements observed in the talus examined (Figure 4.10). For this case Allen (1970 b) gives $\alpha_c$ as being calculated thus;

$$\tan \alpha_c = \frac{1.73 \sqrt{3}a}{2\sqrt{2}b}$$

(Eq. 4.8)

When mean values of a and b for particles in each segment studied on the Similkameen talus were inserted in Equation 4.8, the values obtained did not appear realistic and were much lower than expected. It was concluded that this equation did not provide a good estimate for $\alpha_c$. This perhaps arose because in Allen's theoretical treatment the surface of the spheroids was
Figure 4.9 Histogram of segment angles on Similkameen talus
Figure 4.10 Allen's packing case IV for prolate spheroids thought to apply to talus particle packings
### TABLE V. LIST OF PUBLISHED PEAK ANGLES OF ACCUMULATION (θ_c) FOR TALUS AND SIMILAR MATERIALS

<table>
<thead>
<tr>
<th>Source</th>
<th>Material</th>
<th>θ_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simons (Undated ms.)</td>
<td>Crushed Limestone</td>
<td>42.0°</td>
</tr>
<tr>
<td></td>
<td>Talus (Stockpile)</td>
<td>42.0°</td>
</tr>
<tr>
<td></td>
<td>Talus (Stockpile)</td>
<td>41.0°</td>
</tr>
<tr>
<td></td>
<td>Crushed Granite</td>
<td>40.8°</td>
</tr>
<tr>
<td>Blight (1969)</td>
<td>Quartzite Rockfill</td>
<td>41.0°</td>
</tr>
</tbody>
</table>
considered to be smooth which would in effect neglect the frictional strength gained by irregular particle surfaces.

Based on Allen’s (1970 b) investigations which suggested a relationship between axial dimensions and the value of \( \alpha_c \), further examination of the relationship was carried out. It was found that if mean values of \( a \) and \( b \) for the material in each slope was inserted in Equation 4.9 below and the values obtained were plotted against the mean slope angle (taken to equal, on the evidence presented above, to be equal to a mean \( \alpha_c \)), the resultant data points are very close to the line derived from Carrigy’s (1967) data (Figure 4.11).

\[
\tan \alpha_c = 0.54 (a/b) \tag{Eq. 4.9}
\]

When \( \alpha_c \) was calculated using Equation 4.9 for each setment, the modal value obtained was 39.0° (Figure 4.12) which is in good agreement with the value of \( \alpha_c \) obtained using Equation 4.6.

The above would therefore indicate that Equation 4.9 provides an empirical approximation for \( \alpha_c \) in the Similkameen talus.

4.7.2 Comments on the Similkameen Talus

(a) It would appear from the above discussion that slope angles on the Similkameen talus can be interpreted in terms of the supply induced transformation hypothesis. As such this work has verified a general process-material-response model.

(b) Since slide processes similar to those envisioned in the supply induced transformation hypothesis were shown to be
Data from Similkameen slopes ($\alpha_c$ calculated from axial data using Equation 4.6; $\alpha_r$ mean slope angle for each slope)

- Mean $\alpha_c$ and mean $\alpha_r$ for Similkameen talus

Characteristic and limiting slope angles for talus slopes taken from review in Chapter 2

Figure 4.11 Similkameen talus slope data in relation to $\alpha_c/\alpha_r$ plot
Figure 4.12 Histogram of calculated values for $\alpha_c$ for Similkameen talus
active on the basis of the interpretation of response elements, the distinct mode shown in the distribution ($33^\circ$) was taken to be the angle of rest for the Similkameen material.

(c) The limiting slope was obtained using Equation 4.6 and Equation 4.9. This enables a statement to be made whereby an upper and lower bound can be set for the operation of talus slide processes on the Similkameen talus slopes. These correspond to the limiting slope of $39^\circ$ and a lower bound (the characteristic slope) of $33^\circ$ although there may be some overlap in these figures with transformation events (cf. Hutchinson, 1967a). These slope angles then define the thresholds for talus slide processes on the Similkameen talus.

(d) The talus slopes studied in the Similkameen appear to be in equilibrium with the residual strength of the materials composing them. It is interesting to compare this conclusion with those of Skempton (1964) and others who suggest that natural slopes tend toward an equilibrium determined by the residual strength.

(e) For the purposes of completing the review process begun in Chapter 2 mean slope angles and segment angles from investigations in the Coast Mountains and the Similkameen are added to Figures 2.5 and 2.6 and are presented in Figures 4.13 and 4.14 respectively.
Figure 4.13  Histogram of published mean talus slope angles incorporating data from this investigation
Figure 4.14 Histogram of published talus slope segment angles incorporating data from this investigation
CHAPTER FIVE

RELATIONSHIP BETWEEN MATERIAL PROPERTIES AND TALUS SEGMENT ANGLE

As outlined in Chapter 1, a second objective of this work is to seek statistical relationships between talus slope angle and the characteristics of the material that forms the slope (cf. Caine, 1967; Thornes, 1971). Relationships are thought to exist between talus slope angle and material properties such as size, shape and fabric, which were shown to be important controls on the shear resistance of cohesionless materials similar to talus in Chapter 4.

These relationships will be explored here with reference to the 30 m. segments from the Similkameen slopes.

5.1 Methods of Analysis

The objectives of the exploratory analysis are twofold;

(a) To establish whether material properties and segment angle co-vary in a systematic manner,

(b) To establish the group of variables that are most important in accounting for variations in segment angle.

It may be noted that attention is focussed on the segment scales since they form the elements of slope profiles as discussed in Chapter 3. An appropriate tool to explore the above objectives would appear to be multivariate statistics, specifically multiple correlation and stepwise multiple regression.
analysis. Many workers have used these methods to initially "sort out" geomorphic problems; indeed Carson (1969) has remarked on "the efficiency of the statistical approach in detecting the relevance of alternative models" in slope process-response studies.

The uses of these methods and the interpretation of the results are restricted by certain assumptions. In correlation analysis, for example, the variables are assumed to be random samples from a bivariate normal population. In regression analysis three basic assumptions are involved;

(a) The sample data must be from a population for which the variance is homogeneous, i.e. the variance of the Y values about the regression surface must be the same at all points,

(b) The deviation of the Y values from the regression surface must be independent of each other and normally distributed,

(c) Independent variables must be measured with no error.

As the objectives of this part of the analysis are exploratory it is thought significant information can be obtained from the use of these methods even though a formal test of these restrictive assumptions will not be carried out. This view is shared for similar situations by King (1969) and Snedecor and Cochran (1967). However, because the variables used are means, and in some cases the mean of means, there is some justification, for example, for assuming that the same variables form normal
### TABLE VI. VARIABLES USED IN MULTIVARIATE ANALYSIS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>SEGANG</td>
<td>Segment Angle of 30 m. segments</td>
</tr>
<tr>
<td><strong>Size Related Variables</strong></td>
<td></td>
</tr>
<tr>
<td>PHISIZ</td>
<td>Mean, in Phi-units of 'a' axes measurements</td>
</tr>
<tr>
<td>PHIDEV</td>
<td>Standard deviation, in Phi-units, of PHISIZ</td>
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<tr>
<td><strong>Shape Related Variables</strong></td>
<td></td>
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<tr>
<td>SPHERI</td>
<td>Mean value of Krumbein's Intercept Sphericity ( \Psi ), [ \Psi = \frac{bc^{1/3}}{a^2} ]</td>
</tr>
<tr>
<td>PZINGG</td>
<td>Mean value of Zingg's Flatness Ratio, ( P ), [ P = \frac{c}{b} ]</td>
</tr>
<tr>
<td>PZVARI</td>
<td>Variance in PZINGG</td>
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<tr>
<td>QZINGG</td>
<td>Mean value of Zingg's Elongation Ratio, ( Q ), [ Q = \frac{b}{a} ]</td>
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<tr>
<td>QZVARI</td>
<td>Variance in QZINGG</td>
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<tr>
<td>FZINGG</td>
<td>Mean value of Zingg's Shape Factor, ( F ), [ F = \frac{ca}{b^2} ]</td>
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<tr>
<td>FZVARI</td>
<td>Variance in FZINGG</td>
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<tr>
<td><strong>Fabric Related Variables</strong></td>
<td></td>
</tr>
<tr>
<td>SLODEV</td>
<td>Deviation of Mean Vector from Orientation of Slope</td>
</tr>
<tr>
<td>DIPVEC</td>
<td>Dip of Mean Vector</td>
</tr>
<tr>
<td>VECSTR</td>
<td>Vector Strength</td>
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</table>
populations. With the above limitations in mind the methods outlined above will hopefully supply convenient approximations of the relationships between segment angle and material properties.

5.2 Variables Used in Analysis

In Chapter 4, three basic groups of material variables were established as being important in controlling shear resistance, peak angle of accumulation and angle of repose of granular materials, they being, size, shape and fabric. To obtain parameters related to these groups for each segment certain indices established mainly in the field of sedimentary petrology were derived and are listed in Table VI. Size and shape variables were obtained using a variant of COBLAN, a computer programme developed by Michael Church and a ZINGG programme developed by Michael Patterson who were both at the time colleagues in the Department of Geography at the University of British Columbia.

Fabric variables were obtained by using a 3-Dimensional Rotational Vector Analysis Programme developed by David Mark, also of the Geography Department, which subsequently appeared in the literature (Mark, 1971). The significance tests used in the fabric analysis were those in the 1971 programme which were later corrected by Mark (Mark, 1973). This writer has reviewed the paper by Mark (1973) and has consulted the author as to the status of the results from his original programme. Mark notes in his 1973 paper that the results of the "earlier programme
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</table>

*Value of r significant at the 99% level
+Value of r significant at the 95% level

1 - Segment Angle
2 - Size in Phi-units
3 - Standard Deviation in Size: a measure of sorting
4 - Sphericity (Krumbein's Intercept Sphericity)
5 - Zingg's Flatness Ratio (P)
6 - Variance of P
7 - Zingg's Elongation Ratio (Q)
8 - Variance of Q
9 - Zingg's Shape Factor (F)
10 - Variance of F
11 - Deviation of mean vector from slope orientation
12 - Dip of Mean Vector
13 - Vector Strength
agree fairly well with those produced by the eigenvalue method" (p. 1372). It has not proved possible to re-analyse the fabric data using the eigenvalue method proposed by Mark (1973), but vector strengths have been checked for significance using procedures in Mark's paper. All the vector strengths obtained in the Similkameen talus remain significant at the 99% level.

The rotation interval used in the analysis was 20° based on Mark's (Mark, 1971) statement that "the 20° rotation interval should be accurate enough for most purposes, especially in view of the fact that field measurements so often 'considered to have an accuracy of ±5°' (Andrews and King, 1968, p. 437)" (p. 2663) (cf. Section 3.4.2 above).

5.3 Correlation Analysis

The results of the correlation analysis are contained in Table VII and a diagrammatic representation of the correlation structure is given in Figure 5.1. The following conclusions can be suggested following an inspection of the results:

(a) Statistically significant correlations do exist. At the 99% level of significance, negative correlations are found between slope angle and size, whilst positive correlations are found between segment angle and sorting, the values of the coefficient being .51 and .55 respectively (Figure 5.2).

(b) At the 95% level of significance negative correlations exist between slope angle and sphericity.
PHISIZ - Size in Phi units
PHIDEV - Standard deviation of size (sorting)
SPHERI - Krumbein's sphericity
PZINGG - Zingg's flatness ratio (P)
QZINGG - Zingg's elongation ratio (Q)
QZVARI - Variance in Q
FZINGG - Zingg's shape factor (F)
FZVARI - Variance in F

Value of R significant at 99% level
Value of R significant at 95% level

Figure 5.1 Correlation structure for Similkameen talus
Figure 5.2 Scattergrams of size and sorting variables plotted against segment angle
and between slope angle and Zingg's Flatness Ratio, \((r = -0.34\) and \(-0.32\) respectively).

(c) Many significant correlations exist within the size and shape groups and between them, (e.g. size and sphericity, \(r = -0.58\)).

(d) There is a lack of significant correlation between fabric variables and segment angle or between fabric variables and other material variables.

(e) A correlation does exist between vector strength and the mean vector dip.

5.4 Stepwise Multiple Regression Analysis

Stepwise multiple regression was used in the next stage of the analysis to discover whether a combination of material variables could account for a variation in slope angle. This involves a differentiation between a dependent variable and a set of independent variables. Whilst acknowledging the comments of Melton (1958) on the subject of cause and effect in slope studies and realising that both slope angle and material properties are in a sense "effects", it can be argued that due to the demonstrated relationships between material characteristics and shear resistance and between shear resistance and slope form, that slope form can be considered a dependent variable.

Using stepwise multiple regression, only 37.11% of the variation in segment angle could be accounted for by variation in material characteristics at the 95% level of significance.
The equation obtained is as follows:

\[
\text{Segment Angle} = 45.7122 + 2.6542 \text{ (Sorting)} + 181.005 \text{ (Variance in Elongation Ratio)} \quad \text{(Eq. 5.9)}
\]

Sorting contributed 30.10% and the variance in the elongation ratio 7.01%.

As a result of the multiple regression analysis we are led to the following conclusions:

(a) A large amount, i.e. 62.89% of the variance in segment angle is not explained by the variation in material characteristics as measured in this investigation,

(b) Sorting is the single variable that contributes a major amount to the explained variance in segment angle, i.e. just over 80.00%,

(c) Shape factors contribute very little to the explained variance,

(d) Fabric factors do not contribute to the explained variance.

5.5 Comments on the Multivariate Analysis

5.5.1 The Relationship between Material Properties and Segment Angle; With reference to the second objective of this work, statistically significant correlations were obtained that indicated segment angle varied inversely with size and directly with sorting. The link between shape (sphericity) and segment angle is less marked. Significant correlations at the
95% level suggested that segment angle varies inversely with sphericity. No significant correlations were found to indicate that slope angle varied directly with variation in shapes. A similar absence of significant correlations existed with segment angle and fabric variables contrary to expectation. Increased sorting was related to an increase in slope angle and this variable was also the dominant material variable in accounting for 80.00% of the explained variance in segment angle which was contrary to expectation. This could possibly be explained by the greater interlocking between fragments (Mackey, 1964) of a more uniform sized aggregate and the lack of a matrix of smaller fragments. The low level of "explanation", however, is surprising. It was thought that because of the demonstrated relationships between material properties and various threshold properties in Chapter 4 that a larger percentage of explained variance in segment angle would be attributable to material properties.

5.5.2 **Suitability of Indices;** The possibility exists that the indices used to approximate the parameters such as shape, which were thought to be important controls on segment angle, were not appropriate for that purpose. The measures of shape used here, essentially based on axial measurements, have been open to question for some time by such workers as Lees (1964), Fleming (1965), Mackey (1965) and Mogami and Yoshikoshi (1971), and this fact could contribute to the low correlation obtained.

5.5.3 **Possible Sources of Operator Error in Field Measurement;** A further cause for the low level in the explanation of segment angle variation is the possibility of operator
error in field measurement. Whilst it is claimed that because of the author's familiarity with the technique of axial measurement the operator error would be very small, it is conceded that errors could have occurred particularly on very large boulders (> 3 m.) and boulders of equidimensions as discussed in Section 3.4.2.

With reference to slope angle measurements problems relating to profile roughness have already been discussed in Section 3.4.1. Attention is drawn to the checks made at 15 m. within the 30 m. segment. Whilst the method appears to reduce errors a certain amount of error could arise and this could be in the order of ±1° for the 30 m. segment.

Also in Section 3.4.2 reference is made to the instrument used in fabric measurements. An error of ±5° is considered to exist in the data.

It is realised that some operator error must exist in the data. However, it is suggested that due to the rigid field procedure used that this would be at a minimum and would not be a major factor in the low level of explanation obtained in the analysis.

5.5.4 Possible Sources of Real World Noise: One of the preconditions for field testing of the hypothesis was that the talus slopes in question would be dominated by the rockfall process. The low level of explanation obtained in the analysis may reflect the operation of snow or slush avalanches, or alluvial processes not so much as a dominant process, but as a subordinate process the activity of which is far in excess of that envisioned by this
5.5.5 **Relationships between Mean Material Properties and Mean Slope Angle**; Mean material properties for each slope studied were plotted against mean slope angle. No pattern was discovered in the scatter, reflecting perhaps the variations in material-form relationships within the slope itself.

5.6 **Conclusions on Multivariate Analysis**

Low levels of explanation were found in the analysis. In some ways these results are characteristic of statistical morphometric studies (Melton, 1958; Carson, 1966) where correlation coefficients tend to have low values and scatter diagrams attempting to relate the variables show considerable disarray (Carson, 1966). It may be that the high degree of scatter and the lack of a substantial functional relationship reflects sampling or measurement error, the fact that the variables may not represent those characteristics which were desired, or the fact that material properties/segment angle relationships may obtain at a differing scale (perhaps "between areas") than that studied here.

It is possible that a morphological systems approach (cf. Chorley and Kennedy, 1971) is not appropriate to study a problem of material-form links. The assumption of the approach is that co-variance exists in the data whilst the implication of a material-form link is that it exists at a threshold which, in the same environment and in the same lithology, would tend to be invariant or at least clustered in a very narrow range of slope
angles. Notwithstanding the above, however, significant relationships were found between segment angle and sorting together with size. Shape variables were less important in accounting for variations in segment angle. The significant nature of size, sorting and segment angle relationships are in contrast to some previous attempts to relate form and material properties (Caine, 1967; Thornes, 1971).
CHAPTER SIX

IMPLICATIONS FOR TALUS SLOPE
DEVELOPMENT AND CONCLUSIONS

6.1 Implications for Rockwall/Talus Slope Development Models

6.1.1 Talus Slope Morphology: The results noted above have considerable import in both the evaluation of the talus profile dominated by rockfall and talus slide processes, and the change of slope geometry over time, i.e. slope development.

Talus slopes in the Similkameen and in the Coast Ranges have been noted to be basically concave. In other areas such as Colorado, Spitzbergen and Devon Island slopes dominated by rockfall processes would appear to be similarly concave (White, 1967; Rapp, 1960 b; Howarth and Bones, 1972, respectively).

It is proposed here that the concavity observed in rockfall taluses is largely the result of two stages in the supply-induced transformation process, viz. the accumulation process beneath the rockfall and the redistribution of this accumulation through talus slide processes. It is significant that Rapp (1960 b) and Howarth and Bones (1972), noted the existence of debris slide lobes on the rockfall taluses they studied.

The talus slope affected by such processes would have ideally, 3 distinct zones as indicated in Figure 6.1.

Zone A would represent the zone of accumulation. A wedge of material builds up in this upper zone until the inclination reaches a value of $\alpha_c$ for the material in that condition
Figure 6.1 Schematic diagram of zones on a talus slope dominated by rockfall-debris slide processes (for explanation see text)
and failure takes place downslope. Such a designation for Zone A is consistent with observed patterns of accumulation on talus slopes (e.g. Evans, 1969; Caine, 1969; Carson and Kirkby, 1972).

Zone B represents the area of deposition of debris from the failure in Zone A and according to arguments presented in Chapter 3 and findings reported earlier in this chapter, would assume an angle equivalent to \( \theta \) or \( \phi \).

Zone C would be at a lesser angle because of an end effect of the valley floor, terrace, glacier, etc. It would be the collecting area for boulders that break free from the sliding mass above (as noted by Rapp, 1960 b), for large rockfalls that bypass the upper two zones, or for large debris slides that go beyond the usual limits of such slides (it has been noted that debris slides are usually confined to the upper two-thirds of the slope).

The slope outlined in Figure 6.1 could contain two threshold slopes. In Zone A the threshold or limiting slope would be equivalent to the peak angle of accumulation of the material at its depositional density. The slope of deposition assumed by the debris following the exceedance of \( \alpha_c \) is then equivalent to \( \alpha_r \) or the angle of rest or the angle of internal friction in a looser state. This slope is then equal to the residual threshold slope.

The upper threshold, or peak threshold slope and the residual threshold slope as outlined in this chapter, illustrate the importance of considering residual strength factors in discussions of threshold slopes and slope development (cf. Rouse, undated ms.).
6.1.2 Determinants on the Frequency of Talus Slides; Variations in the activity of the talus slide process take place as a result of variation in a number of factors, the most important of which is primary fragment supply rate. Allen (1970 b) has carried out experiments on the effect of primary fragment supply rate, i.e. in this case deposition from the rock face, on the characteristics of debris avalanches including frequency and thickness of accumulation. The supply rate has its greatest effect in controlling the depositional density of an accumulation (cf. Kolbuszewski, 1948). Four supply situations are thought to apply to talus slopes dominated by rockfall processes;

(a) If the fragment supply rate is high (i.e. extreme frequency) the density of the wedge will be very low. It is possible that primary deposition of high frequency rockfalls results in a slope near to $\gamma$ or $\phi$. At least a very small dilation angle is presumed to form and as a result debris slides will be very infrequent.

(b) If the fragment supply rate is smaller (i.e. intermediate frequency) the depositional density angle would be higher. An increase in wedge volume results which in turn results in a greater debris slide thickness. Greater slide velocity also results after failure and the debris travels a greater distance downslope.

(c) If the fragment supply rate is less than (b), i.e. low frequency, a smaller wedge builds up,
although the dilation angle is high. Small failures take place and "freeze" in the upper portions of the slope building up a secondary wedge which in turn fails by progressive failure in its foreslope. Allen (1970 b) believes this to be the type of debris slide behavior that is common on talus slopes and works on an example given by Rapp from Spitzbergen.

(d) No supply.

A further important variable would also be length of slope, the bottom of which acts as an "end effect" for the processes outlined in a, b and c above.

A consideration of the rate of supply is particularly interesting in the light of indications of decreasing supply rates in postglacial time (e.g. Worobey, 1972). It is proposed here that following the initiation of present talus accumulation processes with the retreat of the glaciers 10,000(±) years B.P., talus slopes in southern British Columbia went through the spectrum of supply conditions a-c. Some have probably reached the inertial state of no supply (d).

The implication of this statement for the magnitude and frequency of debris slide processes is that immediately following the retreat of the ice, through stress release and high intensity rockwall transformation, rockfall was so frequent and depositional densities so low that accumulation wedges did not form, or at least did not form with any high frequency. The slope would under these conditions approximate to a rectilinear
form with a concave base in the presence of an end effect. The slope of the rectilinear portion would be equal to $\phi_r$ or $\phi_{cv}$ because the depositional density would approximate to the loose condition.

As the frequency of the rockfall subsided as in case (b) wedges had the opportunity to develop due to the higher depositional density and debris slides were more frequent. The concavity would have been more pronounced because of the higher angle of slope in the upper portions of the slope developed on the wedge surface.

The frequency further subsided and case (c) became operative. Small wedges gave the slope an irregular profile, the so-called mini-concavities; slides are limited to the upper portions of the slope. Smaller slides build up a secondary wedge further down the slope which subsequently fails on a much larger scale than the primary wedge. The talus slopes studied in the Similkameen seem to have entered this phase of development.

Some talus slopes are inactive with respect to debris slide processes because the rockwalls above them have become stabilized and no longer produce appreciable quantities of rock fragments. In this situation features noted in case (c) became fossilized and vegetation often invades the slope giving the appearance of an inactive talus slope. However, lobes and irregularities are still evident.

The profile will obviously assume a different form in the absence of an "end effect", e.g. where the base of the slope is eroded by waves, rivers and glaciers, since the basal
concavity will not develop.

It will also assume different forms if other slope processes such as mudflows, snow avalanches and overland flow assume dominance as transformation process. Under these conditions the processes mentioned would tend to mitigate against wedge development.

6.1.3 The Problem of the Basal Layer: The model of slope development proposed above is restrictive in that it only considers the mobile layer and the rockfall-debris slide process as a transformation mechanism. As Kirkby and Carson (1972) point out, however, the problem of slope profile development is a multi-process one. The problem here is no exception for it has been noted in Chapter 2 that the structure of talus slopes in general include a basal layer that is susceptible to pore-pressure effects. It is in this context that the origin of the basal layer discussed in Section 2.2 becomes an important consideration because if the layer is till very little change can be expected to take place in its properties. If it is the result of weathering, or the sieving effect, change can be expected to take place. An increase in the thickness will result from the advancement of the weathering front and also by the addition of more material through the sieving effect. However, even the sieving process will become inoperative in time as supply decreases to zero. Under the conditions of no supply, however, weathering will continue. It will be appreciated that if the basal layer increases in depth the layer will tend to increase in density, and, whilst adding to its shear strength would leave
it more susceptible to pore water pressures in a similar way to that described by Carson (1969, 1971). In time this process would result in differing shear strength thresholds being determinants on the morphometry of talus slopes. Thus the existence of the basal layer cannot be discounted in a slope evolution model of talus/rockwall systems.

6.2 Conclusions

6.2.1 General

(a) The verification of a material-response model detailed in this work, both using review and field data, indicates once more the importance of studying material variables in rationalising the form of various landforms, (cf. Strahler, 1952; Chorley, 1966).

(b) The study illustrates an example of a remarkable correspondence between predicted values of threshold slopes based on the model experiments of other workers in the laboratory and the values of characteristic and limiting slope angles in the field.

(c) The problems of cause and effect, the selection of independent and dependent variables and the definition of response elements in a slope system were encountered in this study. These difficulties would appear to be common to investigations based on the familiar process-material-response framework and are particularly acute in studies of strength-stress relationships as noted by Chorley (1966).

(d) The value of the systems approach in seeking
alternative explanations in form-material relationships was also seen.

6.2.2 **Specific**

(a) Based on an evaluation of published works and the distribution of published talus slope angles, the supply-induced transformation hypothesis was proposed to account for observed characteristic and limiting slope angles on talus slopes. These were found to correspond to the angle of repose \( (\alpha_r) \) and the peak angle of accumulation \( (\alpha_c) \) respectively. Testing the hypothesis in the field on talus slopes in the Similkameen Valley, characteristic and limiting slope angles were thought to correspond to \( \alpha_r \) and \( \alpha_c \) respectively for the Similkameen material, and together with other evidence, the supply-induced transformation hypothesis was verified for the Similkameen slopes.

(b) Contrary to the findings of previous workers statistically significant relationships, at the 99% level of significance, were found between segment angle and sorting, and segment angle and size. The relationship between talus segment angle and shape factors was found to be weak contrary to expectation.
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APPENDIX 1

TALUS SLOPE PROFILES MEASURED IN FIELD INVESTIGATIONS
N.B. Two profiles are illustrated for each slope: 10 m. segment profile at left and 15 m. segment profile at right.
H.B. Two profiles are illustrated for each slope: 30 m. segment profile at left and 15 m. segment profile at right.

SIMILASEEN C

SIMILASEEN H

SIMILASEEN 1
2.2. Two profiles are illustrated for each slope: 30 m. segment profile at left and 15 m. segment profile at right.