PROCESS-MORPHOLOGY INTERACTION

ON

ARCTIC DEBRIS SLOPES

PROCESS-MORPHOLOGY INTERACTION
ON
ARCTIC DEBRIS SLOPES, S.W. DEVON ISLAND,
CANADA

by

JOHN GEORGE BONES, B.A.

A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Master of Science

McMaster University
May, 1971

MASTER OF SCIENCE (1971)
(Geography)

McMASTER UNIVERSITY
Hamilton, Ontario.

TITLE: Process-Morphology Interaction on Arctic Debris Slopes,
S.W. Devon Island, Canada

AUTHOR: John George Bones, B.A. (McMaster University)

SUPERVISOR: Professor P.J. Howarth

NUMBER OF PAGES: x, 190.

SCOPE AND CONTENTS: The study assesses process-morphology relationships on 27 debris slopes of an Arctic periglacial environment. A systematic sampling procedure is followed to obtain profile angle and debris size, shape and orientation for each slope. A rigorous test design to analyze size and shape variation has high statistical power and yields reliable results. Vector analysis is employed in the study of debris orientations, while non-parametric tests are performed on geometric parameters. Supplementary studies are made on rockfall accumulation and subsurface meltwater flow. Responses of slope geometry and debris characteristics to three major process groups are independently analyzed and compared in four selected localities, and the nature and effects of each process in the study area are presented. A discussion of interactions between the processes, geometry, and debris concludes with a relative assessment of each process.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Philip J. Howarth of McMaster University for his contributions of both time and effort in supervising this topic, which he initially conceived. Gratitude is expressed to Dr. Howarth for giving the author the opportunity to work in the Canadian Arctic and to pursue the research in his own fashion. Acknowledgements are due to Dr. S.B. McCann of McMaster University, who provided stimulating field discussions and enthusiasm, and to Mr. Philip Charko who served most capably as field assistant during the major part of the data collection period. Discussion with Mr. B.H. Luckman proved valuable in establishing greater understanding of debris slope phenomena. Mr. David Ingram was especially considerate in donating valuable advice and aid in the computer analysis of the data. Finally, gratitude is expressed to the author's wife, Gail, an unlimited source of support and patience throughout all phases of this study.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF PLATES

CHAPTER I

INTRODUCTION

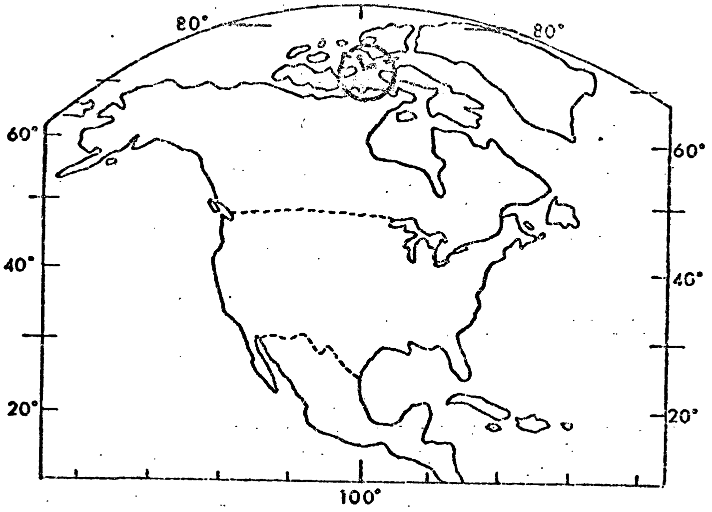
(1) Purpose

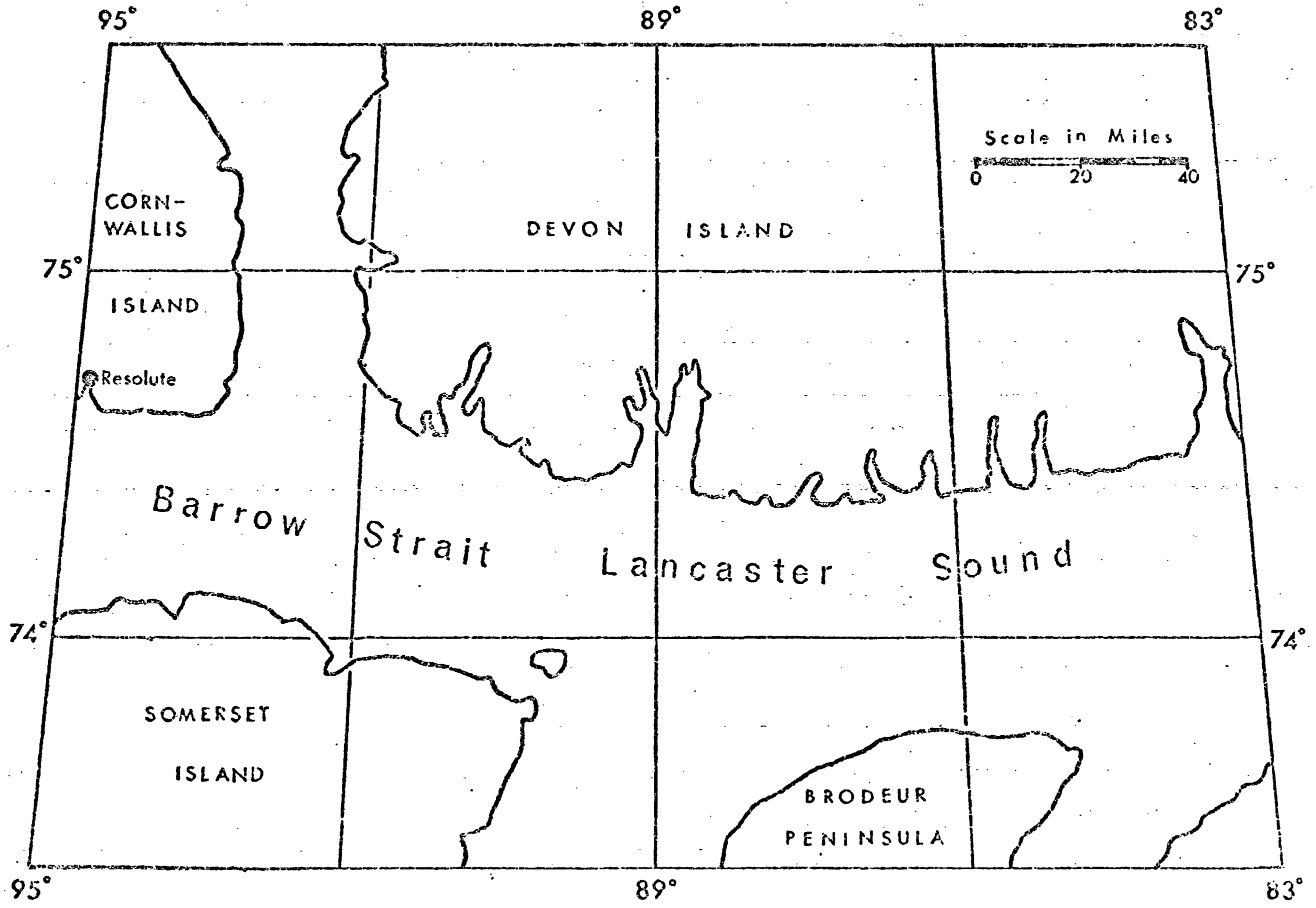
No comprehensive analysis yet exists of the relationships between development of slope form and the operation of slope processes within the periglacial environment of Canada's High Arctic. With the exception of Rapp's (1960a) lengthy report on Spitzbergen, the periglacial environment has been neglected as a favourable location for slope studies; yet the application of slope theories based upon mid-latitude or high-altitude research is not entirely warranted because there is at present no substantive body of proof that the slope processes and situations found in these environments are similarly characteristic of active periglacial areas.

A recent alpine study by Gardner (1968) has pointed out the lack of information concerning the process-morphology relationship on debris slopes. There is a call for further exploration of linkages between geomorphic elements in all morpho-climatic regions. The present study was undertaken as an attempt to satisfy that request in an Arctic periglacial area. Its goal is a valid assessment of process-morphology relationships in a diversity of locations within this setting. The results of separate analyses of slope form and slope processes are combined to determine the degree of interaction that exists between these geomorphic elements.

Figure 1

Geographic location of Southwest Devon Island


80°
80°
60°
60°
40°
40°
20°
20°
100°


95°
89°
83°
Scale in Miles
0
20
40
CORN-
WALLIS
ISLAND
Resolute
DEVON ISLAND
75°
75°
Barrow Strait
Lancaster Sound
74°
74°
SOMERSET
ISLAND
BRODEUR
PENINSULA
95°
89°
83°

(2) Location

Debris slope studies formed part of the geomorphological investigations undertaken by the McMaster University Arctic Research Group on southwest Devon Island, N.W.T. (fig. 1). Devon Island is positioned between latitudes 74°20' to 77°04' north and longitudes 79°20' to 96°50' west. The designated study area is bordered by three major water bodies: Gascoyne Inlet to the west, Lancaster Sound to the south, and Radstock Bay to the east (fig. 2). Within these bounds is located a complex landform sequence, the most pronounced of which are the horizontally-bedded limestone plateau and plateau remnant. Specific emphasis was placed by the author on debris slopes developed beneath the edges of these prominent features in four different localities (fig. 3). A basically uniform lithology prevails throughout these locales, which allowed emphasis to be placed upon the differences in slope form and development found in relation to varying types and intensities of processes.

The initial data collection was undertaken while the author served as field assistant to Dr. P. J. Howarth during a six-week period in 1969, from mid-July to September. A much longer field season, from mid-June to mid-August in 1970 allowed elaboration and completion of the study's data gathering stage. Observations made in the two summer seasons were supplemented by a one-week field excursion to the study area in mid-October, 1969.

(3) Methods

The minimum requirement for accurate analysis of slope form is a standardized survey procedure which can be adapted to slope

Figure 2

Aerial photograph mosaic of the general study area

4


SOUTHWEST
DEVON ISLAND
N.W.T
0 1 2 3 4 5
miles
Erebus Bay
Beechey Island
Radstock Bay
Gascoyne Inlet
Cape Ricketts
Cape Liddon
JGB 1969

types of any dimension. Tacheometric survey methods meet this requirement and were used to record slope morphology, its changes and its irregularities in the study area. The tacheometrically-derived profiles enabled slope forms to be reconstructed and classified for quantitative analysis.

Recognition of the processes operating on a slope and their order of significance was accomplished by both visual evidence of present or past processes and by inferences made from samples of the slope surface characteristics. Samples were collected according to a systematic procedure which required the selection of two samples from each of the upper, middle and basal zones of a slope. The parameters selected as measures of process type and intensity were debris size, shape and orientation. Individual rock type was also recorded to ascertain the proportion of each sample occupied by the two lithologic groupings. The areal variation of these parameters allows an understanding of the nature and form of debris slopes developed in various localities.

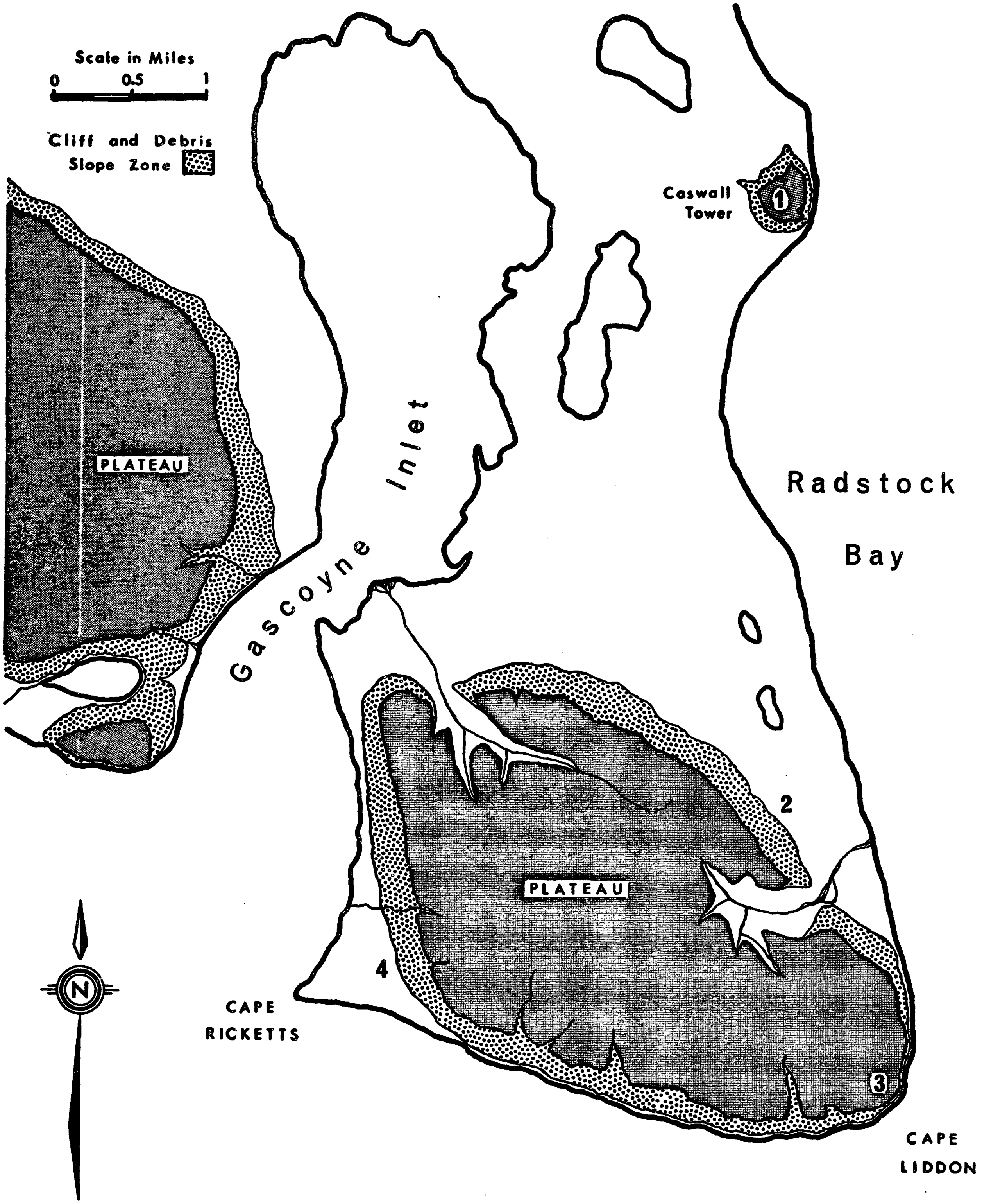
On a smaller scale, certain processes were studied employing additional methods for obtaining information which could not be derived from the major test procedure. Polythene plastic sheets were established on selected slopes to trap rockfall debris during the 1970 field season. The amount and general characteristics of the trapped debris and the areas of its greatest accumulation indicate the nature of the rockfall process in the area during the particular period. A coloured dye was also used on certain slopes during and after the 1970 peak melt period to trace the pattern and rate of runoff from various sources through the slopes.

Figure 3

Geographic position of the selected study localities;

1) Caswall Tower, 2) Inland plateau edge,

3) Cape Liddon, 4) Caswall Tower. ? CAPE RICKETS



LANCASTER SOUND

Results of these tests give preliminary indications of the nature and importance of percolating water and sub-surface conditions on debris slopes developing in an active periglacial environment.

CHAPTER II

PREVIOUS INVESTIGATIONS

(1) Definitions

Terminological confusion becomes evident from studies of previous slope literature. The two terms most widely used, "talus" and "scree," arise from tradition-bound national preferences yet suffer from a lack of proper distinction. Many writers employ the terms synonymously (for example, Rapp, 1960a&b; Caine, 1967) in reference to rock fragments found on steep slopes or at the foot of cliffs; but there is also a basic confusion when they are used to refer to landforms. It is not clear whether talus and scree refer to a particular slope-landform, to its constituent material, or to both (Sharpe, 1938). Talus is most often defined as the slope form created by accumulation of loose debris at the base of a free-faced cliff or mountain wall; while scree is a more inclusive term which incorporates not only talus slopes but those which do not lie below any wall or free-face (Stamp, 1963; Dolphin, 1962). Stamp maintains that scree may also refer to the material which forms a scree slope (and hence a talus slope).

Clarification of terms therefore seems desireable before any slope studies are undertaken. This writer prefers to reject the synonymity of talus and scree in describing both landform and constituent material. Talus is the term retained according to its popular definition as a specific slope type; while scree is employed as a general term only in that it refers to slopes which are not classified as talus slopes. The constituent material of all slopes is re-defined as slope or rock debris in order to avoid the previously-mentioned confusion with landform terms. Finally, when discussion involves all slopes (both talus and scree slopes), the inclusive term "debris slopes" is employed.

Four major types of debris slopes are dealt with in this study. As shown in figure 4, they are:-

(a) single cones formed beneath a rockfall funnel developed in the free-face

(b) talus sheets formed beneath a free-face

(c) a series of talus cones whose aprons have coalesced

(d) scree sheets with extensive lateral variation, formed by debris burial of the free-face.

(2) Process Studies

A debris slope, like any other landform, depends upon one or a combination of geomorphic processes for its present state of development. In the literature one detects a constant attempt to isolate the various slope-forming processes, but many of the investigations are of limited scope and are overly-descriptive.

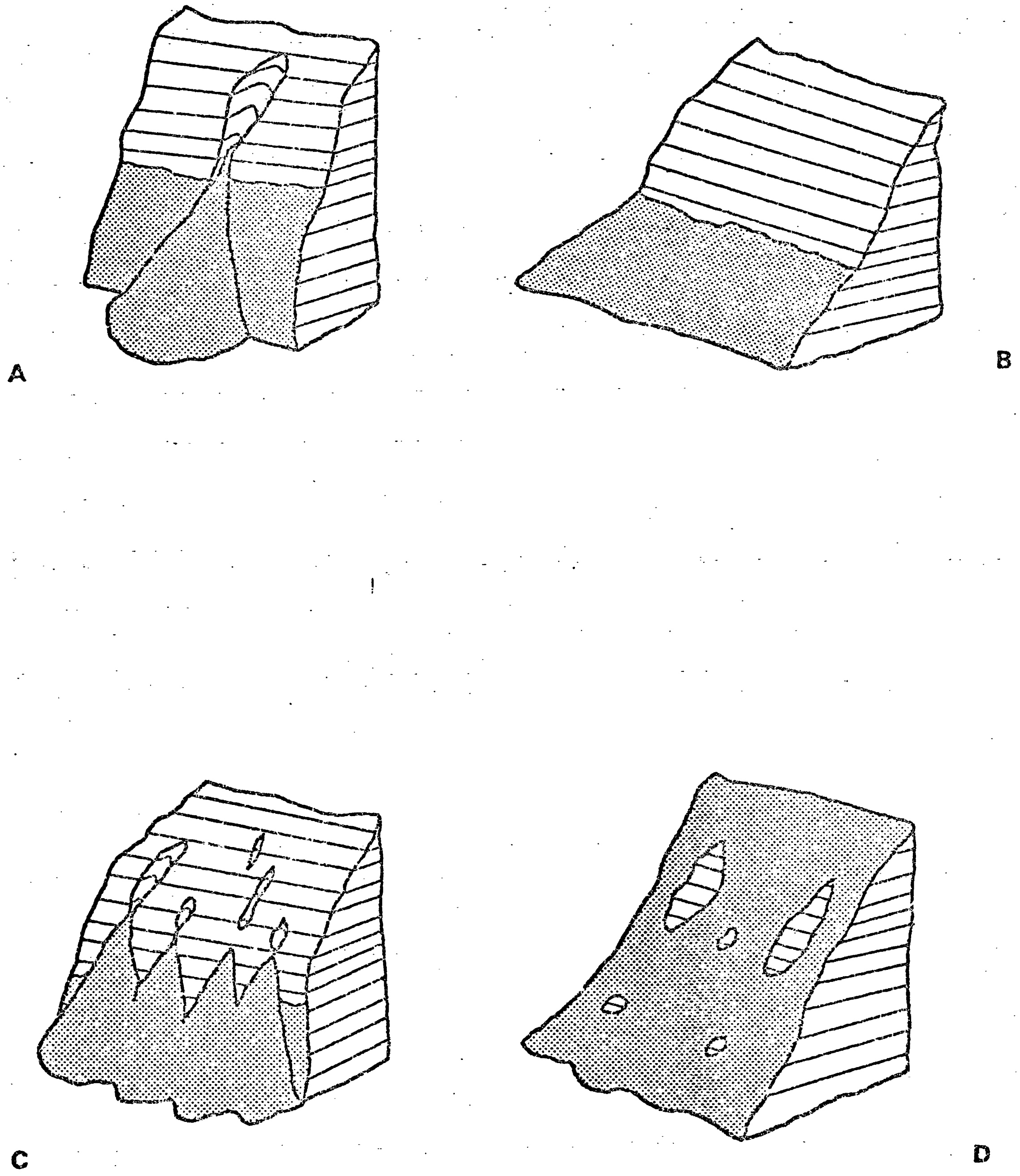
Information on slope processes has accumulated in step-like fashion, the largest stride having been made by Anders Rapp (1960a&b). Behre (1933) first discusses the role of running water in distributing rock debris downslope, and draws attention to the large gullies cut into the debris slopes by water flow concentrating in the overlying rockfall funnels. Blackwelder (1942) has pointed out the erosive

Figure 4

The four major types of debris slopes (from Stock, 1968).

A) talus cone, B) talus sheet,

C) coalescent talus cones, D) scree sheet.


A
B
C
D

power of rolling material on debris slopes. This process operates with the aid of mudflow, stream and avalanche action.

The narrow ridge-form debris "levees" are discussed by Sharp (1942), as features which form along dry channels on slopes in the Yukon. Observations of the composition, form and distribution of these ridges and of active mudflows indicate that they are built when slope material is ploughed aside by mudflow lobes which are carving their own channels or following existing ones.

Ward (1945) attaches importance to fragment slides and rockfalls as types of slope failure. Their characteristic movements and underlying causes are described. Once disturbed, debris rolls freely since little resistance is encountered, and may impart momentum to other slope debris and create a rockstream. Marine and fluvial undercutting of cliffs is cited as a contributing cause of rockfalls.

Jenness (1952) draws attention to the large-scale sliding and slumping which occurs on bare slopes underlain by permafrost when a portion of the ice is exposed to summer air temperatures.

Washburn and Goldthwaite (1958) continue the indexing of process by describing slushflow, which is the downslope movement of water-saturated snow in channels during the spring. Slushflow is common in Arctic areas and is termed a sporadic process of both erosion and deposition on slopes which often leaves natural levees of compacted snow on either side of its path.

With Rapp's publications, process studies become more comprehensive and analytical. Rapp attempts to assess the relative importance of a set of processes, and concludes that rockfalls are more important than rockslides and avalanches in debris slope formation (Rapp, 1959). The same author (1960a) classifies movement in and from a talus slope according to three sets of processes which are debris supply, debris shift and debris removal on a slope.

A continuous study of active slope processes is also made in northern Lappland over an eight year span (Rapp, 1960b). The mass movements characteristic here are an elaboration of those previously mentioned (1960a), and are:-

(a) fall: the rapid individual movement of particles by free-fall or by leaping and bounding

(b) slide, slip, slump: the rapid mass movement along slip planes

(c) flows: the rapid flow movement of a fine, saturated regolith

(d) creep: the slow imperceptible movement of debris

(e) subsidence: the sinking of debris over cavities, and compaction.

Rapp stresses that quantitative slope studies must consider both continuous and sporadic processes; even though they are rather difficult to compare in terms of quantity of debris transported. He ranks slope processes in Karkevagge in the following order of importance:

(a) removal of dissolved salts

(b) earthslides and mudflows

(c) dirty avalanches, rockfalls and frost weathering

(d) solifluction and talus creep

(e) slopewash and wind erosion.

Among his recommendations for further study, Rapp calls for a greater examination of both sporadic and continuous processes. He poses the question of whether or not recent debris slope development is the result of dominant sporadic and catastrophic processes in every type of environment (Rapp, 1960c).

A noteworthy categorization of debris slope processes has resulted from Thornes' (1968) application of queuing theory to debris slopes. Thornes groups slope processes into three sets of variables:-

(a) input processes; ie. those which cause debris to arrive at the top of a slope

(b) queuing processes; ie. those which affect particles on or in the debris slopes

(c) output processes; ie. those whereby particles are removed from the foot of a debris slope to be transported elsewhere. They are related to magnitude and frequency of the operating removal processes.

Thornes suggests that the relationships between variables and attributes may vary from time to time under different environmental states.

(3) Morphology Studies

Descriptive accounts of debris slopes have, in the past, been concerned with the various geometric aspects of form; and only occasionally have slopes been treated as sedimentary deposits with distinctive particle form. Geometric and sedimentary form, the two aspects of morphology, are reviewed in this section.

The mean slope angle or inclination is a descriptive parameter of slope form continually mentioned by field workers. Behre (1933) observed that the maximum angle of rest for bare slopes, regardless of rock size, was 42° in alpine areas above the timber line. The most frequently observed angle was 36.5°. Miner (1934) reported exceptionally high and stable debris slopes in the Gaspé Peninsula with angles ranging from 36° to 40°. In south Britain, Ward (1945) observed slope angles to be characteristically 30° to 35° for dry, gravitational cones. Rapp (1960a) reports debris slopes in Spitzbergen ranging in angle from 29° to 40°; while Andrews (1961) found a characteristic angle of 35° for both Wasdale (England) and Labrador slopes. Tinkler (1966) finds a characteristic angle of 35° and a limiting angle of 36° for debris slopes in North Wales. Caine (1967), working on selected Tasmanian slopes, did not find any slope angles greater than 40°; while Rocky Mountain slopes studied by Gardner (1968) did not exceed 35°.

Young (1960) has defined the characteristic angle of a slope as one which most frequently occurs, either on all slopes in a region or under particular climatic or lithologic conditions. Limiting angles of slope are similarly described as those which define the range within which particular slope surface features occur or particular processes operate. Young's terminology is preferred in this study.

The geometric form of a debris slope also includes its profile form. Profiles are usually associated with slope angle, and display characteristics of three general states: convexity, concavity and rectilinearity (straight). Both slope profile and slope angle have been regularly associated with the sedimentary characteristics of the deposited rock debris. Miner (1934) accounts for the compactness and rigidity of the steep but stable slopes by the elongated shape of fragments and their downslope imbrication. Andrews (1961) has explained the oversteepening of platy materials in the same fashion but credits an upslope imbrication.

In contrast, Van Burkalow (1945) suggests that it is the angular, coarse-grained and massive material which causes steep slopes, while platy, smooth elongated fragments create a more gentle slope.

Van Burkalow has also assessed the relative importance of various slope parameters. When size and shape vary together in perfectly sorted material, shape appears to be the controlling factor of slope angle. But since debris slopes are imperfectly sorted, slope angles will vary directly with size of fragments. When fragment shape is uniform, the slope angle varies inversely with size of material. The influence of size is evident only in perfectly sorted material because when a size mixture occurs, cohesion develops in the mass and allows a steeper slope to be maintained. Ward (1945) regards slope angle as a function of compaction which is directly conditioned by the shape of the constituent boulders. Andrews (1961) emphasizes the strong relationship between slope and shape of materials.

Gardner (1968) has found the surface inclination of a slope to increase with distance from the slope base. As a result, concave profiles are characteristic of alpine slopes. As the top of the slope is approached, the concavity approaches rectilinearity.

Since rock debris slopes are sedimentary deposits of a primary form (Griffiths, 1959), there is a need to survey the various comments made on the debris characteristics, such as size, shape, and arrangement on a slope. When rock debris is separated from a free-face and falls onto the debris slope, a crude size-sorting is generally reported, although there are conflicting reports. Behre (1933) for example, describes debris slopes where the largest fragments lie near the slope top with the smallest at base.

Van Burkalow (1945) acknowledges the common case to be one where a crude sorting occurs with a downslope increase in debris size. Rapp (1960a) points to fall-sorting as creating downslope size increases on Spitzbergen slopes. The height of the free-face, however, may cause a reverse fall-sorting since a growing talus cone will increasingly cover the rockwall and allow low falls to predominate. In this way large blocks may fall short distances onto the top of a slope with no substantial downslope movement. Behre's findings are therefore explained in terms of slope development. A slope composed of extremely flat fragments may also show a reverse fall-sorting. Rapp (1960b) mentions that kinetic energy, particle shape and surface roughness are the main factors controlling distance of travel of a rock fragment.

Andrews (1961) has also found a crude downslope increase in fragment size on the Wasdale slopes. Sub-angular material is expected to display a wide variation in degree and extent of grading, while size grading in platy debris is more regular over the length of a slope. These observations Andrews found to be compatible with the difference in degree of packing observed. Caine (1967), however, found the variations in fragment size and sorting over selected Tasmanian slopes statistically insignificant. The visual trend towards downslope size increases are therefore not statistically justified. Gardner (1969) found debris to be poorly sorted on Rocky Mountain slopes. The size distribution is log-normal at any point on the talus, so that with increasing distance from slope base a logarithmic decrease in average particle size is characteristic.

Concerning debris size and shape, Griffiths (1959) expects these variables to be homogeneous in variation, with little or no layering of deposits because a debris slope represents a very early stage in the dispersal of source material. Gardner (1969) cites rock lithology as influential on debris size and shape, especially in areas of mixed lithology. King and Buckley (1968) submit that size and shape variables are not well-correlated, and thus shape variations are related only to variations in depositional processes. Roundness values are of limited use in debris slope studies since material is invariably angular or subangular.

Fabric orientation is one aspect of the sedimentological characteristics that have only recently been treated in detail. Cailleux (1947), Hamelin (1958), and Klatka (1961) have derived quantitative indices of size and fabric characteristics which indicate that orientations are aligned with local slope directions. Rapp (1960b) recorded the orientation of stones at the edge of a mudflow lobe as transverse to the flow direction. Long axis orientation on dry, gravitational cones is preferred downslope but not pronounced because the rocks interfere with each other's movements. The general point brought out in Rapp's work is that orientations differ according to the slope process in operation.

(4) Interaction Studies

It is insufficient to consider and then abandon the various aspects of slope form and slope processes as separate entities, for an appreciation of both requires knowledge of the ways in which they affect each other. Very few attempts to delimit these relationships have been made, the majority of these merely touching upon the possible cause-effect relationships which seem to be in evidence on the slopes. Carson (1969) recognizes this problem by relating that much current work is trying to establish controls of the rate of operation of certain processes only to infer the dominant processes. There still remains the issue of determining the geometric changes associated with specific processes.

As early as 1945, the influence of various processes upon slope profile was recognized. Van Burkalow noted that rate of debris supply, downslope movement of large boulders, inclination of slope base, plan-view curvature of the slope and height of fall of debris all contribute to concavity or influence the shape of the slope profile. Rapp (1960a) divided his Spitzbergen slopes into groups based upon measured profile and surface forms, according to the dominant processes observed. Differences in slope angle and profile are believed to be the effect of various types of transport processes, and the fact that permafrost lies below the surface seems to have very little effect. The shifting and removal of material, says Rapp is the levelling factor of a slope, reducing it from a convex debris slope accumulation to a low-angled concave alluvial cone. Some of these process-form relationships operate in a system with negative feedback (Carson, 1969), since most debris transport processes depend partly on angle of slope. Hence in a case where the result of debris transport is to lower slope angle there exists a mechanism which retards the operation of that process.

Again based on observation and inductive reasoning, Rapp (1960b) verifies Van Burkalow's (1945) earlier idea that height of fall of rock debris affects the slope profile, and notes that high, widespread falls tend to create a more stable, less steep concave slope than do lower falls. There are, however, many other complicating factors in profile development such as frequency and source of the rockfalls, fragment characteristics, occurrence of vegetation and the presence of a basal sapping mechanism (King, 1966).

Attempts to relate particle shape, size and arrangement to both geometric form and process on a slope have been few (Caine, 1967). Since particle arrangement is primarily determined by the type of process operative, this parameter is useful in recognizing the relative importance of a set of processes which have produced and modified the slope features. Andrews (1961) records a downslope orientation of long axes of shale debris on a gravitational-formed slope. Where the long axes are inclined at an angle to the slope direction, the causal factor is local slope failure. Rapp (1960b) maintains that downslope orientation on dry gravitational cones is due to individual gliding or sliding movement of particles, while transverse orientation is explained as the result of the rolling of stones.

Caine (1967), however, finds a lack of directional preferences which are significant, and maintains that a random or uniform fabric is to be expected on a dry, gravitational cone, and that fabrics are a response to random processes of talus accumulation and creep. On a smooth, inclined plane, debris sliding gives a downslope and rolling a cross-slope orientation; but because a debris slope is not smooth but rough-surfaced, there will be no strong orientations in any direction when accumulation by rockfall is the major factor (Caine, 1969).

The most recent major study of process-morphology relationships has been produced by Gardner (1968). Working in the Canadian Rockies, Gardner has established six major linkages among geomorphic elements:-

(a) a linkage between environment and weathered material

(b) a two-way linkage between environment and slope processes

(c) a direct connection between environment and debris slope form

(d) a two-way linkage between the weathered material and the slope processes

(e) a linkage between weathered material and the slope form

(f) a two-way linkage between slope processes and slope form.

Certain of these elements have been treated extensively in the literature; while others need much greater attention from geomorphologists. It is Gardner's recommendation that these linkages be explored, expanded and applied in other morphoclimatic regions in order to test their spatial variations.

CHAPTER III

THE SETTING

(1) Geologic Environment

Devon Island is underlain by Palaeozoic strata which lie in a westward-dipping homoclinal succession of the Jones-Lancaster Basin, called the Devon Homocline (fig. 5). This homocline appears to be the eastern limb of a major syncline, its axis lying along Wellington Channel and its western limb along the east coast of Cornwallis Island (Y.O. Fortier in Fortier et al, 1963). The lower Palaeozoics within this area have an estimated thickness of 5500 metres (Thorsteinsson, 1958), and are collectively known as the Read Bay Formation. Of predominantly Middle and Upper Silurian strata, this formation extends south under the northern coasts of Somerset and western Baffin Islands. South of Lancaster Sound the Read Bay beds appear to lie across the southerly-striking Devon Homocline, likely due to normal faulting along Lancaster Sound (Y.O. Fortier in Fortier et al, 1963).

The Radstock Bay-Beechey Island area is mapped as bearing rocks of Cambrian, Ordovician, and Silurian age, although the lithological and faunal evidence reveals that the beds are more specifically Upper Silurian. They are westward-dipping and consist of dolomitic limestones with some interbedded conglomerate limestone; argillaceous limestones; silty limestones, crinoidal limestones, calcareous shales and chert. These have been broadly grouped into two classes for field study, namely:-

(i) silty, argillaceous, and dolomitic limestones

(ii) crinoidal limestones.

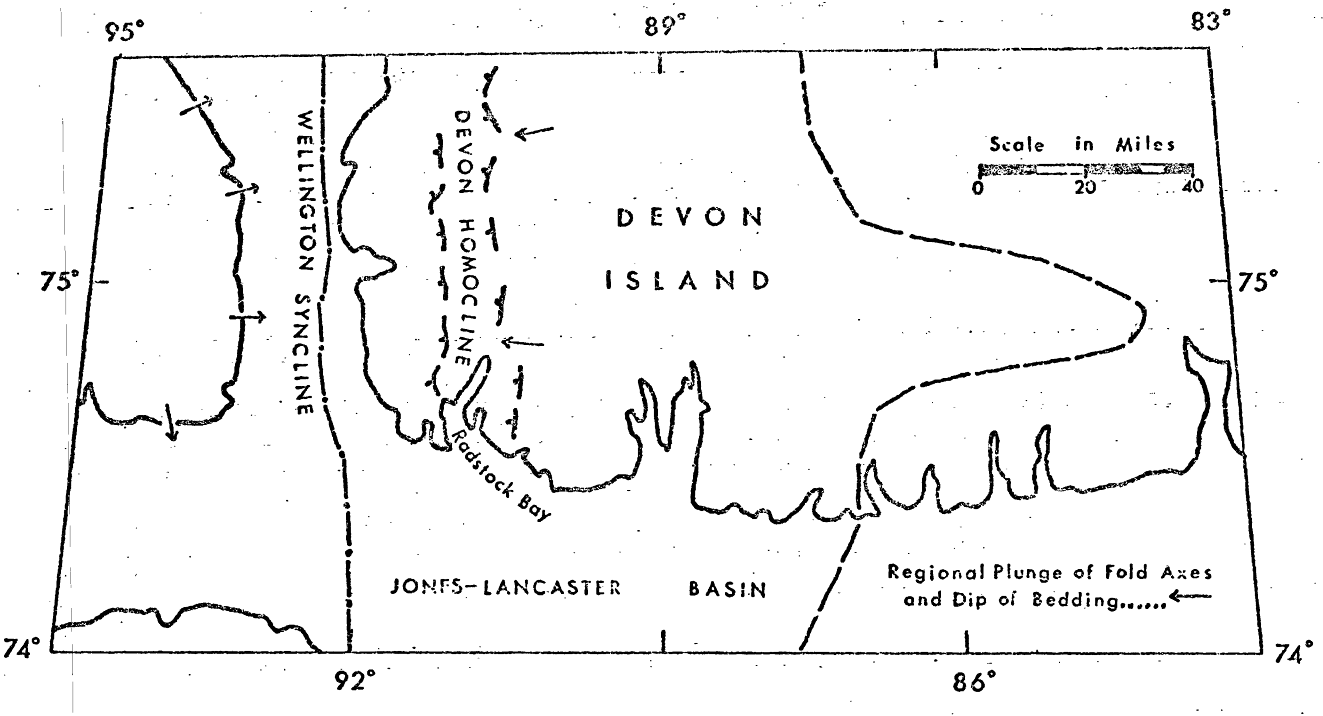
The only stratigraphic sections mapped in the area are approximately 350 metres thick (H.R. Greiner in Fortier et al, 1963). North of Beechey Island a gentle anticlinal flexure is found with its axis trending slightly northwest (fig. 5), and is believed to have been formed at a period later than the establishment of the Devon Homocline (H.R. Greiner in Fortier et al, 1963). On the south of this fold at Beechey Island, beds dip 2° to 3° south, while on the north side at a point six miles north of Caswall Tower, beds dip 1° to 2° north.

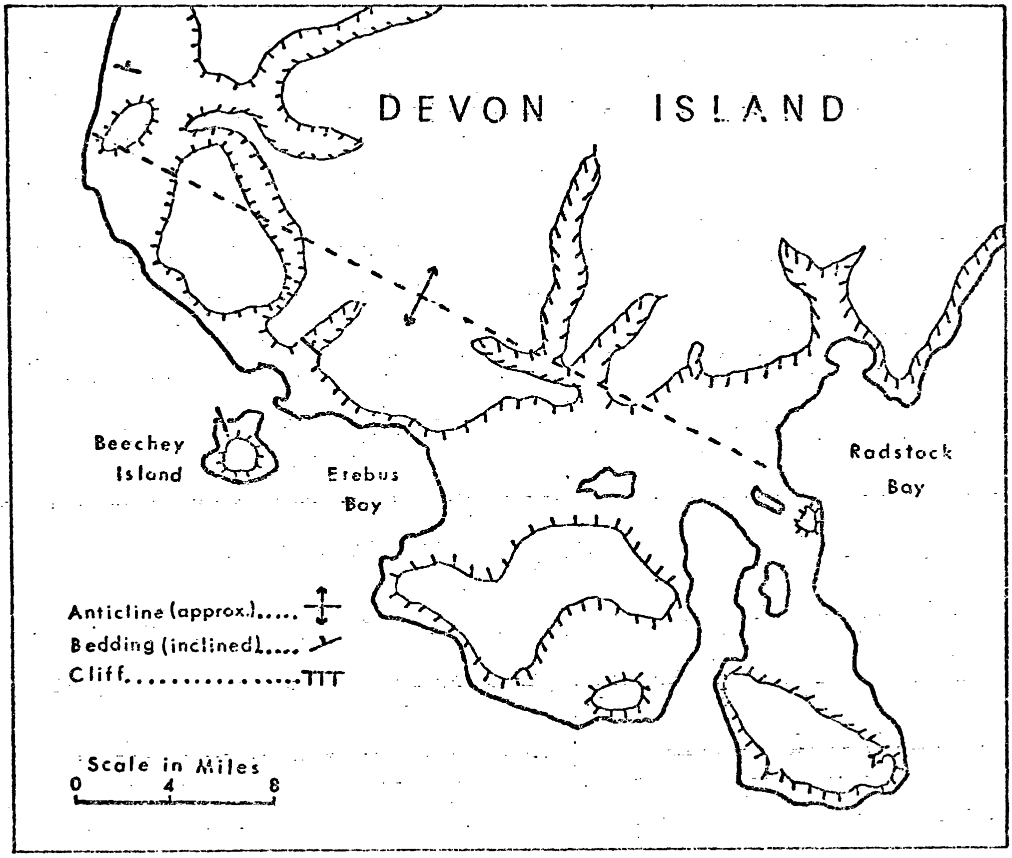
The dominant geomorphic feature of the area is the 320 to 400 metre high Barrow Surface, the erosional remnant of an older and higher surface thought to have been eroded sub-aerially during the Tertiary uplift (Bird, 1959). The initial graben fault lines of the area were believed occupied and widened by a fluvial network which, during Tertiary uplift, began downcutting to create the present-day pattern of channels in this part of the Queen Elizabeth Islands (Fortier & Morley, 1956). This pattern may have been accentuated by glacial scour during the maximum Pleistocene ice stage.

The extent of Pleistocene glaciation in the Queen Elizabeth Islands is generally unclear. It is assumed from available evidence that the mountains and uplands of Ellesmere, Axel Heiberg and Devon Islands were covered by a single ice sheet (Bird, 1967). The erratics of Precambrian gneiss and granite found on the surfaces of plateau areas are the most obvious indications of an ice cover. These are located well above the post-glacial marine limit and could

Figure 5

Geologic structure of southwest Devon Island
(from Fortier et al, 1963).


95°
89°
83°
75°
75°
74°
74°
92°
86°
WELLINGTON SYNCLINE
DEVON HOMOCLINE
DEVON ISLAND
Scale in Miles
0
20
40
Radstock Bay
JONES-LANCASTER BASIN
Regional Plunge of Fold Axes and Dip of Bedding......


DEVON ISLAND
Beechey Island
Erebus Bay
Radstock Bay
Anticline (approx.).....
Bedding (inclined).....
Cliff...............TTT
Scale in Miles
0
4
8

not have been rafted there by sea-ice (King, 1968). Over most sections of Devon Island, the ice sheet was unconfined by topography, and the velocity of basal ice was so low that it appears to have played more of a protective role than an erosive one. Glacial modification of the landscape was largely confined to the valleys which served as outlet channels for the interior ice mass (E.F. Roots in Fortier et al, 1963).

It is believed that the greatest effect of glaciation lies not in any depositional or erosional context, but in the resulting isostatic uplift of the land surface once burdened by the weight of ice. Between approximately 9450 years B.P. and 7000 years B.P., isostatic uplift began to exceed the eustatic rise of sea level caused by melting of glaciers (King, 1968), an event which made the sea regressive on the Devon Island shoreline. In consequence, recently emerged strandlines are found along the south coast up to a height of 95 metres (Bird, 1967). This level is comparable to those reported at Resolute Bay (99 metres) by Bird (1967), and those on the north coast of Devon (106 metres) reported by King (1968). Even above these levels, marine shell fragments can be found (Bird, 1967). On south Devon, wave-cut rock terraces indicate a lengthy still-stand of the sea at heights 11 to 30 metres above present sea-level (E.F. Roots in Fortier et al, 1963). There is no evidence of tilting of the Island during emergence.

Present rates of recovery of the Island are varied, the majority being based on archaeological evidence. Fortier et al (1963) suggest a net downward movement of the land by 3 metres since the Pleistocene.

King (1968) from work on north Devon Island reports that the rate of isostatic uplift has been steadily decreasing since 7000 years B.P., with the result that isostatic equilibrium has at present been attained. Collins (1951) favours a continuing emergence in the area at a rate of 0.15 cm. per year. The only detailed work on southwest Devon, by Owens (1968), suggests a continuing net emergence of the land. From these varied comments it seems reasonable to assume that emergence of the land is occurring in relation to sea-level but at a rather slow rate at present.

(2) Climatic Environment

Climatic data for the study area is sparse, although records kept at Resolute Bay on neighbouring Cornwallis Island can be used as general indicators of Radstock Bay climatic conditions since the two areas are less than 100 miles apart and are at similar latitudes. Their records portray the periglacial conditions which exist and also provide some indication of the magnitude and frequency of diverse climatic events which are of significance in this study.

Select precipitation and temperature data for Resolute Bay over the 1957 to 1967 period has been used in portraying general climatic conditions (Appendix I). Mean annual precipitation for this period reaches 4.8 inches, a figure indicative of the virtual "desert" conditions existing in the area. July has the highest mean monthly precipitation, a meagre 1.04 inches; while August, September and October follow in order as the next wettest months. Precipitation does not exceed 1 inch in any of the latter three months of the year .

Mean air temperatures calculated for the period 1957 to 1967 at Resolute indicate that summer months are cool, with the 37°F mean recorded for July ranking as the highest mean monthly temperature. Maximum temperatures, however, often reach 50°F in mid-July. Mean temperatures are below 0°F for six months of the year and below 32°F for ten months out of twelve. Daily temperatures first begin to climb above the freezing mark in June. Temperature data for a one-week period in October of 1969 has also been collected and seems to conform to the general pattern of the Resolute climatic data (Appendix I (2)).

Wind data is of importance due to its effects upon wave activity and sea-ice movements in Radstock Bay. Again, wind data for Resolute Bay can be used to approximate the study area conditions, as seen by Appendix I (2). Thompson's (1967) summary of wind data at Resolute from 1951 to 1960 suggests that prevalent wind direction is northwest for eleven months of every year. In the summer of 1969, Resolute data indicates that winds blew from the east-to-south quarter over the remaining monthly period July 21 to August 23; while in 1970 predominant wind direction was northwest. In connection with wind data, two periods are singled out for their relevance to this study. These are July 25-28 and August 11-13, both in 1969. These were periods of continuous southeasterlies which gusted to 20 m.p.h. in the former and to 42 m.p.h. in the latter case; and when coupled with the right water and sea-ice conditions these periods of wind greatly influenced the form of debris slopes along the Cape Liddon coastline.

(3) Geomorphic Environment

Devon Island has been described as one of the few active periglacial areas which most clearly indicate the interaction of glaciation, frost action, fluvial action and marine processes (E.F. Roots in Fortier et al, 1963). There are five general landform units within the study area, and this particular section attempts to place them within the frame of reference described above. These units are the plateau, the cliff and debris slope zone, the relict beach zone, the active beach zone, and a small lowland area.

The plateau reflects most clearly the presence of the Barrow Surface (III, (1)). In the study area it dips westward at a slight angle, is elliptical in shape, and reaches heights of 350 metres. The plateau is interpreted as a relict feature which has been uplifted and subsequently dissected, and is characterized by a relatively featureless top surface which is covered by a drift-like material termed "rubble" (Bird, 1967). The rubble is composed of fine silt or clay, approximately one metre thick, and contains limestone particles and erratic rock fragments (Bird, 1967). The surface is mainly vegetation-free except in poorly drained sections where mosses delimit stone stripes and pools of water. Elsewhere, patterned ground nets and polygons as well as felsenmeer have developed on the exposed surface. The plateau ends abruptly on all sides and grades down steeply to enter the next landscape unit, the cliff and debris slope zone.

Cliffs occurring at the plateau edge are either those which form the present coastline of the area or those which were coastal cliffs in the past but are now elevated well above marine action and are debris-covered. Many of the latter display marine trim lines near base or have marine terraces developed below them. A regular continuum of debris slopes is found below both types of cliff, and these are composed of limestone fragments derived from weathering of the cliff-faces themselves. Slope form ranges from convexity through rectilinearity to concavity and the angles are generally steep. The amount of exposed cliff-face varies with degree of slope maturity, being quite extensive along the coast but almost negligible on the more northerly edge. The cliff-face is likely retreating by the process of parallel backwearing, where the debris slope reflects the angle of the underlying rock slope (Bird, 1967).

The relict beach zone serves as a buffer between the cliff and debris slope areas of the coastline and the sea. During de-glaciation, a transgressive sea covered the area as the ice front first retreated; but when the land began to rebound, a sequence of beaches was deposited. The present raised beaches have individual heights of 1 to 5 metres, but collectively form a continuous zone which in places extends as much as 90 metres above present sea-level. The width of the relict zone varies, being generally absent from the Cape Liddon headland area but gradually widening in a north and west direction as the plateau trends inland. This zone reflects the complex depositional processes to which it has been subjected.

The modern beach zone in Radstock Bay has been studied by Owens (1968), and Owens and McCann (1970) who stress both the important but negative role of ice and the role of storm waves. It is the energetic storm waves which produce the beach zone's main characteristics of a steep beach-face slope and a High Water Mark ridge. The beach material is composed primarily of pebble-sized gravels, while sand is generally absent. Longshore transport of material occurs in a south-to-north direction along Radstock Bay, and it is believed that Cape Liddon provides the majority of the transported sediment (Owens, 1968). Normal wave action is limited to eight weeks of the year, and the zone over which it can act is very narrow; so that one would conclude wave action to be currently not of any great importance.

Of the landscape units, the last is an extensive lowland area which lies between Gascoyne Inlet and Radstock Bay south of Caswall Tower. This narrow stretch of lowland connects with an ancient rock bench further north which runs east-west from Erebus Bay to Radstock Bay (E.F. Roots in Fortier et al, 1963). The whole area is similar in appearance, and forms the only extensive lowland area on the south side of Devon Island. Covered with marine deposits and plateau-derived materials (both of which have been frequently soliflucted), much of the lowland is vegetated. Patterned ground features, both vegetated and barren, are widespread. There is an abundance of peat and grasses in the depressed areas, and soil development here is in its initial stages.

To complete the pattern depicted by the five landscape units, attention is turned to two elements which are characteristic to all of them. These are the presence of surface drainage and of mechanical weathering. Surface drainage is generally dis-organized, and the only exceptions are the few large streams which occupy deep V-shaped valleys and flow into the sea. These streams are in flood only during the late June peak melt period, and those which do not later dry up completely experience reduced volumes of flow for most of the summer period. The Inland plateau area also provides a great deal of moisture to the lowland.

Here, streams cascade over the plateau edge at several locations, disappear beneath debris slopes and emerge at the base to meander down towards the lakes and ponds of the lowland. These lakes and ponds are extremely shallow and drainage of their waters into Gascoyne Inlet is a slow process. In early July the results of the peak melt period, coupled with a continuous melting of permafrost and snowpatches, causes a complete saturation of the active zone of the ground. In the coastal cliffs several waterfalls occupy gullies in the rockwall, but the water tends to dissipate upon reaching the beach gravels and does no significant erosional work in the beach zone.

With the exception of the active beach zone, mechanical weathering appears to be the dominant process in rock erosion and disintegration in each of the landscape units. This process depends upon climate and lithology, both of which are optimum for the area. Mechanical weathering involves stresses generated within the rock by the growth of ice or salt crystals, by temperature changes, wetting and drying, and by organic activity (King, 1968). Several of these stresses may act in unison. Frost-riving is accepted as the major form of mechanical weathering in a periglacial climate. Moisture has an important role for it is the medium which enters the rock along joints, pore spaces and fractures to exert pressure upon freezing in a closed system within a rock mass. Taber (1918) has shown that the growth of ice crystals in freezing has a disruptive effect on a rock mass, for ice crystals exert pressure in the direction of growth. Growth is more easily facilitated in the porous, relatively permeable fine-grained rocks; and sedimentary rocks, which exhibit numerous bedding planes are known to shatter quickly.

Bird (1967) estimates that the thin-bedded Palaeozoic limestones can shatter to a depth of 15 cm in less than 1000 years. The rock initially shatters as angular plates and blocks whose size is largely determined by the density of vertical jointing and the distance between bedding planes (King, 1968).

Climatic information has often been used to assess the relative intensity of mechanical weathering by the calculation of the number of freeze-thaw cycles. It is known that the number of temperature fluctuations across the freezing point is lower in the Arctic Archipelago than in southern Canada; and consequently the once widely-held belief that such fluctuations account for the prevailing intensity of mechanical weathering in the Arctic is unfounded (Cook & Raiche, 1960).

Raised beach material may be affected by chemical weathering, although it is regarded as an insignificant process in the High Arctic. Some pebbles are faceted by solution on top and covered with a travertine deposit on their undersides (Owens, 1968). Oxidation of raised beach deposits may occur, and samples near Caswall Tower showed 23% iron oxide and 22% aluminum oxide by weight. Chemical weathering, however, seems restricted to the beach zones and its effects elsewhere are not profound.

The active beach zone is regarded as being affected by neither frost-riving nor chemical weathering. Beach pebbles are protected by shorefast ice for ten months of each year, while during the open-water period they are protected by the medium of water. Physical abrasion of the beach material through its longshore movements is likely the only significant process of weathering in the active beach zone.

(4) Selected Locales

Within the general setting five specific locales were investigated; and although a number of different distinguishing criteria were considered, the following slope groupings by area were devised:-

(a) Caswall Tower talus sheets and talus cones

(b) Northeast inland plateau talus cones and scree slopes

(c) Cape Liddon talus cones and talus sheets

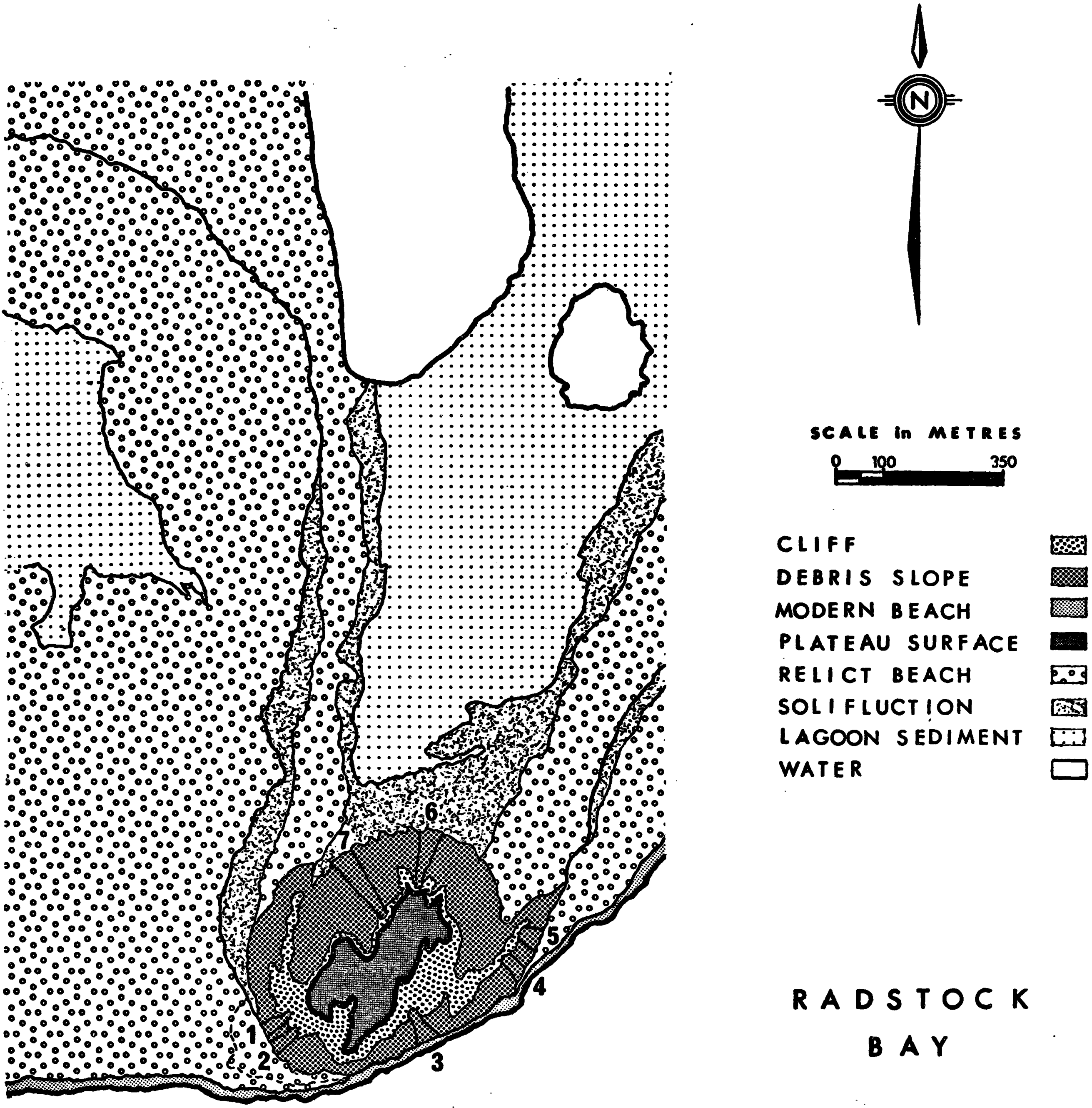
(d) Cape Ricketts talus cones and talus sheets.

The first locale described is Caswall Tower, a circular-shaped plateau remnant composed of horizontally-bedded Read Bay limestones. The Tower rises 196 metres and on its steepest side lies adjacent to the modern beach. Forming a continuum with the Tower edge are two elevated gravel beach ridges which taper off in two directions, one inland to the west and the other north along the coastline (fig. 6). On the Tower's western side, between the two ridges, is found a well-developed talus sheet formation which grades laterally northward into coalescent cones. Moving eastward the type of slope alternates between talus sheets and talus cones developed below a well-dissected and increasingly steepening cliff-face. The easternmost edge of the Tower is also its seawardmost sector, and slopes here are separated from the sea at high tide by only a few metres of beach front. The active beach widens in both northern and southern directions, and coupled with the gradual appearance of a relict beach zone it provides increasing protection from ice-push and storm-wave activity. The majority of the debris on the protected and unaffected slopes on all sides of the Tower are colonized by lichen, which suggests that

Figure 6

Geomorphic map of Caswall Tower

and location of investigated slopes.


SCALE in METRES
0
100
350
CLIFF
DEBRIS SLOPE
MODERN BEACH
PLATEAU SURFACE
RELICT BEACH
SOLIFLUCTION
LAGOON SEDIMENT
WATER
1
2
3
4
5
6
7
N
RADSTOCK
BAY

mechanical weathering is not now as intense as it had been in the past when the majority of the blocks were broken from the cliff-face. Seven slopes were selected in the Caswall Tower locale for intensive study.

The second locale studied is a section of the debris slopes which lies along the northeastern edge of the major plateau. The slopes here grade down from the Inland plateau onto a wide depression which is floored by ancient lagoonal deposits (fig. 7). A wide band of resistant dolomitic limestone is visible mid-way up the debris-covered rock face; and though of limited lateral extent the frequent gulleying of this outcrop has given rise to the several huge talus cones found beneath. These cones are characteristically gullied by meltwater channels and display lobate "flow" features in association with them. The majority of the slopes are scree slopes extending from the valley floor to the plateau top. Four slopes were considered for study in this locale.

The third locale investigated is the Cape Liddon coastal zone, the site of many actively developing debris slopes (fig. 8). The six slopes considered lie along the southeastern and southwestern extremities of the Cape, below a well-dissected cliff-face 200 to 300 metres in height. Both talus cones and talus sheets are found here. Individual cones do not appear to have coalescent aprons but rather are separated by distinctive sheets of debris accumulated from the overlying cliff-face. Some slopes are developed over wave-cut rock platforms whose seaward edges often jut out slightly from beneath slope bases. At high tide only a few metres of gravel beach separate the foot of the slopes from the eroding effects of wave action. The Cape Liddon slopes face south and southeast in the direction of longest wave fetch, a situation which in times of strong

Figure 7

Geomorphic map of the Inland plateau edge and location of investigated slopes.

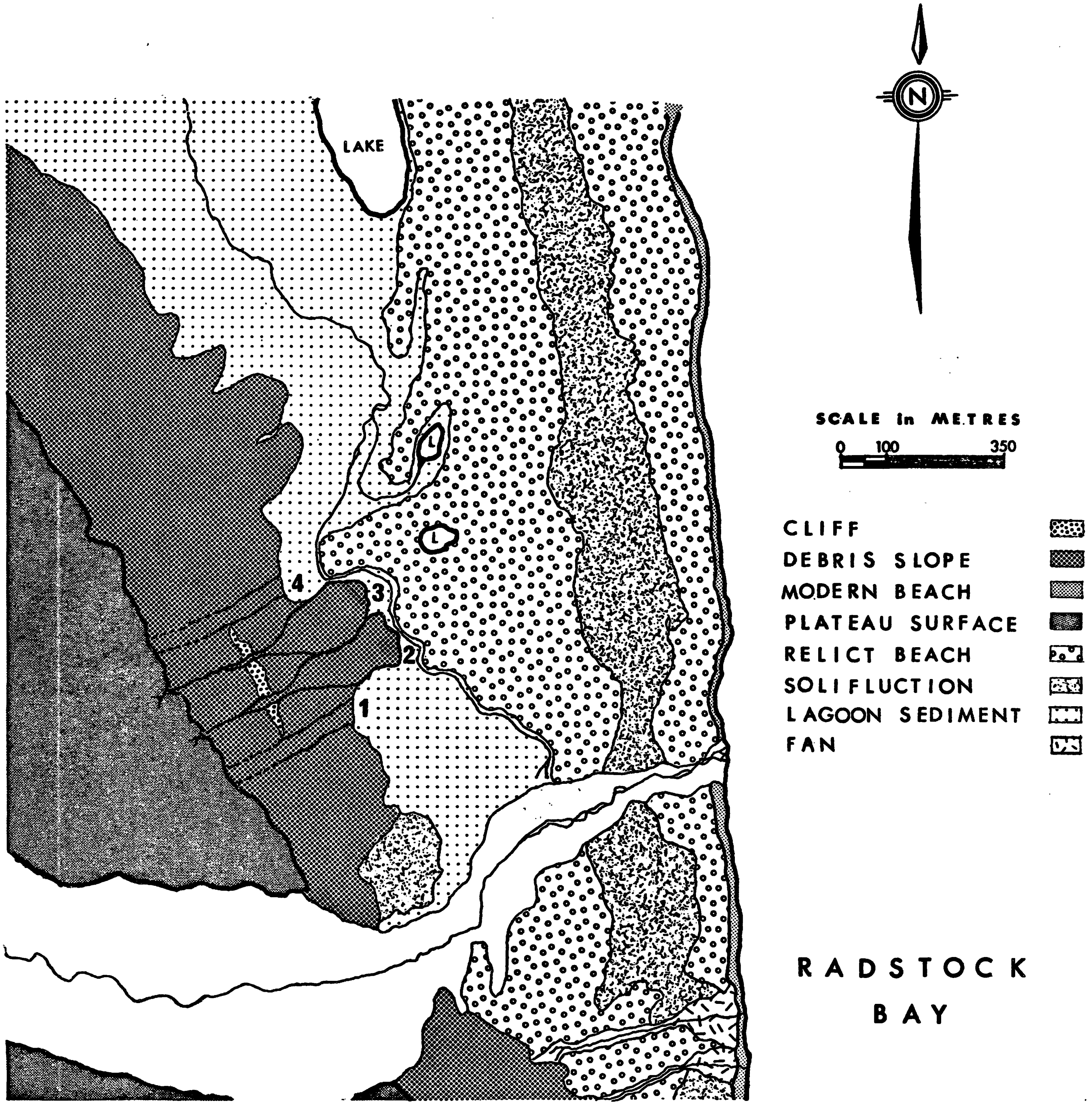
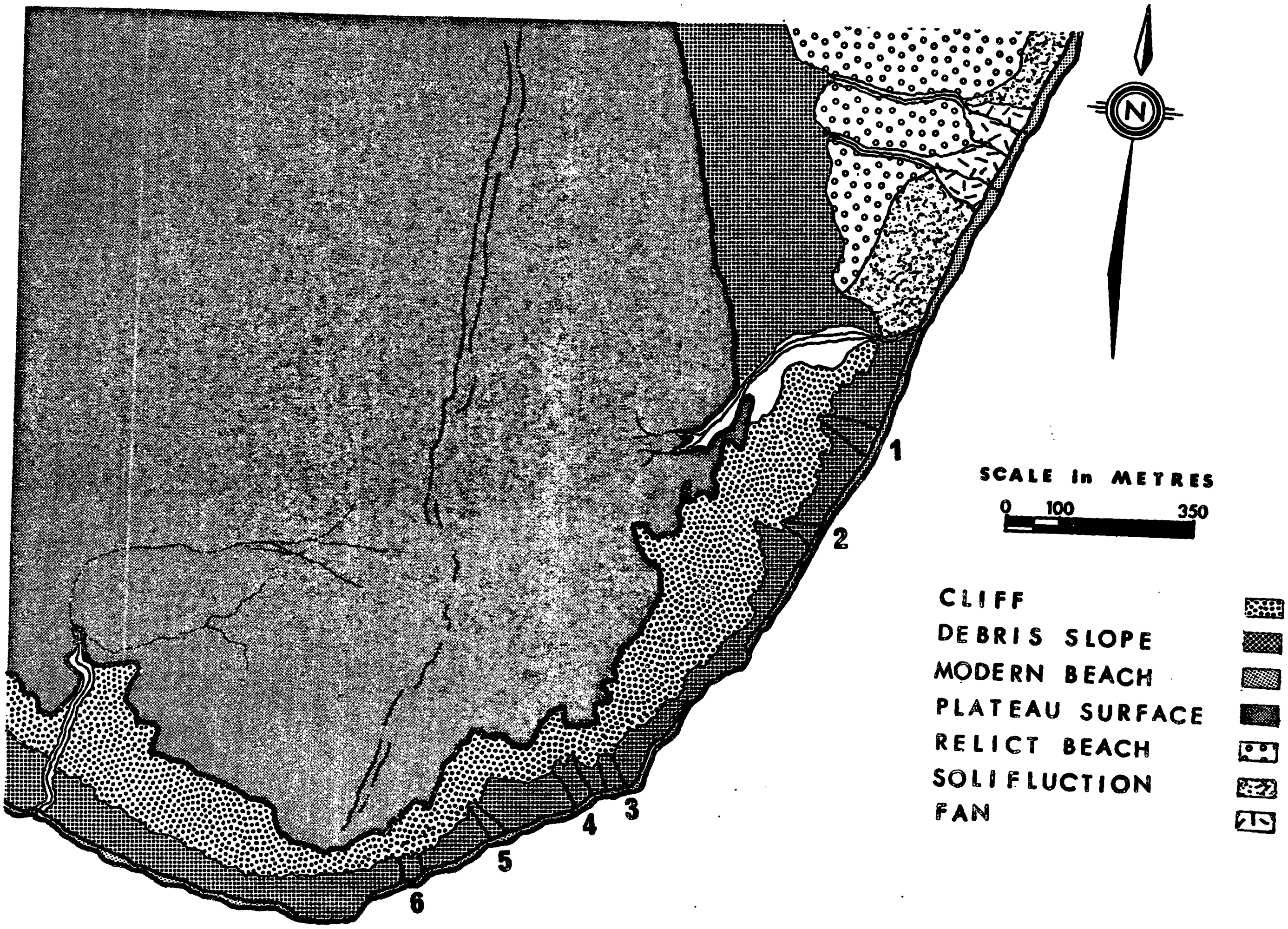

N
LAKE
L
L
4
3
2
1
SCALE in METRES
0
100
350
CLIFF
DEBRIS SLOPE
MODERN BEACH
PLATEAU SURFACE
RELICT BEACH
SOLIFLUCTION
LAGOON SEDIMENT
FAN
RADSTOCK BAY

Figure 8

Geomorphic map of Cape Liddon
and location of investigated slopes.



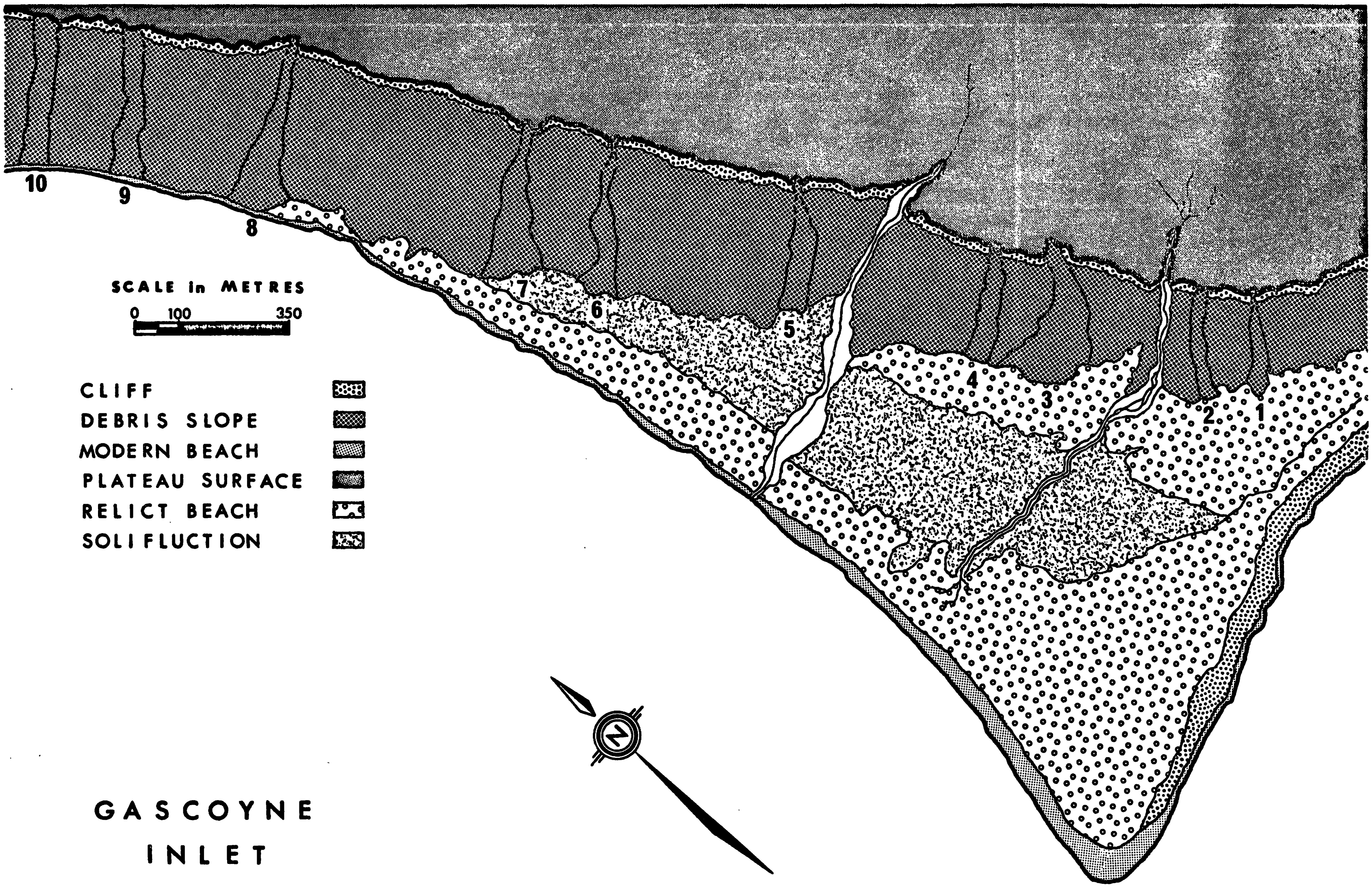
RADSTOCK
BAY

southerly winds coupled with open-water conditions may leave them prone to attack by ice and wave abrasion.

The final locale selected for study is the cliff and debris slope zone of Cape Ricketts (fig. 9). Slopes here are both talus sheets and cones which together extend continuously from south to north along the plateau edge. The slopes are protected from marine action by a series of well-defined marine terraces, a solifluction terrace and a wide expanse of raised beaches behind the modern beach zone. The width of this protective foreland decreases towards the north and Gascoyne Inlet. Plateau height and amount of exposed free-face similarly decrease from south to north, and the northerly slopes appear to have over-ridden the once-protective marine and solifluction terraces. The slopes themselves are vegetation-free, but have been influenced by the meltwater from snow and small pools of water on the plateau surface which runs down the well-dissected cliff-face. Meltwater gullies and lobate "flow" structures are present on most slope surfaces. Ten slopes were studied in this locale and an investigation made of several of the "flow" features.

Figure 9

Geomorphic map of Cape Ricketts
and location of investigated slopes.



GASCOYNE INLET

CHAPTER IV

DATA COLLECTION AND ANALYSIS

(1) Slope Profiles

Various methods of slope surveying are available, each with its own advantages; but whatever method is selected it must be used according to some manner of procedure which is standardized for all slopes and which can be adapted to a great variety of slope conditions. A tacheometric method which employs the Wild T2 theodolite and a survey staff was chosen as the means of surveying debris slopes on southwest Devon Island. Other workers have resorted to a simpler compass and altimeter survey (Crompton, 1968; Stock, 1968; for example), which is much less accurate than the tacheometric survey; but it has the advantage of increasing the time saved on each survey. Since it can fix the location of points in three-dimensional space, the theodolite is a much more versatile instrument in survey work.

The tacheometric survey method was used in a manner designed to record irregularities and changes in form in an upslope direction. The theodolite was stationed more or less in front of the slope base, although its exact position varied because of the range of difficulties encountered in finding suitable sites. For each slope two profiles were surveyed from base to top to represent the right and left sides of the slope. Profile lines were surveyed parallel to each other when a debris sheet was encountered, while for conical slopes the lines converged together as they approached the slope top.

The major problem faced was the inability on unstable slopes to establish or maintain survey stations higher up on the slope surfaces, a situation resulting from the predominance of fine-sized debris and/or the shallow depth of the permafrost table beneath these surfaces. On very steep slopes a minor difficulty arose from the inability to read the staff when it was positioned near the top of the slopes. This problem was remedied by tilting the staff in a downslope direction, which maintains the validity of the survey readings and by special calculation enables the correct height and distance values to be obtained. As regards the problem of instability, the only remedy was to survey as much of the slope as possible. On very long slopes the image of the staff did not always extend across all three telescopic stadia of the theodolite, and so the profile line was discontinued. It would have been possible to continue the profile by re-stationing the instrument upslope, but it was believed that the existing profiles adequately represented the areas of greatest morphological variation.

Tacheometric survey data is converted into values which are used to reconstruct the slope form as a series of straight-line segments. The segments are linked at each field-selected survey station to create a slope profile. Slope angle is then determined from the profile. Profile analysis took place according to a method used by Stock (1968) which provides description, comparison and rank of slope form in terms of the degree of conformity to an idealized slope form. This initial assumption for analysis states that where structural control and the various slope processes are inoperative, and where free-fall of weathered rock debris from a cliff-face above occurs, the debris slope profile approaches a straight line (Stock, 1968). The degree of deviation from this form then infers differential rates of a process or the presence of differing processes. The method is essentially an areal analysis of profiles consisting entirely of straight-line segments. Slope "components" (convex or concave portions) are delimited and used to calculate indices of convexity and concavity for the whole profile. Standardization of slope length is made to allow the creation of dimensionless numbers which are most useful for purposes of comparison. From these indices a sum and a ratio of indices are derived, and the profile is classified according to these terms as one of six types:-

(a) concave
(b) concave with minor convexity
(c) straight
(d) convexo-concave (equal)
(e) convex with minor concavity
(f) convex.

Stock (1968) warns that this method of analysis is inefficient in that it is insensitive to the localized changes which may take place on a slope. On the other hand the system allows comparison of slope form on a quantitative basis, and with the use of dimensionless values a measure of the relative significance of slope form can be made. The southwest Devon slope profiles were placed within the various categories and ranked accordingly (table 1). The profiles for slopes used in this study are shown grouped by locality in Appendix II (1).

An application of Young's (1964) approach to profile form

TABLE 1

Classification of debris slope profiles ranked in order of increasing concavity.

PROFILE NO.	DOMINANT PROCESS	MEAN ANGLE	INDEX OF CONCAVITY	INDEX OF CONVEXITY	SUM	RATIO	FORM
CAS6 (2)	RW	33.60	.0203	.0162	.0365	.8003	4
CAS5 (1)	RW	35.83	.0241	.0080	.0321	.3333	3
CAS3 (2)	BR	37.02	.0261	.0298	.0559	1.1427	4
CAS4 (2)	R	34.23	.0412	.00	.0412	.00	2
CAS1 (2)	R	32.10	.0444	.0737	.1181	1.6584	5
CAS2 (1)	R	33.32	.0455	.0145	.0600	.3182	3
CAS2 (2)	R	33.94	.0482	.0197	.0679	.4086	3
CAS3 (1)	BR	36.72	.0537	.0278	.0815	.5179	3
CAS1 (1)	R	33.02	.0617	.0837	.1454	1.357	5
CAS6 (1)	RW	34.43	.0661	.0058	.0719	.0883	2
CAS5 (2)	RW	33.40	.0698	.0116	.0814	.1665	3
CAS7 (1)	RW	30.65	.0719	.0273	.0992	.3792	3
CAS4 (1)	R	32.73	.1017	.00	.1017	.00	2
CAS7 (2)	RW	31.68	.2567	.0135	.2702	.0526	2
CL1 (1)	R	36.23	.0001	.0032	.0033	28.7273	1
CL2 (1)	R	38.22	.0008	.0004	.0012	.5000	1
CL4 (1)	R	34.00	.0032	.00	.0032	.00	1
CL5 (1)	RW	38.30	.0113	.0056	.0169	.4995	1
CL1 (2)	R	37.02	.0203	.0144	.0347	.7082	3
CL3 (1)	R	36.12	.0608	.0032	.0640	.0526	2
CL6 (1)	BR	39.97	.0699	.6631	.7330	9.4778	3
CL4 (2)	R	37.00	.0722	.0168	.0890	.2323	6

Table 1 Continued:

PROFILE NO.	DOMINANT PROCESS	MEAN ANGLE	INDEX OF CONCAVITY	INDEX OF CONVEXITY	SUM	RATIO	FORM
CL3 (2)	R	35.42	.0841	.0302	.1143	.3595	2
CL2 (2)	BR	37.00	.0857	.0031	.0888	.0364	5
CL5 (2)	RW	36.93	.1225	.0168	.1493	.0138	2
CL6 (2)	BR	39.33	.2373	.5657	.8030	2.3838	3
IN1 (1)	R	33.50	.0358	.0119	.0477	.3334	3
IN1 (2)	R	33.22	.0592	.0072	.0664	.1218	2
IN4 (1)	R	31.75	.0742	.00	.0742	.00	2
IN4 (2)	R	31.68	.0905	.0075	.0980	.0834	2
IN3 (1)	RW	22.53	.1559	.0024	.1583	.0154	2
IN3 (2)	RW	21.92	.2051	.0006	.2057	.0031	2
IN2 (1)	RW	19.78	.2094	.0083	.2177	.0396	2
IN2 (2)	RW	19.75	.2211	.0094	.2305	.0427	2
RK2 (2)	R	33.40	.0227	.0107	.0334	.4703	3
RK4 (2)	R	33.65	.0314	.0085	.0399	.2722	3
RK4 (1)	R	33.60	.0474	.0035	.0509	.0730	2
RK3 (2)	RW	26.85	.0474	.0148	.0622	.3124	3
RK10(2)	R	34.12	.0509	.0092	.0601	.1799	3
RK2 (1)	R	32.90	.0520	.0065	.0585	.1249	2
RK7 (1)	RW	25.95	.0550	.0159	.0709	.2895	3
RK6 (1)	R	30.18	.0588	.00	.0588	.00	2
RK9 (2)	R	32.08	.0657	.0032	.0689	.0493	2
RK10(1)	R	34.90	.0664	.0091	.0755	.1369	3
RK9 (1)	R	31.90	.0677	.0044	.0721	.0657	2
RK8 (2)	RW	29.33	.0694	.00	.0694	.00	2

Table 1 Continued:

PROFILE NO.	DOMINANT PROCESS	MEAN ANGLE	INDEX OF CONCAVITY	INDEX OF CONVEXITY	SUM	RATIO	FORM
RK5 (2)	R	32.06	.0712	.0159	.0871	.2241	3
RK5 (1)	R	31.85	.0775	.0244	.1019	.3177	3
RK8 (1)	RW	29.60	.0838	.0013	.0851	.0157	2
RK3 (1)	RW	31.70	.0885	.0134	.1019	.1515	3
RK1 (1)	R	31.72	.0906	.0115	.1021	.1266	3
RK1 (2)	R	31.70	.0950	.0023	.0973	.0238	2
RK6 (2)	R	30.50	.1389	.0272	.1661	.1959	3
RK7 (2)	RW	24.68	.2319	.0628	.2947	.2708	3

Profiles ranked in order of increasing concavity for each locale.

Key to Form: 1: Straight

2: Concave

3: Concave, minor convexity

4: Convexo-Concave

5: Convex, minor concavity

6: Convex

analysis was attempted but met with no success because it requires both straight and curved slope sectors of which only the curved may be convex or concave. Stock's method is for straight-line segments only and thus was the only method of analysis applicable to the southwest Devon profiles.

One should realize the limitations of slope profiles, since the most that two representative profiles can offer is a very small impression of the overall slope form. Slope form varies greatly both over time and space, and one must be wary of over-theorizing when using straight-line profiles to interpret the events occurring over the whole slope surface (Jahn, 1968b). Much of the interpretation derived from southwest Devon Island slope profiles has fortunately been verified by observation since the area is one in which various slope-forming and modifying processes are still actively occurring.

(2) Slope Samples

A point sampling method was established in conjunction with the survey lines in such a way that each slope would be represented in surface characteristics by six sample sites of 50 stones each (fig. 10). To facilitate comparisons between sectors of a slope and to provide some regularity in selection of sample sites, each slope was divided arbitrarily in the field into upper, middle and basal zones, based primarily on slope length. The survey lines which were run through each zone then allow three points to be selected along each line. The two survey lines then became sample lines from which two representative samples of 50 stones each could be drawn from every slope zone.

The sampling of only six points is justified by the severe limitations imposed by time and the large number of slopes to be covered. The selection of 300 stones by individual sample sizes of 50 to represent the total population of debris on the slope is justified in terms of not only time but also of statistical power analysis which attests to the adequacy of this sample size for correct decision-making in statistical analysis (Cohen, 1969). The division of a slope into three zones was desirable for reasons which include the ease with which such an arrangement facilitates comparison of various areas on slopes of differing dimensions. It also eliminates the task of devising a sampling grid for each separate slope. A more detailed discussion of the sampling procedures and their feasibility will be found in Appendix III.

The system adopted required that for each site a metre-square grid frame was placed over the surface with two of its four sides parallel to the general downslope direction. The frame was then photographed to record the arrangement of the undisturbed debris (plate 1). From the 81 stones hypothetically available for sampling beneath all grid intersections, 50 were removed and the following dimensions were measured:-

(a) A axis: maximum length (mm)
(b) B axis: width, measured at right angles to A (mm)
(c) C axis: thickness (mm)
(d) rock weight: measured on Ohaus Hand Balance (gm)
(e) rock type: one of two major types (III, (1)).

The data for orientation of surface debris is derived from the photographs of the sample grid, according to the method described by Caine (1969).

In this procedure, deviation of the apparent long axis of a stone from the downslope direction is recorded directly into one of nine 20° classes. Vector analysis was employed to determine mean orientation direction and strength for each sample (Curray, 1956). The various levels of significance of the orientation samples were determined by the Rayleigh test tables in Curray (1956). A check upon the validity of the photographic method's use on southwest Devon Island was performed, and is discussed in Appendix III.

Measurement of individual rock fragments provides data which can be manipulated to produce several statistics descriptive of both size and shape. Size parameters chosen for use in sediment studies have varied freely between the three axes measurements. King & Buckley (1968), for instance, use long axis to distinguish between size of sediment in various depositional environments; Crompton (1968) uses intermediate axis for determination of size sorting over slopes; while Caine (1967) has derived size by expressing stone volume and a correction factor as a nominal diameter and converting it to phi units. King & Buckley (1968) also make use of long axis mean and standard deviation to express size sorting values in dimensionless terms, enabling an assessment of overall size differences between samples. These measures were all considered in the attempt to determine size sorting trends in the study area before long axis measurements were finally selected as the most suitable size parameter (Appendix III).

Another valuable use of axis measurements was to compute the following shape parameters:-

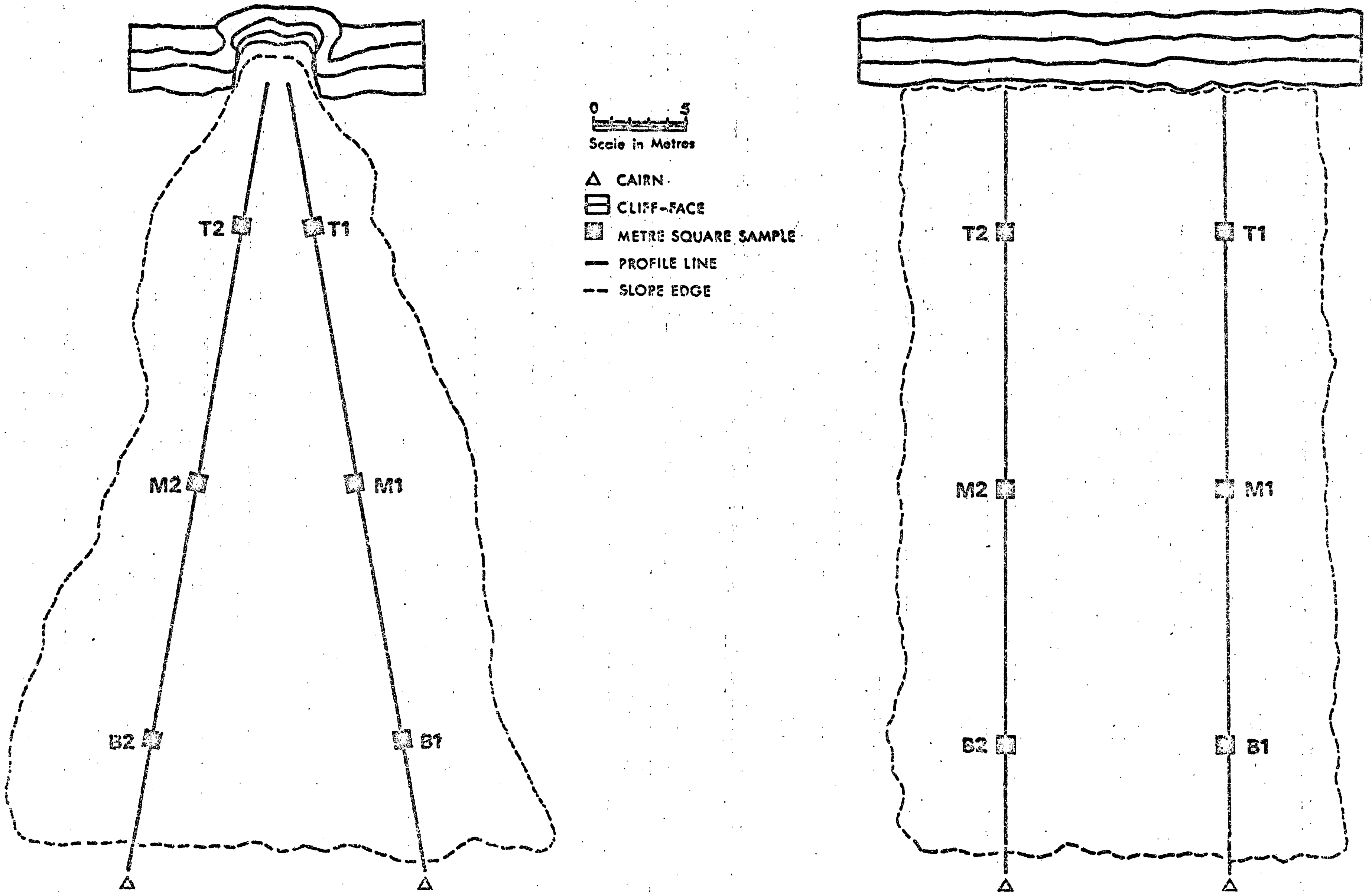
(a) flatness (Cailleux, 1945): $(a+b/2c) \times 100$.

(b) sphericity (Krumbein, 1941): $\sqrt[3]{(bc)/a^2}$.

Figure 10

Sampling grid employed on

debris slopes of southwest Devon Island


T2
T1
M2
M1
B2
B1
0
5
Scale in Metres
△ CAIRN
CLIFF-FACE
METRE SQUARE SAMPLE
PROFILE LINE
SLOPE EDGE
T2
T1
M2
M1
B2
B1

Roundness, generally acknowledged as a valuable assessor of varying energy and process situations for many depositional environments, is not relevant to primary slope deposits in a periglacial setting because the material has not been modified from its frost-shatter inherited angularity. Sphericity provides an index to the equality of rock dimensions and is strongly associated with lithological factors such as width of beds, number of planes of weakness, and the density and spacing of joint patterns. Both flatness and sphericity provide a good measure of the variability of rock shape and tend to be inversely proportional to each other (King & Buckley, 1968). Another method of determining shape, that provided by Zingg's shape categories (Krumbein, 1941), was employed for purposes of visual comparison of the slope samples.

The recording of rock type enabled computation of the percentage of occurrence of each type over the slope in the hope of relating this variable to any noticeable changes in debris shape.

Using the data inputs of axis measurements, rock weight and type for each rock, a computer program was devised to calculate the desired size and shape parameters and their mean, standard deviation, skewness and kurtosis. When tested against the critical values provided in Jones (1969), skewness and kurtosis values prove readily available for instantaneous assessment of the normality of population distributions from which the samples are drawn.

Having met the assumptions of normality and homoscedasticity, data becomes subject to treatment by parametric statistic; and for size and shape a two-way analysis of variance (ANOVA) with a 2x3 factorial design was established to test for basic patterns of arrangement.

This design required the use of all six samples of 50 stones from a slope in an attempt to explain variance in terms of two main sources, namely zonal (upslope) and lateral (cross-slope) sources. The remaining variance, termed error variance in this test, refers to variation that occurs between rock debris fragments. When a significant (at a specified level) test statistic (F) is calculated for any given effect, a specific arrangement of the dependent variable (size or shape) is implied which requires that consideration be given to some observed process or event which has created that particular arrangement.

Conversely, if test statistics calculated for both effects are not at a significant value, it represents the fact that these effects are not significantly greater than error variance. Therefore variation is greatest between rock fragments and the dependent variable is homogeneous on that slope since it shows no systematic arrangement over its surface.

When more than one non-error source of variation is parcelled out, it becomes desirable to know the degree of relationship that each one shares with the dependent variable. The calculation of eta (η), the correlation ratio, provides a relationship (rho) statistic which is valued not only for comparisons of sources within a test, but between them as well (Cohen, 1965). Eta is the degree of correlation between the designated effect and the dependent variable. Eta^2 is similarly valuable not only as an estimate of variance which can be predicted by a source, but as a representation of the proportion of non-error variance accounted for by that source. For these reasons, eta was calculated for all test statistics derived from analysis-of-variance of size and shape data.

Various samples were collected from the slopes which were related not to the studies of slope debris characteristics but to process effects. At the necks of several Cape Liddon slopes, samples were taken in 1969 of the surface material which is derived by weathering of thin-bedded rock in the free-face above. In the prethaw period of June, 1969, a collection was made of the fine-sized debris found overlying snow and beach-fast ice beneath these same coastal slopes. Samples were analyzed for sediment size characteristics and the results compared by both visual and statistical methods. In addition, samples from the material which composes the many debris lobes on the Cape Ricketts slopes were taken and analyzed in the same fashion to determine the basic size characteristics.

Finally, an attempt was made over the 1970 field season to trap debris falling from the free-face above several coastal talus slopes. Metre-square polythene plastic sheets were anchored at six points in the upper, middle and basal zones of each slope in order to obtain some idea of the volume and rate of accumulation by rockfall in this period. The contents of each catchment area, where available, were measured, weighed and identified for later analysis.

(3) Tracer Experiments

During the 1970 field season a limited number of tracer experiments were conducted to obtain general information on the nature of sub-surface meltwater flow in debris slopes. The application of such experiments to debris slopes in mid-latitude regions is not easy because of the high porosity created by the angularity of constituent material. Tracer experiments have not therefore been included anywhere in debris slope studies to this author's knowledge. In contrast Arctic debris slopes provide the opportunity to trace waterflow beneath the surface due to the presence of a permafrost table which minimizes porosity and acts as an impervious layer to force sub-surface meltwater from all sources to flow above it. Its presence at generally less than 60 cm. below the slope surface during the summer enables a reasonable tracing of sub-surface meltwater patterns and rates on Arctic debris slopes.

The tracer tests were divided among three talus cones selected for their favourable dimensions and presence of varied meltwater conditions. Cone T1 (CAS5), is 50 m. long and lies on the seaward-facing, eastern side of Caswall Tower. T2 and T3 are cones of 60 and 70 metres in length, respectively, and are situated approximately 1.6km east of Cape Ricketts along the south-facing, seaward edge of the major plateau. T1 and T2 are "concave, slightly convex" in form, while T3 has a straight longitudinal profile. All three are characterized by convex cross-slope profiles, and their conical shape is delimited by inter-cone depressions which separate them from adjacent cones. Profiles of the three tracer slopes are found in Appendix II (2).

Three basic meltwater situations were studied in relation to their rate and pattern of flow through these three similar cones. Meltwater entering slopes as a waterfall, meltwater derived from the ablation of snowpatches on the cones, and meltwater derived from an ablating permafrost table beneath the cones were the three conditions studied.

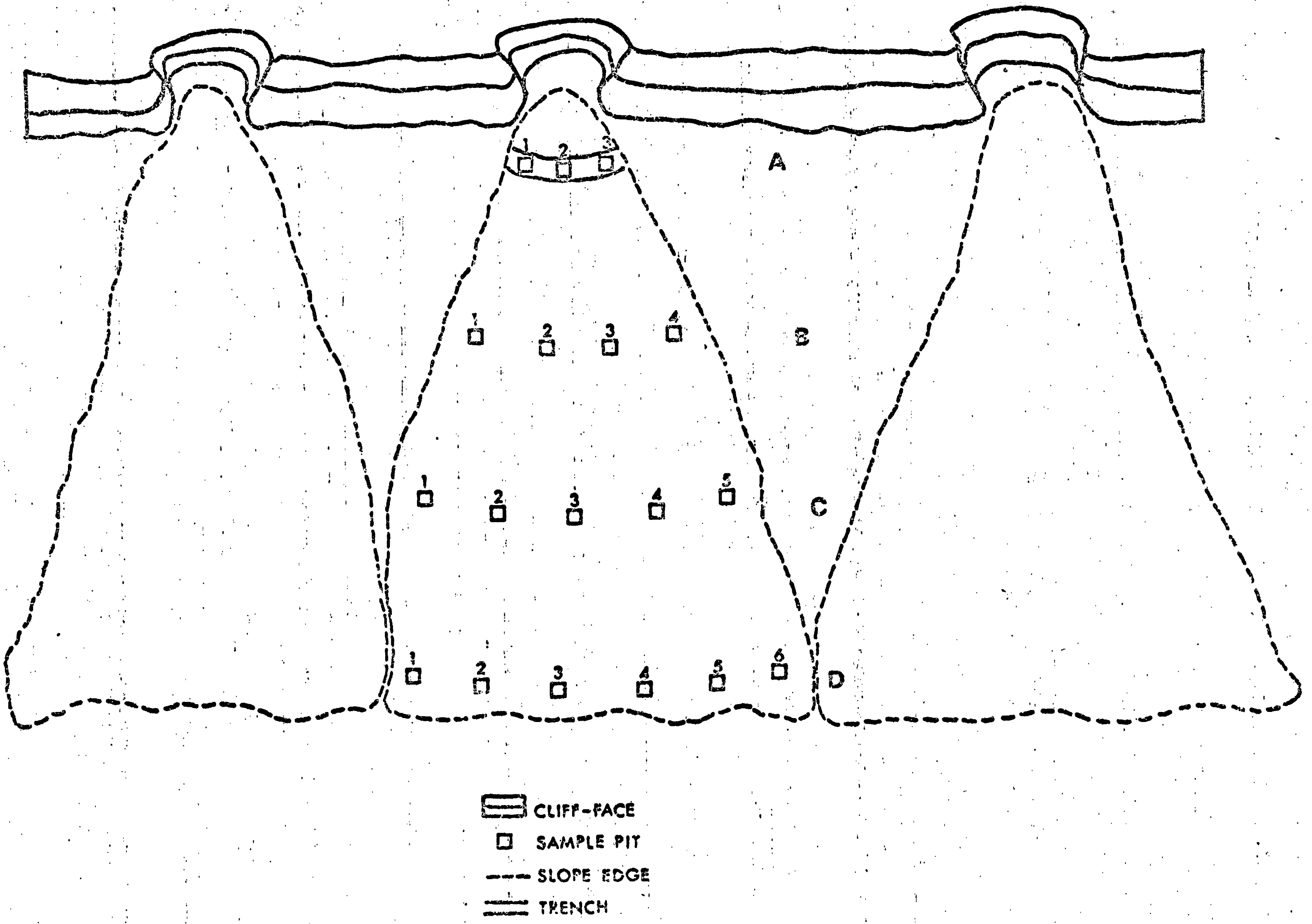
Slope T1 was studied for its waterfall flow, T3 for its ablating snowpatch, while T2 was used to study both waterfall, snowpatch and permafrost meltwater flowage.

Five experiments were conducted throughout the period June 29 to August 7. Waterfall and snowpatch tracer tests were conducted during the peak melt-period of early summer, while the permafrost meltwater study was postponed unitl August, by which time the snowpatch and waterfall on slope T2 had both disappeared. All tests were conducted in the early afternoon on days in which optimum melting conditions were available, ie. cloudless skies, +40°F maximum diurnal temperatures, and a negligible wind factor. The tracer experiments followed a basic but flexible procedure which allowed adaptation to slope width and local relief variations. A measured amount of Rhodamine BN dye (40%+solution) was applied to the most appropriate meltwater entry point in the upper slope zone (either a pit or lateral trench, depending on whether the meltwater is derived from a waterfall or a snowpatch). The time which elapsed before the dye appeared at any of the points in a pre-constructed network of pits was noted. The basic grid system (fig. 11) consisted of a series of equally-spaced pits excavated into the slope surface, and each level was spaced about 20 or more metres downslope from the next. For each excavated pit the depth of the permafrost table and presence of any type of water flow within it was recorded.

The data obtained were combined with additional observations to derive the necessary information about pattern, rate and importance of sub-surface runoff as an active slope process.

Figure 11

Basic grid system employed in
sub-surface runoff experiments on debris slopes.


A
B
C
D
1
2
3
1
2
3
4
1
2
3
4
5
1
2
3
4
5
6
CLIFF-FACE
SAMPLE PIT
SLOPE EDGE
TRENCH

CHAPTER V

SLOPE MORPHOLOGY AND BASAL EROSION

(1) The Process

Basal erosion is defined in this study as the act of any process to undermine a slope and remove material from its base. References to basal erosion in the past have been primarily applied to fluvial undercutting of valley-side slopes (for example, Wood, 1942); but it is known that a different process, marine action, can produce a much more vigorous form of basal attack upon slopes in a cliffed coastal area. Wave energy is applied directly onto a coastal slope, while fluvial energy is expended laterally along valley-sides and is therefore less effective as an erosive force than marine action. Basal erosion has been mentioned in relation to coastal platform development in New Zealand (McClean & Davidson, 1968), but the process is not a direct erosional agent here because it is mass movement which supplies material to the waves. Along sections of the coastline of southwest Devon Island basal erosion by direct marine attack appears to play an occasional but important role in slope development.

Two forms of basal erosion can occur along this coastline, both of which depend upon the existing extent of sea-ice cover and the nature of the pattern of its break-up. Erosion is accomplished through the two processes of ice-push activity and storm-wave activity. For ten months of the year the Arctic coastline in the study area is protected from basal erosion of any type by a solid sea-ice and beach

-ice cover (McCann & Owens, 1970); but as the ice breaks up into sections during the summer and begins to float out into Lancaster Sound, the possibility arises that adverse onshore winds may push this floating ice back into shore. Ice can in this fashion become an agent of erosion on coastal slopes. When the sea-ice cover is eventually removed from the vicinity, strong offshore winds over a long fetch may again foster basal erosion of slopes, this time by storm-wave activity. Open or partially open water conditions may, then, provide the conditions suitable for basal erosion of coastal slopes when combined with adequate wind speed and wind direction.

Basal erosion was observed in both forms along the Cape Liddon coastline, and to a lesser extent along the sea-ward facing Caswall Tower slopes. Both areas were affected because they meet two natural pre-requisites: one, they face southeast towards the direction of longest wave fetch; and two, their slopes are poorly protected by very narrow beach zones and steep offshore relief. These conditions allow pack-ice to reach the beach zone instead of grounding upon a shallow offshore platform which occurs elsewhere. Thus the likelihood is increased that pack-ice pressure caused by strong onshore winds will push the icebergs over the narrow beach and into the base of the slopes at the rear. Similarly the narrow beach and steeper offshore profile allows storm waves to traverse farther over the beach zone where they can influence the slopes with direct contact of waves or wave spray.

Several talus slopes were subjected to marine erosion at base due to the influence of two major storms during the summer of 1969 (III, (2)). The first occurred during the period July 25-26, under conditions of partially-open water. Pack-ice, floating offshore across the entrance to Radstock Bay, was pushed onshore into the base of several Cape Liddon slopes by 22m.p.h. winds blowing from the southeast. The storm of August 11-12 occurred while ice-free conditions prevailed in Radstock Bay. Southeast winds gusting up to 42 m.p.h. generated storm waves with heights sufficient to overrun the beach zone at both Cape Liddon and Caswall Tower with the result that several talus slopes were eroded at base.

(2) Observed Effects in the Study Area

The type of landform modification initially created by basal erosion varied. Where most effective, wave erosion commonly made a near-vertical cut of 2-3 metres in the slope base. On several Cape Liddon slopes erosion uncovered the frontal sections of what appears to be a wave-cut rock platform (plate 2), likely formed before post-glacial debris accumulation when sea-level was higher than at present. Where less effective, ie. where erosion resulted from wave spray, basal areas of slopes were initially bared of surface debris but not appreciably altered in form.

Erosion by ice-push was less distinctive. Icebergs were pressured into the base of slopes, but the presence of a high permafrost table served to minimize the amount of surface debris removed. Push on some Cape Liddon slopes reached a maximum height of 20 metres above beach level. Conditions which followed, such as high tides, caused an eventually removal of the ice from the slopes.

One of the features commonly exposed by ice-push erosion was a layer of crystalline ice protruding from beneath the upslope surface debris. This layer or ledge is quite distinct from the underlying permafrost table because of its coarse crystalline nature, its thickness and lateral variation, and the absence of debris locked within it. These ledges were observed in several different locations and are interpreted as compacted remnants of snowbanks accumulated during winter along the base of Cape Liddon slopes. These snowbanks are overrun in the peak melt period by debris brought down by rockfall and snowmelt, and are consequently compacted and re-crystallized to form ice. Such an origin aids in explaining why the ice ledges are observed to vary laterally in extent and longitudinally in thickness. The layer was traced upslope for several metres at one particular site due to the presence of a slope gulley exposure, and was observed to grow progressively thinner before eventually merging into the permafrost table (plate 3). This explanation of origin by compaction is similarly reinforced by observations at Cape Liddon in October, 1969 when snow accumulations were seen at the basal areas in question. In the early summer of 1970, thick blankets of debris overlay these snow accumulation zones to the extent that the areas were mistaken for actual extensions of the slope foot. It is this debris cover which prevents rapid ablation of the underlying snowbanks and in time aids in the compaction process.

The readjustment of slopes following basal erosion was recorded by interval photography at three basal-cut areas along Cape Liddon following the storm of August 11-13. The sequence of events was similar at all sites, the only variable being the rate and extent of readjustment. Wave erosion on the slopes consistently created a basal-cut area which in some places was topped by an overhanging ice-ledge (described above).

Subsequent melting of the ledge caused debris from immediately above the cut to be transported downslope over the vertical area where it was deposited in a small pile. On all slopes, melting of the exposed ice and permafrost caused flowage of the surface debris below and above it by creating instability in the immediate upslope areas. An upward baring of permafrost by removal and deposition of debris downslope thus began to occur. As the sequence extended farther upslope, the size of material affected became confined to larger debris, and the rate of exposure slowly decreased until local slope areas became stabilized. The material deposited at base eventually buried the basal abrasion scar to create a new slope foot with an angle similar to the one present before marine erosion. Plates 4 and 5 demonstrate the difference between the surface characteristics of a Cape Liddon cone at different stages of readjustment to basal erosion.

Where a rock platform had been exposed by storm wave erosion, the accumulating material from readjustment eventually covered the platform. Plate 6 shows such an area in a later stage of accumulation.

A return to the sites early the following summer indicated that the readjustment phase does not normally extend to the top of the slope; but rather it reaches some critical height at which sufficient material has accumulated downslope to enable slope instability to be minimized. Furthermore, some of the basal-cut areas revisited at Caswall Tower in 1970 had not re-formed over the winter, and so it must be emphasized that readjustment to profile change will be affected by other factors such as magnitude of the basal erosion, rate of accumulation of rockfall material, and the initial nature of the slope debris and profile.

The vertical cuts revealed an interesting stratification of debris within the permafrost layer. A typical cross-section through the deposit is indicated by plate 7. Here, the uppermost part of the 60cm. permafrost layer lies at slope bottom and contains fine silt or sand within it. Above it is found a 40cm. layer of coarse, angular debris incorporated within the ice; while separating it from the present slope surface debris there is a 10cm. layer of granular ice, believed to be derived from compacted winter snow accumulations. In two other basal-cut sections, distinctively rounded and greyish beach gravels were found locked within the permafrost between layers of angular slope debris at heights well above the present sea-level. This type of exposure is shown by plate 8, and indicates above all the complicated sequence of past events and processes in the area.

(3) Profile and Debris Characteristics

The angle and profile form of basally-eroded slopes, along with the size, shape and orientation characteristics of their surface debris suggests that the process in question has a distinctive and pronounced effect upon those slopes. This section analyzes the various characteristics as they appear on slopes at both Caswall Tower and Cape Liddon.

Comparison of the five slope profiles taken from basally-eroded slopes indicates a slight diversity of form, and it is attributed to variations in intensity of marine attack which occur between the various slope locations. Of the six profile form categories employed (Stock, 1968), all are equally represented with the exception of "concavity."

No completely concave profile form was recorded, a fact which is consistent with the expectation that convexity will be introduced into a basically rectilinear slope form when a vertical basal-cut is made. The three profiles from the area most severely affected, Cape Liddon, can be arranged into two completely or dominantly convex and one rectilinear slope. This latter deviation from convexity merely reflects the duration of time allowed before the slope was surveyed; for the slope in question is steep and short, and the readjustment to the basal erosion was rapid enough to restore the slope profile to its former state and eliminate the element of convexity introduced. At Caswall Tower, where marine attack was less severe because of its more-protected location, slopes maintain an element of convexity but it tends to be overshadowed by greater concave components on the slopes. Due to the low magnitude of basal erosion here, the readjustment of the surface became stabilized at a level only a few metres above the basal cut; and thus the convexity introduced into the profile by erosion was insufficient to significantly alter the concave profile inherited by rockfall accumulation. Convexity manages to equal concavity on one profile and form a minor element on the other. That these two CAS4 profiles differ in degree of convexity is offset by results of the non-parametric tests performed, which confirm that no two profiles drawn from the same slope differ significantly in form. Results from both locales then suggest that the convexity introduced to a profile by basal erosion varies in extent and duration depending upon readjustment rates, length and steepness of the debris slopes.

The long-term effects of basal erosion are also reflected in slope angles (table 1).

The values for Cape Liddon slopes are greater than those for Caswall Tower by almost 3° and again the difference is attributed to variations in frequency and intensity of basal erosion between the two areas. Where basal erosion is recurrent, rates of removal of debris from the affected slopes will overtake rockfall accumulation rates unless occasional catastrophic events sharply increase rockfall supply (ie. a blockfall). When removal becomes greater than accumulation, the slopes will become steeper in angle and straighter in form. Since the location of Cape Liddon slopes makes them more susceptible to both storm-wave and ice-push erosion than their Caswall Tower counterparts, the steepening of Cape Liddon slopes is assumed to have been going on for at least the past half-century, given constant rockfall accumulation rates. Since the probability of such a storm is only about one in every seven years (McCann & Ingram, 1971), seven attacks with intervals for readjustment are possible in the last 50 years. This number is more than adequate to account for the steep slope angles experienced here. Slope angles are lower in the Caswall Tower cliff area because of the much lower incidence of basal erosion there. The difference in height of overlying marine cliff may also account for a discrepancy between angles in the two localities; for the higher rockwall over Cape Liddon slopes (300-350 metres) offers not only a greater source area of debris but also a greater height of fall of much of it. If the latter is true, additional momentum created in gravity fall will carry much of the larger debris over and beyond the limits of the slopes below. This means that although the Caswall Tower cliff-face offers a smaller source area (150-200 metres), accumulation below may be greater than upon Cape Liddon slopes and hence angles will be lower.

Values of mean skewness and kurtosis for each debris sample site proved the sample distributions to be representative of normally-distributed populations (Jones, 1969). Consequently analysis of variance tests were used on size and shape characteristics. The test for the two-way factorial design employed here requires that all six of a slope's surface samples be included, and therefore the single basal erosion sample line of slope CL2 was omitted because it provides only half of the required samples. Only two slopes then are available for study as basal erosion slopes.

Results of the analysis in table 2 reveal that of the two slopes only CAS3 is continually characterized by significant arrangement of debris shape into zones or vertical sectors. Both flatness and sphericity show significant zonal and lateral arrangement on CAS3, while the Cape Liddon slope has only one significant arrangement, that of lateral arrangement in flatness. It is concluded that on the whole, shape on CL6 is rather homogeneous since the one significant arrangement accounts for less than 3% of the total variance in shape.

For slope CAS3, shape is heterogeneous over the surface although eta values suggest that zonal effect is more highly correlated with shape than is lateral effect. In fact, both flatness and sphericity values for zonal arrangement are similar in proportion of variance explained. The trends shown in ANOVA results are towards higher zonal than lateral arrangement. Shape is therefore concluded homogeneous on the Cape Liddon slope and heterogeneous on the slope sampled at Caswall Tower.

Analysis of size variation over the slopes indicates that only

TABLE 2

Summary of Test and Relationship Statistics for ANOVA of debris size and shape on Basal Erosion Slopes

Slope Location	SIZE		FLATNESS		SPHERICITY	
	Between Zones 'F' (eta)	Between Lines 'F' (eta)	Between Zones 'F' (eta)	Between Lines 'F' (eta)	Between Zones 'F' (eta)	Between Lines 'F' (eta)
CAS3	11.72^{+} (.27)	0.27ns (.03)	6.66^{+} (.21)	2.04ns (.08)	6.27^{+} (.20)	3.91^{*} (.01)
CL6	0.29ns (.04)	0.60ns (.04)	1.88ns (.11)	8.35^{+} (.17)	1.31ns (.09)	0.24ns (.03)
INLAND	-	-	-	-	-	-
C.RICKETTS	-	-	-	-	-	-

$^{+}$ significant at .01 level

* significant at .05 level

ns: not significant

the Caswall Tower slope has a significant size arrangement (at the .05 level). On the Cape Liddon slope neither zonal nor lateral arrangement in size is significantly greater than error variance, ie. the variation between fragments. Of the total variance, zonal and lateral effects offer the same proportion of explanation, which is less than 1%. In contrast to this size homogeneity, the Caswall Tower slope does portray a significant zonal arrangement which accounts for 7% of the total variance (table 2).

Both size and shape values on CAS3 therefore show zonal arrangement to be significant for size and shape, while on CL6 size and shape are for the most part considered homogeneous. Comparison of all values of the relationship statistic eta indicates that zonal effects are more highly correlated with both size and shape than are lateral effects on the basal erosion slopes. The discrepancy in values between the slopes is believed to arise from the minimal response of slope CAS3 to low-magnitude basal attack compared to CL6's rapid readjustment following high intensity abrasion. The expected consequence of such activity following profile change is the re-distribution of debris of all sizes from the upper and middle-zone areas by downslope shifting over the slope surface. If the reasoning is valid, then the Cape Liddon slope is a typical example of the ideal basally-abraded slope by displaying size and shape homogeneity over the surface and thus no selective sorting.

Since slope CAS3 experienced very little readjustment to counteract its basal-cut the redistribution of material from upslope areas over the surface did not occur; and hence the zonal size arrangements created by fall-sorting of rockfall debris, plus heterogeneous shape arrangements from variations in source lithology, have remained intact. A more vigorous basal attack might have destroyed zonal size arrangements by removing most large blocks from the base and replacing them after readjustment with various other sizes of material derived from both middle and upper slope zones. In the same fashion the various pockets of material with small shape variations within them would be broken up and mixed together downslope.

Orientation analysis of the fifteen basal erosion slope samples resulted in recognition of seven preferred orientation patterns (significant at levels of a=.10 on the Rayleigh test chart in Curray (1956). As shown in table 3, this 47% of the total number of basal erosion sample patterns displays nearly equal preference for downslope and cross-slope directions; and these are similarly prevalent in each of the zonal locations of the samples. However, only one sample arrangement is significant at the a=.05 level, and this is oriented downslope.

On a basal erosion slope's surface one would expect to discover a directional preference in the area of slope readjustment, since the sliding of material occurs. On slope CAS3, though, such a preference is found not in affected areas but in the upper slope zone; although it is only a weak preference (significance level of a=.09). This pattern is a product of rockfall sliding rather than readjustment because the latter process did not reach that far upslope. That readjustment was not intense accounts for the lack of any significant directional preference over the lower slope areas.

At Cape Liddon, preferred orientations are found in each zone of slopes affected by basal erosion; and the significant levels of

TABLE 3

Directional Preferences of Significantly-Oriented Samples on Basal Erosion Slopes

SAMPLE SITE	MEAN VECTOR DIRECTION	SLOPE PREFERENCE	LEVEL OF SIGNIFICANCE
CL2 base 2	160°	D	.09
CL2 mid 2	55°	C	.10
CL2 top 2	86°	C	.06
CL6 base 1	71°	C	.07
CL6 mid 1	17°	D	.05
CL6 top 2	85°	C	.06
CAS3 top 1	25°	D	.09

C: cross-slope

D: downslope

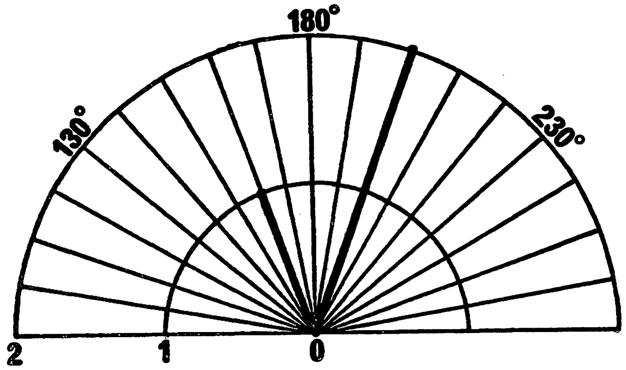
alpha reveal that CL6, the slope subjected to the strongest basal attack, has stronger orientation preferences than does the CL2 slope which has not been so severely abraded. An equal occurrence of both downslope and cross-slope preferences on these slopes suggests that diversities arise due to the varying degree of instability experienced in different areas. Figure 12 indicates that cross-slope orientations are more strongly aligned than are the downslope orientations for basal erosion samples found significant. Rotation of material to any particular direction will then vary from slope area to slope area, although the strongest orientation preferences are generally found in the upper slope zone. No single directional preference can therefore be associated with basal erosion on slopes, but there should be a relatively high probability that preferred orientations will arise from the event.

Considering then the whole range of samples and profiles taken from slopes affected by basal erosion, there arises the recurrent explanation of discrepancies between Caswall Tower and Cape Liddon slopes being due to variations in the magnitude of basal attack and degree of resulting readjustment to the profile change introduced by that action.

Figure 12

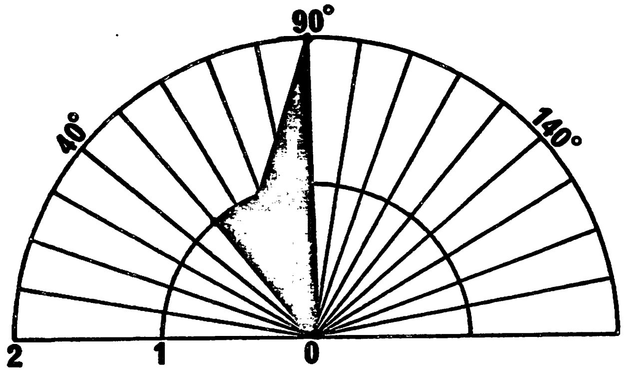
Alignment of significantly-oriented samples on basal-erosion slopes.

A, downslope; B, cross-slope.



A.

DOWNSLOPE DIRECTION = 180°



B.

CROSS-SLOPE DIRECTION = 90°

CHAPTER VI

SLOPE MORPHOLOGY AND ROCKFALL

(1) The Process

Rockfall, with subsequent deposition of the fallen material constitutes the major agent of profile construction on talus slopes (Stock, 1968). The rockfall process entails release and deposition of rock fragments from mountain walls and cliffs by mechanical weathering of the rock face. Deposition occurs by free-fall of the weathered fragments. Variations in the form of weathering involved in rockfall are in part responsible for the type of debris slope which is formed below any particular rockwall. The channelling of debris derived from a concentration of rockfalls on one particular wall section most often results in the formation of a talus cone, enhanced by the gulleying or dissection in the rockwall itself; while random rockfall along a uniformly-surfaced rockwall tends to produce a sheet-like accumulation. The continual channelling of rockfall material onto adjacent cones can result in the lateral coalescing of slope basal zones to form a coalescent cone. Generally the amount of dissection probably affects the rate of rockfall because greater dissection means a greater amount of exposed rock surface on which mechanical weathering can occur.

Rockfalls occur in response to environmental conditions. Rapp (1960b) classifies rockfall on the basis of release mechanisms, which are:-

(a) frost bursting

(b) thermal changes

(c) heavy rains and humidity

(d) snow block falls

(e) ice block falls

(f) chemical weathering

(g) wind

(h) creep

(i) earthquakes.

On southwest Devon Island (a), (b), (c), (d), and (g) are likely the dominant release mechanisms in action, although frost-riving (bursting) is probably the greatest single contributor to rockfalls in this area. This mechanism has been discussed previously (III, (2)) as a cause of primary rockfalls, which involves the breaking and fall from rockwalls of a rock directly onto the slope surface (Rapp, 1960a). In contrast secondary fall implies the fall of rock that was already in a loosened state and resting on ledges, outcroppings, etc. Precipitation in the summer months is primarily responsible for causing secondary falls by rainwash undermining or saturating loose rocks (Rapp, 1960b); although strong winds may also release secondary falls of small fragments. Snowfalls also start off secondary falls when sweeping over the rockwalls. In both primary and secondary fall situations, rockfall occurs as either an individual fall or as a collection or shower of rocks falling simultaneously. It deserves mention, however, that in spite of all the known mechanisms, rarely is it possible to ascribe any one of them to any particular rockfall observed in the field.

Temperature at the rock surface is one of the more important micro-environmental elements, reflecting both air temperature conditions and the effect of solar radiation (Gardner, 1968). A study in the Canadian Rockies by Gardner (1968) shows a covariation between rock surface temperatures and rockfall frequency, with the peak of rockfall activity corresponding to the peak in rock surface temperature. The thermal changes probably affect rates of expansion and contraction of individual rock grains and hence cause mechanical breakdown.

The effect of any rockfall will depend largely upon the nature of the rockwall surface, the height of fall of the fragments, and the size of the initial rock material. The nature of the bedrock in this area is especially favourable to the occurrence of rockfalls. The looseness of the rock, especially on the marine cliffs, suggests that the combination of thin and thick-bedded rock types increases the probability of occurrence of mechanical weathering. An initially large block, falling unobstructed over a long distance will very likely roll or bounce down the talus surface intact after landing. The same block, if in collision with rock ledges and outcroppings on its fall may shatter into small fragments, some of which may not reach the talus slope but will collect upon rock ledges. Of the fragments which do reach the talus neck, many are unlikely to travel far downslope since their acceleration is governed by low mass of the particles. Assuming equal velocities (ie. constant height of fall), the greater the size of a rock the farther downslope it will travel because of the increase in kinetic energy that accompanies a size increase. Under these conditions a crude fall-sorting should occur (III, (2)), with the size of material deposited over the surface increasing in a downslope direction. The downslope sorting will not, however, be perfect, if not because of the action of other processes in altering this condition.

then because of chance factors alone. Shape of the falling debris will affect its nature of fall and thus affect the fall-sorting process. Slope angle and surface roughness created by debris already deposited will similarly vary the rate of loss of kinetic energy of a falling rock and affect fall-sorting.

As material continues to break away from the cliff face, however, erosion of the cliff is progressing at a rate proportional to the rate of mechanical weathering upon it. Rockwall retreat in the form of parallel backweathering then occurs on the upper sectors of the rockwall while continual accumulation lower down begins to cover and protect increasingly larger sections of the lower rockwall. It is the backweathering which produces an irregular, dissected rockwall surface (Bird, 1967). The debris burial of the free-face is not uniform, and so protrusions into the lower debris slope emerge as the more resistant bedding planes. A composite slope of many smaller debris slopes is created before the entire face is covered. Differences in accumulation rates across a horizontal plane are also due to resistant beds and thus they often appear as pinnacles and turrets in the upper slope zones. Bird (1967) believes this combination of events is uniform for limestone cliff evolution under periglacial conditions.

(2) Observed Effects in the Study Area

In the Radstock Bay area rockfalls were observed by the author on sunny, windless days during mid-October of 1969, a period during which maximum diurnal air temperatures did not rise beyond 16°F (Appendix I (2)). In addition, at the time of arrival in the field in 1970 much rockfall activity had already occurred on the coastal slopes yet air temperatures had still to reach 32°F for any lengthy period during the day. Rockfall activity continued throughout the peak melt period and on into the summer; and based on observations in 1969 it probably continues until at least the end of October when consistently cold temperatures, plus the onset of polar darkness, put an end to frost-riving, thermal change and rainfall as significant trigger mechanisms.

Cape Liddon was noticeably the most active locality for rockfalls, having both the highest section of exposed cliff-face in the area (300-350m) and the greatest amount of rockwall dissection. Caswall Tower is the second most active rockfall locality, but activity is confined to a much lower cliff-face which reaches only 175-200m. at the steepest, seawardmost side of the Tower. Rockfall occurs to a lesser extent upon Cape Ricketts slopes, and primarily upon talus sheets; while on the Inland plateau slopes no recent rockfall activity is noticeable.

Along Cape Liddon in mid-June a vast quantity of rockfall debris covered the snow and ice-capped beach and slope base areas, and continued out onto the sea-ice as far as 50 metres. There was a considerable range in material size, varying from several +600mm long boulders to debris of 100mm length. The same situation existed on the beachfast and sea-ice below the Caswall Tower marine cliffs. An early arrival into the field in 1970 enabled the author to recognize and record the high degree of rockfall activity which occurs in late spring and early summer in a High Arctic environment. Plate 9 shows rockfall debris collected upon beachfast ice which will be rafted out to sea to leave no trace of fallen debris below this cliff section.

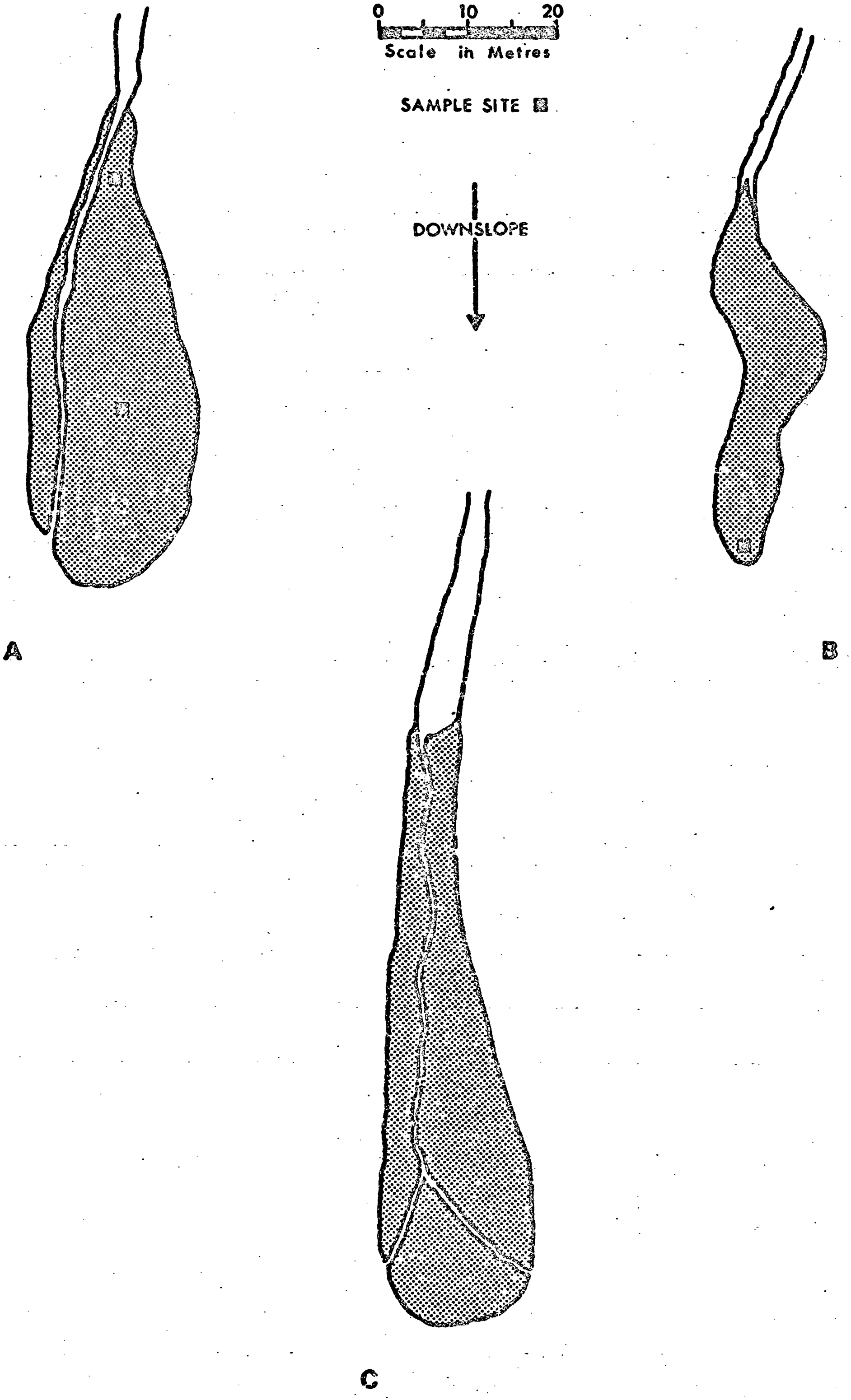
A common feature in the study area that results from rockfall activity is the slide tongue. The process of formation was observed on a Cape Liddon slope during August and is described here as a prelude to discussion of the features as they occur elsewhere. The author witnessed a huge quantity of rockfall debris as it began to roll and bounce down a lengthy, convex talus cone of 38° slope. A fresh scar of lighter-coloured rock was noticed in the rockwall at a height some 30 to 50m above the cone's apex, and covered an area of approximately 15 to 25m square. The scar indicates that a substantial quantity of material had broken away as a primary rockfall. The larger blocks rolled and bounced downslope and eventually reached the sea. This particular cone, however, had been gullied by meltwater earlier in the year and its surface dried and compacted. Consequently, loose surface fines had accumulated in these gullies; and upon contact with them the falling debris set in motion downslope a slide tongue. The main mass of fallen material also moved over the smooth talus surface in sliding motion as a tongue. Plate 10 shows the movement downslope of slide tongues, outlined by the dust they raised. The nature of the tongue features as they came to rest differed due to the courses taken downslope. One slide tongue followed the confines of the meltwater gulley to base where it was forced to split by a meltwater-constructed debris fan which emerged from the gulley base. Other tongues remained intact after overflowing the confines of gulley sides or after flowing directly downslope over the smooth and relatively frictionless talus surface. Plate 11 indicates these diverse slide tongues at rest near slope base. It is possible to regard slide tongues as an occasional or sporadic process of basal accumulation.

In the Cape Ricketts and Inland plateau localities many of these features are situated on the slopes; and they are similarly common to other Arctic localities since they have been witnessed by several writers including Stock (1968) on Baffin Island and Rapp (1960a) on Spitzbergen slopes. The tongues at Cape Ricketts are invariably located on steeper slopes of an area, and are farther upslope than are debris flow lobes which also appear here but are the product of a different process (VII, (2)). The tongues are characteristically elongated or streamlined in appearance due to greater acceleration over the steeper gravity slopes, and are found predominantly on talus sheets which have coarse surfaces. Tongues developed on the steeper surfaces often displayed distinct gullies and small channels extending upslope from the rear of the features. Gullies ranged in length, often covering the full length from the tongue to the rockwall base. In other cases, the gullies wind downslope to dissect parts of the tongue proper and accumulate coarser surface debris, which indicates its sliding movement by a downslope orientation.

Tongue dimensions varied. The maximum elevation of the features is not found at the snout but rather can occur anywhere between 5 and 23m upslope of it. Tongue heights reflect the fact that there is a greater accumulation of debris than is the case for debris flow lobes. Sampled tongues ranged in height from 0.22m to 1.44m, while width at the same point varied between 6 to 20 metres across the widest sector. Below the highest and widest sector of the tongue the feature levels out and narrows until it merges with the surrounding slope surface. Below the "crest" of these lobes the surface is covered by blocky debris. Figure 13 displays the form of the three tongues sampled at Cape Ricketts.

Figure 13

Plan form of sampled debris slide tongues.

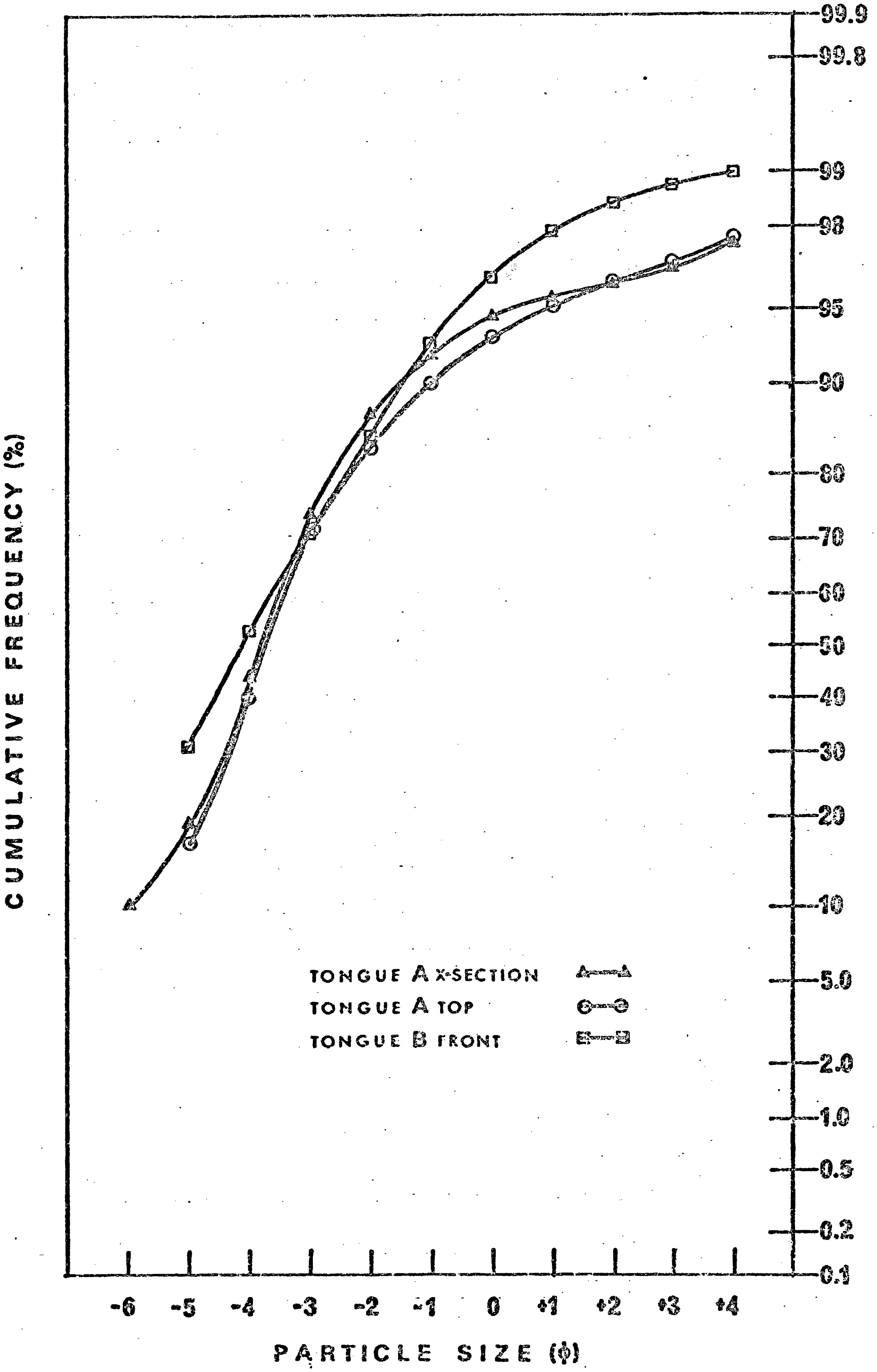

0
10
20
Scale in Metres
SAMPLE SITE ▨
DOWNSLOPE
A
B
C

To facilitate better description of these features, size analysis was performed on the material sampled from various positions on the three tongues at Cape Ricketts. At tongue A sections were obtained only from the top and "widest cross-section" areas down to the permafrost table at one metre's depth, since the front of the tongue was composed of material too large to be field analyzed. These two samples were sieved and their size distribution curves are shown in figure 14. The curves are very similar in shape and indicate that the highest concentration of material lies in the -5.0 to -1.0 phi class range, corresponding to gravel size on the Wentworth scale. Individual percentage scores in each size class reveal that the silt and clay fraction constitutes an equally low proportion of the two samples at 2.44% and 2.45%, respectively. Moreover, a Chi-square non-parametric test on the grouped percentages indicates no significant difference between the two samples (at level of a=.01). The size distribution of material is thus homogeneous in the tongue down to this point. At the tongue front material is generally 100 to 300mm. in diameter, ie. of cobble and boulder size, and fines are not prevalent. It appears that fine-sized material may not reach the tongue front in very substantial proportions, and in any case the percentage that does is generally low.

Tongue B was sampled only at its front since the lobe is quite narrow in size and not very thick. The cumulative percent curve for size of material here is also shown on figure 14, and indicates a high concentration of material in the -5.0 to 0.0 phi class range which corresponds to gravel and very coarse sand. A higher proportion of sand is found in this sample than on those of tongue A, although the

Figure 14

Size distribution curves for debris slide tongue samples.


CUMULATIVE FREQUENCY (%)
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5.0
2.0
1.0
0.5
0.2
0.1
TONGUE A X-SECTION
TONGUE A TOP
TONGUE B FRONT
-6
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
PARTICLE SIZE (ϕ)

silt and clay fraction is a lower 1.01% of the total. Tongue C was not sampled at any location due to the very coarse debris encountered in depth. On the upper tongue several large rock plates with lengths averaging 2250mm were found, with downslope orientations of long axes. At the tongue front it was determined that approximately 60% of the material in depth was cobble-size with the remainder slightly less-coarse.

In summary then the debris slide tongues found on Cape Ricketts slopes have low fine-fraction percentages, with most of the constituent material above permafrost ranging from coarse sand to fine gravels. These findings support the idea that their origin is downslope movement of loose surface debris caused by sporadic rockfall action, such as that observed at Cape Liddon.

(3) Profile and Debris Characteristics

The rockfall catchment experiments mentioned in Chapter IV (2) were designed to supply information on the areas and rates of accumulation on slopes by continuous rockfall activity. Results indicate that of the six sheets placed on each of three slopes the rates of accumulation seem quite low. On slope CAS4, for instance, only the upper two had trapped rockfall debris, and the total number on both catchment sheets was 5 pieces. The material size was less than 60mm, which is low compared to the mean size range of 100-102mm for sample sites in this zone. Shape of the trapped material was disk-like on one site and bladed on the other, which might be interpreted as a preliminary trend towards lateral shape variation in view that sample points had bladed material in this zone.

On slope CL1 similar results were found, for only on one sheet in the upper zone had material accumulated. The mean size of the six pieces was 73mm, much smaller than the 92mm average for the debris sample taken in this zone. Shape, however, conformed to the debris sample findings of a predominantly bladed shape for material on the slope. The study of slope CL4 was more interesting. Here a greater rate of accumulation was found on the upper catchment sheets, with 26 and 44 fragments respectively, found on the two upper sheets with even more unmeasured fragments whose length was less than 25mm. Mean sizes for the sheets were 40mm, and 60mm, respectively and material in both samples was bladed in shape. The sizes were again smaller than those recorded for the slope samples in this area but shape did not differ. Hence, smaller-sized debris is accumulating with no apparent lateral variation in shape. On one basal site a 107mm long fragment, disk-shaped, was found but there was no material on the middle zone sites.

It is concluded that on the slopes tested, the only substantial accumulation of rockfall debris during the study period took place in the upper slope zone. It is reasonable to assume that debris accumulation will be most pronounced and more often monitored here because the debris released by secondary rockfall will land in this zone, and being small in size it will likely remain in this zone. Accumulation here is constantly occurring if this small study is any indication, a situation which complies with the view stated later that minor convexity in profile is created in this fashion.

In terms of results not a great deal was accomplished by this experiment; however some useful comments on the practicality of such a project can now be stated.

First, when material is found on a catchment sheet it cannot be clearly determined whether the material has come directly from the rockwall by way of the fall-sorting process, or has merely slid from the slope surface after disturbance by a) the installation of the sheet itself, or b) the impact of falling rocks. Unless the accumulation of material is closely and constantly surveilled, then results of rock catchment studies must be used cautiously. For instance, on CI4 large rockfall fragment were seen bounding downslope and actually bouncing over the catchment sheets in the middle and basal slope areas before coming to rest. Obviously the small number of catchment sites reduces the probability that rockfall activity will be detected, but it is rather difficult to know how to outfit a slope with traps in a manner which will ensure representative sampling of the rockfall activity. On this particular slope no substantial amounts of debris were found on the middle and lower zone sheets, even though debris was observed to pass over the area quite regularly. It is suggested that catchment experiments are useful only in allocating continuous accumulation areas, and not in determining accumulation rates.

There are 29 profiles drawn from the rockfall-dominant slopes in the study area, from which it appears that "concavity" is the characteristic slope element of this group. In tabulating the various profile forms for rockfall-dominant slopes from table 1, 13 are found to be concave while 12 are classed as predominantly concave. Together these comprise 25 of 29, or 86.2% of the rockfall-dominant slope profiles. Of the remaining four profiles 2 are "straight" forms found both at Cape Liddon while two "convex with minor concavity" profiles are located at Caswall Tower.

Stock's (1968) assumption for slope profile analysis is that unhindered rockfall activity produces an initially straight profile when structural control is absent. On the southwest Devon rockfall-dominant profiles it appears that despite probable variations in structural control between locales, 86.2% of them have developed a predominantly concave-downslope form. The continual rockfall activity over a slope appears to result in gradual extension of slope base in both lateral and forward directions, a development which would account for the creation of a concave slope form. A minor element of convexity will be equally common because of the rapid accumulation of fine-sized debris in the upper slope zone just below the rockwall base. The change-in-slope between this accumulation area and the middle slope zone will cause the formation of a convex profile element. Exceptions in this characteristic form have been found among the 29 profiles, which are attributed to local factors such as aspect of rockwall, which cause modifications to the pattern.

Mean angles for the profiles of rockfall-dominant slopes ranged from 30.18° to 37.02°, with the highest values occurring at Cape Liddon where slope extension is limited by a narrow beach zone and steep cliffs which deter accumulation of debris because of the great heights of fall of weathered cliff material. The lowest-angled slopes are found at Cape Ricketts (mean angles average 32.3°) and at the Inland plateau area (mean angles average 32.5°), where the height of the overlying rockwall is minimal and slopes are long and uninterrupted at base. Caswall Tower rockfall slopes are developed below a cliff-face much higher than those of Inland and Cape Ricketts but lower than that of Cape Liddon, and accordingly show a mean angle for the locale of 33.1°.

The differences in steepness, which do not exceed 3.5° between highest and lowest locale mean, are thus attributed to variations in the height of rockwall as it determines the amount of debris which is falling and the amount which will accumulate on the slopes below.

Results of the two-way analysis of variance performed on rockfall dominant slopes are summarized in table 4 as 'F' values and corresponding eta statistics for size and shape parameters. Ten of the fifteen slopes considered display significant arrangements in size (at the level of $a = .05$), and variation in size between slope zones is significantly greater than between-fragment variation in all cases. On none of these ten slopes is lateral size variation significant. The remaining five rockfall-dominant slopes are homogeneous in size variation, that is to say that zonal and lateral arrangement in size is not significantly greater than the error from all unassigned sources (Griffiths, 1959). Analysis of the eta statistics on all 15 slopes reveals that in all cases but one there is a higher correlation between size and zonal arrangement than between size and lateral arrangement. This result evidences the operation on these slopes of fall-sorting. If the effect of other variables such as slope roughness and height of fall is constant, the larger the rock fragment the greater will be its kinetic energy which in turn determines its length of travel downslope. It is reasonable to expect that there will be a greater visual and statistical trend towards variations in size to occur over downslope rather than across-slope distances.

In viewing individual localities it is found that correlation between size and zonal arrangement is higher on the three Caswall Tower slopes than in any other locality. The two slopes CAS1 and CAS2 bear

TABLE 4

Summary of Test and Relationship Statistics for ANOVA of debris size and shape on Rockfall-dominant Slopes.

Slope Location	SIZE Between Zone 'F' (eta)	 Between Lines 'F' (eta)	FLATNESS Between Zone 'F' (eta)	 Between Lines 'F' (eta)	SPHERICITY Between Zone 'F' (eta)	 Between Lines 'F' (eta)
CAS1	148.59^{+} (.71)	0.01ns (.00)	1.13ns (.081)	23.15^{+} (.27)	3.78^{*} (.16)	84.78^{*} (.47)
CAS2	38.21^{+} (.45)	0.77ns (.05)	1.46ns (.10)	11.72^{+} (.038)	3.49^{*} (.15)	14.85^{+} (.22)
CAS4	18.27^{+} (.35)	0.69ns (.04)	41.76^{+} (.47)	0.60ns (.04)	58.54^{+} (.17)	1.10ns (.063)
CL1	3.03^{*} (.14)	0.03ns (.00)	0.08ns (.00)	0.43ns (.032)	0.60ns (.063)	0.08ns (.00)
CL2	13.20^{+} (.28)	1.24ns (.063)	1.41ns (.095)	0.62ns (.044)	5.76^{+} (.19)	1.37ns (.071)
CL3	2.44ns (.13)	0.07ns (.00)	5.10^{+} (.18)	0.06ns (.00)	5.70^{+} (.19)	0.15ns (.00)
CL4	3.48^{*} (.14)	0.38ns (.032)	1.91ns (.11)	0.72ns (.044)	4.04^{*} (.16)	0.16ns (.00)

Table 4 Continued:

Slope Location	SIZE Between Zone 'F' (eta)	SIZE Between Lines 'F' (eta)	FLATNESS Between Zone 'F' (eta)	FLATNESS Between Lines 'F' (eta)	SPHERICITY Between Zone 'F' (eta)	SPHERICITY Between Lines 'F' (eta)
IN1	1.24ns (.063)	2.29ns (.089)	6.40+ (.20)	13.11+ (.21)	0.28ns (.044)	9.32+ (.17)
IN4	12.90+ (.28)	1.96ns (.084)	17.71+ (.33)	0.00ns (.00)	2.20ns (.12)	0.70ns (.044)
RK1	0.99ns (.084)	0.46ns (.032)	2.42ns (.13)	6.12* (.14)	0.63ns (.063)	4.29* (.12)
RK2	2.76ns (.13)	0.12ns (.00)	3.71* (.16)	1.76ns (.006)	2.57ns (.13)	0.12ns (.00)
RK5	18.01+ (.35)	3.31ns (.033)	3.18ns (.12)	0.38ns (.032)	2.36ns (.13)	0.08ns (.00)
RK6	16.71+ (.32)	0.00ns (.00)	0.79ns (.071)	3.50ns (.11)	1.16ns (.089)	4.08ns (.044)
RK9	2.78ns (.13)	0.98ns (.055)	7.72+ (.22)	6.22* (.14)	3.27* (.15)	5.83* (.14)
RK10	5.63+ (.19)	2.79ns (.095)	0.72ns (.071)	7.73+ (.16)	0.64ns (.063)	5.71* (.14)

+significant at .01 level - *significant at .05 level - ns not significant eta values of 0.71 and 0.45 respectively. At Cape Liddon, three of four slopes have significant arrangement of debris size into zones. The highest correlation, 0.28 is found for CL2, the slope which was partially affected by basal erosion but was included as a rockfall slope because of the requirements of the statistical design. The relationship between size and zonal arrangement is much lower at this locale than at Caswall Tower, and it is proposed that sorting strength has been reduced on the Cape Liddon slopes because of greater slope steepness inherited from such factors as narrow beach zones and higher cliffs.

The only one of the 15 rockfall-dominant slopes on which the lateral effects account for a higher proportion of non-error variance than zone effects is found at the Inland plateau locale. This lateral arrangement on slope IN1, though, is not significantly greater than between-fragment variance, and the slope is statistically homogeneous in size variation. The other Inland slope, IN4, bears a more typical significant zonal arrangement in size. The results from these two slopes are difficult to interpret in terms of fall-sorting because they are scree slopes whose rockwall has long since disappeared. The major influence on zonal arrangement is an area of cliff-remnants where large plates and crags are found; and although it may contribute to zonal arrangement on IN4 it does not significantly affect slope IN1.

On the six rockfall-dominant slopes at Cape Ricketts, only three bear significant zonal arrangements in size. Even where size variation is homogeneous, zonal effects are more closely related to size than lateral effects. Hence fall-sorting is probably still in effect here, although its strength has probably been reduced by the high surface roughness experienced on these slopes.

Both flatness and sphericity values are employed to determine shape of debris. Table 4 shows that 12 of 15 slopes have significant shape arrangements, while the remaining three are homogeneous. Individual locale statistics indicate that all three Caswall Tower slopes bear significant shape arrangements. The two south-facing slopes, CAS1 and CAS2, have both lateral and zonal arrangements in sphericity which are significant, although the eta scores for the former are higher than for the latter. In comparing the two shape parameters, sphericity reveals a higher degree of association with lateral effects than does flatness. On slope CAS4, however, the situations are reversed with flatness and sphericity more strongly correlated with zonal arrangement, while flatness has a better relationship with zonal effects than does sphericity.

At Cape Liddon, three of four rockfall-dominant slopes are found to have significant shape arrangements over their surfaces, and these are all characterized by significant zonal arrangement. Only one of the three also displays significant flatness arrangement. The highest correlations for shape are found between zonal arrangement and sphericity on all four Cape Liddon slopes. Thus even though slope CL1 has homogeneous shape variation, the zonal arrangement in sphericity still bears the best relationship for shape, as occurs on the other slopes.

Both Inland plateau slopes produced significant zonal arrangements in flatness, although on IN1 significant lateral effects in both flatness and sphericity are also found. The correlation with lateral effects, however, is higher than for zonal effects for both shape parameters on this slope.

Finally, table 4 reveals that four of six slopes at Cape Ricketts have significant shape variation. Two, RK5 and RK6, are homogeneous in shape variation, and happen to border the major stream cut in this locale. Both flatness and sphericity have significant lateral effects on two of the four slopes, with flatness having a slightly larger correlation ratio in both cases. On the other two slopes with significant shape arrangements, RK2 has only a significant zonal effect in flatness; while RK9 displays both significant arrangements for flatness and sphericity. Zonal arrangements are best correlated with both flatness and sphericity on this latter slope.

If both size and shape characteristics are combined it is found that 7 of 15 rockfall-dominant slopes have both size and shape arrangements which are significant, while 3 possess significant size arrangements only and 5 display only significant shape arrangements. Gardner (1968) states with accuracy that the term "sphericity" actually is interchangeable with "blockiness" in debris slope studies because of the great angularity of material. Blockiness obviously has greater bearing on studies of debris size than flatness because the former affects the fall-sorting process. The more blocky the rock fragment the greater should be its size and the farther downslope it will travel, given constant surface roughness and slope angle. One might expect zonal arrangement of sphericity (blockiness)then, on slopes affected only by fall-sorting of rockfall material. The data indicate that there is a strong trend towards this zonal arrangement in blockiness, since coefficient ratios show that 10 of 15 slopes do possess this characteristic. It has also been discovered that 14 of 15 slopes have a greater zonal arrangement of size than lateral arrangement. That these trends are discernible attests to the value of the eta statistic. Size and shape then appear somewhat related on rockfall slopes due to the fall-sorting process..

Slope IN1 is the only slope with a lateral effect higher than its zonal effect on size; and it also shares the distinction of being one of the five slopes which do not have zonal arrangement in blockiness. The other four also display significant lateral arrangements in flatness as well as in sphericity. Blockiness is a parameter that will depend upon many variables such as spacing and presence of joint patterns, bed thickness and fracture properties of the parent lithology. However, when flatness is equally dominant on a slope it strengthens the premise that consistent variation in bed thickness occurs. On the 5 slopes in question, then, sphericity varies less in downslope fashion than across-slope because flatness affects the normal action of fall-sorting. ? That flatness varies more in a lateral direction than downslope may be a result of non-uniform dissection of the free-face so that pockets of material with specific flatness characteristics will develop under different sections of the rockwall. Uniformity of shape variation here indicates that dissection of the rockwall and all of the exposed beds within it is uniform, creating an assortment of shapes which are deposited alongside each other. It appears then that there are certain trends in size and shape characteristics of rockfall-dominated slopes, which can be discovered by the use of the relationship statistic when ordinary test results are not especially instructive.

Vector analysis of the 87 debris samples from rockfall-dominant slopes indicates that only 22 of them, ie. a mere 25% display a preferred orientation (significant at the .10 level). Table 5 shows that only

TABLE 5

Directional Preferences of Significantly-Oriented Samples on Rockfall-dominated Slopes

SAMPLE SITE	MEAN VECTOR DIRECTION	SLOPE PREFERENCE	LEVEL OF SIGNIFICANCE
CL1 top 1	262°	C	.08
CL2 top 1	222°	D	.05
CL4 base2	138°	D	.09
CL4 mid 2	143°	D	.01
CL3 mid 1	85°	C	.06
CL3 top 1	139°	D	.05
INI base 2	175°	D	.07
IN1 mid 1	265°	C	.01
IN1 mid 2	137°	D	.10
CAS1 mid 2	88°	C	.06
CAS2 mid 1	251°	C	.07
CAS4 base 1	93°	C	.08
RK1 top 1	87°	C	.05
RK2 mid 2	141°	D	.06
RK2 top 1	49°	C	.07
RK6 mid 1	43°	D	.10
RK6 mid 2	35°	D	.01
RK9 base 1	144°	D	.10
RK9 base 2	70°	C	.07
RK9 mid 1	92°	C	.05
RK9 top 2	232°	C	.07
RK10 mid 2	185°	D	.05

C: cross slope

D: downslope

eight of the twenty-two samples are significantly arranged at the more stringent level of a = .05, and all of these are found in the upper and middle slope zones. At the a = .10 level of significance 11 of the 22 samples are found in the middle slope zone, ie. 50%. Preferences for either downslope or cross-slope directions are approximately the same over the slopes. The diagrams of figure 15 do indicate, however, that cross-slope orientations are much more strongly aligned than are the significant downslope-oriented samples.

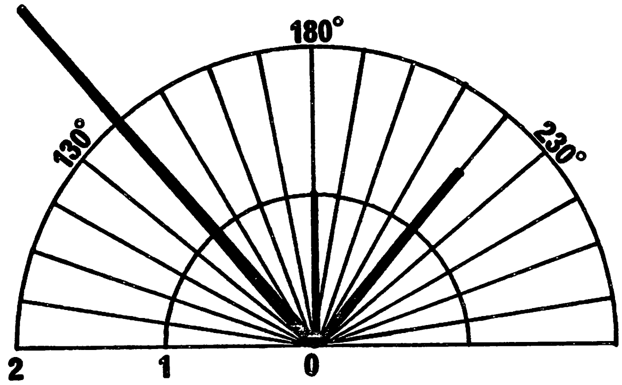
On these slopes it seems that debris found in the middle zone is more likely to bear a significant directional preference which may be either downslope or cross-slope, depending upon whether or not sliding or rolling takes place. However, surface roughness greatly affects the degree of orientation, since a smooth, densely-packed surface will allow sliding or rolling to occur with little interference, and preferences will therefore develop. It is the middle slope zone which first presents surface resistance to larger-sized material moving downslope and thus may bring them to a halt. A frictionless surface is more often found in the upper slope zone because of the small size of material there; and significant orientations are also likely to be found here. The diagram of downslope orientations in figure 15 may reflect the influence of surface roughness, especially in the middle zone; for the final position taken by rolling material here will be affected by a blocky surface. The cross-slope orientation of the long axis, associated with rolling and bouncing of debris, will be rotated downward but will rarely reach 180° (downslope) because of the high friction encountered. Figure 15a indicates this wide variation from the downslope position.

The low number of preferred orientations found on rockfall slopes (25%) is explained then by surface friction encountered by falling material. That the directional preferences are split between downslope and cross-slope reflects the equal likelihood of sliding along the 'A' axis or rolling about the 'B' and 'C' axes of debris after it falls onto the slope. Orientation of material by itself does not then appear to offer any major clue to the process which dominates these slopes; rather it must be related to prior information and observations.

Figure 15

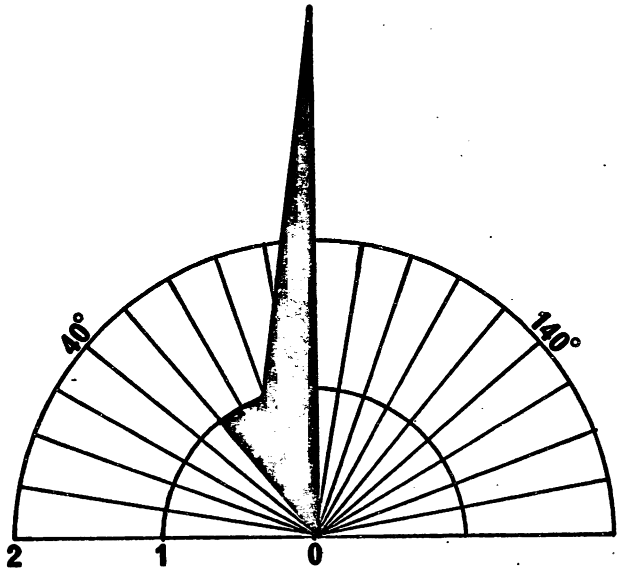
Alignment of significantly-oriented samples on Rockfall-dominated slopes.

A, downslope; B, cross-slope.



A.

DOWNSLOPE DIRECTION = 180°



B.

CROSS-SLOPE DIRECTION = 90°

CHAPTER VII

SLOPE MORPHOLOGY AND RUNNING WATER

(1) The Process

The collective term "running water" incorporates the processes which require substantial quantities of water in order to become influential in slope alteration and development. The category has two primary components in the study area: subsurface and surface flow, with common sources being the melting of both snow and permafrost during early summer. The nature of removal, transportation and deposition of slope material is a necessary part of this discussion, which includes slush avalanches and flow phenomena requiring initial saturation of snow or debris by meltwater.

The importance of meltwater on debris slopes has been generally disregarded in previous work, but observations of its characteristics in the study area indicate that it is worthy of attention. Meltwater first begins to flow during early June on southwest Devon Island when daily maximum temperatures begin to rise above the freezing point. Meltwater is primarily derived from ablation of the surface layers of winter snow accumulation, and its first effect is to permeate downwards into the snow body. Saturation of snowpatches located in rockfall funnels or chutes in the rockwall may result in slushflow, in which a tongue of saturated snow flows downslope and incorporates debris within its flow as it moves downslope.

Occasional +32°F temperatures eventually give way to a period of sustained above-freezing temperatures and result in a period of maximum snowmelt. This is a short period during which peak water flow conditions prevail. During this period surface snow largely disappears and subsurface permafrost begins to melt; but it is when the two forms of meltwater are being produced simultaneously that most of the work of running water is accomplished and most of its associated features are formed. On southwest Devon Island the 1970 maximum melt period occurred between June 25 and July 15, allowing approximately three weeks for the melting of the previous winters unusually high snowfall. Observed during this time, the influence of running water on debris slopes was considered overwhelming in magnitude.

By July 15, most of the surface snow had ablated, leaving only the meltwater derived from perennial snowpatches and the gradually-lowering permafrost table. Rates of melt for the permafrost table decline, however, with increasing depth of the table because the ever-increasing thickness of debris cover becomes increasingly more effective as an insulating layer. By late summer, then, surface runoff has been replaced by an ever-diminishing subsurface flow of permafrost meltwater.

(2) Observed Effects of Surface Water Flow

The presence of running water on debris slopes was most strongly felt along the present cliffed coastline extending from Cape Ricketts to northernmost Cape Liddon. The nature of surface runoff is best illustrated by observations taken from Cape Liddon slopes, while the various erosional and depositional features are described as they occur at both Cape Liddon and Cape Ricketts.

The advent of sustained above-freezing temperatures after June 25 caused plateau-derived meltwater to concentrate its flow down the natural gullies and crevices created by rockwall dissection. Since these gullies often lead into rockfall funnels, many slopes were affected by concentrated gulleying of meltwater. The flow tended to be sporadic in nature, as streams were seen to emerge and disappear at different stages over the same slope. Entrenchment is accompanied by surface erosion of the permafrost table which is very near the slope surface at this time. In areas of thicker debris accumulations, streams often dispersed after entering the material. Meltstreams all reached slope base eventually, either flowing straight down to base or emerging in many rivulet forms at the slope-beach interface. Water was then observed to cross the shorefast ice and carve deep meanders into the sea ice as it streamed out into tidal cracks or leads. Plate 12 portrays the gulleying action of meltwater in operation. The gullies carved out in this fashion were observed to dry up following the cessation of meltwater flow and serve to accumulate and channel rock debris downslope during the summer months. Occasionally they may become infilled.

The surface runoff is similarly an important agent of transportation and deposition of slope debris. Along Cape Liddon many high velocity streams were carrying down organic matter, excretions and other litter from the extensive gull rookeries high in the cliff-face. From the slopes, meltwater transported frost-shattered fragments from the slope necks down to the base and deposited them on the snow and ice covering the slope in this area. Samples of this deposit have been analyzed and compared with samples taken from the slope neck above it.

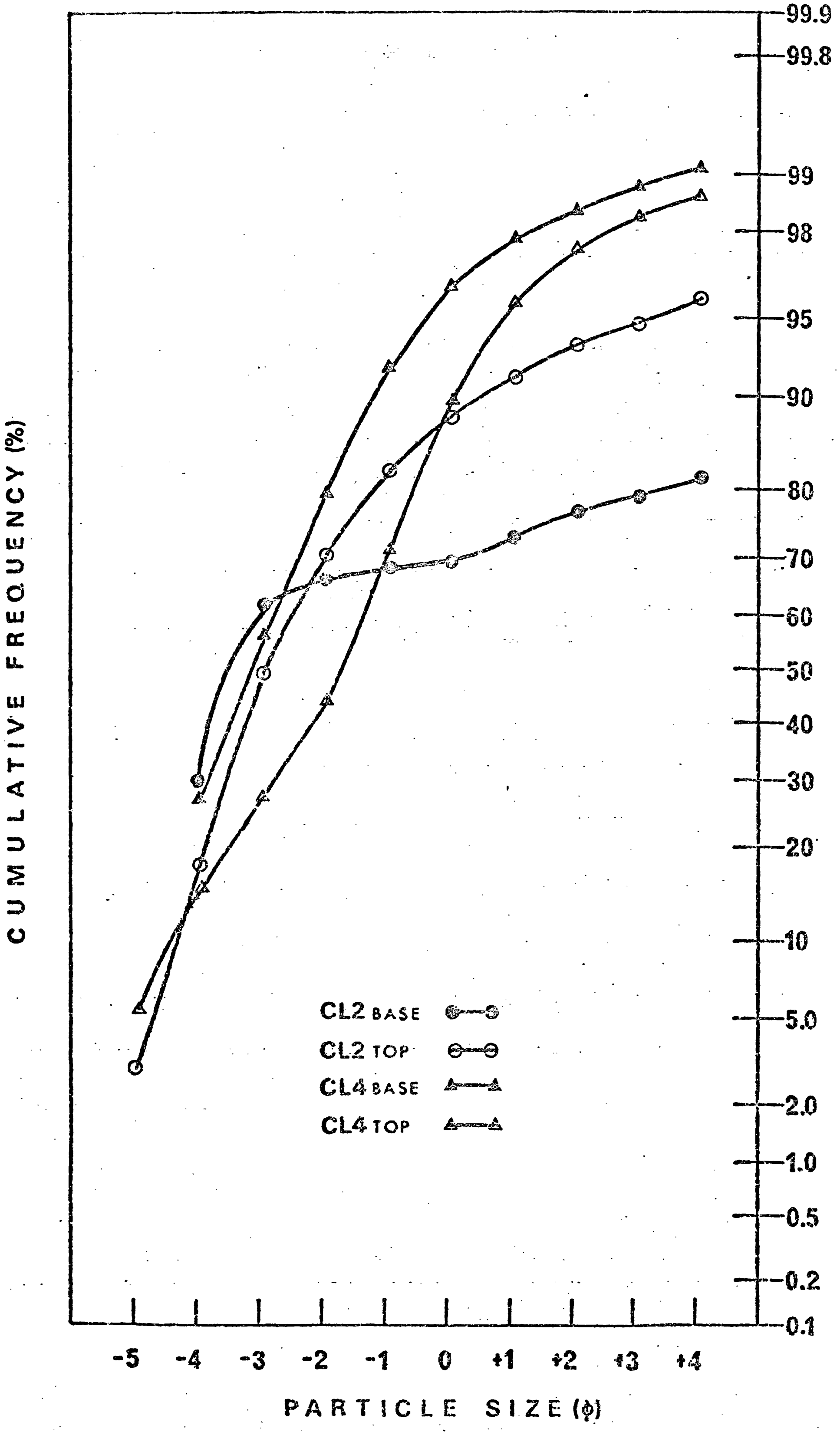
In a similar manner a horseshoe-shaped snowbank extended across-slope at the base of slope CL4 and was capped with fine-sized debris. In 1969 this slope had been covered in one particular basal spot by fine sand and silt overlying the slope debris. Its origin was uncertain, but from observations of this snowbank feature in 1970 it was possible to ascribe the origin to ablation of the snow and subsequent deposition of the material which had flowed onto it from the adjacent slope. This material was also analyzed for size distribution and the results follow.

Figure 16 shows the size distribution curves of both sets of samples. Sieving was performed down to +4.0 phi (.0625mm) diameter. The curves of both CL4 samples are similar in appearance although the basal sample contains much less coarse material. Since the basal deposit was derived from the adjacent slope, it is of no real consequence that non-parametric Chi-Square testing proves the two samples significantly different in size distribution at the .01 level of alpha. The curve does however indicate the size range capable of being transformed downslope by flowing when saturated. Silt and clay fraction of the samples is small, comprising less than 1% of the total weight; while the majority of material is in the -4.0 to 0.0 phi size range.

The differences between samples at the top and base of slope CL2 are quite distinct. They are significantly different in percentage size distributions at the .01 level of alpha, and their curves are highly contrasted. Very little coarse debris is found in the basal sample, while silt and clay comprises 18.3% here compared to only 4.2% of the upper sample. Meltwater then appears to selectively transport fine-sized sand, silt and clay downslope during the meltwater period,

Figure 16

Size distribution curves for meltwater deposits and debris source areas.


CUMULATIVE FREQUENCY (%)
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5.0
2.0
1.0
0.5
0.2
0.1
CL2 BASE
CL2 TOP
CL4 BASE
CL4 TOP
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
PARTICLE SIZE (ϕ)

leaving the coarser debris behind.

The carving of gullies on slopes by surface meltwater streams has in some areas of Cape Liddon been responsible for the deposition of fans composed of coarse-sized debris at slope base. These fans often prove only temporary if built over the shorefast ice; but where they are developed farther back behind the highest storm ridge they do tend to be positive contributions to slope development and profile change by extending the slope foot or in some cases covering a former basal-cut section.

An additional effect of surface runoff in the peak melt-period is the saturation of snow by meltwater to cause "wet" or "slush" avalanches. The snow is often located in rockfall funnells or on the edge of the plateau surface and if the deposit is large enough the saturated snow will eventually begin to flow downslope. A sporadic process, it may be an avalanche or simply a "flow" depending upon the quantity of snow involved. There were many indications of slush-flow activity on Cape Liddon slopes during the initial phase of the peak melt-period, such as the tongues of dirt-and-debris-laden snow-balls resting at base (plate 13). The debris, generally less than 50mm in diameter, is incorporated into the slush as it flows downslope and ends up as constituent material. On a larger scale a slush avalanche had taken place along the coast east of Cape Ricketts. Plate 14 indicates the enormity of the avalanche and the amount of material it picked up as it descended a large meltwater gulley from the plateau surface. The avalanche deposited material over beachfast and sea-ice to a distance nearly 100 metres offshore. Such a feature is not likely to be common except in the unusual coincidence of a high winter's snowfall accumulation and a rapid thaw period in spring.

In discussing the importance of surface meltwater it is important to emphasize the significant role played by ice-rafting in minimizing the changes created by meltwater activity on debris slopes in the area. Many features are obliterated because they are formed on ice which is eventually carried out to sea. Much of the fine-sized debris transported to base is similarly removed by rafting before it can be incorporated into slope basal extensions. Ice rafting thus serves as an output process for the debris slopes and as such exerts considerable influence on slope evolution, though in a negative sense. By limiting the amount of debris available for beach accumulation and transport, it serves to maintain the flimsy protection afforded Cape Liddon and Caswall Tower slopes by narrow beach zones.

(3) Observed Effects of Subsurface Meltwater Flow

The meltwater which moves above the permafrost table but below the actual slope surface is considered separately as a process affecting debris slope morphology, although its effect is seasonal as is the effect of surface flow.

A feature common to the Cape Ricketts, Inland plateau edge, and the south and west-facing Caswall Tower slopes is the debris mound, a basal break-in-slope characteristic of slopes unaffected by basal erosion processes. They have also been reported in Spitzbergen by Rapp (1960a). This accumulation feature is created by subsurface runoff acting in the peak melt-period with a shallow permafrost table. Suspended fines are deposited at the point where reduction in slope gradient is sufficiently large, and they accumulate over the years to form a mound. The characteristic transverse "cracks" which run behind them are formed after the silt and clay mounds have accumulated to sufficient height to force subsiding meltwater flow along the rear of the features, parallel to the mound crest. These mounds generally extend laterally across the whole base of the debris slope. These features are more commonly found on the low-angled slopes between crests of raised beaches in the study area.

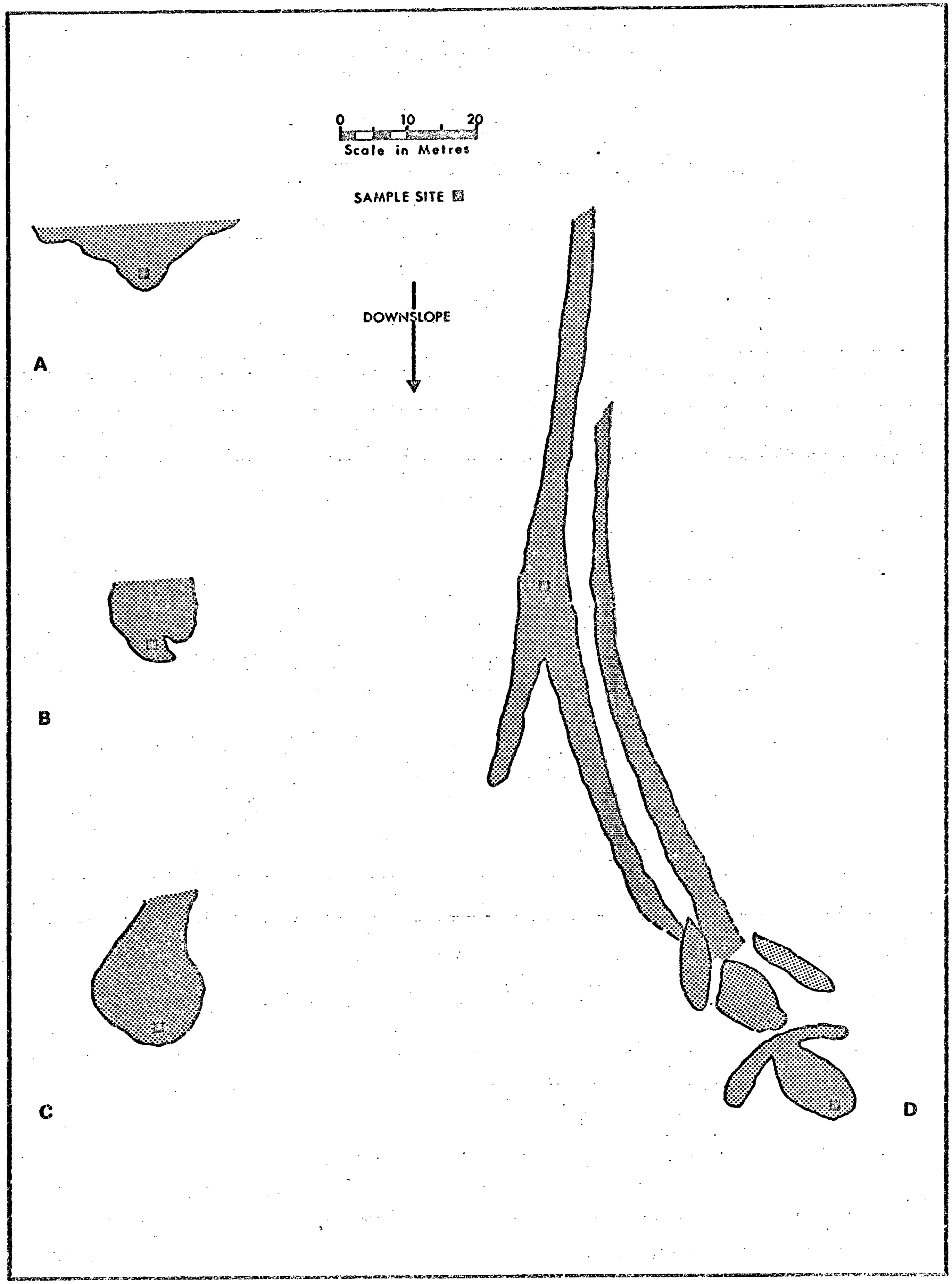
Debris "flow" is also associated with subsurface running water and is common to the Inland plateau edge and Cape Ricketts areas which are similar in slope angle and state of development (VIII, (1)). The process can be termed a flow movement which is very similar to mudflow or earthflow phenomena, but is referred to as "debris flow" for purposes of debris slope studies simply because the former terms make specific implications about the type of material involved (Gardner, 1968). On low angle slopes, especially talus cones affected by snow avalanching, debris flows have been occurring with regularity. The process creates a lobate feature called a debris flow lobe, which stands clearly as a surficial deposit on the debris slope surface (plate 15). The lobes sampled in the study area are shown in figure 17. They have frontal lobes which are more irregular and broader than slide tongues, ranging from 8 to 12 metres in width. They are also lower in height (0.22m to 0.26m). The highest point occurs at the lobe front itself. Their surfaces are generally composed of fines with occasional large slabs whose size ranges from 218mm to 528mm in length. The slab orientation is in a downslope direction but tends to follow the axis of flow of the lobe.

Lobes are commonly associated with surface meltwater gullies which lead into them from upslope areas where fines accumulate. These gullies are not evidence of surface runoff but are evidence of a debris flow which carved its own channel downslope. On many lobes, "ripples" are displayed on their surfaces, appearing as small wave fronts proceeding in an upslope direction (plate 16). The ripples sampled are not very distinctive on the surface, having heights ranging from .095 to .135m at the frontal "lip." The fronts of two samples were 1.5 and 4.2m broad. The ripples appear covered on the surface by much debris which is smaller in size than the lobe surface slabs mentioned above. Samples of the material composing the ripple fronts were taken for comparison with material composing the lobes themselves, and are discussed later in this section.

Slopes on which lobes occur are composed of an upper accumulation zone of fine-sized debris which is loosely-packed. This situation enhances saturation by subsurface meltwater seepage, especially in the early part of the peak melt-period when the permafrost table is close to the surface. Within the fines, resistance to shear is overcome when the material load is increased by water; thus the shear force is increased and the lubrication effect of water is sufficient to reduce the coefficient of friction between particles (Strahler, 1952). The mass then flows downslope in lobate form, leaving a carved channel in its wake by incorporating debris in its path. Velocity of flow is greatest down the flow axis and weakest at the lobe sides. When the cessation of movement occurs wave fronts on the surface may develop. Some lobes have been dissected by surface runoff, which takes advantage of the channels created and uses them to funnel snowmelt or rainwash downslope.

Figure 17

Plan form of sampled debris flow lobes and levee systems.


0
10
20
Scale in Metres
SAMPLE SITE ▨
DOWNSLOPE
A
B
C
D

They may be used again as courses for subsequent debris flows; and when this occurs the features known as debris flow "levees" are often created on the channel sides by the overspilling of flow material (Sharp, 1942). A single debris flow of large proportion may also be responsible for a leveed channel (Gardner, 1968). These forms have been observed elsewhere in Arctic areas (Rapp, 1960a; Stock, 1968) and in the Canadian Rockies (Gardner, 1968), where they are attributed to heavy rainfalls. Heavy rains are unusual in the High Arctic, and in the study area saturated flow is believed due to unusually heavy winter snow accumulation, all of which melts in late spring. Each flow leaves several lobate deposits at the mouth of the gullies, and levees which are high depositional forms on the coarser talus surface (plate 17). Several trends appear from the study of the levee system on slope RK7. The size of debris slabs on levees increases upslope, since larger slabs will be deposited early in a flow. Levee height generally decreases upslope, and on those measured, the highest point was attained where the flow lobes emerged from the gulley. Levee width also decreases upslope, from approximately 4.5m to 2.5m. On RK7 the left levee continues upslope an additional 33m after the opposite lobe fades out; and the left lobe is 3.6m wider and 0.36m higher than the right at mid-slope. At the lower end of the levee system, the right levee is wider and higher than the left.

The type of material within levees is predominantly fine-sized material impregnated with large blocks. The size ranges from pebbles down to fine sand, with 4.9% of a sample taken being silt and clay. The levee sample distribution was found not statistically different (at the significance level of .01) from that of the lobe at its base (D).

Size distribution curves for the lobe and ripple samples are shown in figure 18. Most material is in the range of cobbles to very coarse sand, but the percentage of silt and clay varied slightly. On lobe A it is 4.8%, on lobe B it is 4.7%, and on lobe D it is 9.9%. It is less than 1% on lobe C because the lobe has been affected by meltwater dissection which has removed much of the fine fraction. On lobe D it is high because of the greater amount of activity occurring here. A non-parametric Chi-Square test performed on the ripple distributions showed no difference between the two; but when tested against lobe A there is a difference between ripple and lobe distributions. Analysis shows the ripples to contain smaller silt and clay fractions (less than 1%), and higher quantities of coarse debris than lobe A; and thus they must have been the products of movement of only the upper layer of surface debris on the slope.

Subsurface runoff has been studied in the coastal zone near Cape Ricketts. The pattern and rate of flow have been studied by tracing water movement with Rhodamine BN dye (40%+solution) on three separate slopes under varying conditions of meltwater flow. Profiles of the three cones selected are shown in Appendix II (2).

Figure 19 indicates the waterfall flow patterns. On slope T1 the subsurface course was to the left of the slope and down below the inter-cone depression. The rate of flow increased from point B_1 to C_1, which is due to a greater slope gradient in the direction of the depression. Waterfall meltwater was not traced elsewhere, and flow observed in sites downslope is believed to be permafrost-meltwater. On slope T2 the waterfall followed a similar course in flowing directly off the cone edge and down the inter-cone depression.

Figure 18

Size distribution curves for debris flow lobe and levee samples.

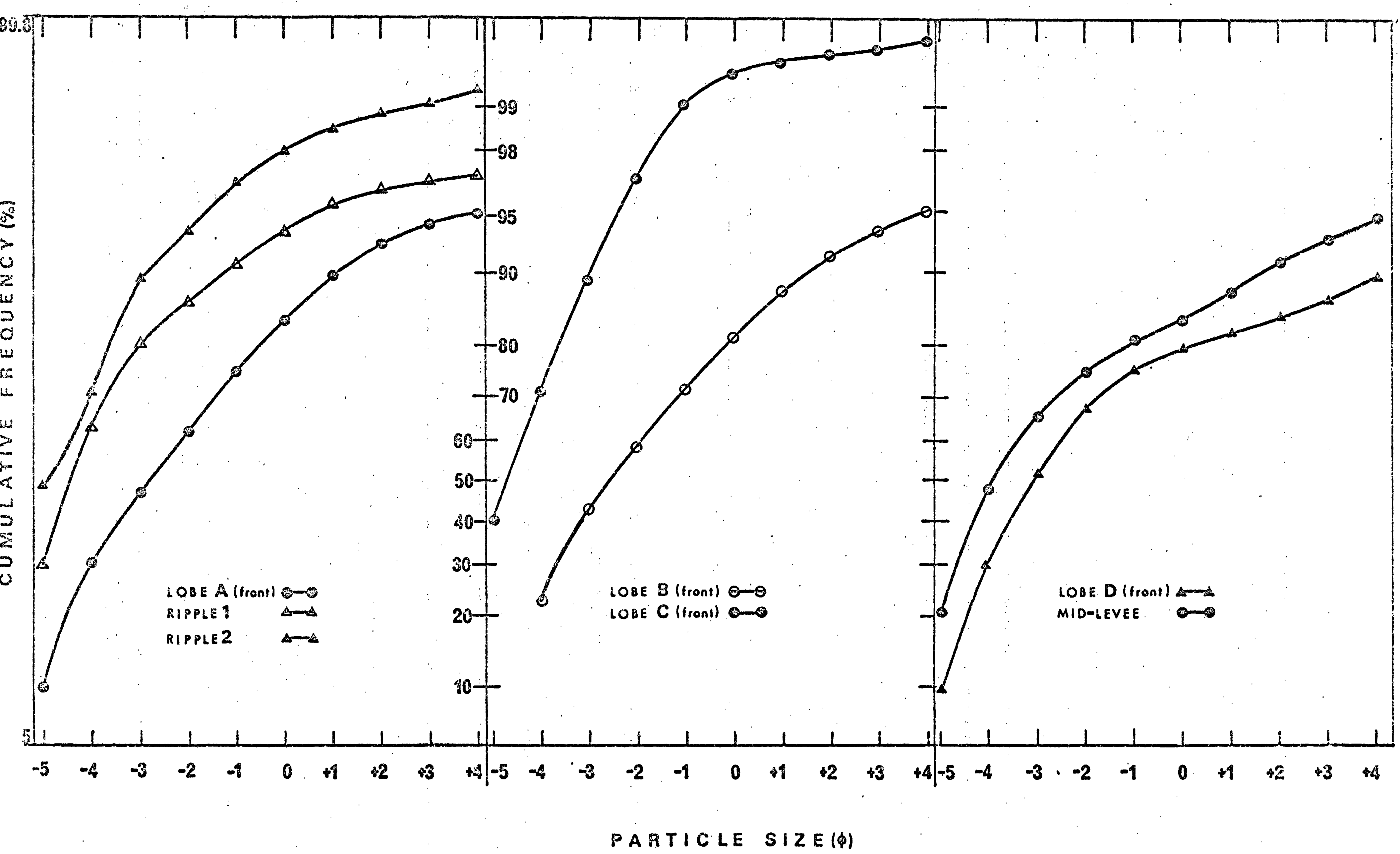

CUMULATIVE FREQUENCY (%)
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
LOBE A (front) ⊗—⊗
RIPPLE 1 △—△
RIPPLE 2 ▲—▲
LOBE B (front) ⊖—⊖
LOBE C (front) ⊗—⊗
LOBE D (front) ▲—▲
MID-LEVEE ⊗—⊗
PARTICLE SIZE (φ)

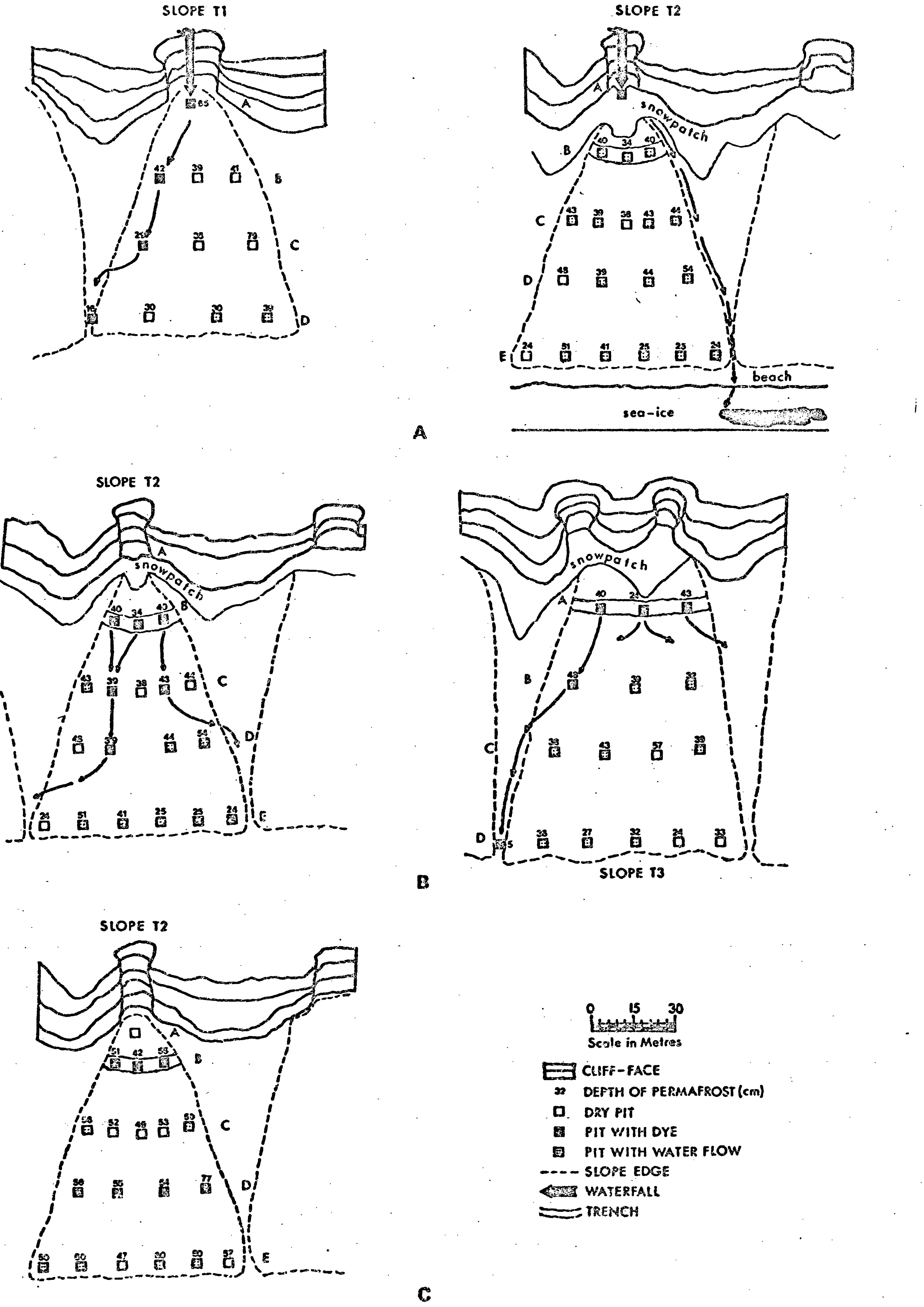
Figure 19

Subsurface meltwater flow patterns.

A is waterfall test;

B is snowpatch meltwater test;

C is permafrost meltwater test.


SLOPE T1
SLOPE T2
SLOPE T3
snowpatch
beach
sea-ice
A
B
C
D
E
0
15
30
Scale in Metres
CLIFF-FACE
DEPTH OF PERMAFROST (cm)
DRY PIT
PIT WITH DYE
PIT WITH WATER FLOW
SLOPE EDGE
WATERFALL
TRENCH

The dye appeared only in a tidal crack offshore, having completely bypassed the network of sample sites on the slope (plate 18).

Rates of flow shown by table 6 indicate high velocities for the waterfall flow, which increases rapidly when the water enters the inter-cone passage. It is likely that snowpatch melt from the adjacent slope neck is contributing to the volume of water passing down the depression.

Patterns of flow for snowpatch meltwater are also shown in figure 19. On the two slopes T2 and T3, 100ml of tracer dye was spread laterally in a trench dug across the cone neck. On T2 some downslope flow occurs to the right, but it is drawn off into the inter-cone depression after only 20m of flow. On the left side the water flows 40m before running into the inter-cone depression on its left. Water which appears elsewhere over the slope is attributed to melting permafrost. On T3 the flow is offslope to the inter-cone depression somewhere beyond 20 metres downslope. No dye was traced on the right side of the slope, but it is likely channelled off to the right. Rates of flow are generally lower on T2 than they are for waterfall flow, ranging from 100 to 125cm/min. on the upper left of the slope, and only 36.4cm/min. on the right (table 6). On T3 the initial flow was 222cm/min., but upon reaching the inter-cone depression its rate increased to 833cm/min.

The permafrost-melt test was performed in August on slope T2, and its flow pattern is shown in figure 19. Dye was first placed at level B; but when it failed to appear downslope after several hours, an equal amount of dye was placed at a lower level D. Although water was observed to flow out from base, no dye appeared from D level,

TABLE 6

Rates of Flow for Subsurface Meltwater Patterns

TEST	SLOPE	SAMPLE POINTS	DISTANCE TRAVELLED (metres)	TIME OF TRAVEL (minutes)	RATE OF FLOW (cm/min)
Waterfall Melt	T1	A_1 to B_1	20	24	83.3
	T1	B_1 to C_1	20	16	125
	T2	A_1 to tidal crack	100	30	333
Snowpatch Melt	T2	B_1 to C_2	20	20	125
	T2	C_2 to D_2	20	30	100
	T2	B_3 to C_4	20	55	36.4
	T3	A_1 to B_1	20	9	222
	T3	B_1 to D_1	50	6	833

20m upslope. It then appears that permafrost meltwater at this time of year is slower than in the peak melt-period because the permafrost table is much lower and thus insulated from heat by a thicker debris cover. Tracer dye must move through more debris at a slow rate, and it consequently adheres to the surrounding material. The permafrost-melt has no defined flow pattern and is likely derived only from localized catchment areas.

(4) Profile and Debris Characteristics

Surface meltwater of all kinds in the melt-period is responsible for the downslope transportation and deposition of large quantities of silt and clay at slope base. This fine fraction is deposited on the beachfast ice at Cape Liddon and is thus removed from the area when the ice breaks up. Some silt is blown away by winds when dry; while silt which adheres to beach gravels is washed away when open-water conditions arrive. At the other three localities, the silt accumulates at base in the absence of removal processes and forms thick silt carpets.

Subsurface meltwater action would not be effective without the variations of the permafrost table slope. The sample points from tracer studies indicate that when talus debris has no significant lateral variation in size, then the cross-slope profile of the underlying permafrost will complement that of the overall slope cross-profile. The exception is when large blocks occur to create a deeper permafrost table, due to large interstitial spaces which allow warm air to penetrate deeper. In the waterfall tracer tests the water flows at high velocity and seeks out the steepest gradient; thus it follows the natural depression caused by convex edges of two adjacent talus cones. With no flow observed in the centre pits (fig. 19), results of snowmelt tests indicate that the permafrost table profile seems to be conducting meltwater off to the sides and downslope. The water entering a slope, then, does not necessarily flow in sheet form downslope, but is concentrated into rivulets by the permafrost "micro-relief." This concentrated flow is less effective in late summer because the permafrost table is lower and smaller quantities of water are available to percolate through an increased volume of debris.

All the various types of flow affect only a small sector of the slope, but at the same time they all enhance the slope profile by removing subsurface fines to the inter-cone depressions and downslope. Snowpatch meltwater follows a flow pattern dictated by the permafrost micro-relief. Since the volume of water is less, then water is less channelled and so it flows further downslope before veering to the left side. That the flow on slope T2 goes both left and right but not down centre again reflects the control exerted by a convex permafrost table. On T3, the permafrost relief is more varied, with a steeper gradient towards the left; and hence the snowmelt flow on T3 is to the left only. Thus the mid-slope areas of a talus cone are not subjected to as much meltwater percolation as the cone sides, which means that more chemical erosion and transportation of fines down the sides is enhancing the cone's surface profile. During the meltwater period then, subsurface flow becomes an erosive and transporting agent important to the development and maintenance of talus slope profiles. Talus sheets, however, are more likely affected by slopewash from melting snow than by channelled subsurface flow.

Running water-dominated slopes are those which are observed to have been recently affected significantly by surface or subsurface runoff and by slush or snow avalanching. The latter process was not actually seen on many slopes, but it is suspected that cones RK3, 7 and 8 have been influenced in their development by slush avalanching. Their low angles, rockfall chutes, smooth surfaces and extensive boulder aprons are indicators of this activity which have been cited by Rapp (1960a).

Twenty profiles are derived from running water-dominated slopes; and of these, concavity is the most dominant form recorded (table 1). Nineteen of twenty, or 95% of the profiles are completely or predominantly concave; while the remaining profile has equality of convexity and concavity. This exception is found at Caswall Tower, where the slope in question has experienced extensive slump action on its long talus foot, adding a convex element to the slope. On other slopes, slushflows and slush avalanches sweep debris out of the slope mid-zone, contributing to the development of concavity by extending the basal foot. Smaller processes such as debris flows and minor slumps will involve only a small proportion of the total slope area and may not therefore be especially important in affecting profile on some slopes. In that case the basic concavity produced by rockfall activity will remain unchanged upon these slopes.

Mean angles for these profiles reveal that the Cape Liddon slopes are steepest at 37.6°. Following in steepness are Caswall Tower, Cape Ricketts and Inland plateau slopes. Surface and subsurface water activity are the only major running water processes observed at Cape Liddon; and because of the short slope lengths and paucity of debris accumulation here, these activities do not alter the basic steepness of these slopes but may even enhance it. Caswall Tower angles are lower at 33.3°, since the slopes sampled are drawn not only from the steeper seaward-facing slopes but also from those more highly-developed and longer slopes on the other sides of the Tower. The mean angle of all slopes at Cape Ricketts is 29.4°, a value approximately 4° lower than the Caswall Tower mean, and which includes three slopes which are slush avalanche slopes. Hence the locale mean is reduced from that of Caswall Tower slopes which are affected mainly by flows and slumps. The Inland locale mean for angles is a low 20.9°, and is due to the fact that the two samples are both slush avalanche-affected slopes. The only recent activities upon them are debris flow and subsurface meltwater activity.

ANOVA test results for size and shape characteristics (summarized in table 7) show that of the 10 running water-influenced slopes, only four are homogeneous in both size and shape variation.

These slopes are first discussed according to the size variation found on their surfaces. Four bear significant size arrangements, all of which are zonal. Two of these also have both zonal and lateral arrangements which are significant, but the eta values show that size is more highly correlated with the former than the latter. On the slush avalanche-affected slopes, of which there are four in the study area sampled, the melting of the snow leaves a wide range of transported slope debris (Gardner, 1968). Size variation should therefore be homogeneous on these slopes; and in fact three of these do show this characteristic. Coincidentally, these three slopes display identical eta values for zonal effect (.09) and near-identical

TABLE 7

Summary of Test and Relationship Statistics for ANOVA of Debris Size and Shape on Running Water-dominated Slopes

Slope Location	SIZE		FLATNESS		SPHERICITY	
	Between Zone 'F' (eta)	Between Line 'F' (eta)	Between Zone 'F' (eta)	Between Line 'F' (eta)	Between Zone 'F' (eta)	Between Line 'F' (eta)
CAS5	4.88^{+} (.18)	0.01ns (.005)	0.22ns (.03)	0.18ns (.02)	0.65ns (.06)	0.13ns (.01)
CAS6	2.06ns (.12)	0.87ns (.055)	0.22ns (.03)	4.98* (.13)	99.76^{+} (.63)	106.57^{+} (.52)
CAS7	1.91ns (.11)	1.27ns (.06)	0.69ns (.07)	0.29ns (.03)	1.58ns (.10)	0.62ns (.04)
CL5	61.46^{+} (.39)	25.76^{+} (.28)	0.01ns (.008)	0.05ns (.014)	0.12ns (.03)	0.08ns (.01)
IN2	3.31* (.15)	0.73ns (.04)	0.33ns (.04)	0.96ns (.05)	0.75ns (.07)	0.71ns (.04)
IN4	1.16ns (.09)	0.40ns (.03)	23.48^{+} (.37)	53.99^{+} (.39)	1.05ns (.08)	3.68ns (.11)

Table 7 Continued:

Slope Location	SIZE		FLATNESS		SPHERICITY	
	Between Zone 'F' (eta)	Between Line 'F' (eta)	Between Zone 'F' (eta)	Between Line 'F' (eta)	Between Zone 'F' (eta)	Between Line 'F' (eta)
RK3	1.16ns (.09)	0.39ns (.03)	0.30ns (.04)	0.28ns (.03)	0.20ns (.03)	0.62ns (.04)
RK4	1.52ns (.10)	1.86ns (.08)	0.25ns (.04)	0.14ns (.02)	0.15ns (.03)	0.01ns (.005)
RK7	10.63^{+} (.26)	5.20^{*} (.13)	1.63ns (.10)	1.84ns (.077)	3.71^{*} (.16)	1.34ns (.06)
RK8	1.16ns (.09)	0.56ns (.04)	0.55ns (.06)	0.00ns (.00)	1.07ns (.05)	0.03ns (.01)

$^{+}$:significant at .01 level

*:significant at .05 level

ns: not significant.

lateral values (.03-.04). This similarity may be indicative of a common effect produced by slush avalanching; but in any case this process clearly tends to create a homogeneous size distribution over the slopes it affects.

Size analysis can be discussed at the level of individual localities. On slope CL5, both zonal and lateral effects are significant. It is a meltwater gulley and an accompanying debris fan which are responsible for the lateral variation in size. However the high rate of accumulation of fines at the cone neck is sufficient to cause zonal variation; and thus rockfall accumulation has acted here to modify the initial lateral variation created by a running water process.

The significant zonal effect on size on slope IN2 has an eta value which is the lowest recorded for that effect on any of the 10 running water-affected slopes. Thus even though homogeneity in size does not occur here as it does on other slush avalanche slopes, the zonal effect is nevertheless weak.

In the Cape Ricketts locale only slope RK7 bears significant size arrangement, with both zonal and lateral effects being significant. This talus cone has been affected by vigorous debris flow activity and levee formation; and thus variation in size is attributed to zonal differences created by flow lobe concentration at base and coarser levee and gulley deposits upslope. Lateral variation, though less highly associated with size, occurs because the flow lobe activity is confined to one side of the cone.

There is a trend on all 10 slopes for zonal arrangement to explain a higher proportion of non-error variance than lateral arrangement. Such a trend can be recognized by use of the eta statistics. Processes like debris flows, gulleying and fan deposition then are capable of creating an apparent size variation.

Flatness and sphericity were used to determine shape characteristics on the 10 slopes, and significant shape arrangement is found on three of them. Slope CAS6 has significant zonal and lateral effects for sphericity (blockiness), although the eta value is higher for the former than the latter. Lateral flatness arrangement is also significant on this slope but has a lower correlation ratio than either of the sphericity effects. The rockwall above this slope is short and has begun to weather into coarse, platy debris which is falling only a short distance downslope. This accumulation creates zonal variation in shape when contrasted with debris further downslope which is being weathered in situ and sorted by slump activity.

Slope IN4 has significant flatness values for both zonal and lateral arrangements, and lateral effect is slightly higher in proportion of variance explained than is zonal effect. Since sphericity is more closely related with size than is flatness (VI, (3)), we can assume that shape may be homogeneous on this slope as it is on IN2 if sphericity is the parameter used for this slush avalanche slope.

At Cape Ricketts the two slush avalanche-affected slopes bear homogeneous shape variations. Of the remaining two slopes, RK7 displays a significant zonal arrangement in sphericity. This slope is the only one of ten which bears significant arrangement in both size and shape, and it is here attributed to the action of debris flows and levee development. Large blocks may tend to be deposited upslope in debris flow activity while the less blocky debris will be carried farther downslope. Blockiness then can vary in a manner related to size arrangement in zones when vigorous debris flow activity is present.

Finally we see that on 8 of 10 slopes, zonal arrangement in sphericity is more highly correlated than is lateral arrangement; and 6 of 10 have higher correlations with zonal effect than with lateral effect and flatness. Two of the exceptions in the latter case occur on slush avalanche-affected slopes.

Vector analysis of the 60 samples indicates that 11 of them have orientation preferences significant at the .10 level of alpha (table 8). This figure constitutes only 18.3% of the total number of samples drawn, and the directional preferences are near-equally divided into 5 downslope and 6 cross-slope directions. A more stringent test level of a =.05 shows that only 3 samples are significantly oriented, and they are shared by all zones and both directions on slopes. Figure 20 indicates that significant downslope orientations are more strongly aligned than cross-slope orientations. Only one slope, IN2, registers preferred orientation in all three zones. Debris flow lobes at one side of the slope base are attributed as causes of the downslope orientation found at base. The cross-slope preference in the upper zone is likely due to the effects of chance, since avalanching should not be responsible for any preferred orientation.

There are three slopes which display preferred orientations in at least 2 of 3 zones, and it is of interest to note that these are all slush avalanche-affected slopes (table 8). On these slopes, surfaces are smooth and compact, and thus provide little resistance to rolling or sliding.

TABLE 8

Directional Preferences of Significantly-Oriented Samples on Running Water-dominated Slopes

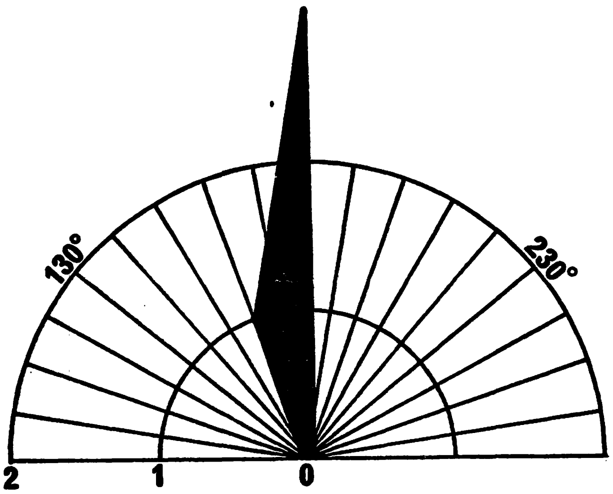
SAMPLE SITE	MEAN VECTOR DIRECTION	SLOPE PREFERENCE	LEVEL OF SIGNIFICANCE
CL5 mid 2	80°	C	.07
IN2 base 1	162°	D	.10
IN2 mid 1	352°	D	.06
IN2 top 2	84°	C	.07
IN3 base 2	0°	D	.01
IN3 mid 1	112°	C	.05
CAS7 base 1	187°	D	.09
RK4 top 2	39°	D	.01
RK7 base 2	131°	C	.07
RK7 top 2	238°	C	.09
RK8 mid 2	70°	C	.08

C: cross-slope

D: downslope

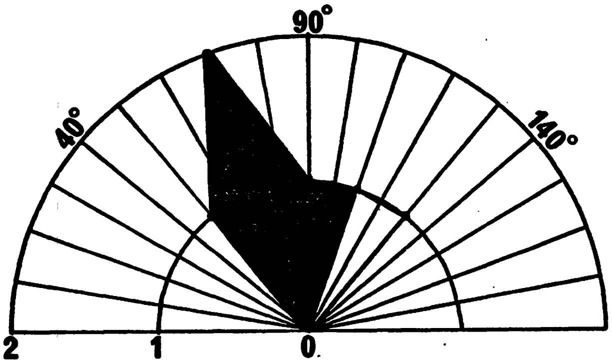
Figure 20

Alignment of significantly-oriented samples on running water-dominated slopes. A, downslope; B, cross-slope.



A.

DOWNSLOPE DIRECTION = 180°



B.

CROSS-SLOPE DIRECTION = 90°

Preferences are more likely to occur on these slopes, where avalanching acts as a smoothing agent. On others, however, where processes of lower magnitude occur, preferred orientations develop only within the periphery of the small surface area affected; thus the expected number of preferred orientations is low.

CHAPTER VIII

INTERACTION

(1) Process and Geometric Form

The latter sections of the previous three chapters have given consideration to the effect of each of the three process groups, on profile characteristics. It is now desireable to consider these characteristics in a perspective which allows comparison of these varied effects.

Slope angle values associated with specific processes were re-grouped according to study locale and subjected to a series of Mann-Whitney U tests, parametric tests being inapplicable considering the type of data used. Of the four localities, Cape Liddon slope angles are significantly greater than those of any other (at the .01 level), regardless of dominant processes (table 9). Caswall Tower slopes are next in overall steepness, and are significantly greater than all but those of Cape Liddon. Tests also reveal no significant difference between the angles of Cape Ricketts and the Inland plateau slopes.

There are two underlying factors common to Cape Liddon and Caswall Tower, and both are related to their geographic position. Both localities are in close proximity to the active sea level, and both display steep, well-dissected marine cliffs, although Caswall Tower is only partially subjected to these conditions. In both locales, only certain slopes show present evidence of marine abrasion,

TABLE 9

Mean angles of slopes grouped by locality and dominant process

	DOMINANT PROCESS		
LOCALE	ROCKFALL	RUNNING WATER	BASAL EROSION
Cape Liddon	35.72°	37.61°	39.37°
Caswall Tower	33.08°	33.29°	36.87°
Inland Plateau	32.53°	20.99°	-
Cape Ricketts	32.27°	29.42°	-

but in the past higher sea levels must have meant a higher number of Cape Liddon slopes were affected by this process. The greater steepness of the slopes in these two localities is attributed to the proximity of slopes to marine activity which by ice-rafting and abrasion of debris accumulations has kept cliffs uncovered and slopes steep. The non-seaward facing slopes at Caswall Tower were probably not affected by these activities, but the fact that the population of slopes sampled does include these affected slopes means that the overall steepness factor of the locale ranks second behind the only other area where this process occurs more fully.

That slopes in the remaining localities do not differ significantly in steepness agrees with the visual similarities that appear to exist between them. Unaffected by recent marine activity, these slopes have developed fully to the point where most of the scarp-face has been buried by its own weathered debris. The slopes are similar in types of process which dominate them, and special significance is given the slush-avalanching which has occurred in both areas.

A second set of non-parametric tests was performed on slope angles to compare the effects of different processes within each locale. At both Cape Liddon and Caswall Tower, slopes affected by marine processes are significantly steeper than rockfall slopes (at the .05 level); but only at Caswall Tower are they also steeper than slopes affected by running water. There is no difference in angles between the latter and basal erosion slopes at Cape Liddon. Similarly rockfall-dominated slopes at both locales do not differ significantly in angle from running water slopes.

These results suggest an over-riding uniformity in steepness of all Cape Liddon slopes, regardless of dominant process, which is attributed to the proximity of all slopes here to the sea. Removal processes are thus allowed to prevent adequate debris accumulations on slopes which would, by basal extension, lower the angles of the slopes. Basal erosion appears to be the only one of the three major processes which significantly affects slope steepness in Caswall Tower and Cape Liddon locales.

At the Inland plateau and Cape Ricketts localities, where only two major process groups prevail, rockfall-dominant slopes are significantly steeper than running water slopes. In these locales, processes connected with running water have been much more frequent in occurrence and much more effective in modification of initial slope angles than at Cape Liddon and Caswall Tower. Signs of extensive debris flow activity are common to slopes, as are those of slush avalanching. The debris shift accounted for by increased flow activity and avalanching has caused significant reductions in slope steepness. In terms of effect upon angles, running water and basal erosion processes are converse to each other.

Non-parametric tests were performed a third time to investigate the differences, if any, between slope types (sheets and cones). At the Inland plateau and Cape Ricketts areas, sheet angles are significantly steeper than cone angles (at the .05 level); but this merely reflects the effects considered above in that all talus cones have been affected by some type of running water process while a great majority of the sheets sampled are rockfall-dominant slopes. The differences in steepness between slope types then reflects the differences found between effects of dominant processes. At Caswall Tower, cone angles are significantly steeper (level of a=.01) than sheet angles, but here the cones are dominated by basal erosion, which would account for the differences. Cape Liddon slopes similarly reflect process variations in that sheet and cone angles do not differ significantly. Previous tests found that only basal erosion slopes were steeper here than others, but the fact that these slopes were both sheets and cones accounts for the lack of differentiation in steepness found between sheets and cones in this locale. In summary, then, these series of tests reveal that process variations are reflected in slope angles on slopes in the study area.

Comparisons have been made between these results and those from previous studies. Regarding slope type, Stock (1968) has suggested that conical talus slopes are generally steeper than are talus sheets in his Baffin Island study area; but his conclusions are based only upon observation of form. Southwest Devon findings are based upon statistical decision as well as observation, and neither support nor reject Stock's results but do suggest that the latter has not given due consideration to the effects of process variation on slope types.

The mean angles of table 9 for rockfall slopes comply with Ward's (1945) 30°-35° range for dry, gravitational slopes in south Britain and those of Andrews (1961) for Labrador slopes. Tinkler's (1966) limiting angle of 36° for such slopes corresponds with the highest locale mean recorded for rockfall slopes in southwest Devon. These values are slightly lower than Behre's (1933) 36.5° characteristic angle in alpine areas, but this is due to the centralizing tendencies of producing a locale mean. Such comparisons show that only slight variations in angles arise as a consequence of environmental differences, and that the characteristic angle to which rockfall slopes aspire is similarly about 36° regardless of environment.

Comparisons were made between Rapp's (1960a) Spitzbergen slopes and those of southwest Devon affected by similar sets of processes. In all cases, testing by non-parametric ANOVA has indicated no significant differences between each set of angles. The Spitzbergen values are slightly higher than those of the study area in all cases and might be regarded as the limiting angles for each set. For rockfall slopes, mean angles range from 33.4° to 35.5°; while for running water and basal erosion slopes the ranges are 30.3° to 31.0° and 38.1° to 40.0°, respectively. Results support the occurrence of a specific range of values for Arctic coastal slopes affected by similar processes.

The treatment of profiles in this study has been based upon the classification system in Stock (1968); but Stock's contention that the creation of the various slope statistics (table 1) enables beneficial quantitative analysis has not been realized. With profiles treated as non-normal data, numerous non-parametric tests were performed only to produce uniformity of results. The statistics were found incapable of sufficient differentiation between form on the various slopes. A comparison of slope "sums" between locales resulted in no significant difference between values; similarly slope "ratio" values gave the same result when subjected to non-parametric one-way ANOVA. The sums and ratios from varied process-dominated slopes in each locale also provided no significant differences.

On the basis of these findings, plus the meaningful results being gained from slope angle analysis, convexity and concavity indices were not tested. Stock himself avoids any statistical use of these data in his own study. The system does, however retain value as a quantitative method of slope classification and is relevant in that respect.

Results of the profile analysis of slopes dominated by separate processes have been given in sections of the previous three chapters. It is found that 25 of 29, or 86% of the rockfall slope profiles are completely or predominantly concave in form, while convexity dominates 2 of 5, or 40% of the basal erosion slope profiles. Running water-dominated profiles are the most pronounced in form, since 95% (19 of 20) are completely or predominantly concave with the one remaining profile convexo-concave.

The overwhelming conformity in profile of running water-dominated slopes is in part due to the nature of this class of processes as re-arrangement or shift processes. All developing slopes are inherently rockfall slopes and will thus be slightly concave or straight by nature. Shifting of debris caused by debris flow, avalanching and surface meltwater transportation of debris will most often occur on the mid and lower slope zones, so that concavity is enhanced as the major profile element. This explains why the proportion of concave slope forms associated with these processes is higher than for rockfall-dominated slopes. An additional reason for the lower number of concave slopes in the rockfall class is the inclusion of Cape Liddon slopes, which for this process are adversely affected by constant removal of basal debris accumulation by either ice-rafting or marine erosion. Thus many of these slopes remain straight, or convex because the only significant accumulation of debris can occur at the top of the slopes. The same is true of some of the coastal slopes at Caswall Tower.

Basal erosion slopes are predominantly convex, the form element being introduced by the basal-cut made by wave attack and imposed upon the existing profile. The predominance of convexity will be much lower if the magnitude of the vertical cut is small. Convexity of such slopes is regarded as a short-term condition, though, because rapid readjustment to the basal instability created usually causes downslope debris shifting to change the form to a straight profile (V, (2)). A slower rate of readjustment may reduce convexity to a minor slope element without necessarily eliminating it.

Very little attention has been paid in the literature to profile form and its relation to process, and therefore comparisons with reports from other studies are limited. Stock (1968) did obtain similar proof of the prevalence of concave form on Baffin Island slopes where 19 of 25 studied were classed as being concave or predominantly concave. In Spitzbergen, Rapp (1960a) relates that talus cones with slide tongues prevailing are straight in form, while those with avalanches and mudflows are reported distinctly and slightly concave, respectively. There appears then to be agreement as to profile form associated with various processes in active periglacial environments.

In summary, geometric form appears to bear direct relationships with the activity of various processes in the study area.

(2) Process and Debris Characteristics

(a) Size and Shape

Debris slopes grouped according to the three dominant processes in the study area were subjected to ANOVA tests on debris size and shape. The group results were discussed briefly and independently. Meaningful trends can be established by now considering these results in respect to each other.

The over-riding trend in size data, which pervades all three groups of slopes is that the correlation ratios associated with zonal variation are with only few exceptions higher than are those associated with lateral size variation. The arrangement of debris size into downslope components then is a feature characteristic to all slopes in this area whether statistically significant or not. This feature directly supports the theory of fall-sorting of rockfall debris as a valid process on slopes; and its common occurrence reflects the fact that the origin of all debris slopes studied, despite groupings, is as gravitational rockfall accumulation. This study makes no attempt to determine whether size increases or decreases in a downslope direction, but only whether a variation in the plane does occur and whether or not it is greater than variation in a cross-slope plane.

A direct comparison of percentages reveals that rockfall slopes are highest in significant size arrangements recorded, followed by basal erosion and running water-dominated slopes in that order. Ten of 15 rockfall slopes (66%) have significant size arrangements, all of which are zonal. Other research on rockfall slopes provides contrasts with the results found here. Caine (1967) found no consistent variation in debris size and sorting with position on the slope; however his results are based on analysis of only two slopes for which

ANOVA was not performed to prove his point about variance. Griffiths (1959) similarly reports that size is homogeneous over a debris slope since modification of the deposit will be small and the detritus represents an initial stage in the formation of the final sedimentary deposit. These results were based on study of one slope; and although ANOVA was performed the results are not considered valid and will be further investigated later in this section. Gardner (1968) reports an "over-riding" downslope sorting of material despite the poor sorting found at any one point on his Rocky Mountain slopes. Variation in size between samples was found significant with ANOVA tests, which lends support to the results found upon analysis of southwest Devon slopes. Going a step further, Gardner (1968) uses regression analysis to determine that variations in position of the slope sample account for 50% of the size variations. For southwest Devon slopes, regression was not used as a means to break down the total variation discovered in simple one-way ANOVA; and instead a more complex two-way ANOVA design was employed which breaks down total variation automatically into the various effects assigned as variables. Furthermore, these results give the variations accounted for by specific positions (lateral and zonal) rather than overall position, and as such represent a more sophisticated analysis. Values of eta^2 rarely reach a level of explanation of 50% such as found by Gardner (1968), but are at the same time the result of a more stringent test which must parcel out variance to more than one source rather than just one as is done in the afore-mentioned study.

Of the two basal erosion slopes, only one is homogeneous in size variation.

It was determined that size arrangement on such slopes is directly affected by the magnitude and intensity of the basal attack (V, (3)). High magnitude basal abrasion not only removes the basal debris, generally the larger of the slope debris onslope, but causes downslope re-distribution of the smaller-sized material from the upper slope zones. In this fashion homogeneity is approached over a short period of slope readjustment. On the other hand, readjustment to minor basal-cuts may not reach the upper slope zones, and the basal-cut itself may not significantly alter the predominance of larger debris found at base. The initial size arrangements may not therefore be significantly altered on such a slope. The size data for basal erosion slopes comply with this initial assumption.

Unfortunately the effects on debris of basally-abraded slopes have not been reported elsewhere in a quantitative manner, so that these results stand as the only support to such hypotheses.

On running water-dominated slopes only 40% of the 10 slopes report significant size arrangements. This proportion is the lowest among the three groups of slopes discussed in this section. It is noteworthy that of the six homogeneous slopes, half are those purported to have been affected by slush avalanches. The three slopes in question, oddly enough, display identical correlation ratio scores for both zonal and lateral effects. The remaining avalanche-affected slope does have a significant zonal arrangement in size, but its eta score is the lowest of all those with significant size arrangements in this class of slopes. It appears obvious from the correlation ratios that slush avalanches have a similar effect in dispersing any fall-sorting arrangements which might have been formed in the earlier development of these slopes. Debris flow and meltwater gulleying, where strong, appear to have reinforced size arrangements. On the two main slopes cited for these activities, not only is size arrangement significant by zones but also by lateral effects. Such arrangements are due to the fact that gulleys and flows will occupy one side of the slope and thereby offer adequate contrasts in size of material between them. Basal accumulations of fine-sized material do not significantly alter the initial fall-sorting of debris on slopes because the sampling has been biased towards the larger rock fragments which rest upon these features.

Rapp (1959) suggests that evidence of snow avalanche activity is present in the form of heterogeneity of particle sizes at specific locations. This suggestion complies with ANOVA size results on such southwest Devon slopes, since the heterogeneity implies a mixing of different sizes of debris from various slope zones. Rapp's (1959) results, though are not validated by statistical testing of samples from all parts of his slopes. For the other running water processes the concentration and downslope shifting of similar size ranges of debris is of considerable consequence to the arranging of slope debris even though other studies do not again reference it in terms of statistical analysis. Gardner (1968), however, does indirectly mention this effect by maintaining that on his slopes size variation does exist.

In summary, all slopes reflect their origin as rockfall accumulations, some of which remain unmodified by subsequent processes. Others, such as basal erosion and avalanche slopes have produced homogeneity of debris by eliminating the fall-sorting arrangement, while many have been altered in a lateral sense only. Results of previous studies do not adequately apply to the variety of debris slopes which they are intending to represent.

Interpretation of debris shape results is not a simple task, for there are many uncontrollable variables which can account for all sorts of shape variations over any slope surface. Furthermore, shape analysis is slightly confusing when considering two measures, flatness and sphericity, both of which are interrelated to some degree (IV, (2)). Greater weight is given the latter because it has a more direct effect upon size sorting, since it governs the mass of the falling particles and hence the distance each will travel (VI, (3)).

Some trends are discernible from the correlation ratio values. In a fashion similar to size, debris shape is more strongly associated with a zonal effect than a lateral effect. The trend is not as widespread as for size, but it does reflect a basic similarity with the size results.

On the basal erosion slopes shape trends conform to those of size in that shape variation is homogeneous on the high-intensity erosion slope and arranged significantly on the less-severely affected slope. On rockfall-dominated slopes, only 7 of 15 have significant arrangements of both size and shape, but on the others which are not associated with size the reported lateral arrangements may be due to a number of factors. The most likely factor postulated is the uneven dissection of the rockwall, which could cause the accumulation down one side of a slope of debris of one lithology which has not been weathered as intensely on the other rockwall section. Such action is possible, for example, from the irregular spacing of joints which may favour one rockwall section and not another. The presence of a varying lithology would cause shape to be arranged in lateral pockets while size arrangement may be unaffected. Gardner (1968) supports this view by stating that the distribution of lithologies at any point on a debris slope should influence the relative blockiness (sphericity) of the material at that point. Since lithological variation has not been accurately assessed in this study, such a possibility remains a likelihood.

Running water-dominated slopes again display the lowest proportion of any group with regard to the number of slopes on which both size and shape are significantly arranged. Only one of ten have this trait compared to 1 of 2 and 7 of 15 for basal erosion and rockfall slopes. The one exception is the slope upon which a great deal of debris flow activity and levee formation has occurred. Only two other slopes display significant shape arrangement, and only one of those is an avalanche-affected slope. The proportion of slopes with significant shape arrangements, 3 (30%) is also the lowest of any other group of slopes. All of these factors point to the similarities between trends in the size and shape data for running water-dominated slopes. Locale variations in lithology are not considered an influencing factor because these slopes are drawn from all four areas.

Finally, comparisons can be made with other comments concerning size and shape variables. Caine (1967) found that with a linkage analysis there was no evidence to suggest a strong linkage between size and shape. Furthermore he found a general uniformity of block shape on the two slopes studied. Griffiths (1959) similarly found no shape variations between samples on his debris slope.

Gardner (1968), with a greater number of slopes, believes that a relationship does exist between size and shape. The effect of lithology is hidden in the relationship since it influences both parameters. The southwest Devon results from ANOVA tests similarly suggest that such relationships do exist, although regrettably the precise effect of lithology has been neglected. The shape variations that are more highly associated with zonal effects are considered evidence of this relationship although it is by no means a consistent one.

Only a limited number of studies are available to provide comparisons with the ANOVA results for southwest Devon slopes. Direct comparisons of F values are statistically meaningless, and thus the proper procedure for analyzing test power is followed. Before doing so it is necessary to outline some of the basic concepts of statistical power analysis. A statistical test of a null hypothesis essentially involves a complex relationship with four parameters, which are:-

(a) test power
(b) region of rejection of the null hypothesis
(c) sample size
(d) effect size, ie. the degree of departure from the null hypothesis.

These parameters are so related that when any three are fixed, the fourth can be determined (Cohen, 1965). This operation is useful for research design, but can also be used to determine the power of statistical tests which have already been performed. Then in order to ascertain statistical power of previous test designs, the common parameters must be of equivalent values. Cohen (1965) recommends that all research plans strive for a "medium" effect size of .25 (defined), a rejection level of .05, and a power of 80% (ie. an 80% probability that the test will yield statistically significant results). These recommendations were adopted as critical factors in the comparison of previous size and shape ANOVA tests.

Besides the present study, ANOVA tests have been done on debris size data by Griffiths (1959) and Gardner (1968). Since each study varies only in sample size, the other parameters are standardized as .05 significance level, medium effect size and a .80 desired power. For each type of ANOVA design, actual power was determined from the tables and formulae provided in Cohen (1969). The respective powers of each test are then used as a valid basis for comparison of results.

The two-way design ANOVA tests for southwest Devon debris size, using sample sizes of 50 provide a power value of 98% for tests of zonal effects and 99% for tests of lateral effects. Griffiths (1959) used two designs, of which the first (two-way factorial) has a sample size of 8 fragments. Consequently with the same fixed parameters its powers are only 51% for a zonal effect (called line variation in his text) and 34% for a lateral effect (operator pairs in his text). The effect of a low sample size on statistical power is clear; and Griffiths' power fails to meet the 80% level recommended for satisfactory statistical work. The results derived from the test of southwest Devon slopes are justifiably believed more reliable than are Griffiths', which essentially point out that size variation over one portion of a debris slope is homogeneous. Griffiths (1959) uses this result to reinforce a hypothesis that a debris slope represents a primary sedimentary deposit close to its source with minor modifications. The southwest Devon results, drawn from 27 slopes, reveal no overwhelming conformity to Griffiths hypothesis. In fact 15 slopes do bear significant size arrangements and 10 of these are dry, gravitational rockfall slopes to which Griffiths has been referring. Griffiths' (1959) basic test design is similar in pattern, however, and so it must be asserted that his results are less satisfactory than those found for southwest Devon samples.

In the same report, Griffiths (1959) also employed a simple one-way ANOVA test for size variation on a set of six randomly selected sample sites, each containing 4 rock fragments. For medium effect size and a .05 level of significance, his test power is determined as a low 11%. Gardner (1968) has performed a one-way ANOVA to determine variation between 30 sample sites of 25 fragments each, drawn from a whole sample population of slopes. With test parameters fixed as for the other test designs, Gardner's probability of yielding statistically significant results is slightly less than 98%. Gardner (1968) reported a significant between-sample variation that is greater than between-fragment variation, the reverse of Griffiths (1959) findings. Due to the very high power of Gardner's tests, his results are taken as more valid than are those of Griffiths.

It must be considered, when comparing southwest Devon results with Gardner's (1968), that the simple one-way design takes account of only one major effect, and consequently its power to correctly interpret one effect will be greater than that of any one effect in a two-way factorial design for ANOVA. The greater number of assigned effects to be considered lowers the probability of correctly predicting any one of them; and thus even though Gardner's (1968) test power is approximately equal to the Devon test, it is passing judgement on only one effect. Furthermore, Gardner's test design involves selecting sites from all of his slopes rather than dealing with variation on each individual slope. Consequently his results are not as meaningful as the Devon results insofar as their relevance to variation over a slope surface.

As a sideline to these sets of comparisons it is possible to understand the importance of choosing sample sizes adequate to obtain the best possible power of a test. The "a priori" selection of sampling designs in geomorphic studies has sorely neglected to consider the power of statistical tests that will be used on the collected data. Consequently many of the studies being used to reference and guide present research designs are unworthy of such attention. The remedies are simple; for instance the same one-way design of Griffiths (1959) would attain the required 80% power simply by an increase in sample size from 4 to 35 fragments.

It is concluded that the southwest Devon ANOVA results are more valid in terms of the experimental design than other similar studies done in the past in that the chances of detecting a significant medium effect between zonal and lateral size samples (powers) are 98% and 99% respectively.

Unfortunately no previous ANOVA tests have been found which deal with shape of surface debris. The powers of the southwest Devon shape tests remain the same as those for size, and hence the results described for shape variation are considered valid.

(b) Orientation

Debris orientations determined by Caine's (1969) photographic method (IV, (2)) are not rewarding in their expected capacity as process indicators. A comparison of the trends in orientation studies discussed according to process groups is now desirable to determine the overall effectiveness of a process in arranging slope debris.

Two levels of significance have been considered in vector analysis of the orientations, .10 and a more stringent .05 alpha level. For .10, 25% of the total number of 162 samples have significant orientations; but at .05 that proportion is reduced to 7%. Even at the higher alpha value, then, the proportion of significant orientations is low when compared to the 71% reported by Gardner (1968) on Lake Louise slopes at the .05 level. It is therefore necessary to analyze the divisions of process-slopes more closely.

At the .10 alpha level, comparisons of processes show that significance occurs for 47% of the basal erosion slope samples, compared to 25% and 18% for rockfall and running-water slope samples, respectively. At .05, these proportions become similarly low in value (less than 10%) in each case, which reflects again the underlying lack of significantly oriented samples on the study area slopes.

The 47% of basal erosion slopes significantly oriented at .10 levels are the product of local slope failure brought about by debris shifting downslope during readjustment to a basal cut. The importance of local slope failure has been reported by Andrews (1961). Downslope and cross-slope preferences are equally frequent among the significant orientations, but the fact that the latter are more strongly aligned suggests that preferred orientation has been initially created by rolling of debris over its 'B' and 'C' axes. Interference from other debris has modified the cross-slope orientations so that many are rotated downslope. Since readjustment to basal cuts is generally rapid, many of these orientations are likely of short duration and hence the long-term importance of basal erosion on debris orientation is small.

The 25% of significantly-oriented rockfall samples are analyzed with respect to previous research since most orientation studies have been made on these dry, gravitational slopes. Early studies (Rapp, 1960b; Andrews, 1961) report downslope orientations on such slopes; but recently Caine (1967; 1969) has found that a random or uniform orientation is to be expected because of the rough nature of a slope surface. Only where the surface acts as a smooth plane will any directional preferences develop. Caine (1969) believes that his more powerful statistical analysis of the data casts doubt on previous assumptions made in this field, and that a random fabric is to be expected. There is some measure of agreement with Caine's (1969) view when the rockfall slopes of southwest Devon are considered; for over half of the significant orientations are located in the upper and middle slope zones where the surface has a greater chance of being smoothed out by compaction of fines. This smoothness allows directional preferences to develop more easily than in basal slope areas. Considering Caine's (1969) contention, though, it is not alarming to find such a low proportion (25%) of preferred orientations at the low alpha level of .10.

The 18% of samples significantly oriented on running water slopes also finds support from previous studies.

Although avalanche activity is unlikely to create any direct orientational preferences, its smoothing and compacting effect on a slope surface indirectly creates the situation necessary for preferences to develop. The orientations then are formed by subsequent rockfall activity. Debris flow movements will cause only specific areas to be subject to orientation, ie. those over which the flows travel. Rapp (1960b) has reported cross-slope orientations on flow lobes, but near-equal preferences for both cross-slope and downslope directions exist on these southwest Devon slopes. As is the case with rockfall samples, the majority of the significant orientations are found on smooth-surfaced slope areas. The surfaces of avalanche-affected slopes prove to be consistently popular for preference development.

It has been established then that weak preferences do result from process activities in the study area; however the low proportions found tend to reinforce Caine (1969) in his hypothesis that random orientations are to be expected. On this basis, analysis of orientation alone is considered insufficient to determine the presence or absence of any slope process.

Comment is required on the use of the .10 level of significance in the vector analysis of orientation. Field observations at the sample sites, together with many rose diagram plots of the orientation data all point to the presence of apparent directional trends. The surface over which any process can act on a slope is generally so large that the higher alpha value is believed necessary to detect the presence of these orientations. Statistical justification is also required, but unfortunately the use of the Rayleigh test (Curray, 1956) makes it impossible to determine statistical power of the orientation results.

An interesting and valid viewpoint is advanced by Cohen (1965) on this matter of alpha levels and is worthy of mention here. Cohen (p. 100) states that in ... "current academic quarters the acceptance of the quasi-official convention of 5% has resulted in its implicit equation with scientific truth for the positive claim and respectability for the claimant." Such acceptance has progressed to the point where many valuable studies have been shelved by authors or rejected for publication by editors simply because the desired effects were not found significant at the .05 level.

Such studies would be found significant at levels slightly higher than this convention, and may furthermore be of greater statistical power than the parallel studies already published which do claim significant results. The use of the 5% convention has thus tended to increase the rate of many spuriously "significant" reports in published research (Cohen, 1965).

Related to orientation results in this study, such information appears to justify a discussion of the findings even though the levels of significance range from .01 to .10 for individual samples. Any restraints on the interpretation should be made by those examining these results, who must bear in mind the level of statistical judgement used in comparison with other work.

(3) The Process-Response Environment

A distinction has already been made between responses of geometric and debris form to the occurrence of the three basic processes in the study area. The more comprehensive relationships which may be found among all responses to processes are worthy of separate consideration.

No consistent relation with preferred orientations and basic slope variables appears to exist. Gardner (1968) found no significant correlations between vector magnitude and either of slope angle, particle elongation, size and size variation. Caine (1967) similarly emphasized that relations between size, shape and debris orientation are no more than fortuitous. On southwest Devon slopes, the proportions of preferred orientations at stringent alpha levels of significance suggest similarly low relationships with process variation. These facts demonstrate that conclusions about processes cannot be determined from sedimentological data alone on debris slopes; instead the lengthy analysis of observations on the processes themselves are more apt to reinforce speculation on the effects they will have made upon sediment and geometric form.

In many cases, the various process-response relationships will entwine, causing either substitution for, or enhancement and continuation of the effects of any one process. For instance, rockfall is capable of infilling the gullies created by both meltwater activity and debris flows. Where slopes are short and cliff-faces high, large rockfalls have been observed to actually reform a slope base left vertical in profile by marine abrasion. Rockfall-induced slide tongues were also observed contributing debris to compensate for marine removal at base. Similarly, meltwater-deposited debris fans provided basal extensions for several coastal debris slopes. Slush avalanches are known to produce slope extension by deposition of boulder "aprons" at the slope perimeter. Evan basal erosion serves to modify the action of other processes by causing a steepening and unstabilizing effect upon a slope. Such actions serve to reduce the amount of subsequent rockfall accumulations by causing much of it to travel straight out of the slope system. The instability increases the frequency of debris shifting, which later reduces the amount of debris available for other running water processes. In this fashion basal erosion serves to produce negative feedback in the slope system. The problem which arises from such interactions, of course, is that the effect of any one process is difficult to assess in isolation.

The primary question to be resolved in this study is to ascertain the importance of specific process-response interactions relative to others in the study area. Various quantitative approaches have been made in past studies, based upon volume of debris involved in the action of processes (Rapp, 1960b; Gardner, 1968); but for southwest Devon slopes volumes of debris were not assessed. Evaluation must then follow a qualitative approach which considers the role of each process, the degree of interaction and various other special consequences of its presence.

Rockfall is the major input process for all slopes in the study area, although only half of these studied are presently dominated by this process. In terms of Jahn's (1968a) concept of denudational balance, such slopes have a uniformly negative balance between debris accumulation and slope transport. On southwest Devon slopes, rockfall is the only "continuous" slope process (Rapp, 1960c) available, and is responsible for the origin of all the debris slopes involved in the study.

The effect of the basic fall-sorting process which accompanies rockfall is present to various degrees on all slopes, as portrayed by the correlation ratio scores for zonal effects. Modifications by other processes, and disappearance of a rockwall source does not obliterate this evidence. Similarly, the basically concave profile form generated by rockfall accumulation is prevalent on all slopes, barring modifications by basal erosion. Running water processes have tended to reinforce and accentuate the form inherited from this output process.

Running water processes can be referred to as shifting, queuing or re-arrangement processes. Jahn's (1968a) categorization would place running water-dominated slopes as equivalently-balanced slopes. Gardner (1968) believes slush avalanches to be the most important of this class on large debris slopes, with slides and local failures ranking second. Rapp (1960b), however, ranks transportation of dissolved salts, slides and flows ahead of dirty avalanches in terms of mass transfer of slope material in Karkevagge. On southwest Devon slopes, running water processes constitute the major body of redistribution processes. In terms of rank, slush avalanches appear to have caused the most significant modifications of the basic rockfall-derived slopes. On slopes affected by this process, slope angles are lower than on all other types, concavity in profile is most pronounced, debris size and shape is most consistently homogeneous in variation, and preferred orientations are most easily developed. Debris flow activity and meltwater gulleying appear likely to have transferred much greater volumes of slope debris; but because this aspect was not covered such activities rank behind slush avalanching, which is contrary to Rapp's (1960b) findings.

These latter forms of re-distribution do, however, have the effect of enhancing the debris size and shape trends established by rockfall. Slopes are similarly concave in form, and in terms of the whole group the running water processes have a pronounced effect upon the debris slope morphology in the study area.

Subsurface meltwater activity is found inconsequential to large-scale morphology in the short term, but does have interesting interaction with the slope micro-relief. A cause-effect relationship appears to exist between meltwater flow and the maintenance of inter-cone relief for the channelling of runoff. Formed initially by the coalescence of laterally-expanding slopes, the depressions serve to attract the larger blocks which have travelled farther downslope from the rockfall funnels. The concentration of these blocks increases the melting of permafrost beneath it since the bigger air spaces which exist between coarse blocks allow penetration of warm surface air. Where fines are concentrated, permafrost is found nearer the surface. Due to the fall-sorting arrangement on most slopes, it has been established that the permafrost table relief conforms to the surface profile (VII, (4)), with exceptions occurring due to irregular pockets of coarse-sized debris. Then the meltwater flow pattern will be indirectly regulated by the size and thickness of the surface debris.

In the peak melt-period, subsurface meltwater is attracted to the inter-cone depressions as it seeks out the most convenient gravity-flow route. The concentration of meltwater here causes a further lowering of the permafrost table which enhances even more the attraction of this channel as a gravity flow route. Chemical erosion of debris in this channel likely occurs at a faster rate than elsewhere on the slope, which may perpetuate the local relief form. In seeking the most economical flow routes, the concentration of water into channels after travelling only short distances down the slope crest reduces the probability of a slopewash effect from snowmelt. Most water on the cones is then influencing very little of the major slope deposits through transportation of fines following the ablation of the winter snow cover. The highest meltwater flow rates consistently occur during the time that water is flowing down the inter-cone depression, since passage is much easier through the large open-space network of interstitial pores found here than it is in the upper slope zone. Hence movement of fines in suspension from the talus cone necks will be lateral downslope and into the depressions between cones. In late summer, though, meltwater produced from the ablation of the permafrost itself occurs at such low rates that the micro-relief cannot exert any but a local effect upon the pattern of flow. Only at this time of year is slopewash likely to occur, but its effect on the slope as a whole is rather small.

The only process considered an output process encountered on the study area slopes is basal erosion. It is also classified as a sporadic process along with those in the running water group, and has a profound impact upon slope morphology. Its effect has been shown to depend on the magnitude and intensity of the process itself (V, (3)). The process is limited spatially in that it will affect only those slopes sufficiently close to the active beach, and temporally because marine activity can occur only over a short open-water season in the summer months. Along Cape Liddon and sections of Caswall Tower basal erosion has affected steepness, debris arrangement and size and shape characteristics on certain slopes. Preferred orientations are more frequent on such slopes than elsewhere, the angles are steeper and profiles are afflicted by convexity introduced as a direct result of the abraded basal-cuts. Readjustment to abrasion tends to cause homogeneity of slope debris variations with no significant size arrangements, although its effects are likely to be short-term due to the interplay of other active processes. In terms of denudational balance such slopes are positively balanced (Jahn, 1968a), since the interference of erosive agencies obstructs the formation of the more typical slope properties.

Continual response to basal erosion along Cape Liddon appears to have far-reaching significance for general cliff evolution in that area. On one particular section of the Cape, denudation of the once-buried cliff-face is occurring in response to active removal processes. The combined effect of basal abrasion and ice-rafting of accumulating debris has been to cause negative feedback in the general system of slope growth to a point where reversion to the initial situation is occurring (plate 19). If the rate of debris removal continues to out-pace the rate of positive accumulation, this entire slope section will be obliterated and the lower cliff-face exhumed to original form. Such interaction of processes has been reported on north Wales slopes (Tinkler, 1966); but in that instance fluvial undercutting had exhumed bare rock or "clitter" slopes from the original, dry, accumulation slopes.

Basal erosion has revealed cross-sections which display crude layerings of slope debris and beach gravels well above present sea level and incorporated in permafrost (V, (2)). The complex interaction of process and climatic variables likely involves an encroachment of the sea upon the slopes, followed by highly active mechanical cliff weathering. Slush avalanching and ice falls may also be major factors causing the differentiation in debris layers, although the precise nature and sequence of process domination or climatic effects is difficult to determine.

Investigations on the Island of Rhum lend positive support to these interactions (McCann & Richards, 1969). In that area, raised marine gravels are reported overlain by up to 6 metres of talus debris derived from slopes at the rear, and pronounced slope debris stratifications were found. As at Cape Liddon these forms involved coarse openwork material and bands of finer-sized debris. Slopes were also found developed over rock platforms, a characteristic of Cape Liddon slopes. It therefore is interesting to find that these interactions in a marine periglacial area may be common to many now-fossil periglacial environments.

Since basic differences do exist in the functions of the observed processes, the final analysis of process-morphology interaction has become a subjective appraisal of the importance of sporadic versus continuous processes. It is difficult, though, to assess their individual significance because slopes in the study area are a response to several interacting processes. The frequency and magnitude of any process varies over time and space, and in this context the continuous process of rockfall is believed to have the greatest relevance for slope development. The sporadic processes, consisting of both shift and removal types, are much more dramatic in their short-term effects upon slope form; and these processes appear to dominate recent slope development in southwest Devon Island. Whether they are continuous or sporadic, this study has found that on both large and small scale, and in both positive and negative fashion, processes and responses to them compose a significant geomorphic relationship in the periglacial slope environment.

CHAPTER IX

CONCLUSIONS

The comprehensive study of process-morphology interaction on Arctic debris slopes has produced the following conclusions.

First, the process of basal erosion has a profound effect upon slope morphology. It is both an output process and a sporadic one, and is limited spatially and temporally in the study area. Differences in frequency and intensity of basal abrasion in the different locales is the attributed cause of variations in angles and the degree of convexity of profiles drawn from affected slopes. Duration and importance of the effects of this process are deemed short-term due to the interplay of other active processes; but in some areas a continual response to repetitions of this process appears to be causing drastic alteration to the present stage of cliff evolution. Exposures made by basal-cuts indicate a complex interaction of several processes with climatic variation, which may be common to many of the now-fossil periglacial marine localities.

Rockfall is the major input process for all slopes in the study area and the only one considered as continuous. The predominance of concavity as a major form element is attributed to basal extension by rockfall accumulations, with minor convex elements appearing as a consequence of debris accumulation in the upslope zone beneath the rockwall base. Other processes tend to have either modified or enhanced the morphological features inherited from rockfall accumulation. Rock catchment experiments indicate that only the upper slope zones are at present accumulating debris in continuous fashion on the slopes sampled. Results from such experiments should be employed with restraint, and preferably only to determine zone and rates of accumulation during the study period involved.

Running water processes constitute the major body of re-arrangement processes in the study area, and have a pronounced effect upon debris slope morphology. Their profiles are more pronounced in concavity, the overwhelming conformity in part due to the nature of these sporadic processes as re-arrangers of slope debris. Slush avalanches appear to have caused the most significant modifications to the basic rockfall-derived slope characteristics, while smaller processes such as debris flows and accumulation of basal fines involve a smaller proportion of the total slope area and are of lesser importance in effect upon slope angle and geometric form. During the peak melt-period, running water is responsible for the down-slope transportation and deposition of large quantities of silt and clay at slope base. Subsurface flow during this time becomes an erosive and transporting agent which appears to hold an interesting cause-effect relationship with the slope micro-relief. Most subsurface meltwater on cones is influencing very little of the major slope deposit, as it tends to channel down inter-cone depressions in seeking the best gravity-flow route.

Trends resulting from analysis of variance tests on size data support the occurrence of fall-sorting of rockfall debris on all slopes in the study area. On basal erosion and slush avalanche-affected slopes, the fall-sorting arrangements have been drastically altered, while meltwater gulleying and debris flow activity on a large scale tend to add a significant lateral slope component to size arrangement. Shape variations are attributed to many variables, any of which are difficult to view in isolation. Spacing and presence of joint patterns, bed thickness and fracture properties of the parent lithology are probably the major variables to be considered. Significant lateral arrangements in shape are believed due to non-uniform dissection of the rockwall; while uniform rockwall dissection will be indicated by uniformity of shape variation over a slope. Comparison of size and shape results with similar studies reveal that because statistical power is greater for the southwest Devon test design the results of this study are more reliable as indicators of the nature of size and shape on debris slopes.

Results of slope angle studies support the likelihood of a range of common slope values for slopes affected by the three basic process groups in maritime periglacial areas. Results of previous studies do not in many cases apply themselves to the varieties of debris slopes which are found on southwest Devon Island. Stock's (1968) various slope statistics were found incapable of sufficiently differentiating between form of the study area slopes; nevertheless they retain value as a means of quantitative profile classification.

Debris orientations determined by Caine's (1969) photographic method are not rewarding in their expected capacity as process indicators. At the .05 level of significance the proportions of significantly-oriented samples on slopes affected by all processes reflect the underlying lack of strong directional preferences associated with the various processes.

At the .10 level of alpha, significant orientations appear determined by variations in the degree of local slope failure associated with basal erosion. On rockfall-dominated slopes, significant directional preferences tend to develop more easily on the smoother-surfaced upslope areas; and similarly, preferences are more likely to occur on the surfaces of slopes affected by slush avalanching than on any other running water-dominated slopes. The low number of significant orientations found suggests that a random fabric is generally to be expected on debris slopes. Justification of interpretation of preferences significant at levels ranging from .01 to .10 is made from critical discussion of visual trends and the present conventions of significance testing.

Conclusions about effect of a process on slope morphology can best be determined by detailed observations of the process itself, complemented by geometric and debris form data. A qualitative assessment of specific process-response relationships must consider the role of each process, the degree of interaction and any other special consequence of its activity. In many cases these relationships will entwine, causing modification, or accentuation of the effects of any one process. Rockfall, as a continuous process, is believed to bear the greatest overall relevance to slope development in the study area. Sporadic processes are more dramatic in their short-term effects and appear to dominate recent slope development on southwest Devon Island.

In a final analysis, both sporadic and continuous processes, and the responses to them compose a significant geomorphic relationship on both large and small scales in the periglacial slope environment.

APPENDIX I

SELECTED CLIMATIC DATA

TABLE 10

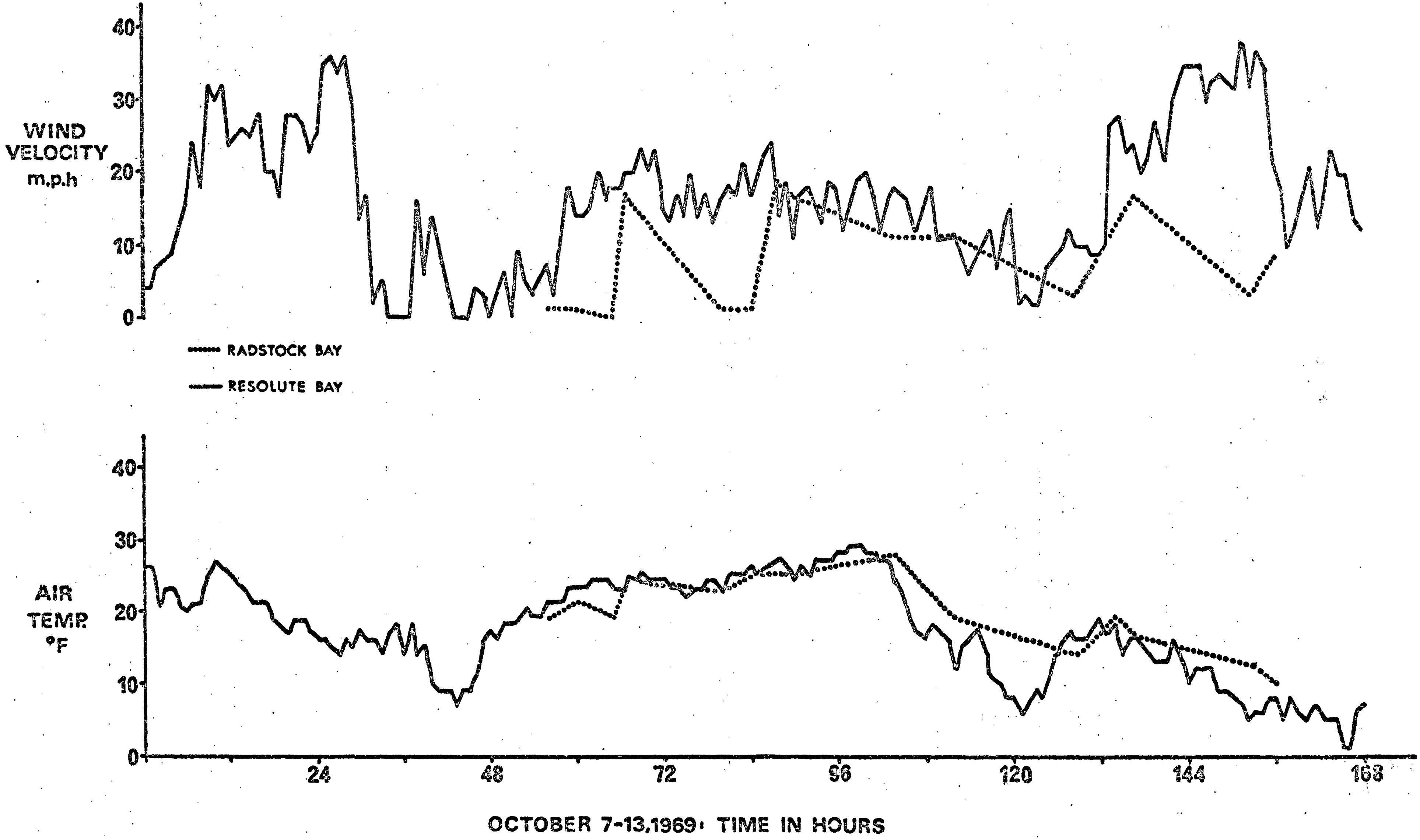
Selected Climatic Data for Resolute Bay, N.W.T., 1957 to 1967 *

MONTH	MEAN MONTHLY PRECIPITATION (inches)	MAXIMUM 24 HR. PRECIPITATION (inches)	MEAN MONTHLY TEMPERATURE (°F)
January	0.09	0.04	-24
February	0.12	0.04	-26
March	0.11	0.04	-23
April	0.21	0.07	-10
May	0.28	0.09	+12
June	0.37	0.10	+29
July	1.04	0.31	+37
August	0.93	0.33	+34
September	0.65	0.20	+21
October	0.59	0.14	+04
November	0.21	0.07	-11
December	0.24	0.07	-17
Mean Annual	4.84	-	-
Mean	-	0.15	+2.16

* Source: "Arctic Summary," Met. Branch, D.O.T., Canada.

Figure 21

Comparison of temperature and wind
data for October 7-13, 1969, between
Resolute Bay and Radstock Bay, N.W.T.


WIND VELOCITY m.p.h
40
30
20
10
0
RADSTOCK BAY
RESOLUTE BAY
AIR TEMP. °F
40
30
20
10
0
24
48
72
96
120
144
168
OCTOBER 7-13,1969: TIME IN HOURS

APPENDIX II

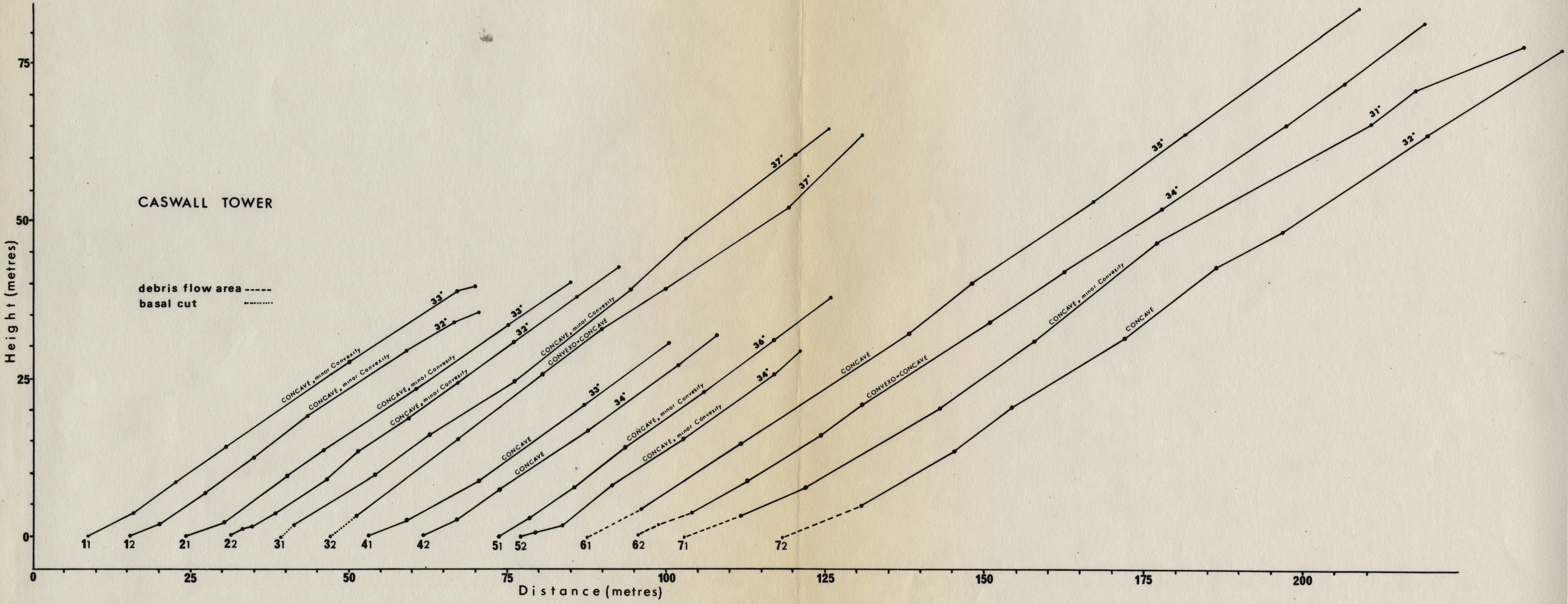
SLOPE PROFILES

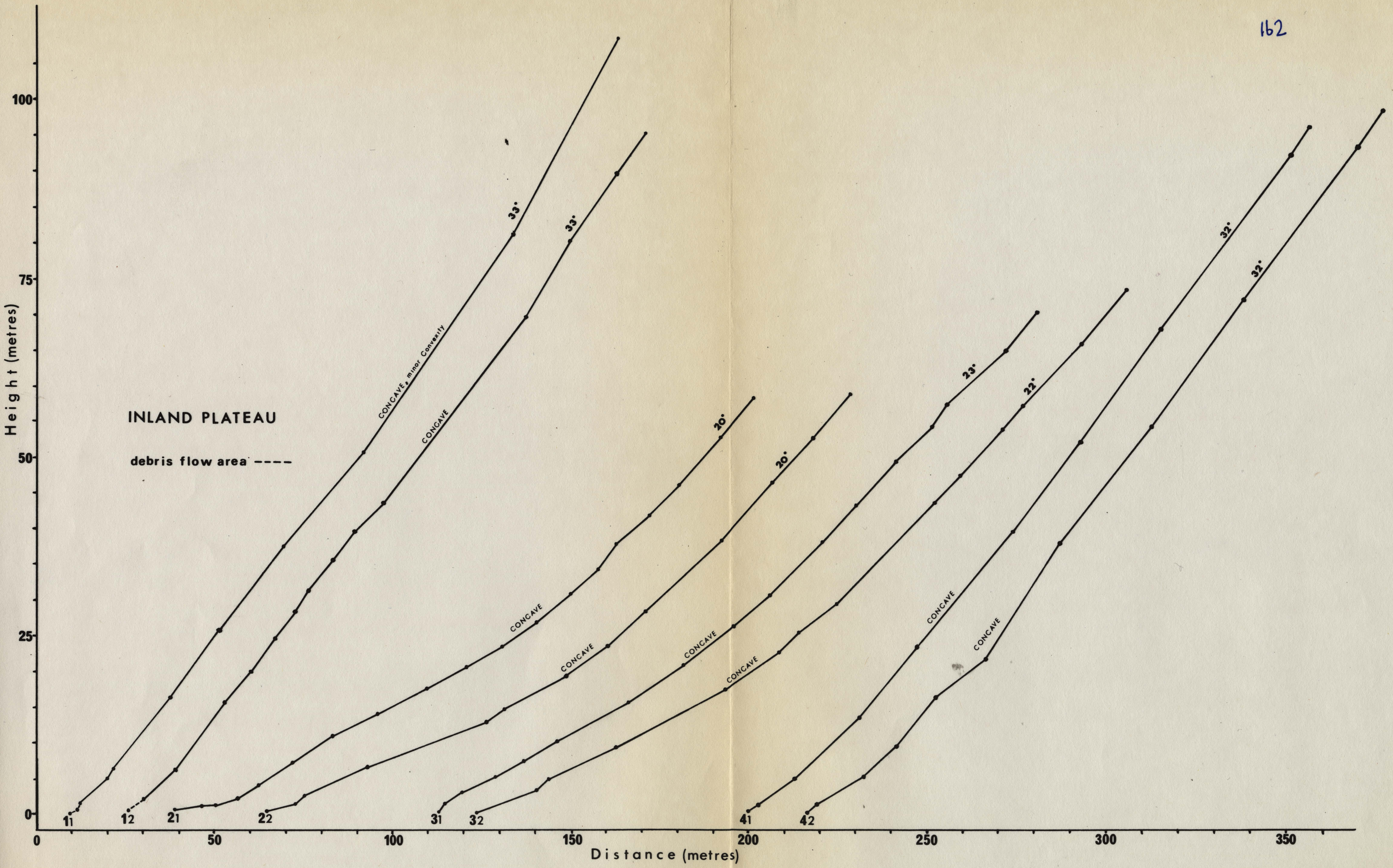
Figures 22-26

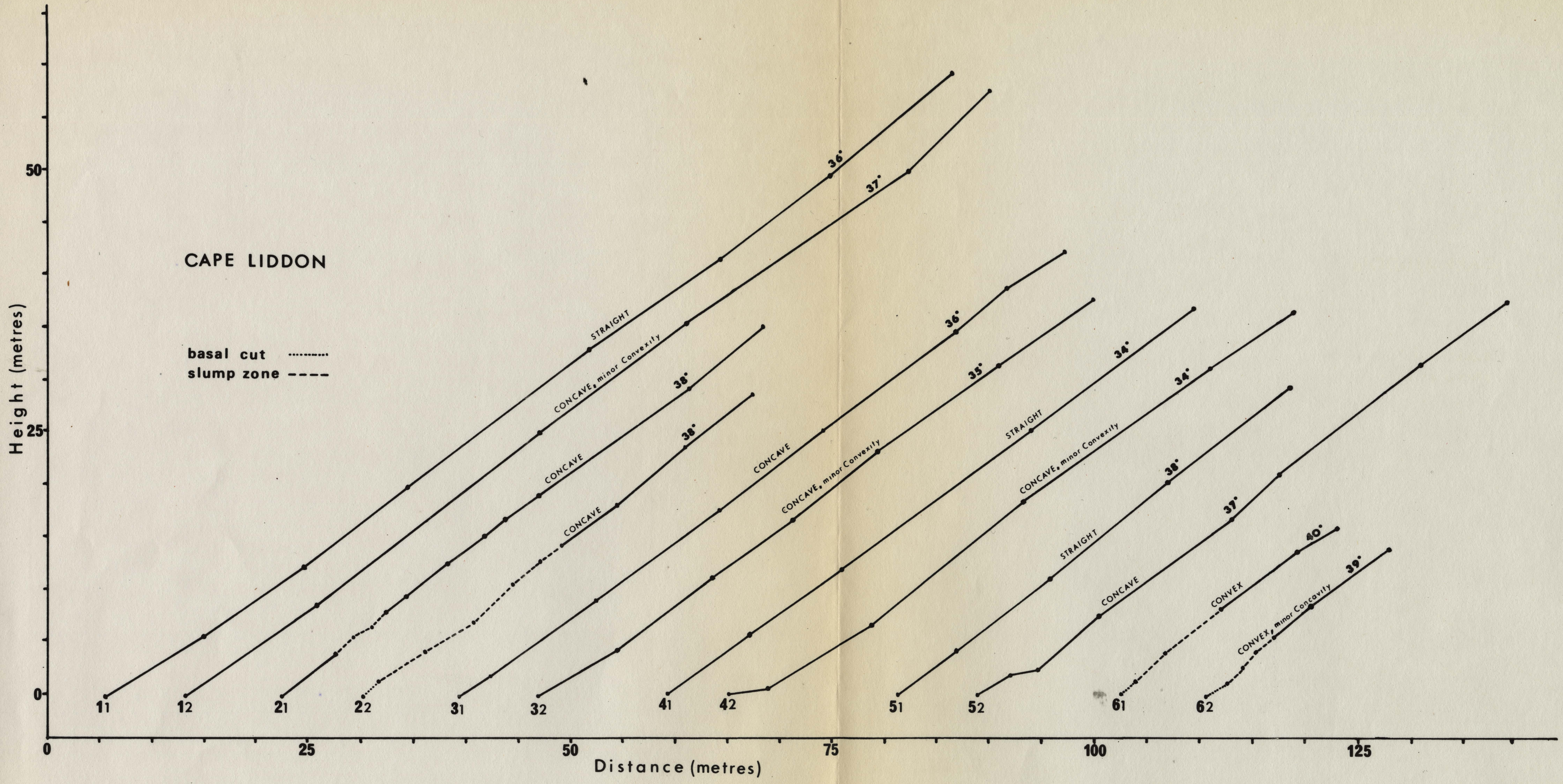
Slope profiles grouped according to locality in the order:

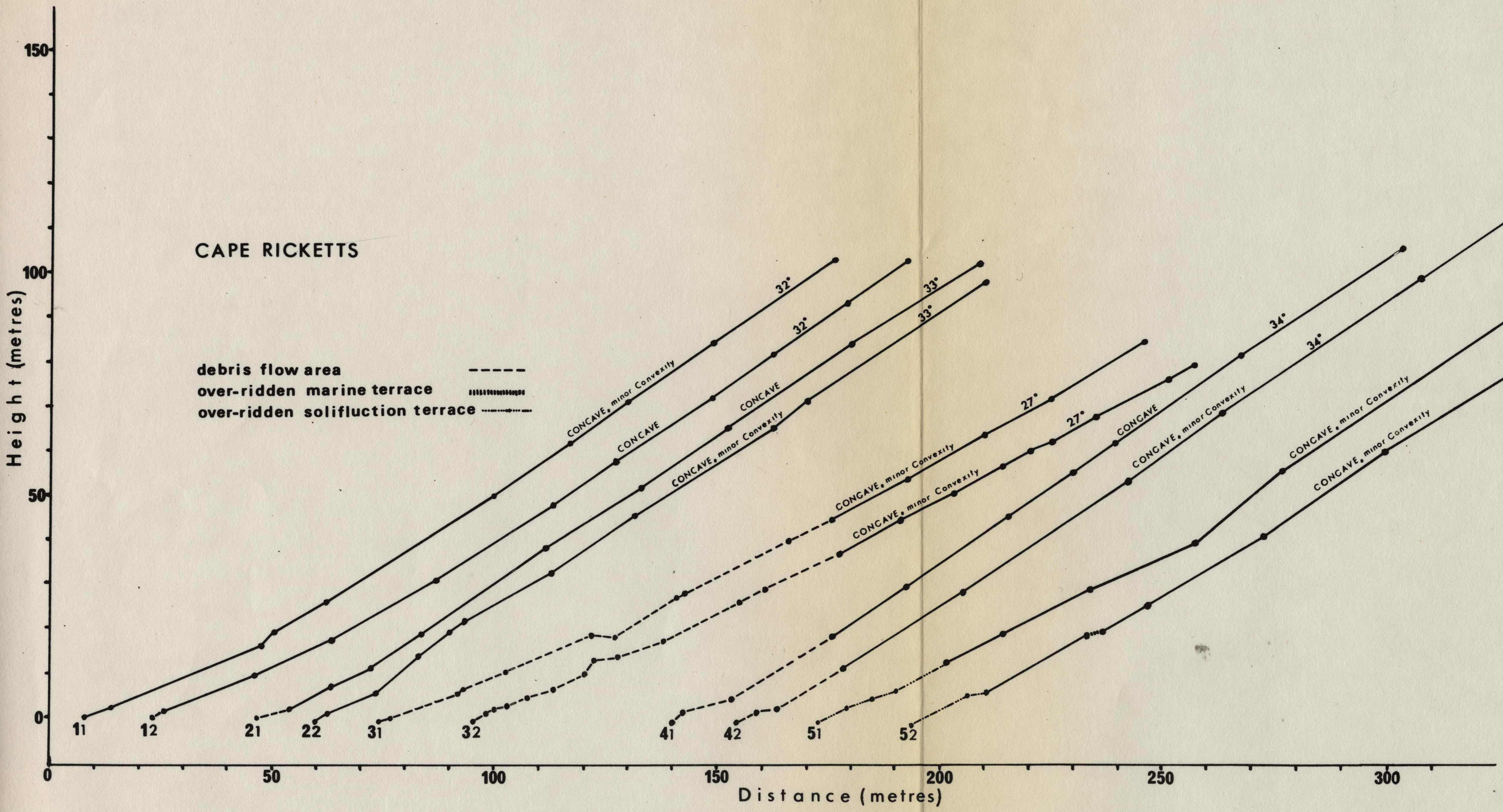
A, Caswall Tower; B, Inland plateau;

C, Cape Liddon; and D, Cape Ricketts.


CASWALL TOWER
debris flow area -----
basal cut ....
Height (metres)
75
50
25
0
Distance (metres)
0
25
50
75
100
125
150
175
200
11
12
21
22
31
32
41
42
51
52
61
62
71
72
33°
32°
33°
32°
37°
37°
33°
34°
36°
34°
35°
34°
31°
32°
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONVEXO-CONCAVE
CONCAVE
CONCAVE
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE
CONVEXO-CONCAVE
CONCAVE, minor Convexity
CONCAVE


INLAND PLATEAU
debris flow area ----
Height (metres)
Distance (metres)
0
25
50
75
100
0
50
100
150
200
250
300
350
11
12
21
22
31
32
41
42
CONCAVE, minor Convexity
CONCAVE
33°
33°
CONCAVE
CONCAVE
20°
20°
CONCAVE
CONCAVE
23°
22°
CONCAVE
CONCAVE
32°
32°


CAPE LIDDON
basal cut ....
slump zone ----
Height (metres)
Distance (metres)
0
25
50
75
100
125
STRAIGHT
36°
CONCAVE, minor Convexity
37°
CONCAVE
38°
CONCAVE
38°
CONCAVE
36°
CONCAVE, minor Convexity
35°
STRAIGHT
34°
CONCAVE, minor Convexity
34°
STRAIGHT
38°
CONCAVE
37°
CONVEX
40°
CONVEX, minor Concavity
39°
1_1
1_2
2_1
2_2
3_1
3_2
4_1
4_2
5_1
5_2
6_1
6_2


CAPE RICKETTS
debris flow area
over-ridden marine terrace
over-ridden solifluction terrace
Height (metres)
150
100
50
0
Distance (metres)
0
50
100
150
200
250
300
11
12
21
22
31
32
41
42
51
52
32°
32°
33°
33°
27°
27°
34°
34°
32°
32°
CONCAVE, minor Convexity
CONCAVE
CONCAVE
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE, minor Convexity

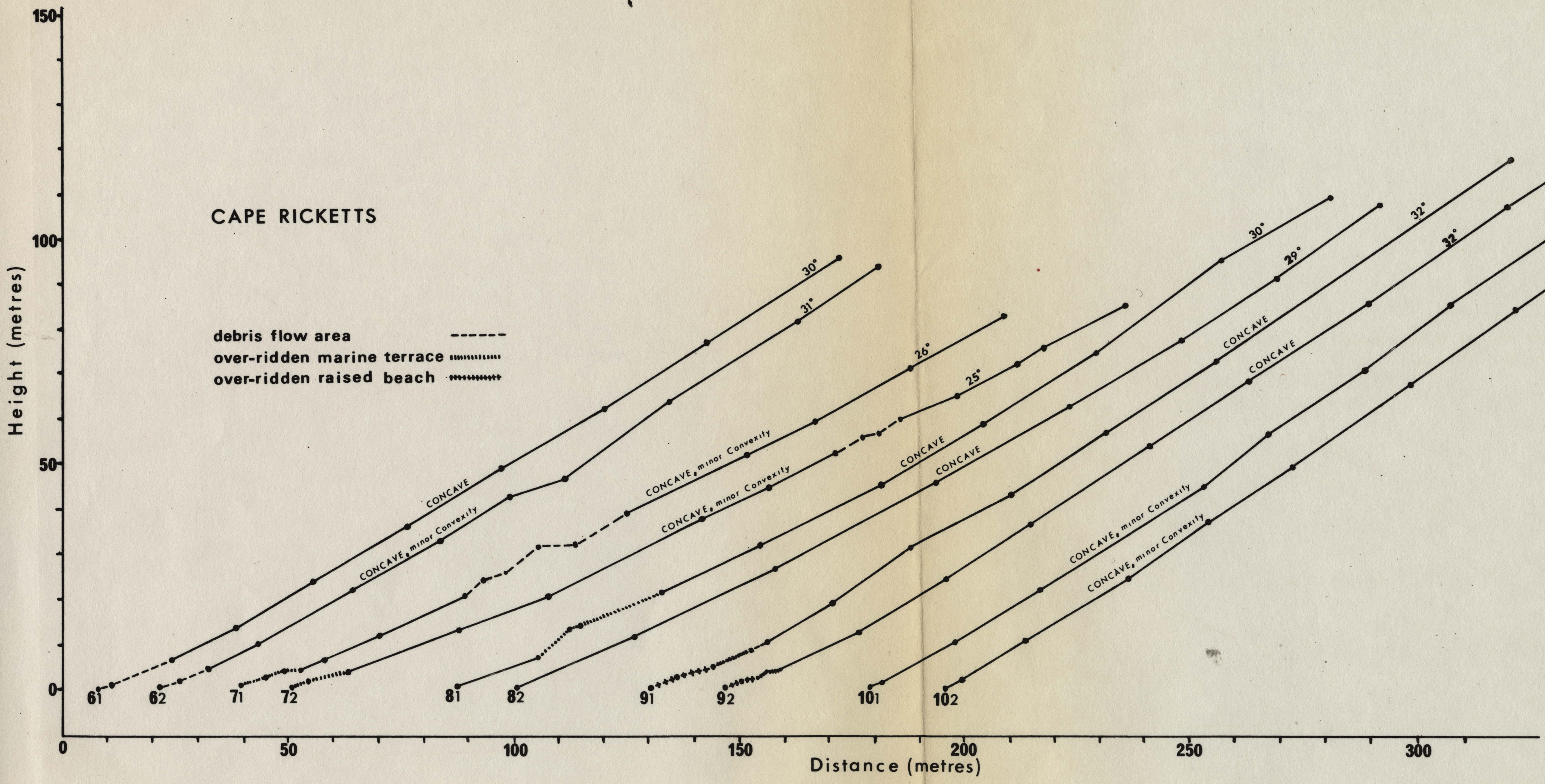
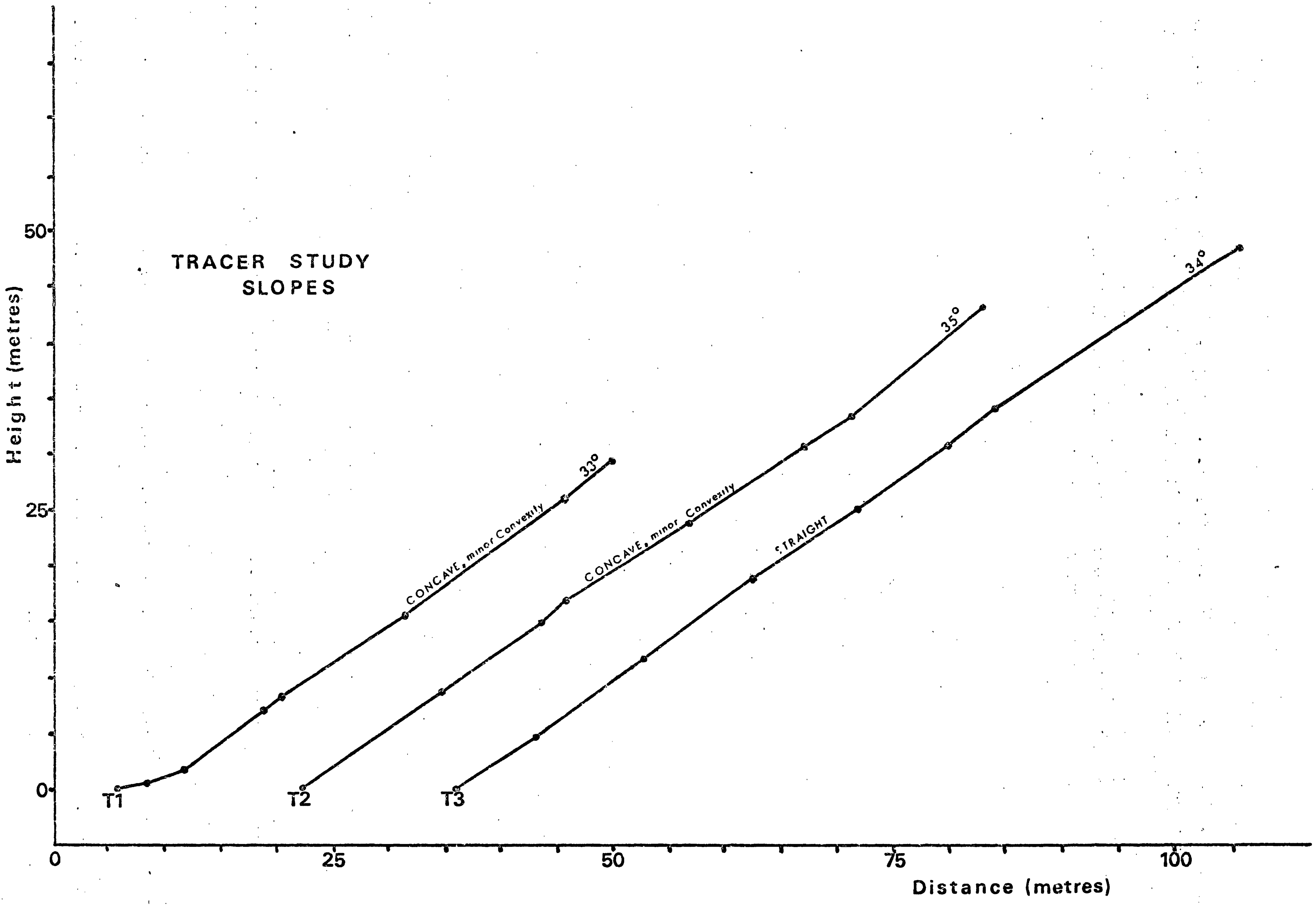

CAPE RICKETTS
debris flow area
over-ridden marine terrace
over-ridden raised beach
Height (metres)
150
100
50
0
Distance (metres)
0
50
100
150
200
250
300
61
62
71
72
81
82
91
92
101
102
30°
31°
26°
25°
30°
29°
32°
32°
35°
34°
CONCAVE
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE, minor Convexity
CONCAVE
CONCAVE
CONCAVE
CONCAVE
CONCAVE, minor Convexity
CONCAVE, minor Convexity

Figure 27

Profiles of the meltwater test slopes.



TRACER STUDY SLOPES

APPENDIX III

SOME COMMENTS ON SAMPLING PROCEDURE

SOME COMMENTS ON SAMPLING PROCEDURES

References to the fundamental concepts of statistical power analysis have been made previously in this study (IV, (2); VIII, (2)), but a final application remains to justify the sampling procedure used. The high power values obtained (98% and 99%, respectively for zonal and lateral effects) were based on the desire to find a "medium" effect at the .05 significance level. The recommended power value of 80% to be attained (Cohen, 1965) is far exceeded in this test design, and on that basis the number of sample sites, six, and the sample size, fifty, is more than adequate to detect a medium effect. Using the tables and formula in Cohen (1969), it is discovered that any further increase in sample size, other factors kept constant, would raise power only slightly to the maximum value of 99.5%. If one considers justification of the number of sample sites used, it must be pointed out that any increase merely reduce the sample size required. A hypothetical increase in factors from a 2X3 to the next highest, a 3X4 design will raise power to the +99.5% maximum if sample size remains at 50. This minimal rise in power which occurs, in effect, from increasing the number of sample sites from six to twelve, is not warranted in terms of the capabilities of the existing 2X3 design. As previously stated, the only major result of a sample site increase will be to reduce the sample size needed to maintain existing power values (in this case from 50 to 30).

On the basis of statistical power analysis the test design employed in debris size and shape analysis in this study is completely justified.

The one weakness in the sampling grid is the arbitrary demarcation of basal, middle and upper slope zones. Since the surface of a slope represents more of a continuum in its characteristics, the zoning is only valid as a convenient frame of reference for various characteristics encountered on a slope. A sampling grid designed with proportioned spacing between sample sites would have been more sophisticated, but this would have required complete compilation of survey data before any sampling could be accomplished on a slope. Such delays over a short field season are inefficient in a time-balanced program, and the descriptive zonation was preferred.

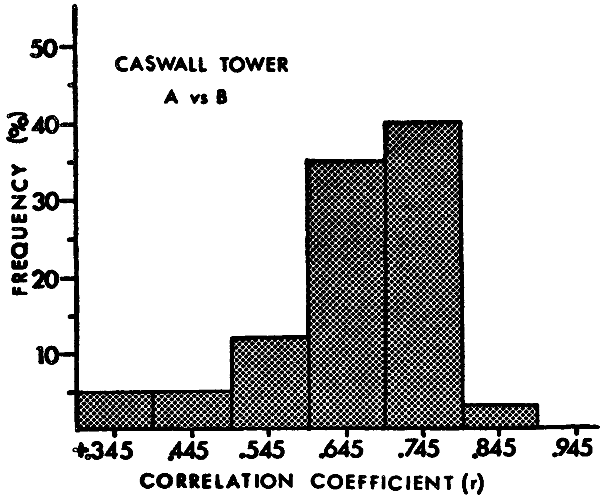
The validity of Caine's (1969) photographic analysis of orientation was tested on southwest Devon slopes by statistical comparison of field and photographically-derived orientation data on a site in each of the three slope zones of RK10. In order to use Chi-square analysis at least five observations must occur in each data class; but because this prerequisite was not satisfied by the original class sizes the nine 20°classes were reduced to three 60°classes. For the basal and middle-zone sites the null hypothesis of no significant difference between field and photo-derived orientations could not be rejected at the .01 level of significance. For the upper zone site this hypothesis was rejected and the alternate accepted that a significant difference does exist between the two sets of results.

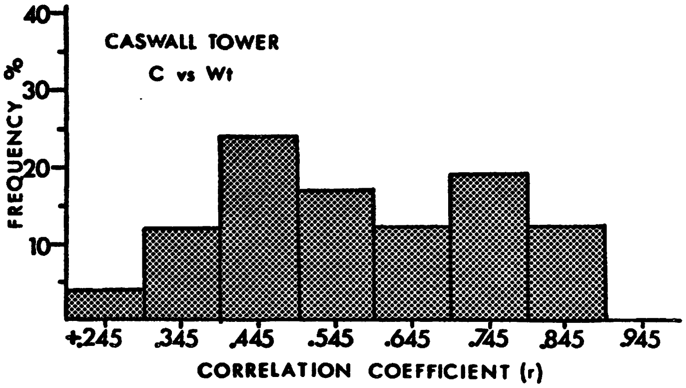
The outcomes of the first two tests conform with those of Caine's (1969) own Chi-square tests of field and photographic orientation data, which have become the basis for his recommendation of the photographic method for other debris slope studies. The lack of agreement found upon testing of the upper zone site of RK10 may be a result of the smaller size of debris in that sample compared to the others. For instance, the sampling system is such that there is hypothetically a maximum of 81 stones from which a sample of 50 may be selected (IV, (2)). If the average size of debris is small, then the maximum number will approach 81 and thus the possibility of selecting the same 50 stones in both field and photo analysis will be low. In contrast, the stones in the sites of the lower zones are larger and usually occupy more than one of the 81 grid intersections. In this case the maximum number of stones available for sampling will be much lower than for the upper zone site, a fact which increases the probability of selecting the same stones in both sets of orientation measurements. Based on the most common results of the Chi-square tests performed, Caine's (1969) photographic method is believed to produce valid orientation data from southwest Devon slopes.

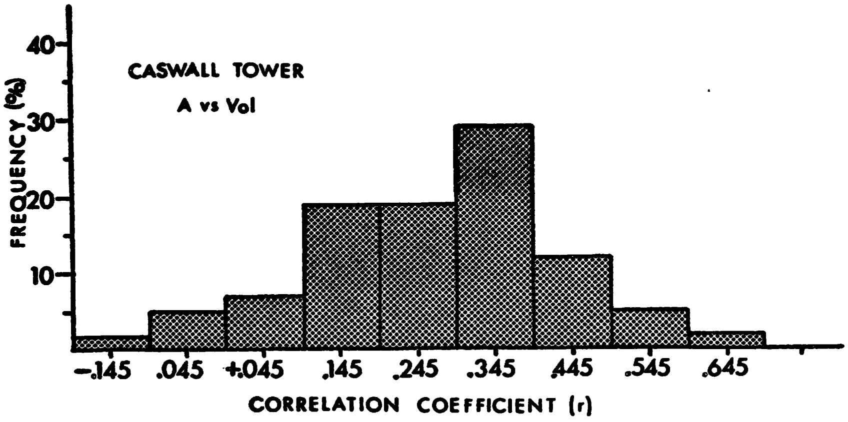
The sampling procedure entailed gathering of axis measurements and weight of all 5000 rock fragments encountered, in order to ascertain the most representative measure of size. As shown in the relative frequency histograms (figs. 28-31), all three axes are significantly correlated with weight, although less so in the case of the short axis. Since both 'A' and 'B' axes are highly correlated with each other in all locales, it was possible to select either one as suitable field indicators of size. Major published reports have generally tended to select the long axis (III, (2)), and therefore it was similarly employed to represent debris size in subsequent data analysis in this study.

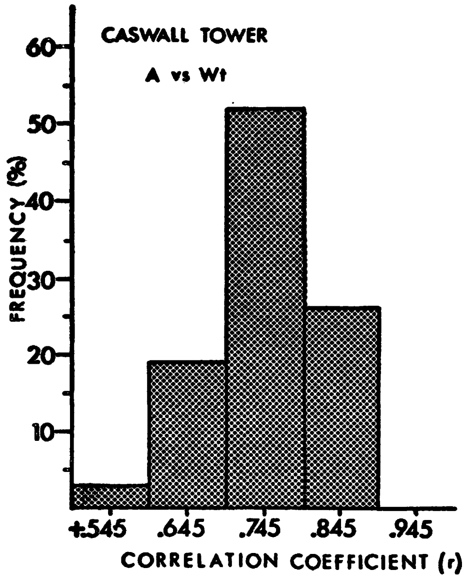
Figures 28-31

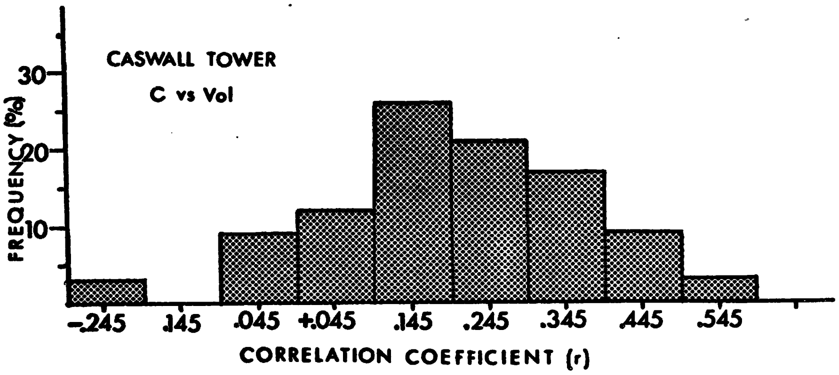
Histograms for linear correlation of selected size parameters for slopes in A) Caswall Tower, B) Inland plateau, C) Cape Liddon and D) Cape Ricketts locales.

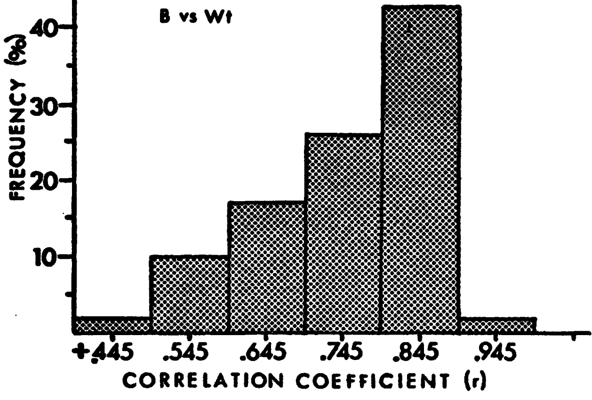

CASWALL TOWER
A vs B
FREQUENCY (%)
50
40
30
20
10
+.345
.445
.545
.645
.745
.845
.945
CORRELATION COEFFICIENT (r)

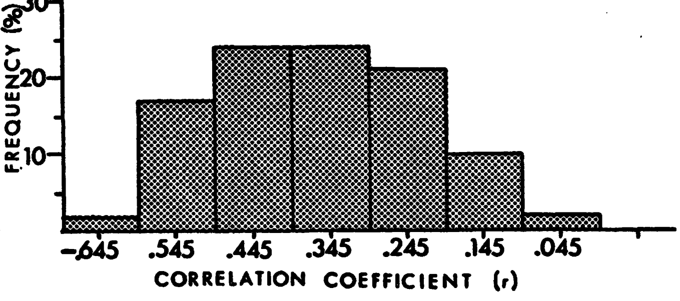

CASWALL TOWER
C vs Wt
FREQUENCY %
40
30
20
10
+.245
.345
.445
.545
.645
.745
.845
.945
CORRELATION COEFFICIENT (r)

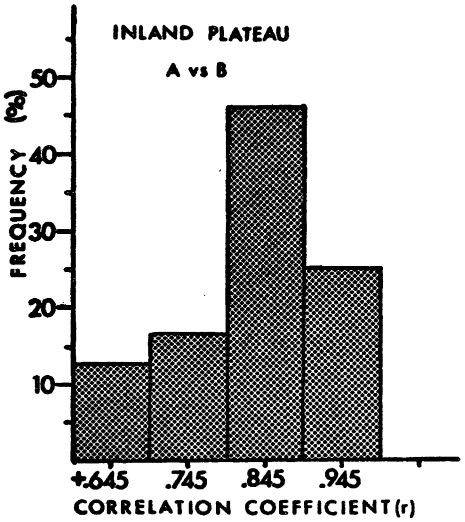

CASWALL TOWER
A vs Vol
FREQUENCY (%)
40
30
20
10
-.145
.045
+.045
.145
.245
.345
.445
.545
.645
CORRELATION COEFFICIENT (r)

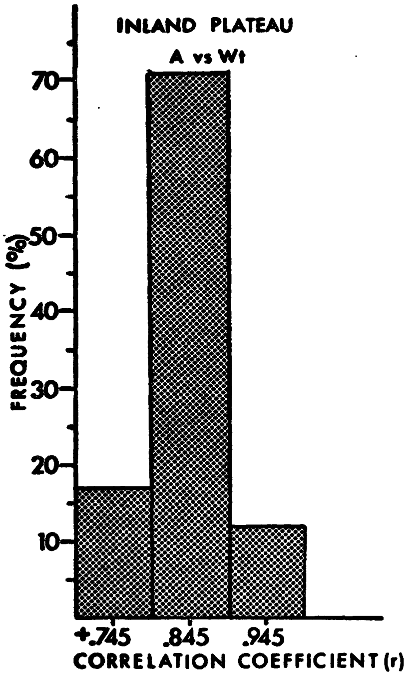

CASWALL TOWER
A vs Wt
FREQUENCY (%)
60
50
40
30
20
10
+.545
.645
.745
.845
.945
CORRELATION COEFFICIENT (r)

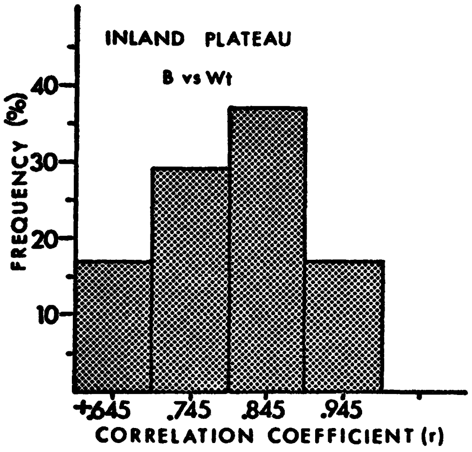

CASWALL TOWER
C vs Vol
FREQUENCY (%)
30
20
10
-.245
.145
.045
+.045
.145
.245
.345
.445
.545
CORRELATION COEFFICIENT (r)

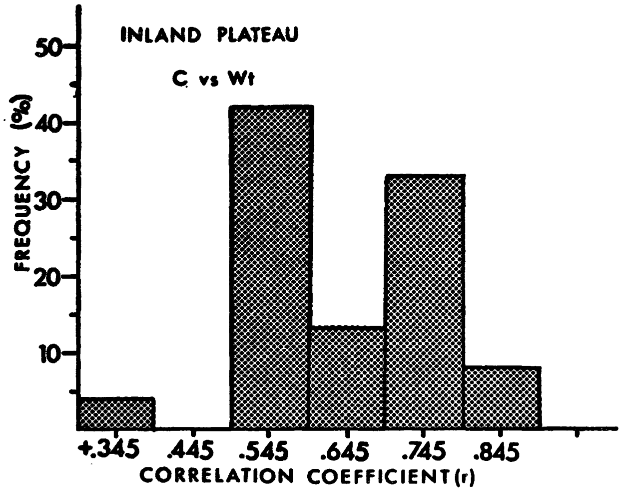

CASWALL TOWER
B vs Wt
FREQUENCY (%)
50
40
30
20
10
+.445
.545
.645
.745
.845
.945
CORRELATION COEFFICIENT (r)

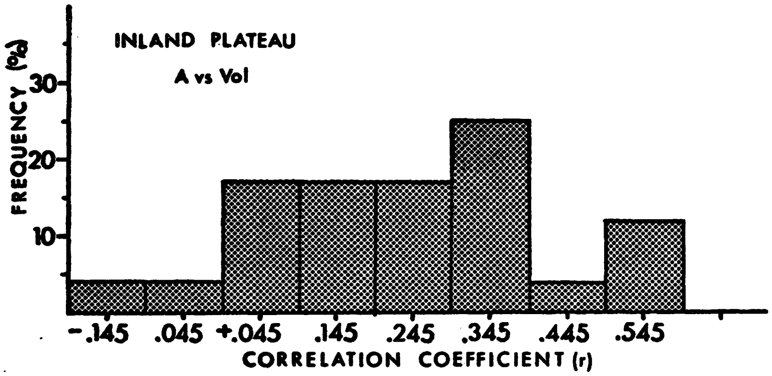

CASWALL TOWER
B vs Vol
FREQUENCY (%)
30
20
10
-.645
.545
.445
.345
.245
.145
.045
CORRELATION COEFFICIENT (r)

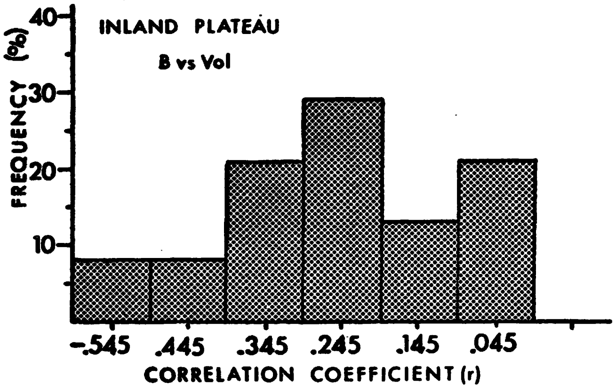

INLAND PLATEAU
A vs B
FREQUENCY (%)
50
40
30
20
10
+.645
.745
.845
.945
CORRELATION COEFFICIENT (r)

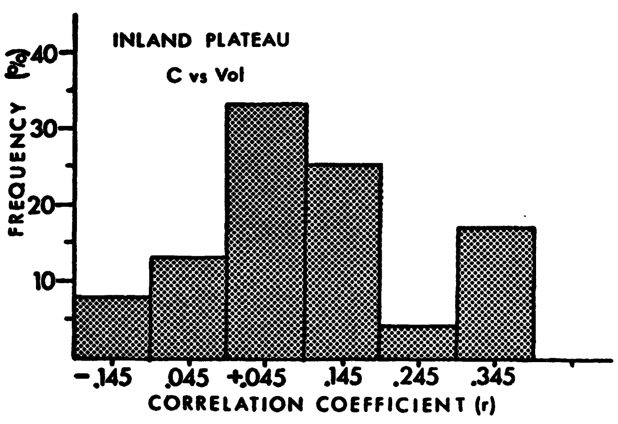

INLAND PLATEAU
A vs Wt
FREQUENCY (%)
70
60
50
40
30
20
10
+.745
.845
.945
CORRELATION COEFFICIENT (r)

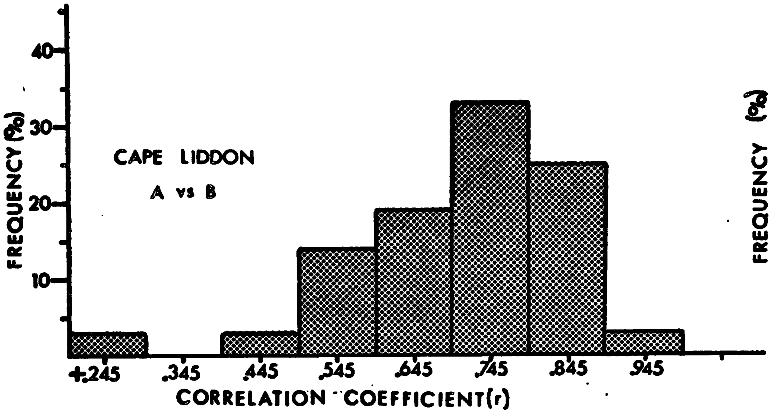

INLAND PLATEAU
B vs Wt
FREQUENCY (%)
40
30
20
10
+.645
.745
.845
.945
CORRELATION COEFFICIENT (r)


INLAND PLATEAU
C vs Wt
FREQUENCY (%)
50
40
30
20
10
+.345
.445
.545
.645
.745
.845
CORRELATION COEFFICIENT (r)

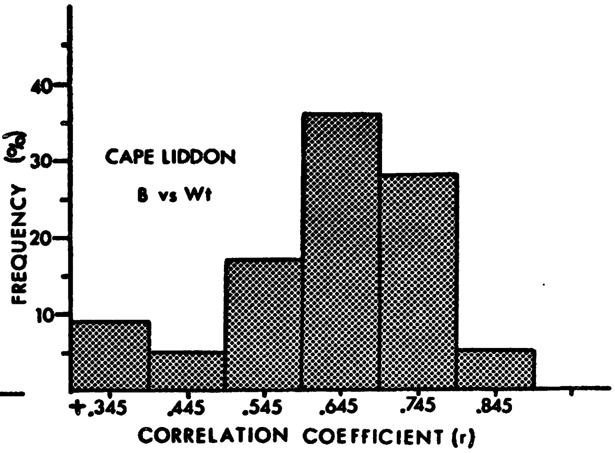

INLAND PLATEAU
A vs Vol
FREQUENCY (%)
30
20
10
−.145
.045
+.045
.145
.245
.345
.445
.545
CORRELATION COEFFICIENT (r)


INLAND PLATEAU
B vs Vol
FREQUENCY (%)
40
30
20
10
−.545
.445
.345
.245
.145
.045
CORRELATION COEFFICIENT (r)

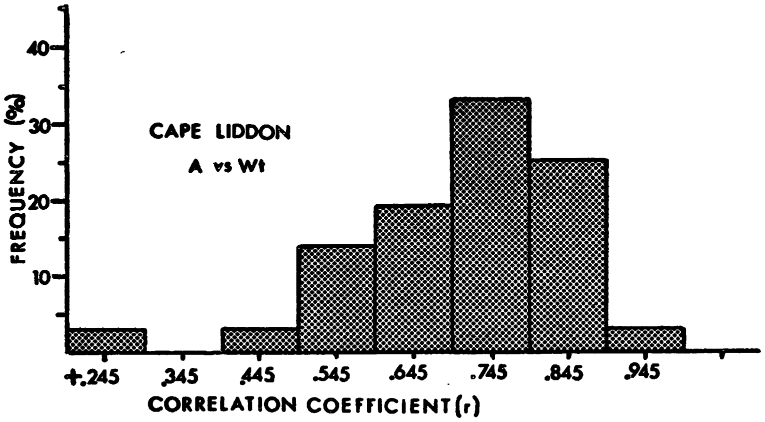

INLAND PLATEAU
C vs Vol
FREQUENCY (%)
40
30
20
10
−.145
.045
+.045
.145
.245
.345
CORRELATION COEFFICIENT (r)



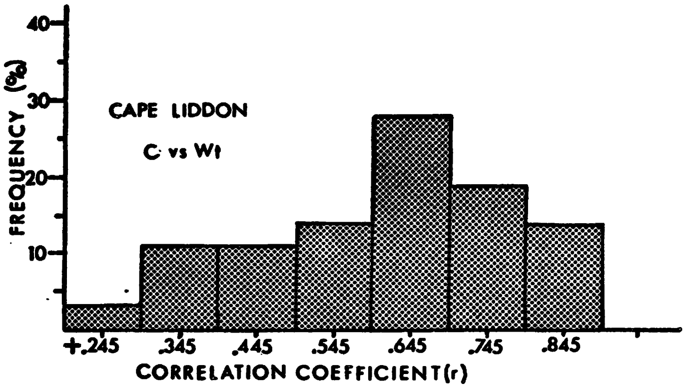
CAPE LIDDON
A vs B
FREQUENCY (%)
40
30
20
10
+.245
.345
.445
.545
.645
.745
.845
.945
CORRELATION COEFFICIENT(r)



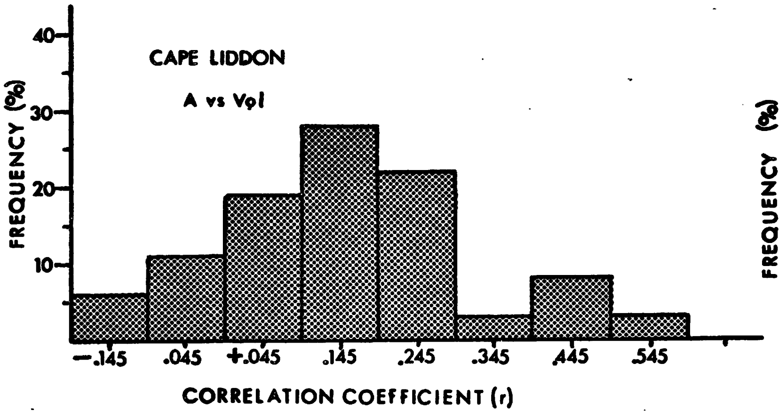
CAPE LIDDON
B vs Wt
FREQUENCY (%)
40
30
20
10
+.345
.445
.545
.645
.745
.845
CORRELATION COEFFICIENT (r)



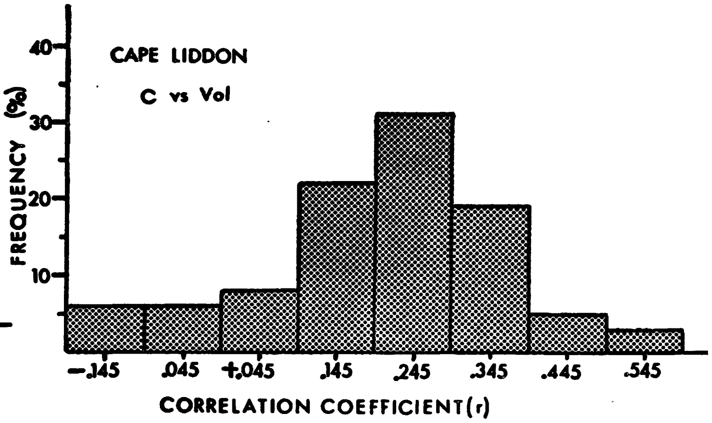
CAPE LIDDON
A vs Wt
FREQUENCY (%)
40
30
20
10
+.245
.345
.445
.545
.645
.745
.845
.945
CORRELATION COEFFICIENT(r)



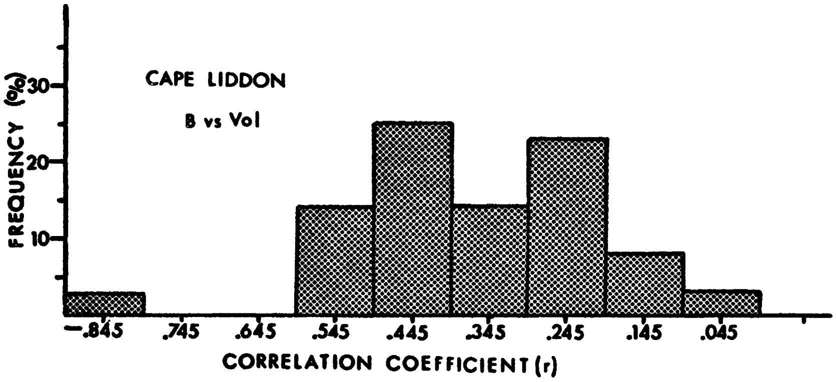
CAPE LIDDON
C vs Wt
FREQUENCY (%)
40
30
20
10
+.245
.345
.445
.545
.645
.745
.845
CORRELATION COEFFICIENT(r)



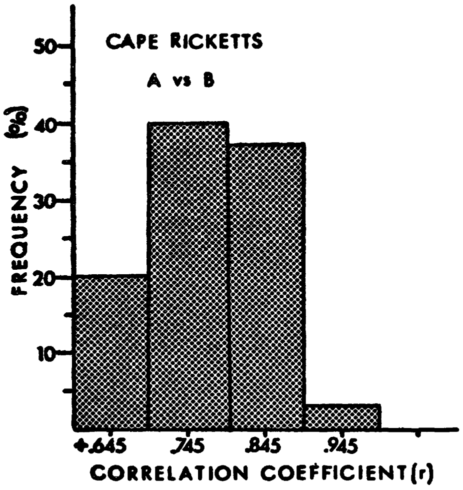
CAPE LIDDON
A vs Vol
FREQUENCY (%)
40
30
20
10
−.145
.045
+.045
.145
.245
.345
.445
.545
CORRELATION COEFFICIENT (r)

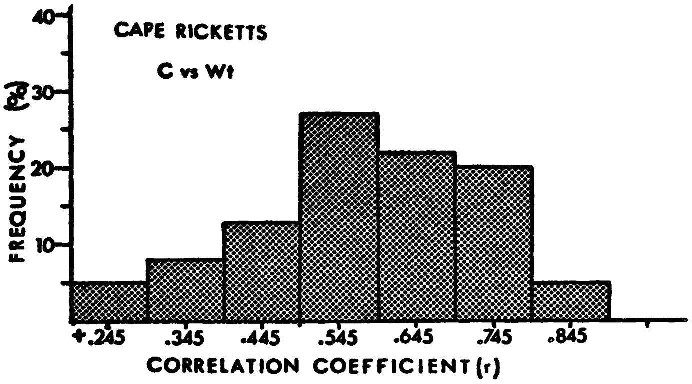


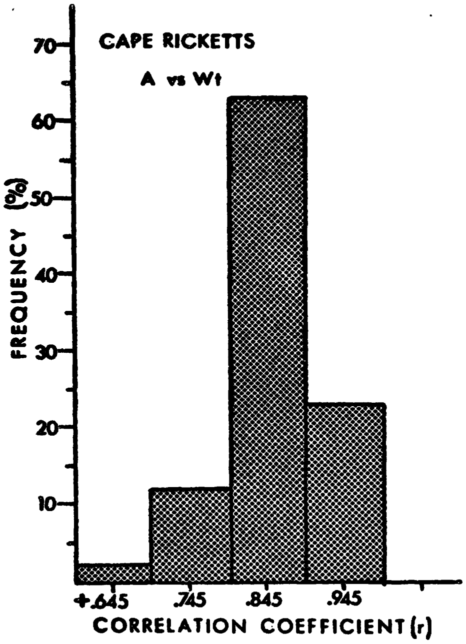
CAPE LIDDON
C vs Vol
FREQUENCY (%)
40
30
20
10
−.145
.045
+.045
.145
.245
.345
.445
.545
CORRELATION COEFFICIENT(r)

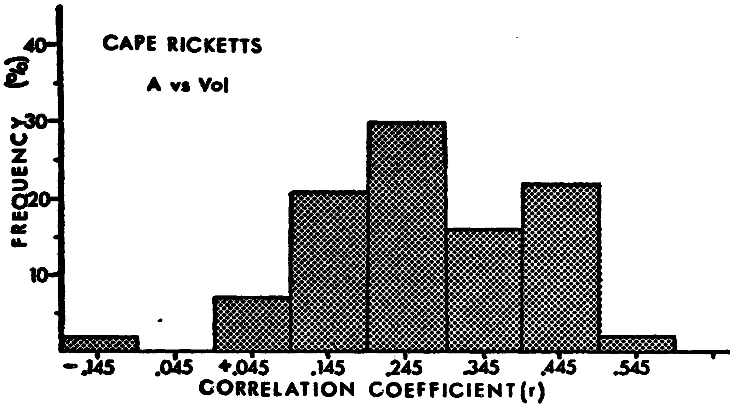


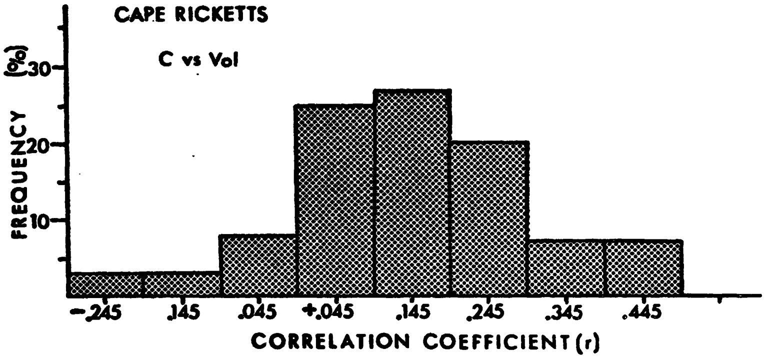
CAPE LIDDON
B vs Vol
FREQUENCY (%)
30
20
10
−.845
.745
.645
.545
.445
.345
.245
.145
.045
CORRELATION COEFFICIENT (r)

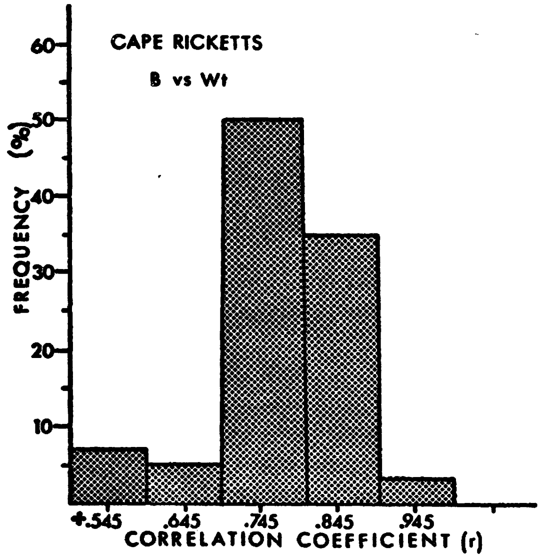

CAPE RICKETTS
A vs B
FREQUENCY (%)
50
40
30
20
10
+.645
.745
.845
.945
CORRELATION COEFFICIENT (r)

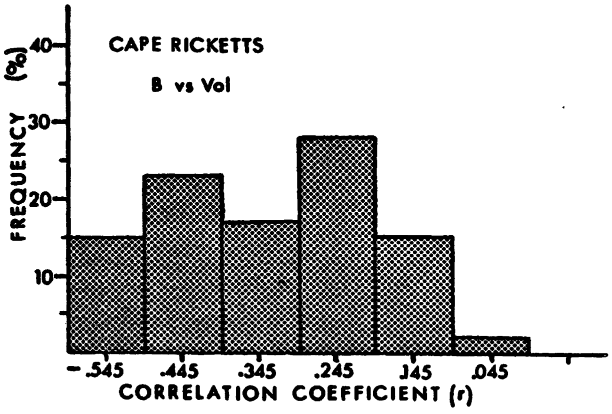

CAPE RICKETTS
C vs Wt
FREQUENCY (%)
40
30
20
10
+.245
.345
.445
.545
.645
.745
.845
CORRELATION COEFFICIENT (r)


CAPE RICKETTS
A vs Wt
FREQUENCY (%)
70
60
50
40
30
20
10
+.645
.745
.845
.945
CORRELATION COEFFICIENT (r)


CAPE RICKETTS
A vs Vol
FREQUENCY (%)
40
30
20
10
-.145
.045
+.045
.145
.245
.345
.445
.545
CORRELATION COEFFICIENT (r)


CAPE RICKETTS
C vs Vol
FREQUENCY (%)
30
20
10
-.245
.145
.045
+.045
.145
.245
.345
.445
CORRELATION COEFFICIENT (r)


CAPE RICKETTS
B vs Wt
FREQUENCY (%)
60
50
40
30
20
10
+.545
.645
.745
.845
.945
CORRELATION COEFFICIENT (r)


CAPE RICKETTS
B vs Vol
FREQUENCY (%)
40
30
20
10
-.545
.445
.345
.245
.145
.045
CORRELATION COEFFICIENT (r)

APPENDIX IV

PLATES

1. The one-metre square sampling grid.

2. Exposed rock platform beneath talus slopes along Cape Liddon.

3. Ice-ledge exposure at talus base along Cape Liddon.

4. Initial surface readjustment to basal-cut

5. End stage of readjustment to basal-cut

6. Basal accumulation of shifted debris over the exposed rock platform of plate 2.

7. Vertical cross-section of slope basal-cut section along Cape Liddon

8. Grey, rounded beach gravels locked in permafrost beneath talus slope along Cape Liddon

9. Rockfall material from cliffs in raft-prone position.

10. Active slide tongues descending a Cape Liddon slope.

11. Slide tongues of plate 10 at rest.

12. Meltwater gulleys on a Cape Liddon slope.

13. Slushflow tongue on beachfast ice of Cape Liddon.

14. Large slush avalanche east of Cape Ricketts.

15. Flow lobe on a Cape Ricketts slope.

16. Ripples on flow lobe of slope RK3.

17. Debris flow levees and tongues on slope RK7.

18. Appearance of Rhodamine BN dye in tidal crack beneath slope T2 in waterfall tracer experiment.

19. Denudation of buried cliff-face along Cape Liddon.

BIBLIOGRAPHY

American Geological Institute, 1962. *Dictionary of Geological Terms*, Garden City, N.J., Dolphin Books, 545p.

Andrews, J.T., 1961. The development of scree slopes in the English Lake District and Central Quebec-Labrador, *Cah. de Geogr. de Québec*, 5(10), 219-230.

Behre, C.H., 1933. Talus behaviour above the timberline in the Western Rockies, *Jour. Geol.*, 41, 622-635.

Bird, J.B., 1959. Recent contributions to the physiography of Northern Canada, *Zeitschr. für Geomorph.* 3, 150-174.

Bird, J.B., 1967. *The Physiography of Arctic Canada*, Baltimore, Md, Johns Hopkins Press, 336p.

Blackwelder, E., 1942. The process of mountain sculpture by rolling debris, *Jour. Geomorph.*, 5, 325-328.

Burkalow, A. Van, 1945. Angle of repose and angle of sliding friction: an experimental study, *Bull. Geol. Soc. Amer.*, 56, 669-708.

Cailleux, A., 1945. Distinction des gallets marines et fluviatiles, *Soc. Geol. Bull. France*, 5 (15), 375-404.

Cailleux, A., 1947. L'indice d'emousse: definition et premiere application, *C.R. Somme, Geol., France*, 13, 250-252.

Caine, N., 1967. The texture of talus in Tasmania, *Jour. Sed. Petrol.*, 35, (3), 796-803.

Caine, N., 1969. The analysis of surface fabrics on a talus cone by means of ground photography, *Arctic & Alp. Res.*, 1 (2), 127-134.

Carson, M., 1969. Models of hillslope development under mass failure, *Geog. Analysis*, 1 (1), 76-100.

Cohen, J.C., 1965. Some statistical issues in psychological research, *Handbook of Clinical Psychology*, B.B. Wolman (ed.), Toronto, McGraw-Hill, 95-121.

Cohen, J.C., 1969. *Statistical Power Analysis for the Behavioural Sciences*, New York, Academic Press, 415p.

Collins, H.B., 1951. Excavations at Thule culture sites near Resolute Bay, Cornwallis Island, N.W.T., Ann. Rep. Nat. Museum of Canada for 1949-1951, 49-63.

Cook, F.A., & Raiche, V.G., 1960. Freeze-thaw cycles at Resolute, N.W.T., Geog. Bull., 18, 64-78.

Crompton, P., 1968. Scree development on Baffin Island, unpub. B.A. Thesis, Dept. of Geography, Univ. of Toronto, 80p.

Curray, J.R., 1956. The analysis of two-dimensional orientation data, Jour. Geol., 64, 117-131.

Fortier et al, 1963. Geology of the north-central part of the Arctic Archipelago, N.W.T. (Operation Franklin), Geol. Surv. Can., Memoir 320.

Fortier, Y.O. & Morley, L.W., 1956. Geological unity of the Arctic Islands, Trans. Royal Soc. Can., Can. Comm. Oceanog., 50, 3-12.

Gardner, J., 1968. Debris slope form and processes in the Lake Louise District, a High Mountain area, unpub. Ph.D Thesis, Dept. of Geography, McGill University.

Gardner, J., 1969. Observations of surficial talus movement, Zeitschr. für Geomorph., 13 (3), 317-323.

Griffiths, J.C., 1959. Size and shape of rock fragments in Tuscarora scree, Fishing Creek, Lamar, central Pennsylvania, Jour. Sed. Petrol., 29 (3), 391-401.

Hamelin, L-E., 1958. Le talus oriental d'eboulis de l'Aiguille Rousse, Rev. Geog. Alpine, 46, 429-439.

Jahn, A., 1968a. Denudational balance of slopes, Geog. Polon., 13, 9-29.

Jahn, A., 1968b. Morphological slope evolution by linear and surface degradation, Geog. Polon., 14, 9-21.

Jenness, J.L., 1952. Erosive forces in the physiography of western Arctic Canada, Geog. Rev., 42, 238-252.

Jones, T.A., 1969. Skewness and kurtosis as criteria of normality in observed frequency distributions, Jour. Sed. Petrol., 39 (4), 1622-1627.

King, C.A.M. & Buckley, J.T., 1968. The analysis of stone size and shape in an Arctic environment, Jour. Sed. Petrol., 38 (1), 200-214.

King, R.H., 1969. Periglaciation on Devon Island, N.W.T., unpub. Ph.D. Thesis, Dept. of Geography, Univ. of Saskatchewan.

Klatka, T., 1961. Indices de structure et de texture des champs de pierres de Lysogory, Bull. Soc. Sciences et Lettres Lodz, 12 (10), 21p.

Krumbein, W.C., 1941. Measurement and geologic significance of shape and roundness of sedimentary particles, Jour. Sed. Petrol., 11 (2), 64-72.

Matveev, N.P., 1964. Dynamics and age of talus material and rock streams in the Bold Mountain Zone of the Northern Urals from the example of the Denezhkin Kamen Massif, Problems of the North, 7, transl. from Problemy Severa, 211-216.

McCann, S.B. & Ingram, D.I., 1971. In preparation.

McCann, S.B. & Owens, E.H., 1970. The size and shape of sediments in three Arctic beaches, southwest Devon Island, N.W.T. Canada, Arctic and Alpine Res., 1 (4), 267-278.

McCann, S.B. & Richards, A., 1969. The coastal features of the Island of Rhum in the Inner Hebrides, Scott. Jour. Geol., 5 (1), 15-25.

McLean, R.F. & Davidson, C.F., 1968. The role of mass movement in shore platform development along the Gisborne coastline, N.Z., Earth Sci. Jour., 2 (1), 15-25.

Meiner, M.A., 1934. Talus slopes of the Gaspé Peninsula, Science, 79, 229-230.

Owens, E.H., 1968. The Arctic beach environment, S.W. Devon Island, N.W.T., upub. M.Sc. Thesis, Dept. of Geography, McMaster University.

Owens, E.H. & McCann, S.B., 1970. The role of ice in the Arctic beach environment with special reference to Cape Ricketts, S.W. Devon Island, N.W.T., Canada, Amer. Jour. Science, 268, 397-414.

Rapp, A., 1959. Avalanche boulder tongues in Lappland, Geog. Ann., 41, 34-48.

Rapp, A., 1960a. Talus slopes and mountain walls at Tempelfjorden, Spitzbergen, Norsk. Polar. Skrifter, 119, 96p.

Rapp, A., 1960b. Recent development of mountain slopes in Karkevagge and surroundings, N. Scandinavia, Geog. Ann., 42, 73-200.

Rapp, A., 1960c. Literature on slope denudation in Finland, Iceland, Norway, Spitzbergen and Sweden, *Zeitschr. für Geomorph.*, Supp. Bd 1, Morph. des Versants, 33-48.

Sharp, R.P., 1942. Mudflow levees, *Jour. Geomorph.*, 5, 222-227.

Sharpe, C.F.S., 1938. *Landslides and Related Phenomena, Paterson,* N.J., Columbia Univ. Press, 137p.

Stamp, L.D., 1963. *A Glossary of Geographical Terms,* London, Longmans Green & Co.

Stock, R.F., 1968. Morphology and development of talus slopes at Ekalugad Fiord, Baffin Island, N.W.T., unpub. B.A. Thesis, *Dept. of Geography,* Univ. of Western Ontario, 84p.

Strahler, A.N., 1952. Dynamic basis of geomorphology, *Bull. Geol. Soc. Amer.*, 63, 923-938.

Taber, S., 1918. Surface heaving caused by segregation of water forming ice crystals, *Eng. News-Rec.*, 81, 683-684.

Tinkler, K.J., 1966. Slope profiles and scree in the Eglwyseg Valley, North Wales, *Geog. Jour.*, 132 (3), 379-385.

Thompson, H.A., 1967. The climate of the Canadian Arctic, *Can. Dept. Transport, Met. Br.*, Toronto, 32p.

Thornes, J.A., 1968. A queuing theory analogue for scree slope studies, *L.S.E. & Pol. Sci. Graduate Geography Dept.* Disc. Paper 22, 16p.

Thorsteinsson, R., 1958. Cornwallis and Little Cornwallis Islands, District of Franklin, N.W.T., *Geol. Surv. Can., Memoir* 294, 134p.

Ward, W.H., 1945. Stability of natural slopes, *Geog. Jour.*, 105, 170-197.

Washburn, A.L. & Goldthwait~~e~~, R.P., 1958. Slushflows, *Bull. Geol. Soc. Amer.*, 69, 1657-1658.

Wood, A., 1942. The development of hillside slopes, *Proc. Geol. Assoc. (London)*, 53 (3-4), 128-140.

Young, A., 1960. Characteristic and limiting slope angles, *Zeitschr. fur Geomorph.*, 126-131.

Young, A., 1964. Slope profile analysis, *Zeitschr. für Geomorph.*, Supp. Bd 5, 17-27.

The following two works have been published during the printing of this thesis:

Gardner, J.G., 1970. A note on the supply of material to debris slopes, Can. Geog., XIV (4), 369-372.

Brunsden, D. (ed), 1971. Slopes; Form and Process, Instit. Brit. Geog. Spec. Pub. 3, Oxford, Alden & Mowbray Ltd., 178p.