SCREE SLOPE CHARACTERISTICS AND PROCESSES IN SURPRISE VALLEY

SCREE SLOPE CHARACTERISTICS AND ASSOCIATED GEOMORPHIC PROCESSES IN SURPRISE VALLEY, JASPER NATIONAL PARK, ALBERTA

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SCOPE AND CONTENTS: This thesis is concerned with the characteristics and development of scree slopes, as illustrated by examples from a small alpine valley. The major controls of scree slope development and processes are discussed with special emphasis on rockfalls and snow avalanches. The results of debris accumulation measurements on networks of cleaned boulders and polyethelene squares at seven screes from 1968-1972 are presented and discussed. The techniques are suggested as a valid means of measuring debris accumulation by avalanches. The surface sedimentary characteristics of five screes are examined in detail with particular emphasis on size sorting at various levels over the scree and possible relationships between sedimentary characteristics and sorting. Detail of the profile form of these screes is also given and the avalanche modification of screes discussed.

ABSTRACT

Scree slopes are formed and modified by several geomorphic processes which may be grouped as input, queueing or output processes with relation to debris movement on the scree. The relative importance and controls of these processes are discussed with reference to the screes of a small area in the Canadian Rockies. The nine screes examined in detail are all basically rockfall or avalanche dominated sites, although there is wide fluctuation in the intensity and influence of each process from scree to scree due to variations in the physical setting of the site.

Rockfall occurs at all sites and is the most important scree forming process in the valley as a whole. Patterns of rockfall activity vary considerably both at and between sites, suggesting that simple arithmetic measures of frequency are misleading and probabilities of rockfall occurrence might be truer estimates of frequency patterns. Avalanche activity is much more localized but where favourable conditions occur, it may dominate the characteristics of the scree. Talus creep was found to be insignificant at sites where fine material was not present near the surface.

These results strongly emphasize the role of avalanches in the development of alpine scree slopes and all the sites had some avalanche activity during the period of study. Avalanches may act in a queueing or input role, providing fresh material to the scree or redistributing surface debris. The relative importance of these roles varies from site to

site but avalanche erosion and redeposition of surface scree is the most effective queueing process seen in Surprise and at some sites avalanches are also the dominant input process. Prolonged avalanche erosion and the downslope transfer of material produces a marked basal concavity and lowers the mean angle of slope of the scree. Strongly concentrated activity may produce avalanche boulder tongues, although several intermediate forms (avalanche cones, bevelled scree cones) have also been recognized.

Debris accumulation was measured on networks of cleaned boulder surfaces and polyethelene squares at seven screes from 1968 to 1972. These measurements were highly successful and yielded a great volume of information on the depositional and erosional activity of snow avalanches, although rockfall accumulation is underestimated. These results also indicate very wide spatial and temporal variations in the depositional activity at these sites. The greatest amount of deposition is associated with sites which have marked avalanche erosion of the scree where average depositional rates ranged between 1-8 mm/year. At the most active site it was estimated that a minimum of 144 m^3 of debris was deposited by rockfalls and avalanches between August 1968 and August 1972. The smallest amounts of deposition were recorded in the basal areas of rockfall dominated slopes.

Detailed studies of the sedimentological characteristics of the surface material were carried out at five screes. These deposits were found to be log (phi)-normal and moderately sorted with significant differences in axial shape measures both between different lithologies and also between different sizes, the smaller fragments having a more irregular shape. Variations in grain size over the scree were examined using an analysis of variance design. All sites examined showed an overall logarithmic increase in grain size away from the cliff but, due to smaller scale lateral and local variations, the gradients were often slightly inconsistent on individual profiles. These lateral variations are most common in the upper and middle parts of the scree and are due to various queueing processes. Many screes often have an area of coarser debris at the base of the cliff and thin patches of coarser debris (termed the floating layer) may be found elsewhere on the scree.

Avalanche activity either destroys or increases the overall down-slope sorting gradient. No simple quantitative criteria could be found to differentiate avalanche and rockfall deposits, although the latter are usually much better sorted. Mean slope angles for the screes studied ranged from 24 to 35^{o} with maximum angles of 35 to 39^{o}.

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SECTION I

INTRODUCTORY MATERIAL

Chapter 1: Introduction

Chapter 2: The Setting

CHAPTER 1

INTRODUCTION

Mountain environments are areas with high potential energy for geomorphic work. Apart from glaciers and the rivers they often spawn, the most dynamic elements of such landscapes are the accumulations of rock debris associated with major bedrock cliffs. Although these screes or talus slopes are a conspicuous and well defined element of the mountain landscape, they have received comparatively little detailed attention from geomorphologists. Until the major contributions of Anders Rapp (1960a, 1960b) to the study of mountain slope development, published observations on screes were generally short and thinly scattered throughout the literature (e.g. Leblanc, 1842; Davison, 1888; Jeffreys, 1930, etc.). Only recently (and mainly within the gestation period of this thesis) have other attempts to provide detailed measurements of scree form, materials and processes become available (e.g. Caine, 1967; Gardner, 1968a; Bones, 1971; Gray, 1971). These, together with Rapp's work, provide the beginnings of a detailed account of the nature and variability of scree slopes and processes in various environments. The major aim of this thesis is to extend and develop several aspects of this earlier work by the detailed observation of scree materials, processes and form from a small area in the Canadian Rockies.

The site chosen for these investigations is a small alpine valley, aptly named Surprise, near Maligne Lake, Jasper National Park, Alberta. It contains a great variety of scree slopes involving different rock types in various combinations of lithology, topographic environment, aspect, current activity and dominant process. This great range within a small, relatively accessible area provides a basis for the comparative study of these slopes and the factors involved in their genesis and evolution. A general description of the valley is given in Chapter 2.

The major contributions of this thesis are in three general areas which comprise the central sections of the presentation: (a) studies of scree slope processes; (b) the sedimentary characteristics of scree material; and (c) scree form. The study of geomorphic processes in the field is a long-term venture; in order to obtain a realistic appraisal of the magnitude of events and the frequency with which they occur, continuous observations are needed over a long period. However, in the absence of such information, limited observations over relatively short periods can make a significant contribution to our knowledge and understanding of these processes.

Section II is in two parts. The first is an integrated review of the major geomorphic processes which affect scree slopes, based on available published material and inventory and experimental data from Surprise. The individual chapters deal with the major roles and controls of processes (3), rockfall (4), snow avalanches (5) and other processes (6). The second part of this section, Chapters 7 to 9, presents the results of a study of debris accumulation on marked surfaces on seven screes from 1968 to 1972 with a discussion of the methods used and the possible inferences about scree slope processes which may be made from such observations.

Most of the attention given to screes in the past has focussed on qualitative generalizations or discussions of slope development theories and measurements of form or materials have been restricted to isolated profiles on a variety of slopes. The main aim of the sedimentological project discussed in Section III was to examine the detailed spatial variability of grain size on four major screes of differing aspect, type, size and lithological composition. This project, therefore, yielded information on the character of scree materials (Chapters 11 and 12) and the variation of size and sorting both across and down the slope (Chapter 13). It also enabled some estimates to be made of the relationships between sedimentological parameters and dominant processes (Chapter 14) and thereby extended the temporal dimension of the process studies by considering their long-term effects on scree slope characteristics.

Scree is a descriptive rather than a generic term, since it is usually defined in terms of the attributes of position, depth and constituent materials rather than form or process. For example, Rapp and Fairbridge (1968, p. 1106) define scree as "rock fragments found on slopes or at the foot of steep slopes and cliffs", while Tinkler (1966, p. 379) refers to "loose rock fragments with sufficient depth for their own physical conditions to determine the angle of repose". Apart from the simple division into cones and straight screes, the detailed morphology of screes varies considerably depending upon the dominant processes. Although rockfall is often assumed to be dominant, most screes are multi-process forms since several other geomorphic processes may modify or, under favourable conditions, dominate the character of a scree (e.g.

snow avalanches, slush avalanches, mudflows, etc.). Scree may also grade into other related accumulations of rock debris such as rockslides, lateral moraine, protalus ramparts, rock glaciers, etc. Although a few attempts have been made to classify such deposits on the basis of process (Rapp, 1959; White, 1967; Wallace, 1967), they essentially form a continuum which can only be subdivided in the more extreme cases. The discussion of scree form in Section IV (Chapter 15) deals mainly with the plan and profile characteristics of the sampled screes, attempts to relate them to the dominant processes at the site and compares the results with available data from other areas. Also, since the accumulation observations emphasize the role of snow avalanches, the long-term effects of this process on scree forms are discussed in detail.

The ambiguity of the term scree has led to considerable discussion of its usage. From the definitions quoted above, it is clear that scree (or talus) has a double meaning--it refers both to the landform and its constituent materials. Some authors have objected to this duality (Gardner, 1968a; Bones, 1971) and suggest the alternative term debris slope for the form. However, this too is open to very wide interpretations and therefore the term scree is retained throughout this study, qualified where necessary to clarify its meaning. There has also been considerable discussion of the equivalence of the terms scree and talus (see for example, Rapp and Fairbridge, 1968; Bones, 1971). This author considers the terms synonymous expressions differing only in the cultural bias of their users. The use of scree throughout this work is simply for consistency; talus could be substituted in all cases and has, in fact, been used elsewhere (e.g. Luckman, 1971).

CHAPTER 2

THE SETTING

Surprise Valley is a small alpine valley in the Queen Elizabeth Ranges of Jasper National Park, about 25 miles by road from Jasper townsite (Figure 2.1). The valley is approximately ten miles long and one and one half miles wide running parallel to the adjacent Maligne River Valley. The lowest part of the valley is just below 1676 m.a.s.l., whilst the higher peaks rise to 2750-3020 m. Most of the screes studied lie between 1825-2150 m.

The general outline of the valley is shown on the aerial photograph (Figure 2.2). The valley is unnamed on topographic maps, but was christened Surprise by D. C. Ford, partially following local custom (Ford, 1968a, p. 7). All place names within the valley are therefore unofficial, most of them reflecting the author's whims.

Little has been written about Surprise, except for the work of Ford (1968a, 1968b, 1972) and Brown (1970, 1972) which deals mainly with the karstic phenomena of the area. No detailed geological survey is at present available, although sections have been measured along the ridge between Surprise and Maligne (Paull, 1953; McLaren, 1956). Mountjoy (1964) has published a general account of the geology of the area including a map based largely on air-photo interpretation. This account has been supplemented by the author's field observations and details of stratigraphy from similar areas (e.g. Macqueen, 1966; Macqueen and

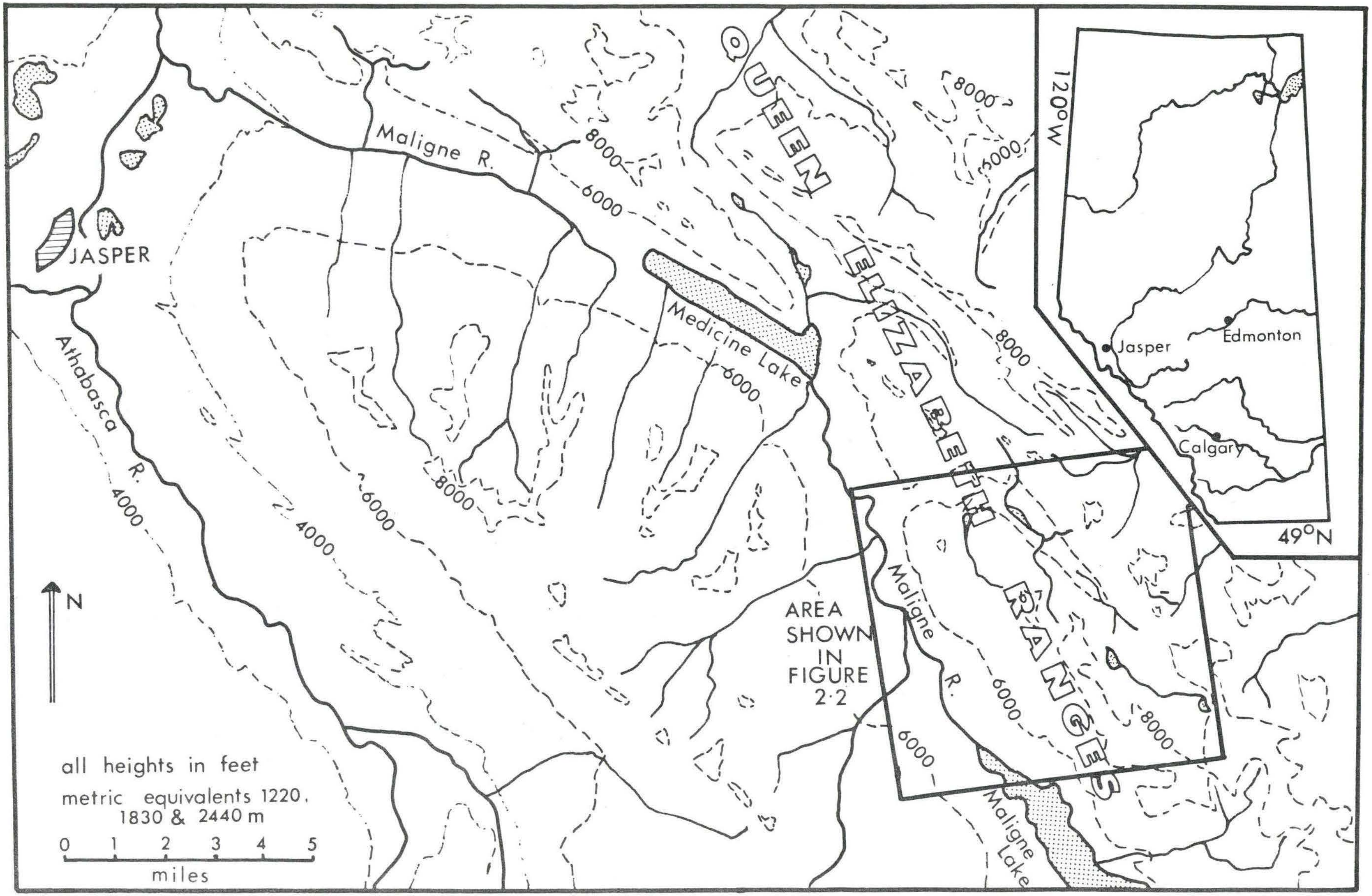
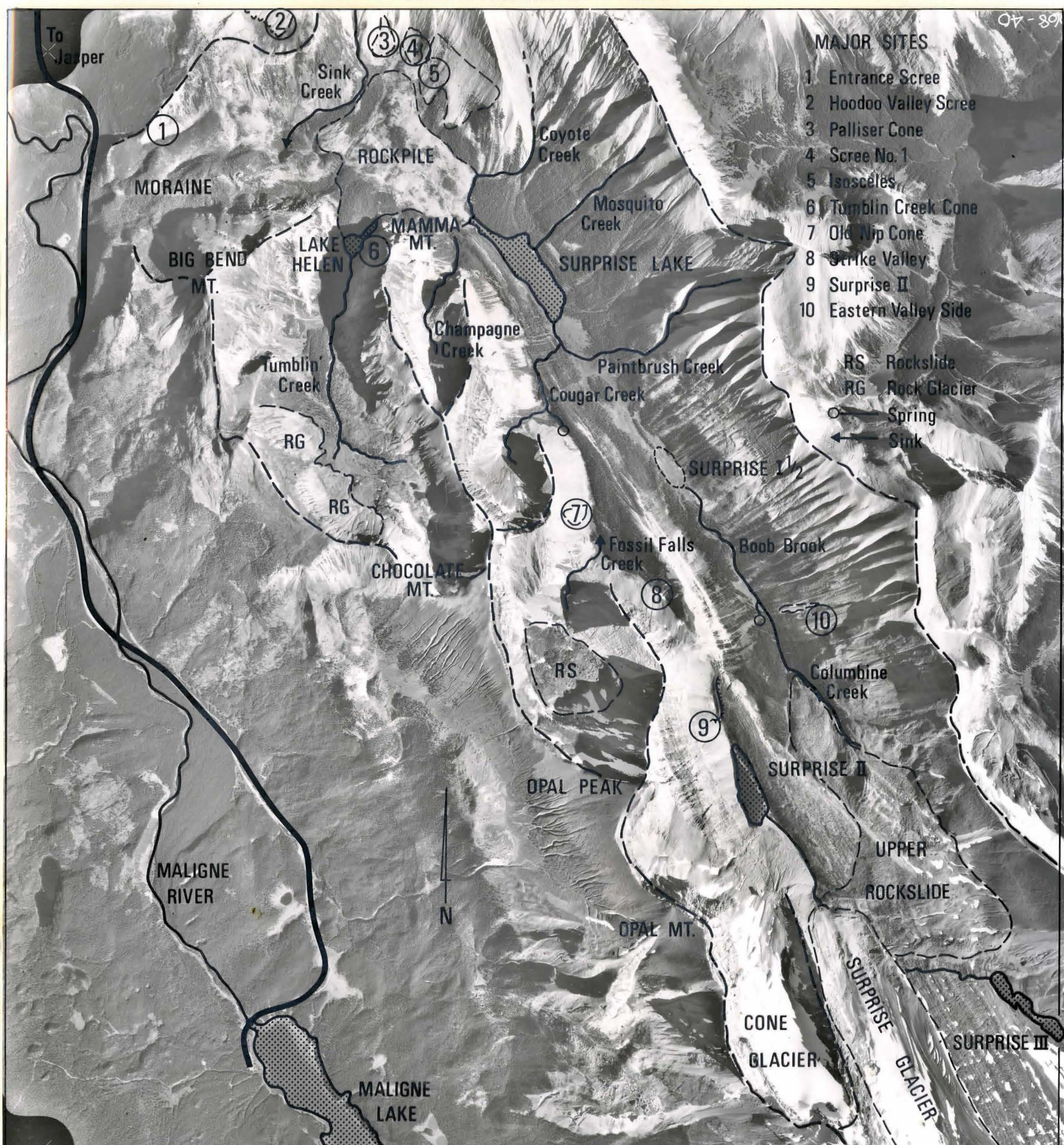


Figure 2.1 Location of Surprise Valley

Fig. 2.2 Aerial Photograph of Surprise Valley

SCALE APPROXIMATELY 1:50,000



Bamber, 1967; also, see references in Price and Mountjoy, 1970).

The landforms of Surprise are dominated by its geology which is relatively simple. The Front Ranges of the Rocky Mountains are composed of a series of thrust plates of sedimentary rocks, the major thrusts running in a northwest to southeast direction. Surprise lies wholly within one such block involving rocks of Cambrian to Triassic age. Within the thrust block, the dip is to the southeast or east-southeast and steepens considerably eastwards. Thus, since the main valley parallels the strike (except for the lower portion where it breaks through to the Maligne Valley), the valley sides show marked contrasts in geology and resulting form. The western flank is composed of massive scarps of gently dipping Mississippian and Upper Devonian limestones (Figure 2.3), whilst the eastern valley side is a steep dipslope of the underlying Lower Devonian shales and limestones (Figure 2.4). Three features complicate this simple picture:

(i) The Mississippian cliffs have been breached by a series of small valleys (Champagne Creek, Cougar Creek, Fossil Falls Creek and the two valleys above Surprise II) which have been considerably modified by glaciation into cirque-like forms. Further west a larger tributary valley (Tumblin' Creek) parallels the main valley for about two miles, joining it at the bend of the main valley.

(ii) A minor thrust with associated drag folds or, north of Lake Helen, a series of small thrusts, repeats part of the Mississippian-Triassic sequence in the ridge between Surprise and Maligne. This line of thrusting runs from the mountain west of Lake Helen along the west side of the Tumblin' Creek Valley and is well exposed in the cliffs in

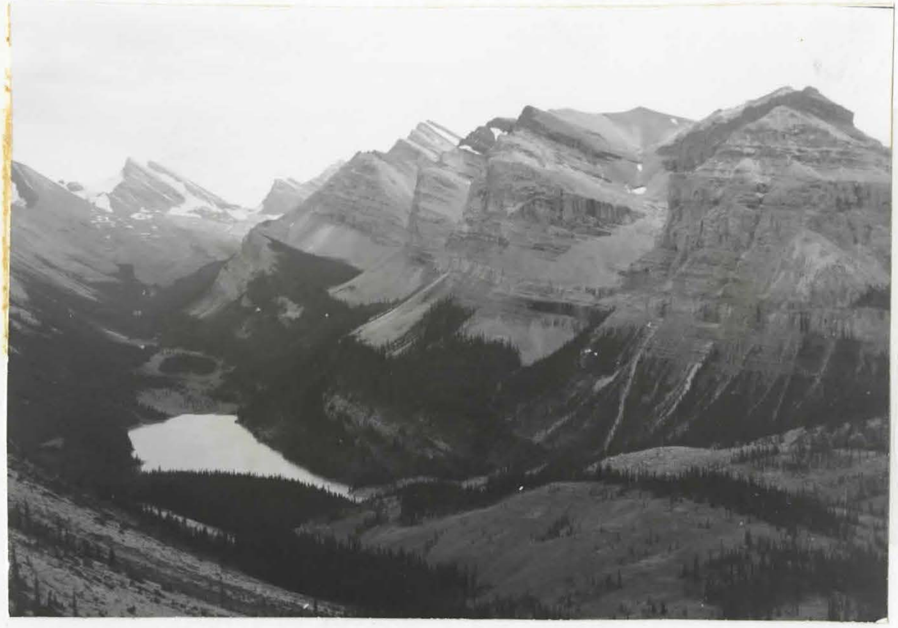


Figure 2.3 Looking upvalley (south) from Isosceles. The geology is clearly displayed in the Mississippian cliffs from Mamma Mountain (right) to Opal Peak (centre). The massive bed immediately above the scree is the Pekisko Limestone and the small dark cliff capping the main face is the Rocky Mountain Formation. On the west side of the lake the tree covered Palliser Bench rises to its highest point at Strike Valley. The basal parts of the Isosceles screes and Rockpile form the foreground. September 1969.

Figure 2.4 The eastern valley side from the Palliser Ridge above Surprise II. The form of the slope is clearly controlled by the massive limestone bed in the Fairholme. Note the gullies and the associated avalanche tracks on the lower slopes. The toe of the Eastern Valley Side site is visible in the bottom right hand corner. 13th July 1970.

Fossil Falls Valley and at Surprise II.

(iii) The dip on the western side of the valley steepens southwards from about 5-10^{0} in the north to 30-40^{0} south of Surprise II.

The rocks exposed within Surprise are mainly limestones and dolomites ranging in character from pure massive limestones or dolomities to silty or sandy carbonates and calcareous siltstones. Their major characteristics are summarized in Table 2.1. Since all the major landforms are structurally controlled, the effects of geology are most easily discussed across the valley from east to west.

<u>Sassenach Formation and the Fairholme Group (Devonian)</u>

The Sassenach Formation forms the backbone of the eastern valley side from the Rockpile to Surprise III. It is generally divisible into two parts, an upper resistant silty and sandy limestone about 30 m thick and a lower recessive unit of calcareous silty mudstones and argillaceous limestones (30-180 m thick) which is very similar to the underlying Mount Hawk Formation (Mountjoy, 1964). The upper member forms the dipslope cliff above Scree No. 1 and is clearly visable on Figures 2.2 and 2.4 as the massive bed, being dissected by gullies between Paintbrush Creek and Surprise II. The dip is about 40-50^{0}. Where this bed has been breached by fluvial erosion, streams have dissected the underlying shales and limestones of the Fairholme Formation into a series of jagged sawtooth ridges east of Surprise I.

The main valley floor appears to have been excavated along the junction between the Sassenach and the overlying Pallister Formation. Mountjoy's map (1964, Figure 1) indicates that most of the valley floor

TABLE 2.1: TABLE OF FORMATIONS EXPOSED IN SURPRISE BASED ON MOUNTJOY (1964) WITH SOME ADDITIONS FROM MACQUEEN (1966) AND PAULL (1953)

Period	Group	Group or Formation	Lithology	Thickness
Triassic		Whitehorse Formation	Carbonate, light grey breccias, red mudstone, gypsum	30-455
		Sulphur Mt. Formation	Siltstone, dark brown grey; thin bedded silty mudstone	90
			Disconformity	
Permian and/or Pennsylvanian		Rocky Mountain Formation	Massive grey chert; cherty brown sandstone	15-30
			Disconformity	
Mississippian	Rundle Group	Mt. Head Fm.	Dolomite, dense, cherty, medium bedded	90-108
	Rundle Group	Turner Valley Fm.	Dolomite, brown, porous, coarse grained	90-120
	Rundle Group	Shunda Fm.	Limestone, dark grey, fine grained, thin bedded	90
	Rundle Group	Pekisko Fm.	Limestone, light grey, crinoidal, coarse grained, thick bedded	60
		Banff Fm.	Limestone and calcareous shale, dark brown, thin bedded	153-214
			Disconformity	
Devonian		Palliser Fm.	Limestone, dark grey, massive, fine crystalline, dolomitic	214-245
	Fairholme Group	Sassenach Fm.	Sandstone, fine grained; siltstone, silty shale, silty carbonates	30-184
	Fairholme Group	Mt. Hawk Fm.	Limestone, brown-grey, argillaceous; and brown calcareous shale	75-214
	Fairholme Group	Perdrix Fm.	Shale, black, fissile, thin limestone interbeds	60-108
	Fairholme Group	Maligne & Flume Fms.	Limestone dark grey, thin bedded, argillaceous, limestone dark brown, cherty with stromatoporoids	45-75
			Unconformity	
Lower Ordovician		Sarbach Fm.	Carbonates, cliff forming	0-245

is underlain by Palliser limestone but this is incorrect. Sections in Columbine Creek show up to 90 m of calcareous mudstones (Sassenach) and similar material is exposed in gully sections below the Palliser Ridge. The upper unit of the Sassenach is exposed by the stream just south of Surprise 1½ and at the base of the scree of Palliser debris on the west side of the valley. The two linear ridges in the valley floor are also bedrock but, like the rock exposed on the east side of Surprise I, they are difficult to identify conclusively. The occurrence of calcareous mudstones within 15-25 m of the lakeshore suggests they are probably Sassenach Formation. The Palliser Formation is only exposed in the valley floor on the west side of Surprise I lake and in Paintbrush Creek close to the base of the Palliser Bench. The only area where the Palliser-Sassenach junction is clearly exposed is in the uppermost part of the valley near Surprise III. In this area, however, differential erosion has not occurred and the junction is marked only by a slight rise in the ground surface.

Palliser Formation (Upper Devonian)

The Palliser Formation is a dense, massively bedded micritic limestone which is very resistant to erosion. It forms a major bench on the western side of the valley between Surprise I and Strike Valley, rising in relative height above the valley floor from 60-90 m at the northern end to 270-300 m at the head of Strike Valley (Figure 2.3). Due to the increasing dip, the feature becomes more scarplike further south and at Surprise II it is a ridge some 150-180 m high (Figure 2.5). At both ends of the valley, the Palliser outcrops on the eastern side of the valley forming well-marked peaks (Figures 2.5 and 2.6).

Figure 2.5 Surprise II from the north. Surprise and Cone Glaciers are still snow covered, centre and right. The protalus rampart can clearly be seen in the foreground, against the well marked ridge of Palliser Limestone. Photograph courtesy of Jim Gray, 6th June 1969.

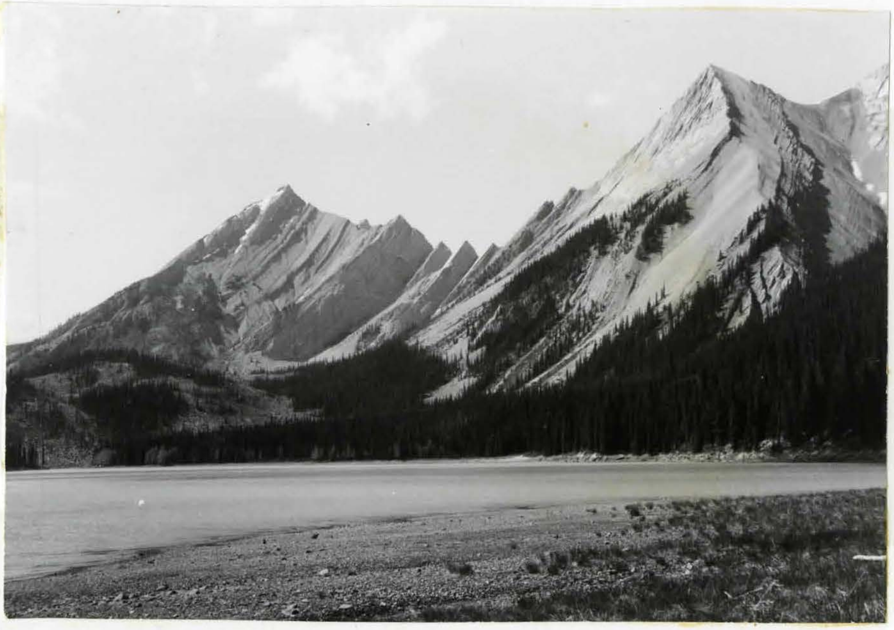


Figure 2.6 Isosceles and Fairytale Mountain from the south end of Surprise Lake. A complete stratigraphic section can be seen from the Pekisko Limestone cap on Fairytale Mountain (centre, left), through the Banff and massive Palliser cliffs above the Rockpile, to the Fairholme on Isosceles and in Coyote Creek (extreme right). Note the small thrust on Fairytale Mountain and the tree covered Coyote Creek fan in the foreground. 18th June 1970.

Banff Formation (Mississippian)

This formation is divisible into three units (Macqueen, 1966) and consists of micritic and ecinoderm limestones interbedded with shales. The lower unit (106.4 m) is composed mainly of shales, whereas the middle unit is more resistant and limestones dominate (19.1 m). The uppermost unit is about 30 m of silty dolomites. Sandwiched between the resistant Palliser and Rundle limestones, the Banff Formation has been etched out as a series of classical interconnected strike valleys or benches, depending upon the dip in the major cliffs on the western side of the valley. The largest of these is at Surprise II, where fluvial and later glacial erosion have excavated a 150-180 m deep blind strike valley, most of which is still occupied by the stagnant Surprise Glacier (Figure 2.5). Sink Creek and Strike Valley are mainly of fluvial origin.

Rundle Group (Mississippian)

The Rundle Group consists of a variety of massive to thickly bedded limestones and dolomites which may be divided into four units--the Pekisko, Shunda, Turner Valley and Mount Head Formations (Mountjoy, 1964; Macqueen, 1966). The Pekisko and Turner Valley are massive cliff formers, whilst the Mount Head is slightly recessive. The Shunda is also recessive in the Tumblin' Creek Valley, forming typical castellated mountains (see Figure 8.35) but has little effect on the form of the cliffs in the main valley. The Pekisko Formation forms a particularly massive 30-45 m high cliff at the base of the major cliffs (Figure 2.3) and at tributary valley junctions producing classical hanging valleys and ribbon-like falls.

Rocky Mountain Formation (Pennsylvanian-Permian)

This unconformably overlies the Rundle Group and is a massive chert bed 15-30 m thick producing a very characteristic brown cliff at the top of some of the major cliffs (Figure 2.3). It weathers to very small angular fragments.

Sulphur Mountain Formation (Triassic)

This formation is exposed over a large area of the dipslope of the ridge between Surprise and Maligne. It is a brown, thinly bedded sandy siltstone or mudstone about 90 m thick (Paull, 1953). It also occurs below the thrust in the cliffs at Surprise II, causing a minor gullied bench.

Whitehorse Formation (Triassic)

Approximately 180 m of massive arkosic quartzitic conglomerate is overthrust onto the Sulphur Mountain Formation on the west side of the Tumblin' Creek Valley (Paull, 1953) and would appear to be part of the Whitehorse Formation. This provides the coarse blocky debris which feeds the rock glaciers in that valley.

Glaciation

Four glaciers occur in Surprise at the present time. The largest, Surprise Glacier, occupies the strike valley at the foot of the east facing Mississippian cliffs south of Surprise II. It is flat, debris covered and stagnant. Debris covered ice, dissected in places by meltwater streams, extends to the neoglacial moraines and there is a very marked contrast between this area and the adjacent, virtually debris free bedrock Palliser slabs.

Cone Glacier occupies a tributary valley above Surprise II and appears to be a more or less stagnant corrie glacier. Its well marked neoglacial moraine extends to the lip of the hanging valley overlooking Surprise II, where a large outwash cone was built (Figure 2.2). This is being dissected by the present stream. The other two glaciers are merely large permanent snowbanks south of Surprise III and on the peak at the south end of the valley. However, ice was exposed by prolonged melting at both locations in 1970 and there is a small moraine 200-300 m from the glacier at Surprise III.

During the Pleistocene, the whole of the valley was probably filled with ice and the west flank tributary valleys have all been modified by glacial erosion. However, apart from the Entrance area, there are no distinctive glacial landforms within the valley apart from those associated with the present glaciers and the modified tributary valleys. Large areas of the valley floors are covered with rockslide, scree (in the higher valleys) or gravel spreads and fans from the eastern side of the main valley. The irregularities of the main valley floor (e.g. the 10 m rise downvalley of Surprise 1½) are probably of glacial origin, but the absence of sections or distinctive morphology makes it impossible to determine the mode of formation. A small amount of till is exposed in sections around Surprise I; most of the other available sections in stream banks show aggradational gravels or bedrock.

The main Maligne Valley is choked with extensive glacial deposits between Medicine and Maligne Lakes. These deposits extend into and block the entrance to Surprise forming irregular rolling terrain with a relief of 100-200 m and a well marked bench on the south side of the valley at about 1825 m. The surface characteristics of this moraine are very similar to the rockslide debris and it contains many huge boulders; the main differences between the two types of deposit are in their composition (the rockslide is either Palliser or Sassenach, the moraine contains Mississippian and Triassic debris as well), the greater development of vegetation on the moraines and their spatial pattern.

A single, sharp crested ridge 90-120 m high runs northward from the Entrance cliffs paralleling the Hoodoo Valley Screes (Figure 8.3). Although this was originally interpreted as rockslide (see Luckman, 1971, Figure 1), it appears to be a major lateral moraine of the Maligne Valley Glacier, since the only possible source area is a Pekisko cliff and many blocks from the Turner Valley and Rocky Mountain Formations may be clearly identified on its surface. A smaller moraine, possibly at the terminus of a glacier from Surprise which was sandwiched between the Maligne Glacier and the Pekisko cliff, extends obliquely up to about 2150-2180 m. The angular till is strongly cemented, probably by percolating groundwater in the limestone rich till, and is superbly exposed in a series of hoodoos 18-22 m high.

No data are available on the deglaciation of this area but from the limited neoglacial advances and the lack of other evidence, it would seem safe to assume that most of the valley has been ice free for about 8,000-10,000 years (see discussions in Shaw, 1972; Harris and Boydell, 1972) during which the present screes have developed.

Rockslides

The combination of steep, undercut dipslopes, alternating strata of differing strength and high relief has resulted in four major landslides (rockslides, Mudge, 1965). All of these slides are in similar topographic situations involving the downdip collapse of a section of steeply inclined dipslope, breaking away cleanly (usually as a single stratigraphic unit) leaving a straight scar running directly downslope. The largest rockslide forms the Rockpile at the north end of Surprise I and involved the collapse of Palliser and Sassenach Formations from the cliffs at Scree No. 1 and Isosceles (see Figures 2.6 and 8.5). The debris is really two separate slides, although they may have occurred at the same time. Two complex, parallel arcuate ridges were formed. The further, higher ridge is composed of huge, rillenkarren covered blocks of Palliser debris, whereas the Sassenach debris forming the inner ridge has been broken down much more easily by physical weathering and has more gentle contour. This combined mass of rock rises over 200 m above Surprise Lake forming an area of more than a square mile of often barren chaotic blocks. At the southern edge of the slide, the Palliser debris has a thicker tree cover and forms a distinctive separate feature blocking the Tumblin' Creek Valley. Whilst this is definitely landslide material from its composition, the thicker vegetation cover and relationship to the main rockpile suggest it might be an older slide.

The upper end of the valley, opposite Surprise II, is also filled by a slide involving the sandy unit of the Sassenach and the underlying shales. Again, the two separate lithologies form two distinct areas. The coarse blocks of the upper unit form a tongue-like deposit which extends over a mile down valley from the source area. Several well defined transverse, almost flow-like, ridges indicate it was moving at high speed, probably on a layer of trapped air (see Kent, 1966; Schreve, 1966, 1968). Part of this slide overtopped the Palliser Ridge, almost reaching Surprise II where it is buried beneath the Neoglacial moraines of Surprise Glacier. The mudstone-siltstone debris has been considerably modified by periglacial processes and now consists of an area of gently rolling topography covered with either small surficial stone stripes or areas of angular frost shattered debris surrounding the ruins of large boulders. There is another smaller scree of Sassenach material at the extreme head of the valley which is snow covered for most of the year.

The fourth rockslide involves the Sulphur Mountain Formation which slid from the dipslope above Old Nip, filling the floor of the Fossil Falls Valley. Due to problems of access, however, it has not been examined in the field.

The age and detailed origin of these rockslides is not known. From their appearance, degree of surface weathering and the size of associated geomorphic features which must postdate them (e.g. the several alluvial fans of Sink Creek and possibly the 30 m deep gorge of Columbine Creek where it skirts the landslide), the two large ones are relatively old and probably date from soon after deglaciation of the area.

Drainage and Karst Phenomena

There are no surface drainage outlets to Surprise. All drainage either flows to one of the three major lake sinks (Surprise I, Surprise

II and Lake Helen), drains into small sinks on the Palliser Bench, Rockpile or moraine areas or seeps into the fluvial gravels on the main valley floor. These karstic phenomena have been reported elsewhere (Ford, 1968a, 1968b; Brown, 1970), although some additional details may be given here.

The differences in geology result in marked contrasts in the fluvial systems within the valley. Streams flowing from the eastern valley side are turbid and heavily debris laden during periods of thaw or summer rainstorms. Almost all the gravels in the main valley floor are derived from this source, together with the thick deposits of silt and mud which floor Surprise I. By contrast, there are far fewer streams on the western side of the valley, but the valleys are much larger. Usually, the streams are clear and there is almost no suspended or bed load movement--all the load is in solution. Many of the streams have small sinks on the Palliser Bench, although in periods of high flow these may be insufficient for the volume of flow and are bypassed. For most of the latter part of the summer the stream channels in the lower part of the floor of the main valley are dry since the water percolates into the gravel bed. During the late snowmelt period, the sinkpoint may fluctuate over a range of several hundred yards in response to daily rhythms of flow.

Whilst the three major lakes all sink and vary considerably in level during the summer in response to input/output rates, their characteristics are quite different. Lake Helen has a steep, mainly boulder bed and probably drains every year, filling up rapidly in June and July. The deepest part of the lake is just south of the Tumblin' Creek Cone but since the lake lies within the upper part of the Banff Formation, the drainage is probably by percolation through the moraine rather than a series of discrete sinks.

Surprise II sinks into the upper part of the Palliser Formation, and, at the lowest water level observed, at least six sink depressions may be seen on the east shore of the lake. This lake probably also drains in winter, although it receives additional inputs of water and sediment from the meltwater streams of the two glaciers. These have built a large gently sloping fan into the south end of the lake below the fossil outwash fan.

Surprise I is remarkably similar to Medicine Lake. It has a gently shelving mud floor and may also drain completely in winter. All three lakes show evidence of continuing drainage after they freeze over, since thick beds of collapsed ice cover their floors in the spring. The lake sinks into the middle or lower part of the Palliser Formation, probably on the western side, south of Mosquito Creek (the deepest part) since the area close to the Rockpile is mud floored and very shallow. However, in the late summer, Champagne Creek and Coyote Creek both sink (into the Rockpile and fan respectively) before reaching the lake.

Scree Slopes

The combined effects of geology, glaciation and post-glacial processes have produced a large number of slopes of rock debris within Surprise. Apart from the rockslides, moraines and alluvial cones, major scree slopes occur along all the major valley sides. The great number and relatively easy access to these screes makes Surprise an ideal location for their study. The screes range from very active avalanche or rockfall dominated slopes to fossil screes, now covered with soil and vegetation. Examples of all the major types of scree accumulation are present except for large complex coelescing cones and this enables the selection of sites where the geology is simple, the form unmodified by other processes (e.g. basal erosion) and the dominant processes are fairly well defined. The sites studied within the valley were chosen on certain basic geologic and design criteria, plus their accessibility. They are described in detail in Chapters 8 and 13.

Climatic Data

The nearest Department of Transport Meteorological station is at Jasper, about 25 miles northwest of Surprise and some 600-700 m below the level of Surprise I. The mean annual temperature at Jasper is 37.3^{o}F with mean monthly temperatures ranging from 11.5^{o}F in January to 56.8^{o}F in August (Brown, 1970, p. 18). However, mountain temperatures are notoriously variable even within a small area due to differences in aspect, elevation, etc. and the range of temperature found within Surprise is probably very similar to that observed by Gardner (1968b) in the Lake Louise area. An attempt was made to operate a daily thermograph in Surprise in 1969 but calibration problems with the equipment make it useful only in relative terms (see Chapter 4).

Measurements of precipitation were made at Maligne Lake (1676 m) from October 1963 until the 1971-72 winter when the warden was moved. These figures (Table 2.2) provide a general guide to winter conditions in Surprise, although snowfall in particular increases with elevation

TABLE 2.2: PRECIPITATION RECORD FOR MALIGNE LAKE, 1963-1971

Month	1963	1964	1965	1966	1967	1968	1969	1970	1971
Jan.		14	12	14	17	32 (1.85)	4	10	37
Feb.		14	14	14	17	20	14	11	9
Mar.		15	7	17	31	11	2	28	18
Apr.		30	25	15	8	40	10	19	11
May		7 (0.5)	22 (1.5)	10 (0.27)	8 (0.45)	15 (0.24)	4 (0.51)	0 (0.67)	0 (0.85)
June		(1.05)	(2.17)	(0.95)	(2.17)	(3.48)	(1.44)	(1.79)	
July		(1.45)	(3.00)	(4.58)	(3.33)	(2.08)	(2.81)	(1.74)	
Aug.		(1.50)	(1.95)	(3.52)	(1.09)	(2.74)	21 (1.84)	(0.75)	
Sept.		(3.06)	3 (3.45)	(1.90)	(1.70)	(1.83)	3 (2.04)	3 (0.39)	
Oct.	5	4	5	11 (1.81)	8 (0.75)	6 (1.61)	4 (0.77)	5	
Nov.	12	13	11	28	12	19	12	16	
Dec.	9	8	14	14	29	18	8	18	
Total Rainfall		7.56	12.12	16.03	9.49	13.83	9.41	6.49	
Total Snow		106	107	103	134	167	77	95	127

NOTE: This total is for the preceding winter, i.e. August-May
Also, all measurements are in inches.

SOURCE: S. M. Elder

and at 2150 m on the Bald Hills (three to four miles west of Maligne) it is approximately one third greater than that recorded at Maligne (S. M. Elder, private communication). Precipitation appears to be divided almost equally between rain and snow with 10.5 inches of rain and 115 inches of snow over this eight year period. However, the amounts are extremely variable with the two extremes recorded in consecutive years (unless the August 1969 snowfall is excluded from the 1970 data) and heavy snowfalls may occur in any of the months from November to May and occasionally during the summer. The snowfall in the 1971-72 winter was at least as great as any of the previous years of record (S. M. Elder, private communication).

SECTION II

SCREE SLOPE PROCESSES

Chapter 3: The Controls of Scree Slope Processes

Chapter 4: Rockfalls

Chapter 5: Snow Avalanches

Chapter 6: Other Major Processes Affecting Scree Slope Development

Chapter 7: The Collection of Accumulation Data

Chapter 8: Results of the Measurement of Debris Accumulation

Chapter 9: Discussion of the Results of the Accumulation Measurements and Their Wider Implications

CHAPTER 3

THE CONTROLS OF SCREE SLOPE PROCESSES

Scree slopes are part of the total population of slopes in a mountain area and, like those slopes, are exposed to a wide range of geomorphic processes. The surface characteristics and position of screes favour the dominance of certain processes in their development but, under suitable conditions, any of the slope processes associated with high alpine areas may influence the development of scree slopes.

This brief introductory chapter outlines the conceptual framework of the study and the main factors which influence the relative importance of the major processes controlling the development of scree slopes. Each of these processes will then be discussed in an integrated review of published work and observations made in Surprise (Chapters 4, 5 and 6). Finally in Chapters 7 to 9, the results of the study of debris accumulation on boulders and squares will be presented and discussed with reference to the previous chapters.

CONCEPTUAL FRAMEWORK

Few attempts have been made to provide any framework for the study of processes which affect screes. Apart from studies of individual processes or subdivisions into depositional processes and debris shift, the most useful framework is that proposed by Thornes (1968, 1971).

Thornes attempted to provide a queueing theory analogue for scree slopes and, although there are problems associated with the applications suggested by Thornes (see Robinson, 1971; Thornes, 1971), the queueing theory analogue provides a useful framework within which the discussion of scree slope processes may be carried out.

Thornes (1968) divides scree slope processes into input processes (I), queueing processes (Q) and output processes (O). This is analogous to the division into processes which deliver material to the scree, processes which modify the scree material in situ or transfer it downslope and those processes which remove debris from the scree (see Table 3.1).

From the basic input-output relationships, four states may be described and used in comparisons of different screes:

(i) I = 0, O = 0; In this case, weathering on the cliff is negligible and the cliff is stable or buried by debris. The scree is inactive and possibly covered by vegetation and soil.[1] Many fossil scree slopes of this type have been described from Europe (Guillien, 1951, 1964; Watson, 1965; Ball, 1966). In Surprise, the basal part of the eastern valley side between Surprise I and the "Eastern Valley Side Scree" is covered with fossil scree of this type which is occasionally exposed in gully sections.

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[1]It is generally assumed that the presence of vegetation on a scree is in some way a reflection of the lack of geomorphic activity on that scree. Since many of the active screes in Surprise may have a low cover of shrubs, flowering plants or grasses, whilst the heavily lichen covered less active screes do not, it seems pertinent to suggest that, while scree activity may affect vegetation patterns, these patterns are basically controlled by water availability and the presence of fine material close to the surface. Thus, in many cases, the absence of vegetation merely reflects the coarse nature of the scree surface.

(ii) $I > 0$, $O = 0$; The large majority of screes in Surprise are of this type since, apart from solution and the eluviation of fines, there is virtually no basal removal of debris from the scree.

(iii) $I = 0$, $O > 0$; Since this state involves the degradation of a scree which is essentially fossil, very few examples have been described. Some of the examples of fossil screes in Britain are of this type where they are exposed by fluvial erosion (Luckman, 1966, p. 219). The only example of this type noted in Surprise is where Coyote Creek is undercutting a fossil scree at the northern end of its fan.

(iv) $I > 0$, $O > 0$; Depending upon the relative rates of supply and removal, there are a wide range of possibilities in this state, including the development of a "steady state" (Thornes, 1968). However, unless the removal processes are powerful or the supply very small, it is difficult to envisage the scree merely as the storage for a system involving the throughput of debris from cliff to stream, glacier or sea. Since screes are essentially accumulation forms, it might be easier to think of them as a sieve through which only a few random or special particles pass (i.e. those that are very large or very small). It would be irrelevant at this stage to discuss at length the ramifications and speculations which arise from this interesting framework (see Thornes, 1968; Robinson, 1971). However, it provides a useful frame of reference for process studies on screes and is used in the following discussion.

Table 3.1 shows a division of scree slope processes grouped according to the queueing analogue put forward by Thornes. It can be seen that certain processes may fall into any or all of the above roles. It seems reasonable, therefore, from considerations of presentation, to discuss individual processes systematically, emphasizing their different roles, rather than splitting up the discussion of individual processes into several parts.

Before proceeding to a consideration of individual processes, it is interesting to discuss the factors which control the relative importance and intensity of these processes in any specific area. Since the bulk of this thesis is concerned with input processes and their effects on screes, the major part of this discussion is related to these processes and the factors which control them.

TABLE 3.1: CLASSIFICATION OF SCREE SLOPE PROCESSES USING A QUEUEING THEORY ANALOGUE

1. INPUT PROCESSES:	rockfalls rockslides snow avalanches slush avalanches icefalls mudflows fluvial activity debris flows
2. QUEUEING PROCESSES:	as (1); plus rockfall impact creep compaction surface and subsurface weathering (chemical and physical) solifluction shallow surface slides major slope failures washing down of fines solution frost heave, etc. snow table gliding
3. OUTPUT PROCESSES:	as (1), when debris carried beyond the scree, basal removal (fluvial, marine, glacial), washing out of fines and solution by percolating water and springs.

THE MAJOR CONTROLS OF INPUT PROCESSES

The controls of the geomorphic processes which remove debris from rock cliffs may be divided into two broad groups: climatic parameters which govern the availability and state of water and physical parameters which relate to the nature and arrangement of particles on and within which those processes take place. Considerable interaction and feedback takes place within these two groups and some of these relationships are shown diagrammatically in Figure 3.1. Since the current state of the system embodies a considerable historical legacy, a time dimension has been added to the diagram.

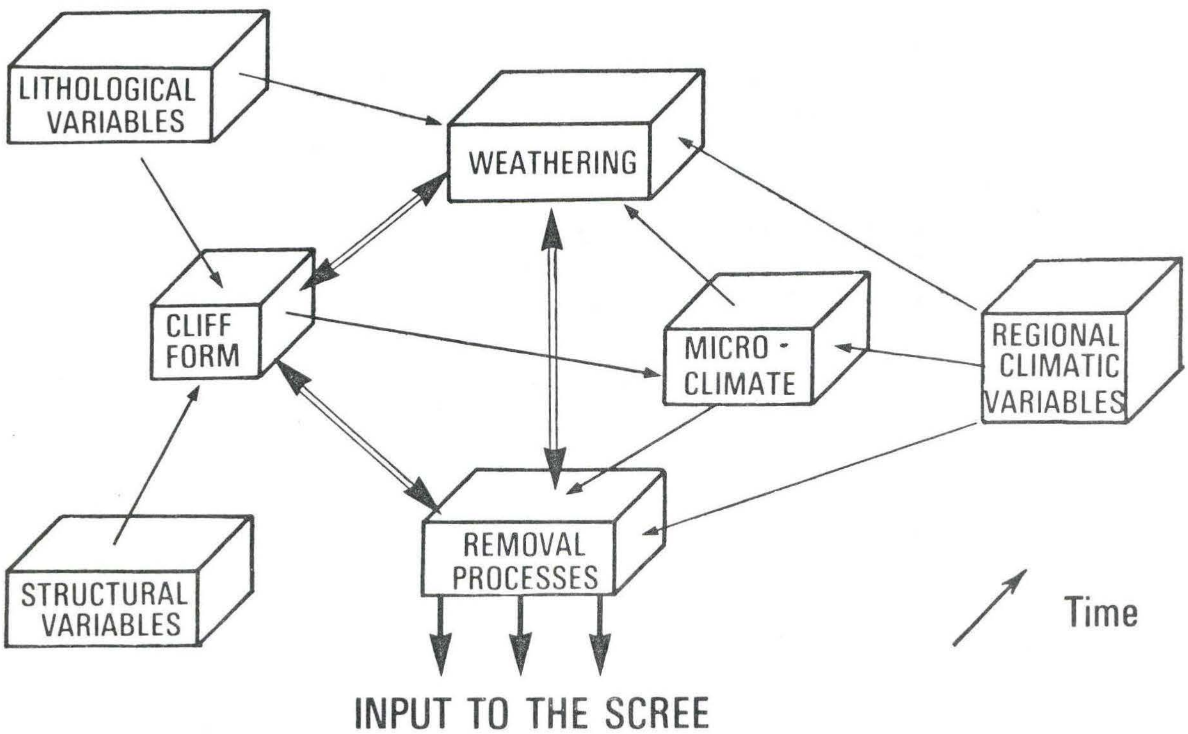


Figure 3.1 Diagrammatic representation of the variable groups influencing the input of debris to scree slopes

Climatic Controls

Screes consist essentially of relatively unweathered rock debris. The ratio between the rate of production of such debris and its destruction by other weathering processes has been termed the Talus Weathering Ratio (Schumm and Chorley, 1966). In cases where this ratio is less than one, scree accumulation does not occur; for example, in their study of the development of cliffs in the Colorado Plateaus, Schumm and Chorley (1966) found that, even though the cliffs were producing rockfall debris, the fragments either shattered on impact or were rapidly broken down by weathering so that no scree accumulation takes place. Where the T.W.R. is close to one, there is a scattered veneer of rock debris on the lower slope which is best referred to as clitter (Tinkler, 1966). Scree occurs only when this ratio is, or has been, greater than one and is therefore restricted to areas dominated by mechanical weathering. Such areas are obviously controlled by climatic parameters and may be either hot and dry or subject to frost action (Wilson, 1968). Although there are a few references to screes in arid regions (e.g. Lawson, 1915; Bryan, 1922), no detailed descriptions are known to the author from such areas; the majority of screes are restricted to areas which experience, or have recently experienced, a climate with significant freeze-thaw activity.

Despite this limitation, gross variations of climate can lead to differences in the nature and intensity of the geomorphic processes which control the development of screes. The availability of water and the number and intensity of freeze-thaw cycles are obvious controls on the weathering of rockwalls. Recent work (Guillien and Lautridou, 1970; Potts, 1970) indicates that frequency is probably more important than the intensity of the freeze-thaw cycle in the breakdown of rock material and therefore regional variations in the number of freeze-thaw cycles (see, for example, Fraser, 1959) will significantly affect the provision of debris to scree slopes with resulting implications for scree form. Similarly, the amount, distribution and character of precipitation is an important control of process. Frequent or intensive rainstorms may cause intensive gullying (Rapp, 1960b, p. 155) or lead to massive slides of saturated scree material (Rapp, 1963). The amount and distribution of snowfalls is an obvious limitation on the activity of snow or slush avalanches, whilst the average period and character of the snow cover on the scree have considerable influence on the "queueing" processes. Thus, even within the fairly narrow confines of the presence of freeze-thaw activity, there may be considerable variations in the relative intensity and importance of processes which are due merely to regional differences in climate.

Differences of a similar nature may also occur within a relatively small area due to variations of "mesoclimate" resulting from the configuration of relief. The relationship between the distribution of corries and aspect is well documented (Temple, 1965; Embleton and King, 1968, pp. 196-98); much of the snow which occupied these forms would be carried down the backwall by snow avalanches and the patterns of snow accumulation and drifting are therefore also important in determining the location of perennial avalanche sites. Rapp's comment that "The strong predominance of avalanches on lee-side slopes, mainly facing east, but also facing north and south, is a general condition in Northern Lappland" (Rapp, 1960b, p. 131) is equally true for the Front Ranges of the

Canadian Rockies, particularly where avalanches are spawned by large drift-fed cornices.

Aspect is also important since it controls the seasonal and daily rhythms of temperature on the cliff faces. West facing slopes lose their snow cover early, whilst snow remains and continues to avalanche for a much longer period on east or north facing slopes. If snow remains on the cliffs (for example, in deep gullies) until most of the snow has ablated on the scree below, the erosional effect of avalanches is heightened since they move in direct contact with the underlying scree. The meltwater from such snow may considerably prolong frost action in the cliffs. The daily temperature regime of the cliff face (and such related factors as frost bursting and rockfalls) is also controlled by aspect (see, for example, Rapp (1960b), Figure 7a). Thus, east facing cliffs which heat up rapidly in the early morning may have their peak rockfall activity at that time, whereas west facing slopes may not begin to thaw until late morning or early afternoon.

Even within a small area, therefore, the relative position and aspect of slopes may, through its influence on climatic variables, result in differences in process which lead to differences in the form of the rockwalls and associated scree slopes. On any individual cliff differences in microclimate due to small variations in aspect, length of time in shadow, the presence of snowpatches, etc. will affect the detailed location of weathering processes. It can thus be seen that at all scales-micro, meso and macro-climatic factors exercise considerable influence on the character and intensity of the geomorphic processes which are important in the development of scree slopes, since they control the nature and availability of the major agents involved in those processes, namely water, snow and ice.

Physical Controls

Probably the most important physical factors governing the development of screes are the form of the rock face and its constituent materials. These two factors are, of course, linked since lithological variations, the attitude of the beds, the presence of lines of weakness, etc., influence the rate and location of weathering and erosional processes on the cliff face. The form of the rockwall is of paramount importance since, together with climatic parameters, it controls the nature of the processes which remove material from the cliff as well as the character and lateral variations in intensity of deposition on the screes below. Thus, unless the depositional area has distinctive characteristics, e.g. a marked bench, some form of constriction or very active removal processes, the character of the scree is controlled by the variations in the rate, manner and distribution of the material brought down from the cliff.

Rapp (1960a) has put forward a simple threefold division of scree slopes showing the transition from a straight scree (apron scree) below an undissected rock wall, through a stage of simple scree cones to multiple coelescing cones as gully and scree development continue. These gullies (chutes or couloirs are alternative terms) are initiated by differential weathering probably due to variation in the physical characteristics of the rock or the presence of water seepage or drainage down the cliff which locally provides a suitable environment for intensive freeze-thaw activity. Once irregularities begin to appear on the rockwall, the pattern of processes gradually changes from a fairly random distribution of rockfalls to one in which more intensive deposition takes place below the developing gullies forming cones. The causes for this relative increase in deposition are twofold: the development of the gully funnels rockfall deposition to the scree below the gully from a much wider area than before and, as the development continues, the gullies provide channels for water flow and slush or snow avalanches. Although snow avalanches may occur on undissected cliffs, if they are fed by large cornices at the top of the cliff, the development of gullies provides accumulation areas and well defined channels which may become perennial avalanche sites. Alternatively, gullies may develop into small stream valleys and the scree takes on the characteristics of an alluvial cone. Thus, with increasing dissection of the cliff, the spectrum of possible processes is widened and the majority of the large, well-developed cones may exhibit the effects of several processes, although one of them is often dominant.

The profile form of the cliff is controlled largely by bedrock structure and lithology and may also influence the nature of the scree. For example, a nearly vertical cliff, usually composed of fairly massive or horizontally bedded rocks, is more likely to break down by large primary rockfalls (Rapp, 1960a; also, see Chapter 4) and the screes below such cliffs tend to be very coarse, e.g. those at Old Nip and the Entrance Screes in Surprise. However, where benches occur on the cliff or the cliff is a dipslope, e.g. Scree No. 1, Surprise II, much of the debris may come to rest on these benches and further weathering takes place before it reaches the scree below. With more opportunity for weathering the debris tends to be smaller and the majority of the rockfalls would be secondary rockfalls, redistributing this material. Benched cliffs also may provide collecting areas for snow avalanches or sources of rock debris which may be incorporated into avalanches.

QUEUEING AND OUTPUT PROCESSES

It is difficult to generalize about the controls of queueing and output processes. Some of the queueing processes are controlled by the action of input processes moving over the slope. Most of the others are controlled by the characteristics of the surface material on the slope (grain size, sorting, shape of fragments, etc.) and climatic parameters (rainstorms, freeze-thaw activity). The interaction of these two sets of variables may give rise to such diverse processes as talus creep, frost heaving or mudflows. The controls will be discussed more fully in the section on individual processes in Chapter 6.

Output processes are dominated by the location of the scree and its relation to major erosional agents such as glaciers, rivers or the sea. The only other factor of importance is the character and development of the groundwater system within the scree and its role in the transport of dissolved and suspended sediment from the scree.

CONCLUSIONS

The main purpose of this discussion has been to illustrate the possible variations in the processes which affect screes and the factors which control them. Screes are not simply produced by rockfall (although it is frequently the dominant process in scree development); they may result from the action of several different processes, the dominance and relative importance of which is controlled by climatic and physical variables. As cliff development produces a more complex form, the available range and possible combination of processes increases. These combinations, together with variations in the state and availability of water which are controlled basically by climate, may produce a wide variety of scree forms. The characteristics of the scree will therefore vary according to both the state (Thornes, 1971) and the dominant processes (Rapp and Fairbridge, 1968; Robinson, 1971) which influence the scree. Thus, it becomes very important when comparative studies are made to realize what particular type of scree one is looking at. Much of the conflicting information about scree characteristics in the literature, such as the profile or the variations in grain size, probably stems from the assumption that screes are all more or less the same and can be attributed to similar processes, i.e. rockfall, and that one can compare, for example, the characteristics of coarse dolerite screes in Tasmania (Caine, 1967) with screes in the Gaspé (Miner, 1934) or the multiple process cones in the Lake Louise area (Gardner, 1968a). The wide range of scree types in a small valley such as Surprise indicates the need for a much closer scrutiny of the characteristics of individual screes before comparisons are made. Only then might it be possible to say something about the relationship of the various attributes of the scree to the processes involved (Thornes, 1968).

CHAPTER 4

ROCKFALLS

Rockfall may be defined as the free, bounding or rolling movement of rock debris down a steep slope under the influence of gravity. Such falls may be divided into two types (Rapp, 1960b, p. 104). Primary rockfalls occur when material breaks away from the cliff face and moves immediately downslope. Secondary rockfalls involve the shift of previously weathered debris down the cliff, either from ledge to ledge or onto the scree. If the queueing analogue (Thornes, 1971) is applied to debris movement on the cliff, primary rockfalls may be thought of as input or throughput processes whereas secondary falls are queueing or output processes. Primary rockfalls, since they involve the failure of a part of the cliff face, tend to be larger in size and constituent fragments than secondary falls and are also the major cause of rockwall retreat. The most frequently observed falls on cliff faces are small secondary pebblefalls moving debris down the cliff or on to the scree, except where the cliffs are vertical.

Despite the fact that rockfalls are assumed to be the dominant process in scree formation, there has been surprisingly little work devoted to their detailed study. Most of the relevant available accounts restrict their observations to inventories of rockfall occurrence or debris accumulation (Rapp, 1960a, 1960b; Schumm and Chorley, 1964;

Gardner, 1967, 1968a, 1969b; Stock, 1968; Prior et al., 1971). Some of these (Rapp, Gardner and Stock) attempt to link the frequency of occurrence to climatic parameters whilst Prior et al. compare the quantity of deposition of different formations with their physical characteristics. The only study devoted to the movement characteristics of rockfalls is that carried out by Ritchie in relation to highway safety procedures (Ritchie, 1966). Within this chapter, rockfalls will be discussed under certain topics in an integrated review of these authors' observations and observations made in Surprise.

RELEASE MECHANISMS

It is logistically impossible to observe the release of rockfalls from the face in the vast majority of cases. However, by inventory studies of the frequency and timing of rockfalls and the contemporaneous monitoring of relevant climatic parameters and events, it is possible to make certain general inferences about the factors which trigger rockfalls.

The major causes of rockfalls have been outlined by Rapp (1960b) and Stock (1968). Observations made in Surprise give similar results to these two studies and will be discussed in the accounts of the rockfall inventory.

Before proceeding to this outline, it is important to consider the relevance of the primary/secondary division of rockfalls. On intuitive grounds, it seems probable that certain processes may influence primary and secondary rockfalls differently. Table 4.1 is a qualitative assessment of the relative importance of the major release mechanisms, incorporating Rapp and Stock's observations with data from Surprise.

TABLE 4.1: RELATIVE IMPORTANCE OF THE RELEASE MECHANISMS OF ROCKFALLS

	Primary Rockfalls	Secondary Rockfalls
(1) Frost bursting	highly important	probably insignificant
(2) Rain storms	Possibly important	important
(3) Drizzle	possibly important in association with (1)	probably insignificant
(4) Spalling, pressure release	possibly important	insignificant
(5) Thermal changes	possibly important	possibly important
(6) Creep	nil	possibly important
(7) Chemical weathering	possibly important locally	probably insignificant
(8) Rockfall impact	negligible	important
(9) Wind	nil	important
(10) Snow block falls	negligible	important
(11) Ice block falls	possibly important	important
(12) Earthquakes	rarely important	rarely important

The most important process producing primary rockfalls in alpine and high latitude areas is frost bursting (Rapp, 1960b). During freezing the volumetric expansion of ice in cracks produces considerable strain on the rock which may result in rupture. When the ice melts, the ruptured blocks are devoid of support and fall. This process is obviously related to the number of freeze-thaw cycles in the area (C.N.R.S., 1970) but also depends upon the presence of water. The importance of the character of the available water is well shown by several recent experiments (Potts, 1970; Guillien and Lautridou, 1970). This release mechanism, together with snow and ice block falls, is the major component of the spring maximum observed by Rapp and Gardner (1967), although such rockfalls may occur at any time during the summer in alpine environments.

Heavy rainfalls are considered by Rapp to be of little importance in the release of large primary falls. It is probable, however, that such rainstorms may be important in generating pebblefalls by dislodging debris directly or by surface flow. Most of the other possible causes of rockfalls are fairly evident from their description in Table 4.1.

ROCKFALL INVENTORY

The occurrence of rockfalls, avalanches and icefalls was recorded during the time spent in Surprise. The location, time of occurrence and, where observed, the size and nature of movement were noted in an inventory similar to those of Gardner and Stock. The records for 1968 and 1970-72 are fragmentary; the former due to the varied and reconnaissance nature of the work in that season and the latter because of the shorter periods spent in Surprise. The data from the 1969 season are more complete, covering the period from mid-May to late September. This record may be divided into two parts:

(i) "controlled" observations: These are observations which were made during periods of work on scree slopes and refer only to events occurring in the cliff above or in adjacent cliffs.

(ii) "general" observations: These are movements recorded at other times, e.g. rockfalls heard at camp, during travel into and within the valley or at sites other than that at which the observer was stationed. They also include qualitative statements such as "very frequent rockfalls" or "occasional small pebblefalls" which occur in the record and some observations from situations similar to (i) where adequate control is lacking.

This record of "general" observations cannot reasonably be quantified, since the duration of the periods of observation is not usually known. Other variables such as distance from the cliff, wind direction, heavy rain on the tent, periods of sleep, etc. filter out many of the smaller events and only moderate to large ones are recorded. These results are not, therefore, comparable with the "controlled" observations, although they may be used in a generally descriptive manner.

The "controlled" observations are also subject to variations in quality, since many of the rockfalls were not seen by the observer but identified and located by the noise they produced. The sound of small rockfalls may be masked during bad weather or lost in the roar of nearby waterfalls, especially if the wind is in the wrong direction. The only other major source of bias in this data is produced by variations in the character and length of the various periods of observation. This problem is discussed in detail below.

Figures 4.1 and 4.5 show the total number of observations in 1969 on a daily and hourly basis, together with certain meteorological data. All other diagrams and references to the data in this chapter refer to the "controlled" data unless otherwise specified.

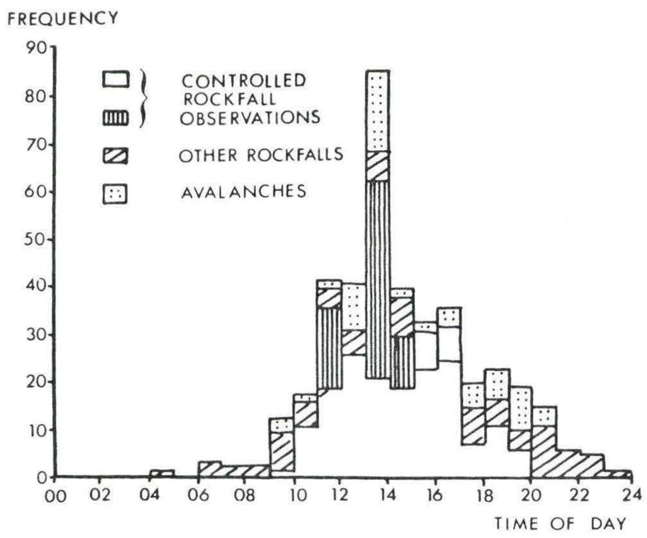


Figure 4.1 Absolute hourly frequency of observed rockfalls and avalanches in Surprise in 1969

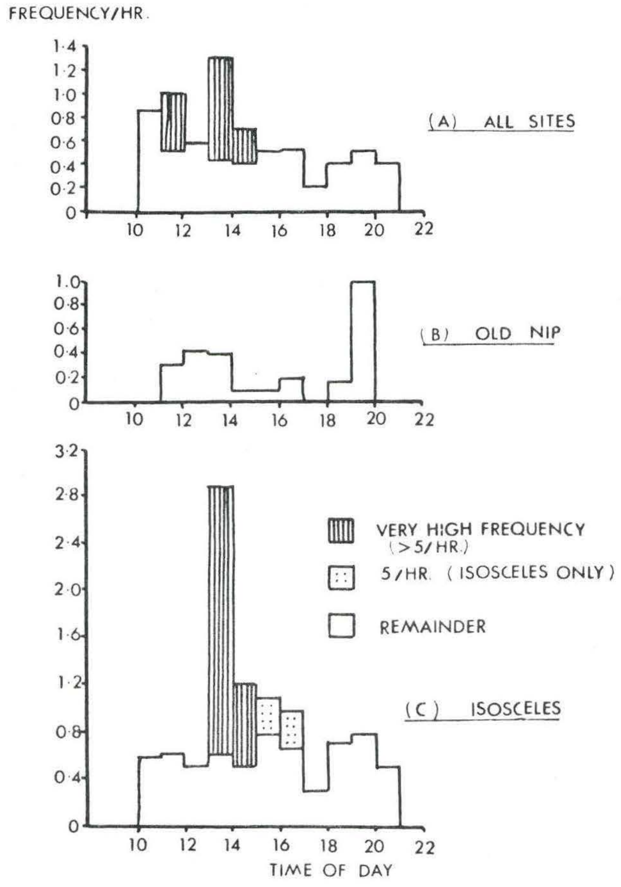


Figure 4.2 Frequency of rockfalls per hour of controlled observations in 1969

Daily Frequency of Rockfalls

Gardner's Work and the Concept of the Average Day

Some of the problems involved in the statistical treatment of this kind of data have been discussed by Gardner (1967, 1968a, 1969b). He divided the day into hourly periods and the number of rockfalls in each period was determined. In order to remove inequalities due to differences in the number of times each period was observed, the total number of rockfalls is divided by the number of hours of observation to give an average rate of rockfall per hour for that period. Figure 4.2 shows histograms of this type using the 1969 data from Surprise. Where the total observation period is small, this method may produce anomalous results which must be discounted, e.g. 1900-2000 hours (Figure 4.2B).

Using this data, Gardner devised the concept of the "average day" to describe the average diurnal variations in rockfall activity and to discuss the relationships between rockfalls and temperature. However, there are certain limitations and criticisms of this technique and its application, particularly relating to the meaning of the "average day". These may be illustrated using the "controlled" data from Surprise.

(i) The Effects of the Aggregation of Data

Gardner used data from a number of sites in the Lake Louise district over a three-year period. Averaging the data from several different sites of varying character, aspect and activity ignores the inherent differences between these sites which may be reflected in the observed pattern of rockfall activity. The actual observations on any particular day are controlled by the following factors:

(a) The period of observation.

(b) The character of the site: considerable differences may occur in the number and nature of rockfalls at different sites depending upon, for example, cliff form (see discussion in Chapter 3). Thus, the relative number and periods of observation at "high frequency" as opposed to "low frequency" screes will have a considerable effect on the average rates of activity.

(c) The daily temperature rhythm of the face which is mainly controlled by aspect: this may well effect the timing of rockfall activity and obviously interacts with (a) and (b).

(d) The weather in the period prior to and during the observation period: rockfalls may be triggered by meteorological events producing variations to the "normal" daily pattern. Seasonal effects may also be important (see discussion below).

Thus, the resulting average data presents a version of reality which aggregates the characteristics of several sites or sets of variables but may not be characteristic of any of them. This can be demonstrated by considering two of the sites observed in Surprise. Old Nip and Scree No. 1-Isosceles are the two sites with the longest periods of observation in 1969 (Table 4.2). When these sites are compared with each other and the total observations, considerable differences in the daily frequency of rockfall are immediately apparent (Figure 4.2). These are discussed below but, when shown in this form, they demonstrate the site to site variations which are obscured by aggregate diagrams.

(ii) <u>The Influence of Periods of High Activity</u>

On two occasions, the rockfall inventory had to be abandoned after one or one and a half hours observations, due to the high frequency

TABLE 4.2: CONTROLLED ROCKFALL DATA FOR SITES IN SURPRISE FOR 1969

(A) ALL SITES

	Hours Observed	Total Rockfalls	Rate	Probability	Frequency per Hour 1	2	3	4	5	>5
9 - 1000	1	0	0.00	0.0						
10 - 1100	13	11	0.83	0.44	2	3	1			
11 - 1200	35	35	1.00	0.40	9	3	1	0	0	1
12 - 1300	43¼	25	0.58	0.32	6	3	3	1		
13 - 1400	47	62	1.32	0.23	3	4	3	0	0	1
14 - 1500	43	29	0.67	0.37	13	2	0	0	0	1
15 - 1600	43½	22	0.51	0.23	7	1	0	2	1	
16 - 1700	45½	24	0.53	0.33	11	2	0	1	1	
17 - 1800	39½	7	0.18	0.18	7					
18 - 1900	24½	10	0.41	0.29	5	1	1			
19 - 2000	9½	5	0.53	0.53	5					
20 - 2100	2½	1	0.40	0.40	1					
	347¼	231			69	19	9	4	2	3

(B) OLD NIP

	Hours Observed	Total Rockfalls	Rate	Probability	Frequency per Hour 1	2	3	4	5	>5
9 - 1000	0	0	-							
10 - 1100	2	0	0.00							
11 - 1200	10	3	0.30	0.30	3					
12 - 1300	12	5	0.42	0.25	2	0	1			
13 - 1400	13	5	0.38	0.23	2	0	1			
14 - 1500	13	1	0.08	0.08	1					
15 - 1600	13	1	0.08	0.08	1					
16 - 1700	13	2	0.15	0.15	2					
17 - 1800	12¼	0	0.00	0.00						
18 - 1900	8	1	0.13	0.13	1					
19 - 2000	1	1	1.00	1.00	1					
20 - 2100	1	0	0.00	0.00						
	98¼	19			13	0	2			

(C) SCREE NO. 1-Isosceles

	Hours Observed	Total Rockfalls	Rate	Probability	Frequency per Hour 1	2	3	4	5	>5
9 - 1000	1	0	0.00	0.00						
10 - 1100	8½	5	0.59	0.37	1	2				
11 - 1200	14¾	9	0.61	0.40	3	3				
12 - 1300	18	10	0.50	0.33	3	2	1			
13 - 1400	18½	53	2.86	0.38	2	3	1	0	0	1
14 - 1500	17¼	21	1.22	0.50	7	1	0	0	0	1
15 - 1600	16½	19	1.16	0.48	4	1	0	2	1	
16 - 1700	18	17	0.94	0.50	4	2	0	1	1	
17 - 1800	16½	5	0.30	0.30	5					
18 - 1900	13½	9	0.69	0.44	4	1	1			
19 - 2000	6½	5	0.77	0.61	3	1				
20 - 2100	2	1	0.50	0.50	1					
	151	154			38	1	3	3	2	2

NOTE: In the calculation of the observation times, a partially observed hourly period is counted at face value unless a rockfall was observed in which case, for probability considerations, the whole hour was included in the calculations. This explains the apparent discrepancies in the table.

of the rockfalls. The rockfall inventory in Surprise (and probably also in Gardner's study) was always incidental to the main projects being carried out on any particular day and when it seriously hampered the execution of these projects, it had to be curtailed; it is impossible, for example, to book rockfalls at the rate of two or three a minute whilst trying to carry out a theodolite survey. The influence of these periods of high frequency activity is shown by the hachured areas of Figure 4.2. It can be seen that they dominate the histograms creating peaks which are merely a function of the timing of the period of observation. This, admittedly, is a rather extreme example, due to the short observation period and the high intensity of the rockfalls, but it is a very good illustration of the effects which these factors, either singly or combined, may have on the "average day". The number and timing of observations on "high intensity" screes or "high intensity" days has a critical influence on the final averages.

An excellent example of this can be seen from the frequency of all mass movements on the average day in the Lake Louise area (Gardner, 1967, Figure 1). Since 63.4% of all the mass movements are snow avalanches and 62.3% of the avalanches were observed in four days (out of approximately sixty), 39.5% of the population consists of avalanches on those four days. Since this short period dominates the figures for the whole year, it is essential to realize the particular importance of the weather, site location and period of observations on each of these days and see whether they are similar to the rest of the observation period. It is quite possible, for example, that the distribution of rockfalls throughout the day is different on low intensity or high intensity days or that the high intensity is a response to a particular meteorological event and gives an atypical daily pattern of rockfalls (or avalanches).

The dominance of low frequency, high intensity events is further shown in Figure 4.3, which is a "magnitude-frequency" plot (where magnitude is equated with the number of occurrences). The number of rockfalls in each hour of the "controlled data" was extracted from the 1969 data for Surprise. These observations were then ranked and plotted as a cumulative frequency diagram in which the data are expressed as a percentage of the total number of rockfalls and the number of hours of observation. It can be seen that over 50% of the rockfalls occurred in less than 5% of the time and no rockfalls were observed for 71% of the hourly periods. In such highly skewed distributions, the average loses any real significance, since it is largely dependent upon the maximum value of the distribution, unless there are a large number of observations to offset it. Since the median value is always zero, it becomes very difficult to draw any reasonable conclusions about relative frequencies based on data of this type as it gives undue emphasis to the low frequency, high intensity events.

Rockfall Probability

An alternative way to express this data and overcome the problem would be to consider the variations in the probability of observing a rockfall at different times of the day. The probability of observing a rockfall during a particular hour can be empirically defined as $P(R) = \frac{N}{O}$, where N is the number of hourly periods during which a rockfall was observed and O is the total number of hours of observation. Frequency considerations may be introduced by redefining P as the probability of observing more than X rockfalls in a given hourly period. By expressing the data in this manner, a meaningful index may be defined to compare diurnal variation in rockfall intensity; the only major complication arises when the total period of observation is short. The data for the two individual sites were reworked in this fashion and are presented in Figure 4.4. Although the general form of the histograms is similar, considerable differences in the detail and relative height of the peaks can be seen; for example, the marked peak between 1300 and 1700 hours on Figure 4.2C is almost eliminated on Figure 4.4.

The comparison of these two sites leads to some interesting conclusions. Both sites were observed over much the same period of the day but show quite different patterns of activity. The obvious major contrast is the overall difference in activity between the two sites. Old Nip has relatively few rockfalls, mainly in the form of isolated pebblefalls, whereas Scree No. 1-Isosceles is much more active both in terms of the probability of rockfalls and also their frequency. These differences may be attributed to the basic characteristics of the cliffs; Old Nip is a massive vertical cliff and nearly all the observed falls were small secondary pebblefalls from the debris at the top of the cliff rather than primary falls. The cliff at the Scree No. 1-Isosceles site, on the other hand, is a dipslope with many small ledges and benches which would contribute many secondary falls. It is possible, however, that some of the observed differences are the result of the timing of the periods of work on the relative screes, since the cliffs could never be both observed at the same time and work on the screes was spread over two months during

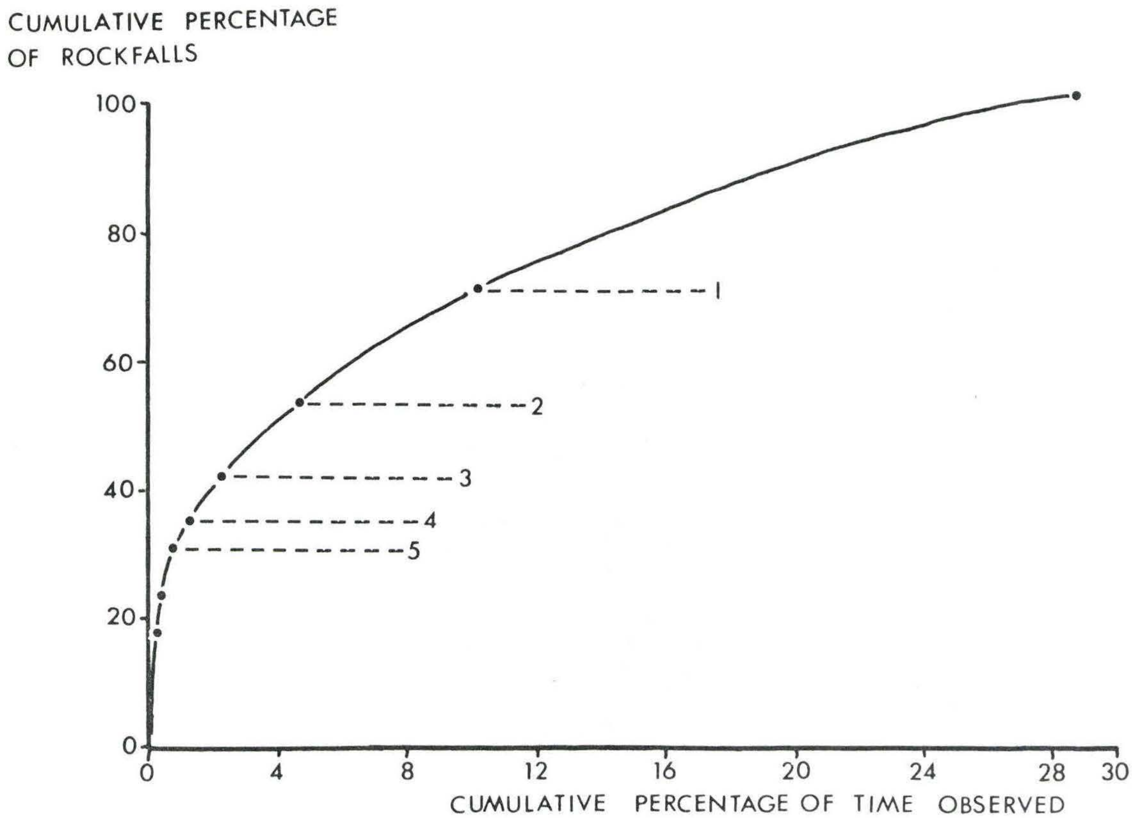


Figure 4.3 Cumulative frequency plot of observed rockfalls against hours observed

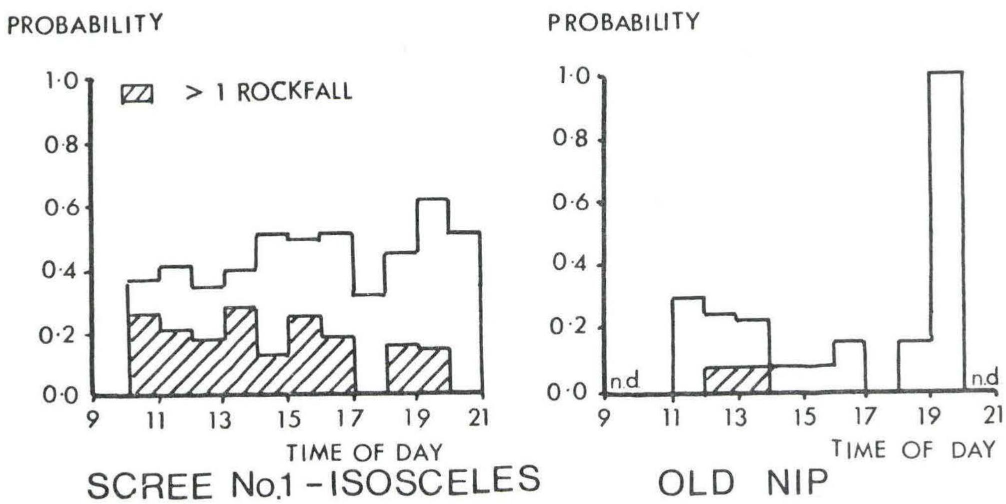


Figure 4.4 Probability of observing rockfalls in selected hourly intervals

which there were quite marked variations in rockfall activity.

Both sets of data were tested to see if the observed distribution of probabilities was statistically significantly different from a uniform distribution. This was done by expressing the calculated probabilities for each hour as percentages of their sum and testing this distribution against a distribution with equal percentages in each class using the chi-squared test. Only those time periods with more than five hours observation were used (1000-2000 for Scree No. 1, 1100-1900 for Old Nip). The results are shown in Table 4.3.

TABLE 4.3: RESULTS OF CHI-SQUARED TEST

Data	Chi-Squared	Degrees of Freedom	Significance
Old Nip	32.68	7	99% level
Scree No. 1-Isosceles (all rockfalls)	2.62	9	n.s.
Scree No. 1-Isosceles (> 1 rockfall)	20.11	9	95%

The results in Table 4.3 show that, for Scree No. 1-Isosceles, the hourly distribution of rockfalls is not significantly different from a uniform distribution and that the deviations from this pattern are probably random. The distribution of probabilities at Old Nip and for probabilities of observing more than one rockfall at Scree No. 1-Isosceles are both significantly different from a uniform distribution. Thus, for Scree No. 1 there is an almost uniform probability of observing rockfalls between 1000 and 2000 hours combined with a decreased probability of observing more than one rockfall as the day progresses. At Old Nip there is a marked peak in rockfall activity between 1100 and 1400 hours.

The reasons for these differences are not clear; obviously more information is needed, particularly for the period from dawn to 0900 which is a serious gap in the record. It is striking, however, that this activity coincides with the periods when the sun is on the cliff face, i.e. dawn to about 1400 at Old Nip, 0800 to 2100 at Scree No. 1. Any confirmation of a causal relationship between these observations would, however, need considerably more sophisticated observation techniques over a much longer period.

Gardner's observations (1967) show an early morning peak (0700-0900) outside the range of these observations and a broader peak between 1200 and 1600 hours which is more clearly defined than the observations at Scree No. 1. Since the general meaning of his data for the average day is questionable, it is pointless to compare the two sets of results in detail.

Conclusions

In summary, it is argued that the results given by Gardner for the Lake Louise area are difficult to assess and interpret, since they aggregate data from several sites and the use of average figures tends to lay undue emphasis on high intensity, low frequency events which may have a considerably different diurnal pattern than high frequency events. By restricting the data to one site and uniform observation conditions and by expressing the results in terms of the probability of occurrence, many of these difficulties may be avoided. Some of the data from Surprise in 1969 fits these requirements reasonably well and these results are discussed. However, they should only be seen as a pilot scheme, since a much longer period of observation is needed to counter the effects of short-term characteristics such as individual events triggered by storms.

Seasonal and Day-to-Day Fluctuations in Rockfall Activity

Figure 4.5 shows the distribution of rockfalls and avalanches in Surprise during 1969, together with basic meteorological data. Although these data are rather crude, they do permit some generalizations to be made about the seasonal variation in rockfall activity and the response to individual climatic events.

Climatic Data

The climatic data were recorded on the edge of the Rockpile at the northern end of Surprise I. Temperature observations were made on a daily thermograph sited on a boulder and covered with a white plastic sheet. This was anchored down with rocks in such a way as to allow the free circulation of air. The thermograph was calibrated using a minimum thermometer at the same location. Temperatures shown on Figure 4.5 are maxima and minima from the thermograph trace. The calibrations indicate these are 5 to 6 degrees too low, but if one allows a lapse rate of 2.5-3.0^{0}F/300 m (Gardner, 1968b), they correspond to temperatures in the cliff zone (i.e. about 2280 m). The hachured area of the graph corresponds to the freezing point at elevations between 300-600 m above the camp.

The rainfall data were recorded in a small copper raingauge close to the thermograph. The measurement period is usually from about 0830 to 0830 hours, i.e. the period 0830/12-0830/13 is shown as the rainfall for the 12th on the diagram.

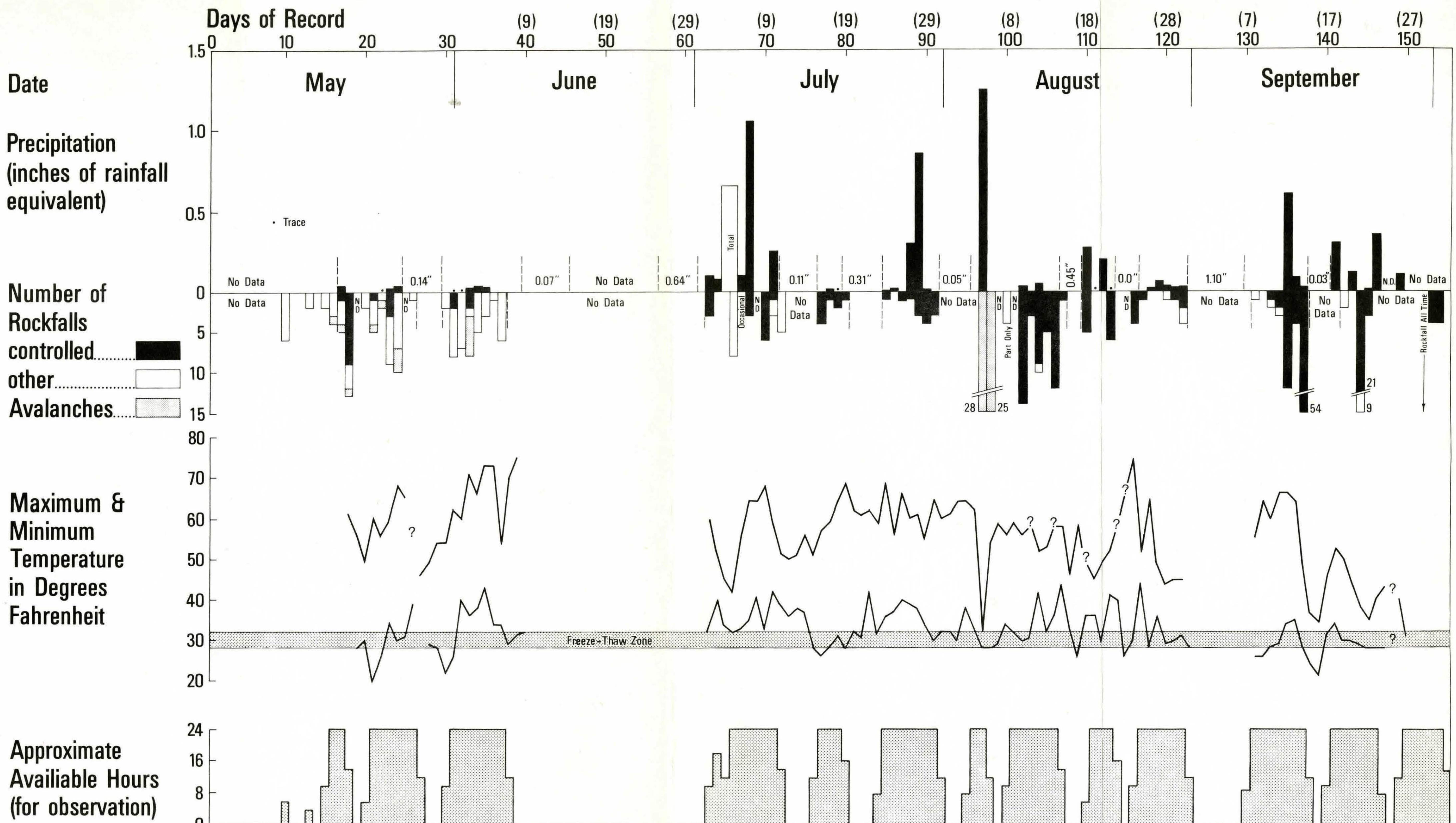


Figure 4.5: Relationships between Temperature, Precipitation and Rockfalls for the 1969 Season in Surprise Valley

These climatic data make no pretensions to any great accuracy. It is merely a comparative record to provide a crude guide to day-to-day variations within the valley. Variations in the local climate of alpine valleys are such that this record may differ considerably in detail from sites elsewhere in the valley when differences in aspect and the tracks of individual rainstorms are considered. For a proper evaluation of the control of climatic parameters, several micrometeorological stations would be needed at each site.

The Seasonal Pattern of Rockfall Activity in 1969

The field season may be divided up into several parts on the basis of the data in Figure 4.5. During the period 10th May-8th June, most of the research activity was concentrated in the lower part of the valley because of the snow conditions. This period represents the latter part of the spring thaw and a considerable amount of rockfall activity was observed. Since nearly all the rockfalls recorded are "general" observations, the data in Figure 4.5 are a very conservative estimate; the majority of the rockfalls were observed at distances of up to a mile away from the cliffs and therefore are medium to large in size. Many smaller rockfalls would not have been noted at that distance.

Apart from the rockfalls following the heavy rainstorms of the 4-5th and 8th July, the period from the 2nd July-4th August has relatively few rockfalls. A freak storm on August 5th deposited 13 inches of snow at camp and higher amounts elsewhere (21 inches at Maligne Lake, 3.63 inches of rain at Jasper). Large numbers of avalanches resulted from this storm, together with a considerable number of rockfalls, possibly including some of those in the high activity period which extends to the 14th. From the 18th August-11th September, conditions were similar to those before the storm and few rockfalls were observed. For about half this period, work was being carried out at Old Nip but similar low frequency observations were also made on Scree No. 1.

From the 12th September to 2nd October, the weather was much cooler and very cloudy with occasional rain or snow showers. Temperatures in the cliff zone probably went down below freezing every night and on three or four occasions the previous night's snow remained on the screes until 1000 or 1100 hours. During this period, the rockfall inventory was not complete although considerable rockfall was noted (see Figure 4.5). This renewed activity was probably due to the resumption of freezing temperatures at night and possibly snowmelt on the cliffs triggering rockfalls in the mornings.

From these data, the annual pattern for 1969 season may be generalized into a spring maximum and a smaller secondary maximum in the autumn. The majority of these rockfalls were probably released by freeze-thaw activity. Between these two periods is a period of much lower activity punctuated by short periods of higher frequency associated with major storms. Most of the rockfalls associated with this period were probably released by rainwater percolation or were secondary falls.

The detailed relationship of rockfalls to meteorological events is far from clear. From Table 4.4 it appears that the rockfalls are triggered by the shower on the 12th and yet a similar number of rockfalls occurred on the 14th when there was no rainfall. Given similar responses under different conditions (and different responses to the same conditions) at the same site suggests that either some random or unrecorded processes were operating or that the observation techniques were inadequate and more detailed information on climatic parameters and the character of the rockfalls is needed. Since the same process input may have differing importance in the initiation of primary and secondary rockfalls, it would seem that it would also be useful to try and ascertain the release mechanism more closely. However, observing the initial movement is impossible without a great deal of luck; most of the debris is small and it is difficult to pick it out as it descends. Most of the observed falls in 1969 appeared to be secondary falls, although many of the "general" observations could be primary falls.

TABLE 4.4: ROCKFALLS AT SCREE NO. 1 ON THE 12TH AUGUST 1969

Time	Comments
1200	Observations commenced
1430-1500	Shower (0.08" at camp)
1455	Multiple pebblefall (Scree No. 1)
1515	Multiple pebblefall (Isosceles)
1517	Pebblefall (Scree No. 1)
1520	Pebblefall (Scree No. 1)
1520	Single boulder (Scree No. 1)
1625-1630	Three small falls (Scree No. 1)
1645	Small pebblefall (Scree No. 1)
2000	Boulderfall (Scree No. 1)
2015	End of Observations

Thus, one is left with the conclusion that the available data are not good enough to be able to answer the kind of questions one would like to ask and only vague generalizations are possible. These appear to agree with the generalizations of other authors in several cases. The spring maximum and low activity during the summer were noted by Rapp and Stock at some of their sites. Rapp also records a secondary autumn maximum in some locations, although he suggests this might be connected with heavy rains. Gardner found a different pattern in each of the three years he studied with no general overall pattern and the variation between the sites given by Rapp and Stock also suggests that the pattern varies from site to site and from year to year. The major release mechanisms would appear to be freeze-thaw activity and the effects of heavy storms, the former mainly for primary falls, the latter for secondary falls. A great deal more work is obviously needed with a more rigorous experimental design to overcome the statistical problems as well as the obvious physical difficulties and dangers. It is hoped, however, that this review, although it has raised more problems than it has attempted to answer, might provide a basis for such studies in the future.

Magnitude and Frequency of Rockfalls

Rapid mass movements of rock may range in volume from a few cubic centimetres to several million cubic metres. Rockfalls form the lower part of this spectrum and can be differentiated from rockslides (Rapp, 1960a; Kent, 1966; Mudge, 1965) by their size and nature of movement. Nevertheless, there is a considerable range in the size of rockfalls and the relationship between their magnitude and frequency is an important part of their study, particularly when attempts are made to assess the significance of year to year variations in the quantity of deposition.

The problems of data acquisition are similar to those for inventory studies with the additional complication that a considerable time period is needed to assess the significance of various events. Unless it is possible to identify or isolate fallen debris, the volume of falls must be estimated visually. Aural observations do not allow accurate estimates of this type to be made because of factors such as echoing and variations in wind direction. Visual observations in Surprise suggest that the large majority of rockfalls are small (less than 1000 cc) and that rockfalls greater than 0.1 m^3 were rarely observed. The largest rockfalls noted in Surprise are shown in Table 4.5.

Table 4.5 is an incomplete account since falls could only be detected if they were seen or moved beyond the limits of the screes. The largest boulders measured in the accumulation survey (Chapter 8) were usually of the order of 0.02-0.04 m^3. It is not possible to obtain an estimate of the magnitude-frequency spectrum from these data since, with the exception of single large boulders, it is unjustified to assume that all the debris was deposited by rockfall. The range of boulder sizes involved in rockfalls might be obtained by a random sampling of the scree particles but this only measures the individual components of rockfalls and not the volume of the falls themselves which may involve any number of individual fragments. However, the information on grain size in Chapter 12 suggests that such distributions tend to be logarithmic and it seems reasonable to assume that the volume of rockfalls might follow a similar pattern.

TABLE 4.5: LARGE ROCKFALLS IN SURPRISE

Date	Est. Vol.(m^3)	Comments	Location
?	100-200	Distinctive white limestone debris spread over large area of scree	Strike Valley
1966-68?	25 (min.)	Large primary rockfall, several large blocks freshly bruised, and fresh bump holes	Old Nip
1969-70	10-15	Primary boulder fall from low cliff onto grassy slope, movement 15-20 m downslope	Tumblin' Creek (near stream)
1968-69	3 (min.)	Primary fall from Rundle cliffs (see Figure 8.6)	Surprise I
1968-69	3	Large boulder resting on the top of a felled tree in full leaf	Isosceles
Spring '71	2-3	Large fresh boulders	T.C. Cone
21.5.69	1-3	Large single block, observed from camp, not located, 1830 hours	Mámma Mt.
Spring 1972	1.5-2	Several large fresh blocks on the cone, largest seen 0.6 m^3	T.C. Cone
1.7.70	0.25	Fresh boulder on snow	Surprise II
9.6.70	0.12	Secondary fall from top of the cone	Tumblin' Creek

This is borne out by the observations of Rapp and Gardner (Table 4.6). Both authors indicate that the most significant volumetric contributions are from large boulder falls and that the frequently observed pebblefalls contribute only a small part of the total deposition. The size range of the rockfalls discussed by Rapp and Gardner are similar to those seen in Surprise, except that some of Rapp's observations are much larger in size. This could merely be a function of the longer period of observation.

TABLE 4.6: THE MAGNITUDE AND FREQUENCY OF ROCKFALLS

(a) Rapp (1960b)--assembled from the data in Chapter 4, pp. 97-117.

Type of Fall	Volume Per Annum	Frequency Per Annum (Nine-Year Average)
Larger boulder fall	35 m^3	1
Small boulder fall	10 m^3	6 - 7
Pebblefalls	5 m^3	not given

(b) Gardner (1969b)--assembled from Table IV, p. 19.

Magnitude Class	Total Volume (estimate) m^3	Frequency	Cumulative % Volume	Cumulative % Frequency
16.4(10^6-10^7)cm^3	30.2	1	40.6	0.02
" (10^5-10^6) "	20.8	5	68.6	1.47
" (10^4-10^5) "	16.9	22	92.4	5.38
" (10^3-10^4) "	5.2	76	98.4	25.43
" (10^2-10^3) "	1.0	154	99.7	63.08
" (10 -10^2) "	0.1	127	99.9	94.13
" (1 -10) "	$<$0.1	24	100.0	100.00

NOTE: These are two year's observations, the frequency minimum in the lowest class is thought to be due to observational errors.

As a general conclusion, it appears that the majority of the rockfalls noted in the field contribute only a small amount of debris to the scree. The most significant events are large (5-10m^3), usually primary, falls occurring with an undetermined frequency pattern which may well be clustered in favourable years, such as Kärkevagge in 1953 (Rapp, 1960b, Tables 14 and 15).

Rockfall Movement and "Fall Sorting"

The nature and characteristics of the downslope variations in size sorting of surface debris are one of the most frequently discussed attributes of scree slopes (e.g. Caine, 1967; Luckman, 1970; Gardner, 1968, 1971). It is therefore difficult to leave a discussion of rockfalls without briefly referring the movement of particles over the scree and the mechanism of "fall sorting".

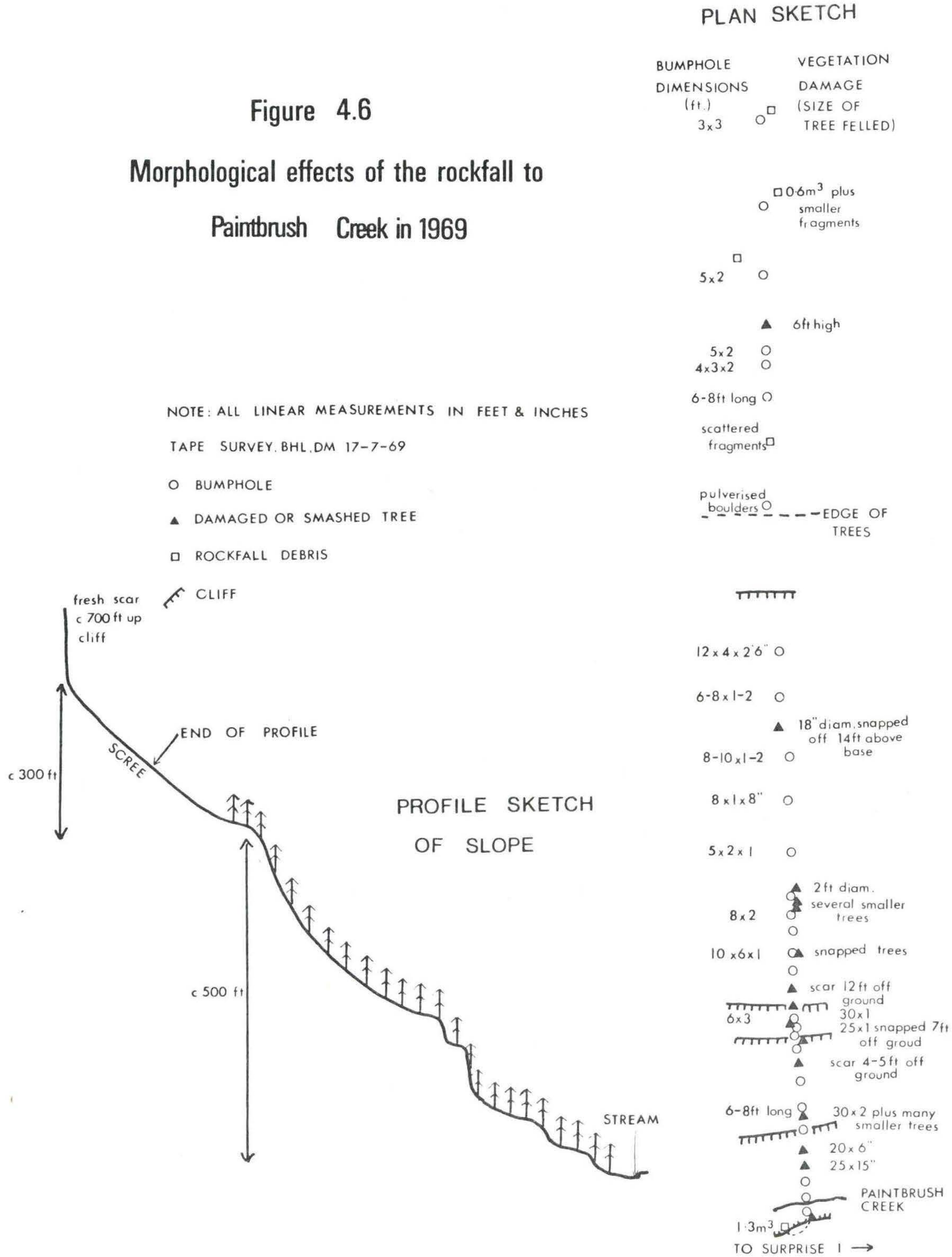
The movement of rockfalls may be studied theoretically or by observation. Large rockfalls are rarely observed in the field and therefore most of this information comes either from experimentation ("trundling" of boulders) or from the examination of "bump holes" or skid marks on snow covered or grassy slopes. Ritchie (1966) has photographed the movement of rocks down cliff and quarry faces and describes the effect of cliff form on rockfall movement. The depositional patterns and tracks of individual rockfalls are well illustrated by Rapp (1960a, Plate XVII(b), 1960b, pp. 98-100). Similar features may be seen throughout Surprise; for example, Figure 4.6 shows some of the results of a rockfall near Surprise I in 1969.

It is possible from such observations to build up an empirical knowledge of the way rockfall debris moves across a scree and eventually comes to rest. This information may be supplemented by theoretical considerations based on simple mechanics.

The momentum of a block falling down a cliff face is a product of its mass and its velocity. The velocity is a function of the height of fall, since it is determined by the acceleration due to gravity (it is also controlled by the shape and angle of slope of the cliff which

Figure 4.6

Morphological effects of the rockfall to Paintbrush Creek in 1969



affect the number of impacts, see Ritchie, 1966). The momentum of the block is therefore a function of its mass and the height of fall. If one assumes, for simplification, that the slope at the base of the cliff has uniform gradient and friction and that all rockfalls are from a similar height, the largest particles will travel the greatest distance because they have the greatest momentum. This simple fact is the basis of "fall sorting".

Once the block begins to move over the scree, the acceleration due to gravity decreases to a value which is proportional to the sine of the angle of slope and therefore the distance a boulder will travel is affected by the characteristics of the slope over which it is passing. The most important of these characteristics is the friction between the block and the slope surface. Since friction is a measure of the roughness of the surface, it is dependent upon the relative sizes of the boulder and the irregularities of the surface. If the boulder is much larger than these irregularities, the surface is relatively "smooth" and the boulder loses little momentum; if the relief of the surface is larger than the boulder, momentum is rapidly lost through repeated major impacts or the boulder lodges in a gap between boulders on the surface. Should the moving boulder strike the upslope face of a much larger object, it loses its forward momentum and comes to rest. In this way, the initial fall sorting pattern is perpetuated with boulders coming to rest when they land in areas of blocks of similar or greater size.

Having put forward this fairly simplistic model of size sorting on screes, it is possible to relax some of the assumptions and introduce some of the complexities of reality by varying factors such as the height of fall, the shape of the boulders, and the nature of the surface. Variations in the length of fall will affect the initial momentum of particles at the top of the scree. However, the importance of this would seem to be small when compared to the possible range of variations in mass. A boulder falling five metres in free fall hits the scree at a velocity of ten m/second, from 120 m it would arrive at 48 m/second. This kind of variation might lead to a small spread of debris of a certain size but when compared to differences in mass between particles, it does not seem to be of great importance except where the fall is exceptionally small, e.g. large blocks from the base of the cliffs remaining near the top of the scree.

Empirical observations suggest that the most efficient shape of block for movement down screes is an equidimensional one. The only exceptions are large tabular or square blocks which, if they land on their c axis, cartwheel down the slope in long straight or slightly curved paths. If such boulders do not land in an upright position or attain it after the first few impacts, they rapidly slide to a halt on their a/b face. Differences in shape or the chance orientation on impact can therefore lead to considerable differences in behaviour of boulders of similar mass or height of fall.

Spring and winter rockfalls may land on a scree with completely different frictional characteristics from its normal state. If the snow is deep, soft or wet, the boulder may remain where it lands (unless it triggers an avalanche) and is unlikely, when the snow melts, to move any great distance further down the scree. If the snow is hard-packed or refrozen, or remains at the top of the scree well into the summer, the boulders may slide or bound over its surface for a greater distance than they would normally. This mechanism has, for example, been proposed to account for the formation of protalus ramparts (see Andrews, 1961). In such conditions, shape may also play an important part in the different types of movement. Shapes which are conducive to sliding are often the most efficient (depending upon the snow conditions) and, to use the example of the tabular blocks again, the situations would be reversed, since those blocks landing on their a/b face would slide down the snow whilst blocks landing on edge would probably break through the snow crust and mire where they had landed.

From this simplified discussion, it can be seen that the factors controlling the nature and amount of size sorting of rockfalls on screes may vary widely, even on the same scree. For any individual rockfall, a number of random factors will determine where it will eventually come to rest on the scree below. However, from the fact that many screes do show some evidence of size sorting, it appears that these random factors act in such a way as to make it more probable that a particle of a given size will go a certain distance down the scree. Thus, the nature and clarity of size sorting may perhaps be used as an indication of the dominance of rockfall in building a particular scree or the amount of rockfall activity which occurs when the scree is snow covered.

CHAPTER 5

SNOW AVALANCHES

Snow avalanches[1] are rapid mass movements of snow which redistribute the snow cover on slopes. They vary considerably in size from small surface "sluffs" (U.S.D.A., 1968) of a few cubic metres to masses of several hundred thousand cubic metres of snow (Allix, 1924; Schaerer, 1967). In exceptional cases, much larger volumes may be involved. Denza (in Allix, 1924) describes an avalanche of over 3,000,000 m^3 in the Italian Alps and Maksimov (1965) refers to 6,400,000 m^3 of avalanche snow in the Padshaata Basin of Tien-Shan in February 1952. Because of the destructive power of avalanches and the hazards to life and property in alpine regions, there is a considerable literature on avalanche control, prediction and defence in areas such as the Alps, Japan, the U.S.S.R. and the U.S.A. A reasonable cross-section of this work may be seen in A.I.S.H. 1966, I.L.T.S. 1967, U.S.D.A. 1968, Mellor, 1968 and Hayes and Poppe, 1969.

However, except for incidental observations in these texts, there is comparatively little published material on the geomorphic role of avalanches. Apart from the early work of Allix (1924), the most important

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[1]The term 'avalanche', as it is used in this thesis, refers exclusively to snow avalanches unless otherwise qualified (see Rapp, 1960b, p. 125)

and comprehensive studies are those of Rapp (1957, 1958, 1959, 1960b) in which most of the earlier literature is summarized. More recently, several articles have appeared reporting similar observations from Bulgaria (Peev, 1966), New Zealand (Caine, 1969a) and North America (Gardner, 1968a, 1970a; Potter, 1968; Ryder, 1968; White, 1968; Luckman, 1971). Before considering the geomorphic results of avalanches, a general account will be given of their causes, character and frequency.

Types of Avalanches

Snow avalanches are a part of a continuum of rapid mass movements involving various combinations of water, snow and rock. Figure 5.1 shows a schematic classification of these movements adapted from Nobles (1966, Figure 4). The scales are ordinal and the subdivisions gradational. Slush avalanches are differentiated from snow avalanches and discussed separately in Chapter 6.

Snow avalanches may be classified in many ways, depending upon the specific characteristics chosen and the purpose of the classification. Movement characteristics, release mechanisms, potential hazard, water or debris content may all be bases for classification and several discussions of this type occur in A.I.S.H. 1966. A more general classification is given in U.S.D.A. 1968. The details of classification are not relevant to the present study and it is sufficient to note that avalanches may be composed of dry or wet snow, be "clean" or "dirty" (i.e. contain rock debris) and may travel in contact with the ground, over a snow surface or become airborne.

Causes of Avalanches

Avalanches result from the instability of the snow cover under conditions of loading. This failure may occur in several ways, the most common of which are:

(i) Heavy Snowfalls.--The addition of large amounts of new snow may cause instability in either the new or the old snow cover and release avalanches. Such "direct action" avalanches may be dry or wet, depending upon the characteristics of the snow, and are the most common avalanches in areas of heavy snowfall. The amount of precipitation needed to release avalanches of this type may be estimated for local conditions. Schaerer (1962c, Table V) and U.S.D.A. (1968, p. 34) suggest that a fall of over ten inches (25 cm) in 10-12 hours would produce avalanches in mountain areas. The presence and strength of wind and the amount of wind drifting are important additional factors in such calculations.

(ii) Structural Weaknesses in the Snowpack.--One of the most important controls of the stability of the snowpack is its stratigraphy. The snow cover is not uniform but composed of snow from several different storms which may have widely different characteristics or may be in various states of compaction and metamorphism. These differences, together with former surface crusts or poorly bonded layers (which may act as sliding surfaces) can produce potentially unstable states where the action of a suitable trigger causes a sudden failure of a large area of the snow surface. Typical triggers might include cornice falls, rockfalls or even a skier moving over the slope. The most dangerous of these "delayed action avalanches" is the slab avalanche which, as its name implies, involves the release of a large slab of surface snow which moves

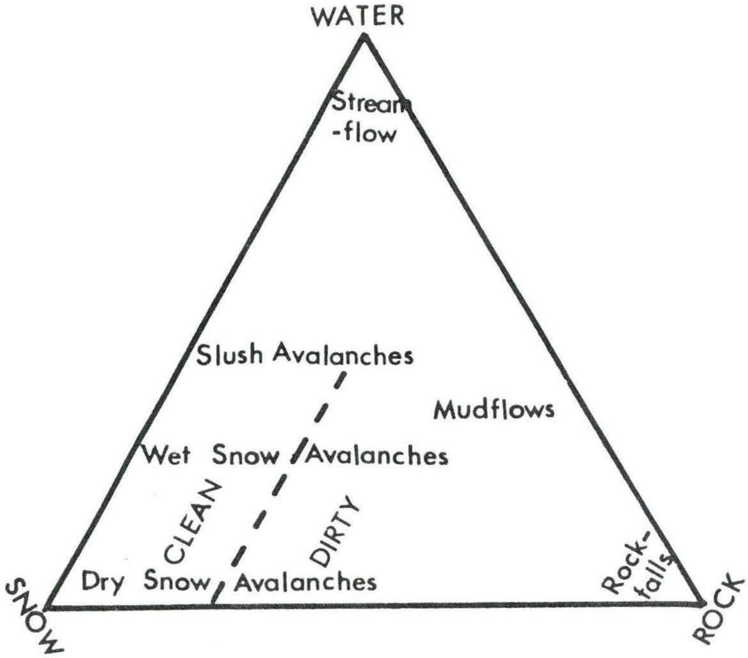

Figure 5.1 Schematic classification of rapid mass movements (after Nobles 1966,Figure 4)

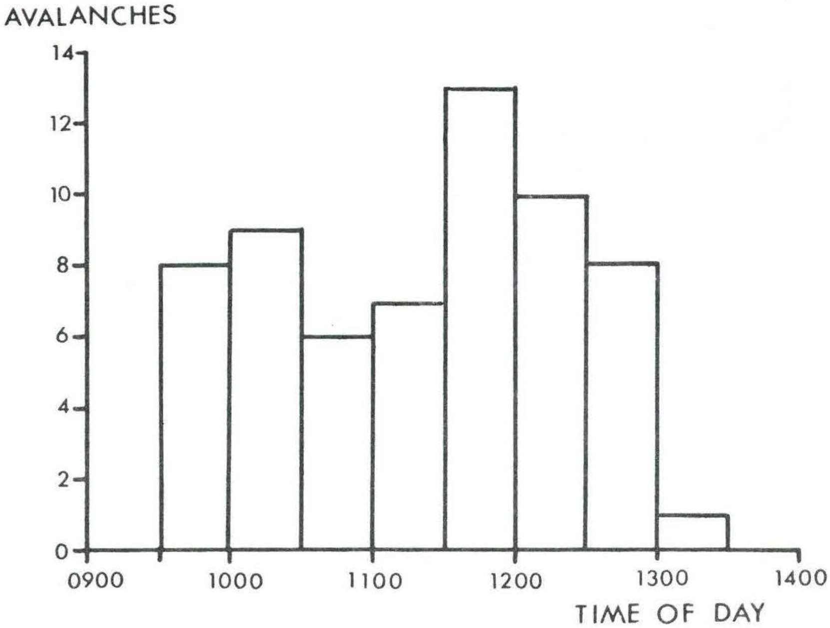

Figure 5.2 Avalanches at Surprise II, 0900–1304 hours,9th June 1968

downslope, breaking up into numerous smaller blocks.

(iii) Loss of Cohesion in the Snow Cover.--This is frequently caused by the percolation of meltwater and is the major cause of spring thaw avalanches. It may also occur during warm spells in the winter, especially when heavy rainstorms follow a fresh snowfall.

The avalanches affecting screes are usually due to (i) or (iii). However, slab avalanches can occur in the snow cover of the scree itself, although they are not very common. According to U.S.D.A., large avalanches most frequently originate on slopes between 25 and 60^{o} and "the common danger zone lies above 30-35^{o}" (1968, p. 29), i.e. above the surface slope of most screes.

Avalanche Frequency

The subject of avalanche frequency can be considered under three main subdivisions: diurnal, seasonal and annual variability.

(a) Diurnal Frequency

The diurnal frequency pattern depends upon the cause and type of the avalanche. Avalanches which are related to major storms or to other external triggering forces show patterns which are related to those forces. An example of this is the avalanches associated with the storm of August 5th 1969 in Surprise. The storm began as rain and changed to snow. At 0800 hours, there were three to four inches of snow on the ground and it continued to snow steadily until about 2200 hours. Avalanches were noted from Champagne Creek at the following times: 0900, 1210, 1215, 1335, 1500, 1615, 1745, 1747, 1755, 1810 (very large), 1813, 1827, 1830, 1833 and 1850. Another eight avalanches occurred before 2045 hours and there were numerous avalanches in the night. The following morning they were far less frequent; about six were observed between 0800 and 1200 hours, one of which was very large and over 100 m wide. More than 20 avalanches were observed on Scree No. 1-Isosceles on the trip out in about two hours (1200-1400 hours). The occurrence and increasing frequency of the observations from Champagne Creek clearly reflect the influence of the storm. Those at Isosceles on the following day were observed to be largely due to the melting of the snow and probably reflect a spring thaw type of pattern.

The frequency diagrams of Gardner (1967, 1968a, 1970a) are clearly also for spring thaw avalanches. They show a maximum in the middle of the day since they are indirectly controlled by the intensity of snowmelt and most of them would be in areas which are in the shade in the afternoon. These diagrams are open to similar objections to those raised in Chapter 4. Unfortunately, avalanches were not observed frequently enough to provide similar data for Surprise and the only observations of interest are those made during the first trip up valley in 1968. The weather was overcast and the thaw was well underway, although large amounts of snow were still lying in the upper valley. The large number of avalanches observed were a convincing demonstration of their importance (Figure 5.2).

(b) Seasonal Frequency

There are two main periods of avalanche activity. During the winter direct and delayed action avalanches predominate, the former strongly associated with storms. This tends to produce a pattern with isolated periods of intense activity, e.g. during the winter 1968-69 all the avalanches from the slope above the Medicine Lake road consisted of dry snow avalanches and were restricted to four days: 10th January (6), 11th January (7), 4th February (4) and one on 14th February (W. Pfister, private communication, 1969). The distribution of spring thaw avalanches is controlled by the characteristics of the spring thaw, although a few avalanches may be released later in the season from remnant, high level snowpatches. This pattern is well shown in the Lake Louise data (Gardner, 1970a, Figure 1).

(c) Annual Variability

There is considerable variation in the magnitude and frequency of avalanches from year to year which can be clearly seen in Gardner's data (1968a, Figures 33 and 34) and is also apparent from the observations in Surprise (see Chapter 9). Since avalanches are responses to certain combinations or sequences of meteorological events, or to the occurrence of events of a certain intensity, it is difficult to estimate avalanche activity from any particular parameter. The most obvious parameter is total snowfall but available results are conflicting. Loup and Lovie (1967, see Figure 5.3) found no relationship between the number of avalanches and the total snowfall in Tarentaise. In fact, the worst year on record (1903-04, 101 avalanches) had only 431 mm of precipitation. In contrast, Judson (1967, p. 1155) reports that 80% of the avalanches affecting Colorado's highways occur during storms and the data from Rogers Pass (Figure 5.4) also suggest a strong relationship between the volume of snowfall and the number of avalanches. From these examples, it can be seen that the relationship between snowfall and avalanche activity

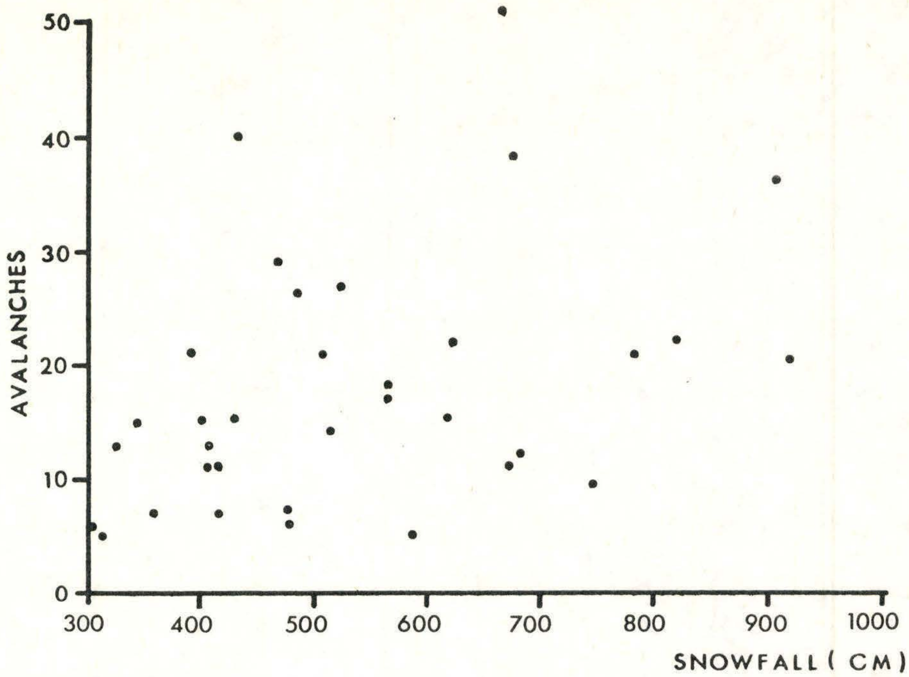

Figure 5.3 Relationship of snowfall to the number of avalanches in "Haute Tarentaise" 1921/22–1964/65 (from Loup and Lovie 1967,Table 5)

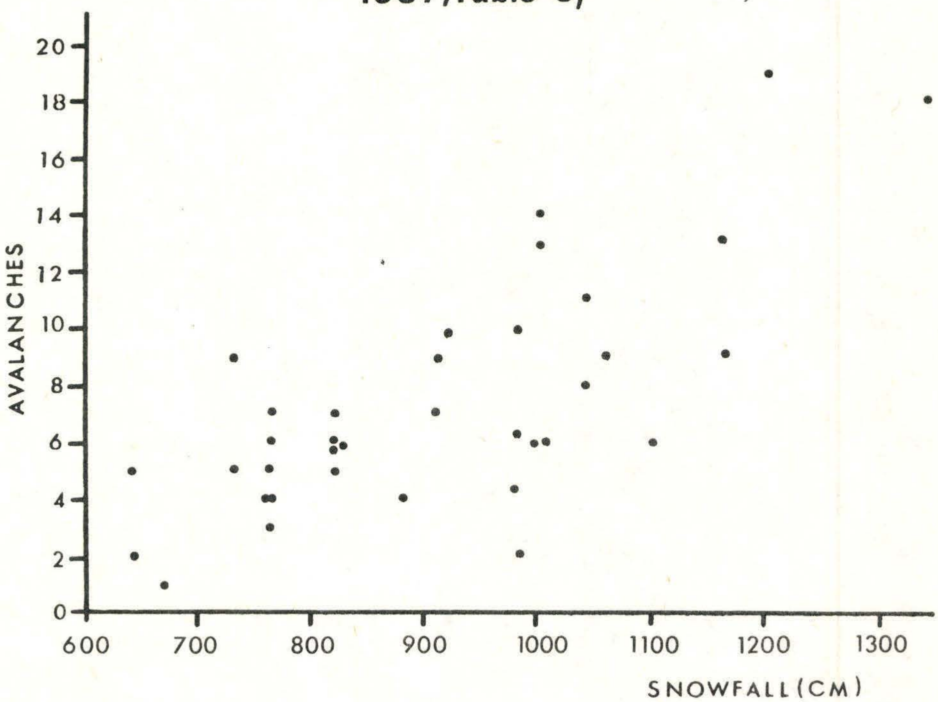

Figure 5.4 Relationship of snowfall to the number of avalanches at Rogers Pass 1955/56–1959/60(data from Schaerer 1967,Table 1)

is a very variable one; it is of little use when the majority of avalanches are "delayed action" or spring thaw types. The number and size of avalanches is therefore a reflection of the total pattern of the winter and spring conditions and the characteristics of the individual sites.

Several authors have presented data showing the variation of avalanche activity over a long period of time (30 to 50 years). From their data, Kahn (1966) and Toushinsky (1966) suggest that the variations in avalanche activity may be associated with variations in solar activity. Loup and Lovie (1967) divide the variations into two thirty-year cycles whilst Schaerer (1962c) noted three peaks in the activity in Rogers Pass from 1909-1960 but does not comment on any periodicity.

It is obvious that there is great variation in avalanche activity from year to year at the same site and that there is probably some type of magnitude-frequency spectrum to this activity. However, apart from observations of the kind made by Schaerer based largely on meteorological considerations (Schaerer, 1962c), there is no readily available data on which to make generalizations of this kind.

THE CONTROLS OF GEOMORPHIC ACTIVITY BY AVALANCHES

The avalanches which accomplish significant geomorphic activity are only a limited subset of all avalanches; most avalanches merely redistribute the snow cover without coming into contact with the underlying surface. There are four major factors which limit the effects of avalanches.

(i) Vegetation Cover.--The presence of a vegetation mat tends to protect the underlying surface from erosion by avalanches. Although trees may be bent, broken or uprooted, the low vegetation cover remains unbroken and no evidence of turf stripping by avalanches similar to that described by Warwick from Norway (in Robinson, 1971) has been seen in Surprise.

(ii) The Nature of the Surface.--The optimum conditions for surface modification by avalanches are where loose, unconsolidated debris mantles the slope. This is shown by published observations (Rapp, 1959, Potter, 1968, Gardner, 1970a) and results from Surprise (see Chapters 8 and 14). An abundant supply of debris leads to the creation of distinctive accumulation forms such as the avalanche boulder tongues described by Rapp (1959). Where little debris is available, the only morphological evidence of avalanching may be a diffuse scatter of boulders in the lower part of the avalanche track. Steep bedrock slopes only contribute significant amounts of debris to avalanches when there are numerous ledges or couloirs (gullies) where weathered debris can collect.

(iii) Snow Cover.--Avalanche erosion on debris covered slopes is also controlled by the type and character of the slope's snow cover at the time of avalanching. Erosion can only occur where the lower slope is bare of snow or where the avalanche incorporates the whole depth of the surface snow cover. Thus, the occurrence of spring thaw avalanches from the cliffs after the lower slope has ablated or been denuded of snow and avalanches (wet snow or slab) which slide at the base of the snowpack may be particularly important in influencing the role of avalanches at a particular site.

(iv) Magnitude-Frequency Characteristics.--Certain threshold conditions have to be overcome before an avalanche occurs and these conditions vary for different sites and combinations of events. Thus, some sites produce avalanches more frequently than others. The geomorphic work performed by an avalanche is not necessarily proportional to its size; although there is a tendency for larger avalanches to produce a greater amount of disturbance, the controls listed under (i) to (iii) may be of equal or greater importance. The amount of work done may, however, be related inversely to the frequency of avalanches in any particular track. For example, a gully which is swept by avalanches every year will only yield a small amount of debris, whereas an avalanche of the same size in a track which "runs" only once every five or ten years may do far more work simply because there is more available material. It is therefore very difficult to draw conclusions about variations in the geomorphic activity of avalanches from year to year from a consideration of the magnitude-frequency spectrum of avalanche activity.

From these considerations, it is apparent that the geomorphic role of avalanches is mainly restricted to certain favourable conditions which most commonly occur in areas of scree or other unconsolidated deposits. It is therefore surprising that the role of avalanching in the evolution of screes was largely ignored before the studies of Rapp (1959, 1960b). This work, together with more recent contributions by Peev (1966), Potter (1968), Gardner (1968a, 1970a), Caine (1969a) and Luckman (1971), forms the basis of the discussion of the geomorphic activity of snow avalanches which concludes this chapter. A large part of this discussion will refer to avalanche activity related to screes and provides the background to the discussion of the data to be presented in Chapter 8.

THE GEOMORPHIC RESULTS OF AVALANCHE ACTIVITY

(A) Erosional Activity

This may be subdivided into three parts according to the nature of the surface over which the avalanche passes.

(a) Cliffs and Other Bedrock Slopes

One of the most striking features created by avalanche activity is the dissection of mountain walls by narrow parallel or funnel shaped gullies known as "couloirs d'avalanche" (Allix, 1924) or "avalanche chutes" (Matthes, 1938; Rapp, 1959). The rounded "U" shaped cross profile of these forms cannot be attributed to stream erosion (streams are rarely present in such features) and they are thought to be produced by long continued, concentrated, avalanche erosion. Allix (1924) first recognized these features in the Alps and they were described from North America by Matthes (1938) in the Sierra Nevada. More recently, the problem has been discussed by Rapp (1959, 1960) and Markgren (1964) in Scandinavia, whilst Davis (1961) and Peev (1966) have described examples from California and Bulgaria. Poorly developed chutes occur high in the cliffs at Surprise II but the best examples in Surprise occur near the exit of the Tumblin' Creek Valley. The cliffs from Champagne Creek across to Big Bend Mountain have several well developed chutes with small cones at their base, whilst the site at Tumblin' Creek itself is fed by a well marked chute above the Pekisko cliff (see Figure 8.33).

The mechanism of formation of these features is not known but it is thought that abrasion by the basal debris in the avalanche (see Peev, 1966, p. 362) with possibly some plucking of debris from the gully walls

(Allix, 1924, p. 545) are the main types of mechanical action involved. Probably the most important factor, however, is the constant sweeping away of the weathered debris which continually exposes fresh rock to the weathering processes.

As these chutes continue to develop, they may become occupied by intermittent or permanent streams. However, even when streams do occupy these valleys much of the removal of debris from their valleys is done by avalanches rather than floods. This point is clearly made by Veyret (1960, p. 17; also, see Rapp, 1961) and could be supported from observations in the Rockies; many of the cones at the mouths of these "torrential streams" are the result of avalanche transport of debris.

(b) Scree Slopes

As well as eroding and transporting debris from rockwall chutes and gullies in the cliff (Peev, 1966, p. 360), avalanches may carry out considerable erosional activity on the scree itself. Both Rapp (1960b) and Gardner (1970a) cite examples of the incorporation of scree material into the basal portions of wet avalanches and observations in Surprise suggest that wholesale quarrying of the scree surface may occur (Chapter 8). This erosion may lead to the stripping of the coarser surface debris from the higher parts of the slope (see Chapters 8 and 13) and Rapp refers to examples where such erosion has lowered the upper limit of the scree re-exposing parts of the rockwall (Rapp, 1960b, p. 136). Rapp (1960b) and Potter (1968) both observe that the larger boulders on avalanche modified slopes are swept to the base of the scree or form a diffuse cordon marking the limit of avalanche activity on the slope.

Several authors (Allix, 1924, p. 545; Morawetz, 1933 (quoted in Rapp, 1960, p. 130); Peev, 1966 and Akif'eva and Kravtsova, 1967, p. 58) refer to grooves or channels with parallel embankments which were cut into screes by avalanche activity. Similar features do occur in the upper parts of several screes in Surprise but they appear to be due to fluvial or mudflow activity rather than avalanche erosion (see Chapter 6).

The overall effects of continued localized avalanche erosion on a scree involve a considerable modification of its form, either by the denudation of the upper part or, if it is a cone, the distinctive flattening of the cross-profile. These features, coupled with the characteristic depositional forms discussed below, produce a number of distinctive landforms which Rapp (1959) has called avalanche boulder tongues.

(c) Other Slopes

Occasionally, avalanches may modify or create landforms beyond the limits of the scree or on the other loose rock slopes. For example, White (1971, Figure 7) shows the erosion of the surface of a rock glacier by avalanching. Several distinctive landforms created by avalanche erosion have been described by Peev (1966) from Bulgaria. He quotes examples of avalanches eroding alluvium and stream bed material, later depositing it as mounds on the other side of the valley. Repeated avalanche impact may excavate "avalanche pits" in soft materials. Similar "avalanche scour pits" have also been described from the Sierra Nevada (Davis, 1961) although they are smaller than Peev's examples. Where the avalanches cross valleys, they may carry out erosion on the opposite slope of the valley and even break down rock cliffs (Peev, 1966, p. 361).

(B) Depositional Activity

The erosional action and transport capabilities of avalanches are most clearly demonstrated by the volume of rock material contained in avalanche snow. Large numbers of the spring avalanches are "dirty" and estimates may be made of the volume of debris in individual avalanches (Rapp, 1960b; Gardner, 1970a). Considerable amounts of material may be involved; Mougin (in Allix, 1924) measured avalanche deposition in Savoy from 1907/08 to 1911/12 and estimated that 43,340 m^3 of material was carried by the avalanches of which 23,079 m^3 occurred in 1909/10 and over 2000 m^3 was found in one avalanche. Of this total, 79% was carried by "ground avalanches" and another 19% by ice avalanches (see Chapter 6). Jäckli (1957) estimated that 250,000 m^3 of debris was transported annually by avalanches in the Upper Rhine Valley. This figure is derived from calculations of the mean size of avalanche debris and the area over which avalanches act. It may be rather high, since it is over ten times as large as the maximum figure for Savoy and, when converted to tons per square metre per year (9,000, Leopold, Wolman and Miller, 1963, p. 92), is several orders of magnitude greater than the comparable figure for Kärkevagge (15.4, Rapp, 1960, Table 32).

The deposition of debris by avalanches leads to the surface modification of existing features or the creation of new landforms. The extent of this modification depends upon the volume of material carried by the avalanches, their frequency, the areal concentration of avalanche activity, the characteristics of the depositional zone and the relative importance of other processes in the depositional area. Avalanche deposition mantles the surface with an irregular cover of loose, angular, poorly sorted debris. This may be merely a few fragments scattered on top of the vegetation or an almost continuous cover. On screes where avalanche deposition is widespread, the depositional zone is characterized by similar deposits and such areas may be recognized by their heterogeneity, poor sorting and a loose, unstable surface with many "balanced" or "perched" boulders (Rapp, 1960b; Gardner, 1970a; also, see Chapters 7, 8 and 14).

Continued localized deposition leads to the production of avalanche cones or avalanche modified landforms. The larger and more complex of these features have been termed "avalanche boulder tongues" by Rapp (1959). These are tongues or fans of accumulated debris swept downslope by avalanches. They were first recognized in Lappland but, more recently, similar forms have been described from the American Cordillera (Potter, 1968; Gardner, 1970a; Luckman, 1971). These features are often developed from modified scree slopes by the building out of the lower part of the slope by avalanche deposition. Rapp distinguished two main types of tongue, "roadbank tongues" and "fan tongues", which were differentiated by their form and degree of development. These forms and associated features are discussed in Chapter 15.

Both Jäckli (1957) and Peev (1966) consider that protalus ramparts ("lawinenmoranen", literally avalanche moraines, in Jäckli) may be produced by avalanche deposition at the base of the scree. Although avalanches may contribute debris to such features, it does not appear that they could produce a more or less linear landform which runs across the slope because, although their depositional pattern is generally linear or lobate, it usually extends down the slope. Therefore, unless avalanche movement is limited by a transverse ridge across the slope which causes deposition on its upslope side, it is difficult to explain protalus ramparts in this way.

(C) Indirect Effects of Avalanche Activity

The annual redistribution of snow by avalanches does have important hydrological and glaciological implications. Avalanches are one of the major contributors of snow (and in some cases rock debris) to corrie glaciers and some glaciers may be almost exclusively fed in this manner. Also, since snow avalanche deposits are considerably denser than normal snow, they take a much longer time to melt and may last until the following year. Exceptionally large avalanche deposits of this type may produce temporary lakes (Allix, 1924) and contribute to serious flooding (Tricart et al., 1961). The redistribution of snow and delay in melting may therefore have important effects on the hydrological characteristics of mountain catchments.

The most striking visual effects of avalanche activity are on the vegetation cover. In areas below the treeline, the forest may be dissected by avalanche swaths where most of the larger trees have been demolished and the area has been recolonized by "avalanche brush". Major trimlines may be formed by catastrophic avalanches and dated by dendrochronology (Potter, 1968). In tracks where avalanching is frequent, tree growth may be inhibited and, in some cases, it is possible to estimate avalanche activity from the vegetational characteristics of the tracks (see Kozhevnikov, 1967, p. 88; Schaerer, 1972). Avalanche tracks with varying degrees of recolonization are a common feature of the wooded lower slopes in Surprise (see Figures 2.2, 2.4 and 8.1). The only geomorphic effects of such slides are related to the hydrological effects of the avalanche snow and the occasional uprooted tree, although a few avalanche transported boulders may occur amongst the deposits of twigs, branches and smashed trees in the lower part of the track.

CONCLUSION

Snow avalanches are not as widespread as rockfalls and their activity tends to be limited to certain areas because of climatic conditions or the characteristics of individual sites. However, in these limited areas, they can become the dominant factor in the development of scree slopes. When snow avalanches come into contact with loose debris they may erode, transport and redeposit considerable amounts of material. Snow avalanches may therefore play two basic roles with regard to scree slope development. They act as an input process, sweeping debris from the cliff to the scree and modifying cliff form, and as the most effective "queueing" process on the scree itself, carrying out considerable erosion and transferring the surface debris downslope. Concentrated activity of the latter type leads to the production of avalanche boulder tongues (Rapp, 1959; Potter, 1968). It must be emphasized, however, that snow avalanche activity is often strongly localized and of variable intensity so that there is a wide range of possible modifications of which avalanche boulder tongues are only the extreme form.

CHAPTER 6

OTHER MAJOR PROCESSES AFFECTING SCREE SLOPE DEVELOPMENT

Snow avalanches and rockfalls are the dominant processes in the evolution of scree slopes in Surprise at the present time. There are, however, several other processes which occur to a lesser extent and may be locally important in scree slope development. These processes will be discussed within this chapter following the framework outlined in Chapter 3.

INPUT PROCESSES

(a) Slush Avalanches

Slush avalanches involve "the mudflowlike flowage of water-saturated snow along stream courses" (Washburn and Goldthwaite, 1958, p. 1657). They occur during rapid spring thaws on sloping glacier surfaces (Nobles, 1966) or are associated with the breakup of streams (Washburn and Goldthwaite, 1958; Rapp, 1960b). Because of their high water content, they may be initiated on slopes of $10\text{-}15^{o}$ and move over slopes with gradients of less than 2^{o} (Nobles, 1966). Both Nobles (1966) and Washburn and Goldthwaite (1958) indicate that they may transport considerable amounts of debris and Rapp (1960b) describes several individual avalanches from Lappland which carried over 200 m^3 of debris. He also considers that "they (slush avalanches) have had the greatest geomorphic capacity of all avalanche types in Kärkevagge and probably also in Lappland and the Scandes as a whole" (Rapp, 1960, p. 147).

The examples quoted by these authors suggest that slush avalanching usually occurs where there is some impermeable substrate (usually ice) or impediment to drainage which causes the ponding of meltwater within the snow, turning it into slush. This ultimately fails either when the water begins to seep out of the snow as springs (see Nobles, 1966, pp. 268-69) or when the impediment is removed, the latter often producing a sudden catastrophic flood of water, snow, ice, slush and rock (see descriptions in Rapp, 1960b, pp. 138-145).

Such conditions are rarely found in cliffs, steep gullies or on screes because of their steep slopes and the tendency for meltwaters to drain away fairly easily. Possibly some of the wet snow avalanches from the shale gullies at Surprise II may be of this type (see Chapter 8) but it is difficult to ascertain this from the deposits on the screes. It is also possible that the largest avalanche seen in Surprise was a slush avalanche. It began in the Cougar Creek corrie where an ice dam at the lip could impound a considerable volume of wet snow before bursting. The avalanche swept across the Palliser Bench, destroying mature trees in a 100 m wide swath which extended almost to the main valley floor.

From his work in New Zealand, Caine (1969a) suggests that slush avalanches are important agents in the redistribution of the snow cover and its included rockfall debris over screes during the spring thaw. However, further explanation of this process suggests it is not common in Surprise. Referring to conditions in the Colorado Rockies, he says "...I...don't find anything at all like the New Zealand situation.... The New Zealand avalanches...were "true" slush avalanches, i.e. wet snow and meltwater starting high on the talus,or, more usually, in scree-floored gullies in the cliffs above" (Caine, private communication, 29th May, 1969). Small slushflows of this type with a maximum length of 1-2 m have only been observed on the Tumblin' Creek Cone, where meltwater was flowing through the snow cover on an ice carapace at the apex of the cone (see Chapter 8). This resulted in small downslope displacements of one or two rock fragments. Slush levees (Nobles, 1966) have been observed by the author on alluvial and scree cones along the Banff-Jasper Highway in 1968 and at Moraine Lake in 1970. No trace of these features has been seen in Surprise.

(b) Icefalls

These involve the free fall of ice masses down the cliff face, usually from hanging glaciers, and their frequency characteristics in the Lake Louise District have been discussed by Gardner (1967, 1968a). Their geomorphic work is accomplished by "plucking" debris from the rock face or by impact effects. Exceptionally large avalanches of this type may be very destructive; the initial Huascarán ice avalanche carried over 13,000,000 m^3 of ice and rock (Morales, 1966) and the recent disaster was several times larger (Welsh and Kinzl, 1970).

There are no suitable hanging glaciers to act as sources for such falls onto the screes in Surprise, although small "ice-block falls" (Rapp, 1960b, pp. 109-110) have been observed during the spring breakup of frozen waterfalls at Tumblin' Creek and Surprise II. These may "pluck" or dislodge material on the face or as they roll down the scree but the volume of material involved in such movements is small.

(c) Fluvial Activity and Mudflows

These are not very important input processes in Surprise. Small amounts of debris may be transported or dislodged by streams occupying the gullies in the cliffs above Surprise II and small mudflows have been observed on the apex of the Tumblin' Creek Cone. The maximum dimensions of these features were 5-10 m long and 0.5-1.0 m wide and they carried mainly soil debris from the benches flanking the throat of the cone.

(d) Rockslides

The division between large rockfalls and small rockslides is an arbitrary one, although it involves considerations of movement characteristics as well as size (see Chapter 2). Several scree-like forms have been produced by a single event of this type, e.g. the small "rockslide tongue" (Rapp, 1959, p. 35) of Palliser Limestone on the east side of the ridge at Surprise II (Figure 2.2). Parts of the screes along the Mississippian cliffs have an important rockslide component but none of the sites examined in detail have detectable falls of this type.

"QUEUEING" PROCESSES

The movement of debris on or over the scree surface is a complex phenomenon involving many interrelated processes. Several attempts have been made to measure the total movement of surface debris, often termed "debris shift" (Gardner, 1969c), by placing lines of markers, stakes or painted stones on the scree and recording their displacement. One of the earliest studies of this type was carried out by Michaud (1950) in the French Alps and later reported on by Pissart (1964). Similar studies have been carried out by Rapp (1960b, 1962), Barnett (1966), Wallace (1967) and Gardner (1968a, 1969c) on screes and by Smith (1960) and Caine (1963) on clitter[1] slopes.

The detailed data presented by Rapp, Barnett, Wallace and Gardner show considerable variation in the amount of movement between stones at individual sites and between sites. No attempt is made to distinguish different types of movement and observed values range from no movement, the most common case, to 70 m in two years (Gardner, 1969c). Both Rapp and Gardner note that the movement is greater on the higher parts of the scree.

Observations and Measurements in Surprise

General Comments

During August, 1968, experimental sites were marked out on several slopes to investigate debris movement and rock breakdown. These sites consisted of spray painted lines on the ground surface, lines of marked stones or stakes and painted squares on rock faces or rock debris. The sites were located on the Entrance Screes, Palliser Cone, Eastern Valley Side, Surprise II, Strike Valley and in the Columbine Creek gorge. Most of the sites were photographed after they were set up and several were rephotographed in May or June, 1969. Although the results demonstrated considerable activity in several cases, the project was abandoned in 1969 because of problems of measurement and experimental design. However, several interesting qualitative observations may be made using the results of these experiments.

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[1]The term 'clitter' refers to "loose rock fragments whose angle of repose is determined by that of the underlying materials" (Tinkler, 1966, p. 379), i.e. a thin veneer of debris over a bedrock or soil covered slope.

The painted lines were set up on a variety of surfaces and slope types ranging from bare gully sides to scree and clitter slopes. Even in 1971, after three years, the lines painted on the coarse scree (greater than 20-30 cm median diameter) remained intact apart from a few isolated stones which had moved on to or just below the line. However, where fine material was at or close to the surface, the lines had disintegrated or were considerably distorted. The only exception to this generalization was the line on coarse debris at Surprise II which was destroyed by avalanche erosion (see Chapter 8).

Experiments with Lines of Painted Stones

Experiments were set up at three sites to examine the movement pattern and to see whether debris placed on the surface moved differently than the undisturbed surface. At each site between 25 and 50 of the larger surface fragments were collected, painted white and replaced, evenly spaced, along a spray painted line (red or yellow) on the slope surface and subsequent displacements measured.

Results

(i) Strike Valley.--This site was laid out on a veneer of shale debris 20-30 cm thick above bedrock. The slope angle varied between 29 and 32^{o} and in places poorly developed stone stripes occurred. When the site was revisited on 10th August, 1968, 15 days after it was set, several of the white stones had already moved a small distance from the line (Table 6.1). During that period, 2.5 inches of rain had fallen at Surprise 1½ in a series of heavy storms and, since a small length of line was also displaced, it is probable that some genuine movement occurred due to the excess moisture as well as movement due to the initial instability of the stones.

TABLE 6.1: MOVEMENT OF MARKED STONES AT STRIKE VALLEY BETWEEN JULY 26th AND AUGUST 10th, 1968

Movement	No. of Stones
No movement	28
0.5	7
0.75	1
1.0	5
1.5	4
2.0	1
2.5	1
	47

NOTE: All the measurements were made in inches.

When the site was revisited the following spring (Figure 6.1), the line had been destroyed but its original position could be reconstructed by portions remaining on large boulders embedded in the slope. The spread of the debris from the line appeared to be more or less inversely proportional to the size of the underlying debris and some of the periodicity apparent in Figure 6.1 may be attributed to the stone stripes.

(ii) Columbine Creek.--Two lines were set up on August 9th, 1968, on a slope of loose, very mobile shale and mudstone fragments 30-60 cm thick, resting on bedrock. The slope angle was not measured but is probably close to the angle of rest. The fragments are dominantly narrow, triangular slivers or plates similar to the material at Isosceles

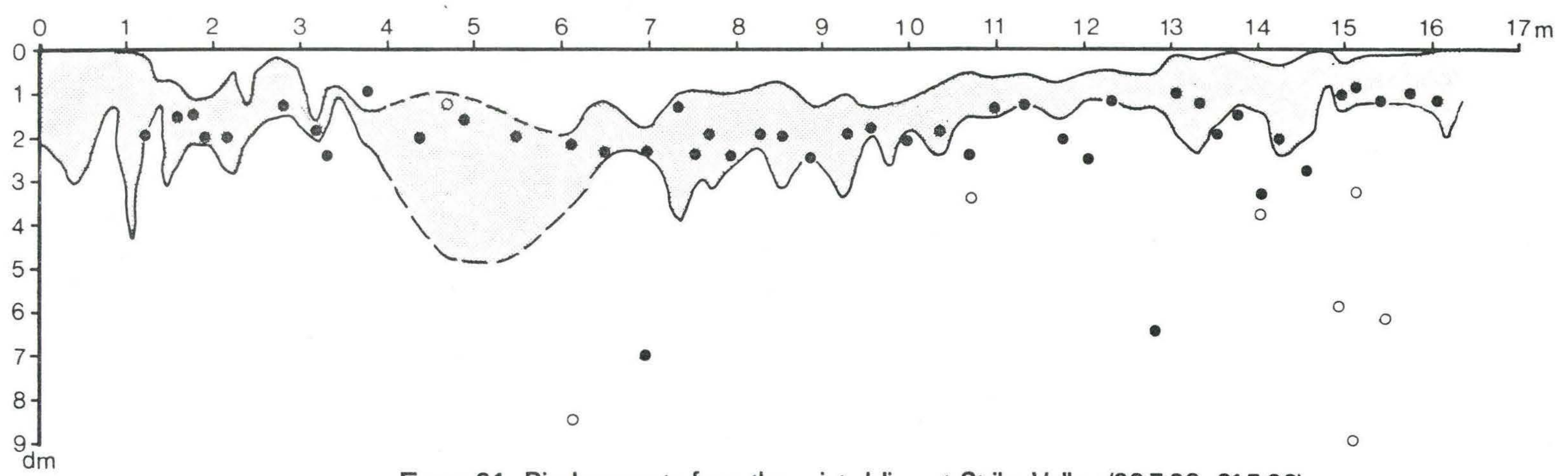

Figure 6.1 Displacements from the painted line at Strike Valley (26.7.68–31.5.69)

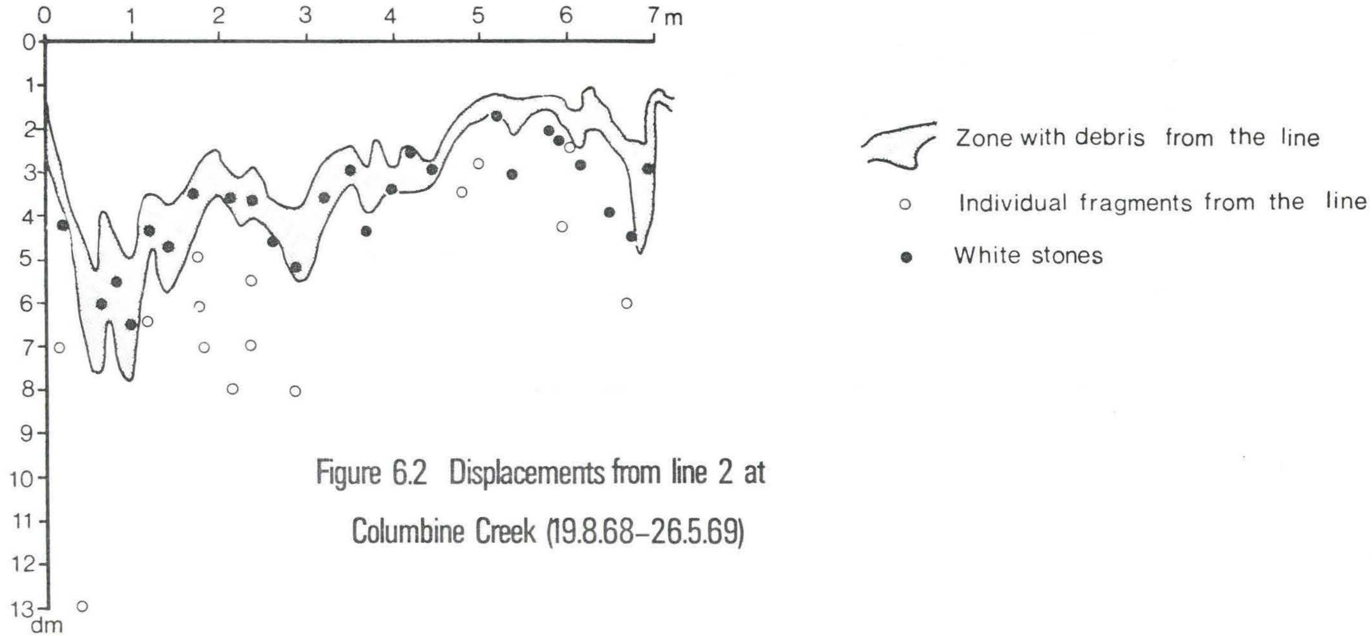

Figure 6.2 Displacements from line 2 at Columbine Creek (19.8.68–26.5.69)

(Chapter 11). When the site was revisited in 1969, the lines had disintegrated and fragments were scattered over the slope below the original line. The shaded area of Figure 6.2 gives a general impression of the area over which debris was spread from one line. The furthest travelled fragments recovered are individually shown. Most of the white boulders, like those at Strike Valley, stayed within the scatter of debris from the line.

(iii) Eastern Valley Side.--This line was set up across a 29° slope between sample sites 137 and 138 of the accumulation project (see Chapter 8). In the first two years, the line remained almost intact, although several large slabs moved onto it and a number of boulders were displaced downslope (Table 6.2). Despite the coarse nature of the debris at this site, relatively large amounts of movement were observed in comparison with other sites. This may be ascribed to the extremely platy nature of the debris which slides very easily.

TABLE 6.2: MOVEMENT OF STONES FROM THE LINE ON THE EASTERN VALLEY SIDE SCREE, 10 AUGUST 1968 to 21 AUGUST 1971

Movement (cm)	0	0-10	10-100	100-1000	1000+	Not located
10 August 1968 to 24 May 1969	30	4	3	-	1	1
18 July 1970	28	3	3	-	-	5
21 August 1971	8	Not measured--maximum displacement 70-80 m				

In 1971, the line was destroyed by avalanche erosion and the boulders were scattered up to 70-80 m downslope (see Chapter 8). Only two short sections of the line (with their boulders) remained at the edge of the track.

Conclusions

Although these results cannot provide accurate quantitative data, they do indicate considerable surface debris shift at some sites. Apart from sites with avalanche erosion, the amount of activity is strongly linked to areas of clitter or bare slopes where there are fines (less than 2-3 mm) and in such cases the major processes are similar to those found on other vegetation free slopes in the periglacial realm. The coarser materials appear to be relatively stable over the short period of observations, unless acted upon by some outside force such as rockfalls, avalanches or goats.

The other point which arises from these observations is the complexity of movement patterns; there is considerable micro-scale variation in the amount of movement between adjacent stones and the larger fragments may behave differently than the surface on which they rest. This complexity arises from the aggregated measurement of movement from many different processes without differentiating them or establishing their relative importance. Therefore, this discussion of queueing processes will conclude with a review of the major processes involved in debris shift and the factors which govern their activity.

Major Queueing Processes

(a) Talus Creep

Talus creep is analogous to soil creep and involves the slow downslope movement of particles under the influence of gravity. Where fine materials occur close to the scree surface, true soil creep may occur since the fines can retain the moisture necessary for freeze-thaw and wetting and drying cycles which are the major causes of displacement in soil creep (Blong, 1966; Selby, 1966; Kirkby, 1967). Where only coarse material is present, neither of these processes can operate and thermal expansion is the most probable cause of downslope displacement. Although this process has been demonstrated theoretically (Scheidegger, 1961; Matveev, 1964), available measurements of movement are not sensitive enough to differentiate such creep from other forms of debris shift. The lack of movement of coarse debris observed in Surprise and on the lower parts of other screes (Rapp, 1960b; Gardner, 1969c) suggests that talus creep is not as important as has been suggested in the past, except where water-holding materials are present. In such cases, the shape of the fragments is an important contributary factor to the amount of movement (see Schumm, 1964) and the results from Surprise indicate that plates or blades are the most suitable shapes for movement, although the nature of any imbrication pattern may also be important (see Miner, 1934; Andrews, 1961).

It is also possible that surface creep may occur as a result of movements within the scree. Many screes have fines at depth and, although freeze-thaw and wetting and drying cycles will be less frequent than at the surface, displacements at this depth may be transmitted through the overlying materials and contribute to surface movement. However, more detailed experimental work and observations are needed to demonstrate this process and to establish the true nature and importance of talus creep.

(b) Rockfall Impact

As boulders roll, slide or bounce over the slope, they excavate "bumpholes" in fine debris or dislodge surface debris which may roll or slide downslope. Once dislodged from a stable position such debris may travel a considerable distance before coming to rest. Such isolated extreme displacements or small gaps in sample lines due to rockfall impact are common in observations of debris shift (e.g. Barnett, 1966).

Another important effect of rockfall impact is as a packing process. During the impact, some part of the momentum of the moving particle is transferred to the underlying materials, resulting in small readjustments of their relative positions. Over a long time period, such readjustments may lead to a crude vertical size sorting of the debris by a "sieving" effect, since there is an obvious tendency for smaller particles to move downwards through the voids leaving the coarser debris closer to the surface. This sorting pattern has been observed on the higher parts of several screes in Surprise and is discussed further in Chapter 13.

(c) Settlement and Compaction

Scree is an unconsolidated, often rapidly accumulating, sediment and, as it becomes thicker, there will be internal readjustments which tend to reduce the number of voids. These readjustments may be the result of rockfall impacts or be loading phenomena causing small scale collapses which trigger shallow slides (see below). The only observation of settlement of this type has been made by Rapp (1960b, pp. 171-172) on the uppermost part of a very rapidly accumulating cone. The importance of such processes in the long-term development of screes is not known.

(d) Surface Slides

Shallow dry surface slides occur on screes when continuing deposition builds up the surface slope to an angle greater than the angle of internal friction of the material. Small slides of this type can frequently be seen on the tailings of gravel pits and have been noted by Fisher (1952) and Andrews (1961) on screes. Behre (1938) has described surface slides associated with rainfall which are probably associated with the presence of fines close to the surface of the scree.

The most comprehensive account of dry slides is by Rapp (1960a). Using old photographs, he was able to identify 12 slides on the cones at Templefjorden in the period 1882-1954. Rapp estimates that they contain "an average of at most 75 m^3 of material (width, 5 m; length, 30 m; depth, 0.5)" (1960a, p.77) and considers that they are the most important agent of debris shift on these slopes, moving materials from the upper to the middle and lower parts of the cones. More recently, Allen (1970) has developed a theoretical model of "avalanching"[2] on dune slopes which he considers can be applied to screes, quoting Rapp's data as an example. Both authors suggested that these slides are instantaneous deformations producing a low tongue-like deposit. This hypothesis is partially confirmed by Bones' observation of such a slide, set in motion by a major rockfall (Bones, 1971, p. 75). Bones also describes several other examples of "debris slide tongues" and concludes that all had a rockfall trigger (1971, pp. 75-80). However, it is quite possible that

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[2]Allen uses the term 'avalanching' to refer to loose surface slides of surface material and not in the sense it is used throughout this thesis.

spontaneous movement could produce small slides on rapidly accumulating cones as Rapp and Allen imply. From Rapp's observations, such slides are of medium to low frequency in Spitzbergen, i.e. one every 10-50 years, but obviously the magnitude-frequency spectrum would vary widely between sites, depending upon supply conditions, available triggers and the influence of other queueing processes.

A few small tracks and scars of this type have been observed on the higher parts of some of the cones at Surprise II, although they are not very common. This may reflect the dominance of other queueing processes at the rapidly accumulating sites where such slides might be anticipated. Rapp considered that slides only occurred on slopes greater than 34^{0}, whilst slopes dominated by other queueing processes generally have lower angles (Rapp, 1960a, Table V) which would prevent the development of slides.

(e) Fluvial and Mudflow Activity

Fluvial activity is not usually associated with screes and yet gullies and mudflow tongues can be clearly seen on many scree slopes, e.g. Potter, 1968, Plate 4; Thornes, 1971, Figure 4; Luckman, 1971, Figure 11. White (1968) and Rapp and Fairbridge (1968) distinguish a special type of "alluvial talus" produced by materials washed down after heavy storms or by mudflows. On coarse screes, rapid percolation prevents any concentrated runoff but where fines are present at, or close to, the surface, gullies or mudflows may be initiated by heavy rainfalls. Avalanche dominated screes may show this type of development where avalanche erosion has removed the loose, coarse material from the surface of the upper slopes exposing a zone with interstitial fines (see discussions of Old Nip in Chapters 8 and 13).

The gullies seen on screes in Surprise are usually fed by drainage lines coming down the cliff face. Many of the smaller gullies die out a short distance from the cliff and are probably the result of annual snowmelt or storm runoff patterns. Larger, isolated gullies extend considerable distances down the scree and are often flanked by levees in their lower parts (e.g. Figure 10.7). Such channels appear to be fossil forms resulting from mudflows or gullying associated with rare, very high intensity storms such as the one in Kärkevagge in October 1959 (Rapp, 1960b, Figure 54). The fact that Rapp considers the geomorphic effects of that storm to have a recurrence interval of the order of 100-1000 years (1960b, p. 185) and together with the identification of only one new mudflow on the screes in Templefjorden from 1882-1954 (Rapp, 1960a, p. 73) suggests an infrequent catastrophic origin for these features. The examples examined in Surprise appear to be inactive, since their floors are often choked by loose rockfall or avalanche debris. Most seem to have been created by single events, although they could have been later reoccupied and extended, as were Rapp's examples (1960b, Figure 54).

Although there is little surface flow, many screes have a considerable throughput of water below their surfaces. Rainfall and streams from the cliffs reappear as springs or lines of seepage at the base of the scree; in the lower parts of Scree No. 1 and the Strike Valley Screes apparently considerable streams can be heard some distance below the surface. Recently, Bones (1972) has published initial observations on flow through times and patterns for several screes underlain by permafrost.

However, at present, there is no published material available to indicate the amounts of material which may be transported in solution or suspension by such streams. In limestone screes, like most of those in Surprise, this may be one of the most important transfers of debris within the scree.

(f) Small Scale Processes Associated with Fine Material

The alpine environment is one where, given suitable materials, frost action is a dominant factor in the development of the landscape. Therefore, where fine materials occur at or close to the surface of the scree, many of the "periglacial" slope processes may be found because of the water holding capacity of the material and its volume changes associated with freeze-thaw cycles. Malaurie (1960) has described solifluction from screes in Greenland and, although this has not been observed in Surprise, active stone stripes occur on the Palliser Cone (see Figure 13.9) and at elevations of less than 6,000 feet at Tumblin' Creek. Similarly, frost heaving of stones and frost creep (Washburn, 1967) probably also occur. In these respects, therefore, screes are no different from other slopes in Surprise, except that the area suitable to such activity is limited mainly to the upper parts of the cones where fines occur.

(g) Snow Table Gliding

During the ablation of avalanche snow on the scree slopes, large boulders within the deposit may protect the underlying snow from ablation, resulting in the formation of boulder capped snow pedestals (e.g. Rapp, 1960b, Figures 33 and 34; Theakstone, 1966, Figure 3; Luckman, 1971, Figure 4; and Figure 8.33). Eventually, the capping becomes unstable and rolls or slides off and may continue to move downslope. The distance travelled depends upon the size and shape of the boulder, the angle of slope and the snow conditions; Rapp has described displacements of up to 100 m by this process (Rapp, 1960b, p. 131).

(h) Illuviation and Sheetwash

Fines deposited on the surface by avalanches are rapidly washed into cracks, depressions in the boulder surfaces or voids by heavy rain. This process has been frequently noted during the collection of the accumulation data (Chapters 7 and 8), although it does not involve great quantities of material; most of the debris removed in this way is less than one cubic centimetre in size. This material accumulates at depth within the scree, although some of it may be carried away by percolating groundwater.

(i) Avalanches

On many of the screes in Surprise, avalanches are the dominant queueing process. The results of this activity are discussed fully in Chapters 5, 8 and 9.

OUTPUT PROCESSES

The majority of these processes are associated with input or queueing processes which carry materials beyond the confines of the scree, e.g. rockfalls, avalanches, etc. Other dominant output processes involve the basal removal by fluvial, marine or glacial action. Since these do not occur at the sites studied in Surprise to any notable extent, these processes are not discussed in detail here. Examples of the characteristics of screes which are dominated by output processes may be found in Thornes (1971) and Bones (1971).

CONCLUSION

The processes discussed in this chapter tend to be either infrequent catastrophic events of considerable geomorphic significance or imperceptibly slow, continuous or possibly annual movements for which little quantitative data are available. Many of them are also restricted to limited areas of the scree where the surface character and slope conditions are favourable. In most cases, this means that they are insignificant or only of very local importance (i.e. a part of one particular scree). Where fine material is present, a wide variety of processes may operate and scree slopes are, for all intents and purposes, similar to other bare slopes in alpine environments; where the surface material is coarse, very little contemporary activity appears to be going on, apart from that associated with rockfalls and avalanches.

CHAPTER 7

THE COLLECTION OF ACCUMULATION DATA

The observation of large volumes of rock debris on snow covered screes in Surprise during June and July, 1968, indicated that considerable deposition had taken place in the previous winter. It also suggested that reasonable estimates of the amount and pattern of deposition on scree slopes might be obtained, even over a short time period, by the measurement of the accumulation of debris on marked surfaces spread over the scree. In August, 1968, a number of sites were set up in Surprise to measure accumulation on seven screes using polyethelene squares and cleaned boulder surfaces. In 1969, additions were made to the sampling network at four sites as a result of the first year's experience. Debris accumulation was measured annually on all sites from 1969-1972.

Several other authors have attempted to measure debris accretion on screes using inventory methods for discrete events or accumulation on marked surfaces. Such surfaces include squares of sacking (Rapp, 1960b; Gardner, 1970b) or canvas (Czeppe, 1970); strips of wire netting (Rapp, 1960b), tarpaulin (Stock, 1968) or creosoted fish netting (Gray, 1972); inventories of debris on snow (Jäckli, 1957; Rapp, 1960b; Gardner, 1968a, 1970a; Stock, 1968; Caine, 1969a; Gray, 1972); trays (O'Loughlin, private communication, 1969) and wooden boxes with netting floors (Prior et al., 1971). Iverona (1964, 1969) has also made "comprehensive measurements" of debris accumulation but no details of the techniques used are given.

Most of the data collected by the above methods refer to isolated events or only involve a small number of sites. The most comprehensive data are that of Rapp (1960b), covering an eight-year period, and Gray (1971, 1972).

Both the techniques and the layout of sample sites used in Surprise were experimental. The main aim was to see whether the boulders and squares would yield reasonable results and the original sample designs were confined to transects or profiles of particular screes to give some indication of the character, extent and magnitude of deposition.

Techniques Used for the Measurement of Debris Accumulation

Sample Boulders

One of the basic characteristics of areas of avalanche deposition is the presence of numerous small fragments perched or balanced on larger boulders on the lower parts of the scree (see Chapter 14). Several large boulders on the slopes examined were completely covered with such avalanche debris, stimulating the idea to use such sites for the measurement of debris accumulation. The boulders selected as sample sites (hereinafter termed sample boulders or sample sites) were relatively large with respect to the adjacent scree, had a smooth or easily cleaned surface without obvious "in situ" breakdown and a major face inclined at less than 20-30^{o}. Nearly all the sampled boulder surfaces stood above the general surface of the scree to avoid the effects of creep. The boulder was carefully swept clean with a hearthbrush and numbered using coloured spray paint.

Most of the sampled boulders used were between 0.1 and 0.75 m^2 in area, although the range and size distribution varies from scree to scree (Table 7.1). The size distribution of sampled areas is generally log-normal in form (Figure 7.1) reflecting the size characteristics of the scree as a whole (see Chapter 12).

Sample Squares

The network of sample boulders was supplemented by polyethelene sheets 1.5 m (five feet) square. Polyethelene was chosen because it was readily available, cheap, light and durable and could be easily packed, carried and cut to the requisite size. The new squares set up in 1969 and 1970 used 4 ml thickness polyethelene since it was tougher than the 2 ml thickness originally used. By 1970, several of the 1968 squares had begun to perish along the original folds of the thinner polyethelene. The squares were anchored in position by a continuous border of cleaned boulders (henceforth referred to as marker boulders) from the adjacent scree which were identified with a blob of coloured spray paint. In 1969, small troughs were made at the downslope edge of the squares to prevent the fine material being washed from the square.

Inventory Methods

Inventories of debris on snow were occasionally used to estimate the volume of individual avalanches or maximum concentrations of debris. Although this is the most obvious form of measurement, considerable practical difficulties occur. The large area to be covered by sampling, great variations in the size and concentration of debris, as well as the need to be in the field at the correct stage of the melt season, all

TABLE 7.1: CUMULATIVE PERCENTAGE DATA FOR THE AREA OF SAMPLE BOULDER SITES

Percentage of Boulders Smaller Than

Area (m^2)	E.V.S.	Ent.	Old Nip A-X	Old Nip 1-32	Pall.	S.V.	S.II	T.C.	Total
0.1	1.5	8.3	29.2	3.2	2.4	0.0	8.1	5.6	5.5
0.2	29.3	36.0	75.0	19.3	24.4	4.9	31.4	37.1	29.2
0.3	52.4	44.5	83.4	32.2	49.6	9.8	48.3	55.8	49.2
0.4	74.4	61.2	83.4	41.8	71.6	22.9	60.4	69.2	64.2
0.5	83.3	69.6	87.6	64.5	78.8	41.0	72.8	77.3	74.4
0.75	94.3	83.7	95.9	77.1	91.4	52.5	83.4	90.8	86.5
1.0	97.9	89.1	100.0	80.5	95.4	73.8	90.8	95.2	92.5
1.5	99.3	97.2		90.4	98.6	91.9	96.0	97.2	96.8
2.0	99.3	100.0		93.6	99.2	98.4	98.4	99.6	98.9
2.5	100.0			96.8	99.2	98.4	99.6	99.7	99.5
3.5				96.8	100.0	100.0	100.0	99.7	99.8
4.5				96.8				100.0	99.9
5.0				100.0					100.0
No. of Sites	137	36	24	31	125	61	261	321	996

NOTE: E.V.S. = Eastern Valley Side; Ent. = Entrance Screes; Pall. = Palliser; S.V. = Strike Valley, S.II = Surprise II; T.C. = Tumblin' Creek.

For the complete data, see Appendix 3.

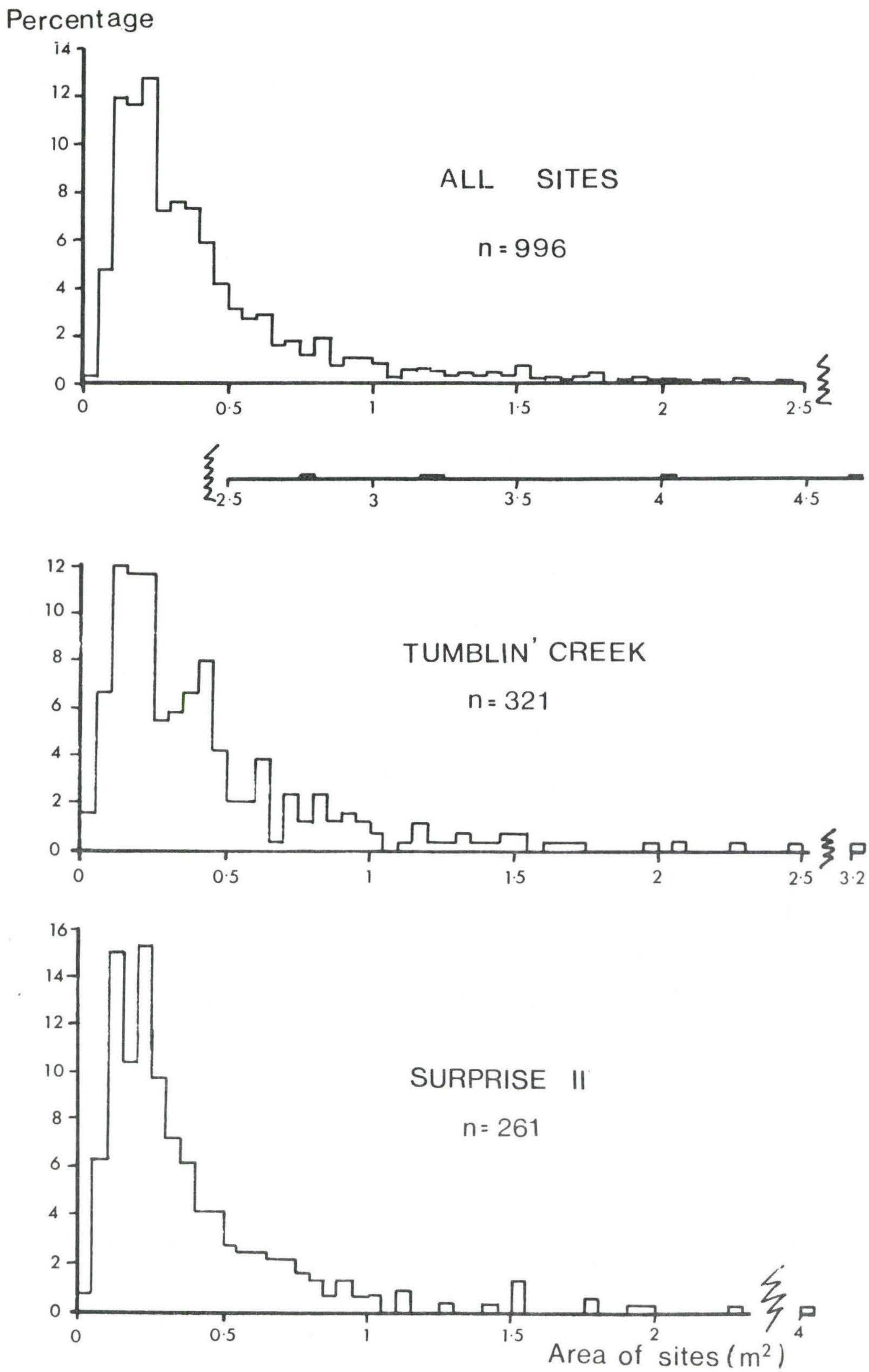

Figure 7.1 Area of sample boulder sites in Surprise

make sampling rather difficult. Sampling has to be done on a two dimensional basis and, since the rock debris is distributed throughout the snow, a true estimate of volume cannot be made until the snow has almost disappeared. In such cases, it was difficult to differentiate between the avalanche debris and the underlying scree because basal regelation of the snowpack may lock both layers into one solid mass of ice. Some attempts were made to sample selected areas or volumes of snow to extract debris but the need to melt large amounts of snow made it a very messy procedure and a lot of the fines were lost.

The great advantage of sampling on snow is that the sample network may be chosen after the event, considerably reducing the number of samples needed and enabling purposeful sampling of, for example, individual avalanches to determine their characteristics. The sample network of squares and boulders must be laid out before the winter season. Since avalanches and rockfalls have an extremely irregular distribution, both in space and in time, this necessitates a very large number of sites. The probability of having sites which actually collect rockfall or avalanche debris is therefore a function of their number, position, the amount of that activity, and a considerable element of chance.

In 1968, lines of sample boulders and squares were laid out along the base of scree slopes or in profiles up them. Seventy-two squares and 730 boulders were set in 1968[1] and 46 squares and 299 boulder sites were

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[1]The number of boulder sites given in this thesis differs from those given in Luckman, 1971, Table 1. After the 1969 season, the numbering system of the sites was rationalized and groups of boulders with the same number were treated as one site rather than several, hence the smaller number of sites.

added to the network in 1969.

Data Collection

The sites were revisited annually from 1969 to 1972. Triaxial measurements were made of the coarser debris and converted to volumes using the empirical relationships discussed in Appendix 2. In 1969, the finer material ("a" axis less than 30 mm) was collected and its volume estimated by immersion in water. In subsequent years, the volume of these smaller fragments was estimated in the field.

The debris recovered from the sample sites ranged from fine silt to a boulder of 1.03 m^3, from single fragments to layers of debris up to 10 cm thick (see Figures 9.1 and 9.2). The fine material (less than 10 mm) may be washed off the site by the first major rainstorm after it ablates from the snow. Losses of this kind rarely amount to more than 1-2 cc and are not therefore quantitatively important but samples of this material are necessary to obtain an accurate picture of the true size range of avalanche material.

A more important problem is the loss of larger particles which roll off the sample boulders. Freshly ablated debris adheres to the rock surface, probably due to a binding layer of fines; particles of over 10 cc have been observed clinging to near vertical faces in this manner. However, with subsequent rewetting, this debris eventually falls off or only remains on the more gently inclined surfaces. Thus, these accumulation measurements must really be considered as minimum figures unless measurement of debris can take place as the sample site is ablating from the snow.

At the other extreme, measurement problems occasionally arose where large freshly bruised or broken rock fragments rested against (or slightly overlapped) the surface of the sample boulders. If the fragment rested on the cleaned surface at any point, it was considered to be "on" the sample boulder. Fresh debris resting against such a fragment but not covering a part of the sample boulder was excluded. This is a thorny problem since large rock fragments which do not ablate squarely onto the sample boulder tend to roll off its surface to assume a more stable position, usually resting partially against the surface of the sample boulder. During the collection periods in 1969 and 1970, particular care was taken to remove possibly ambiguous fragments of this kind or to mark them with a blob of paint.

THE STATISTICAL MANIPULATION OF THE DATA

One of the basic problems in the evaluation of the accumulation data from sample boulders is that the sites are not identical. Variations in the amounts of deposition due to differences in the shape, slope and roughness of the sampled surface are assumed to be negligible except in certain cases where the sites were rejected from the sampling network (see Table 9). The major difference between the sites is their size.

The surface area of the sampled boulders ranges from extremes of 0.04 to 4.6 m^2 (Appendix 3). It is necessary to correct for such differences to compare the accumulation on different sites and the nature of that correction depends upon the characteristics of the population sampled. The distribution of rock debris throughout the snow may be envisaged as one of two basic patterns.

(a) A Point Pattern.--Deposition occurs as a series of point located events, as is the case with single rockfall boulders. In this case, the volume of accumulation is independent of the area sampled, except that an increase in the size of the sample site increases the probability of deposition. However, since the initial probability for any site is very small, this difference may be ignored.

Given a distribution of this type, any adjustment of the raw accumulation data in accordance with the size of the sampled area could produce anomalous results. For example, if the deposition consisted of randomly scattered particles of equal size, the "corrected" accumulation values would merely reflect the variation in size of the sample sites. Thus, if the smaller sites were higher on the slope, the results would apparently show that deposition was greatest on the upper parts of the slope.

(b) An Areal Pattern.--Deposition occurs either uniformly or within areal units which are distributed in some manner over the slope. In this case, the volume of accumulation on a boulder surface is a function of boulder size plus the mean density and local variability of deposition within that areal unit. This type of distribution is typical of snow avalanche deposition, the "areal units" corresponding to individual avalanches. In this case, if the volume of accumulation is not corrected for boulder area, a similar example to that discussed in (a) above would show an apparent increase in the amount of deposition downslope.

The accumulation patterns recorded by the sample sites contain components of both distributions. Near the top of the scree, many small rockfalls may give a pattern closer to (b) than (a) and, depending upon the distribution of debris throughout the snow, avalanche deposition may also produce either pattern, particularly if the debris is thinly spread throughout the avalanche. Even within a single avalanche, there can be great local variability of debris content (see Chapter 8). Thus, unless a decision is made on the basis of the results at each individual site (together with the assumptions and inconsistencies which this involves) errors of one type or the other will occur.

To examine the possible consequences of adopting either pattern as a model, several calculations were carried out on the 1969 and 1970 accumulation data. Table 7.2 summarizes the relationships between the height of a boulder site above an arbitrary base point and its area, for those sites where height data were available. The only site showing a statistically significant relationship is the Tumblin' Creek Cone in 1969 but the wide scatter of points, high standard error and low "percentage explanation" (r^2) suggest it is not a very strong relationship. These results therefore indicate that, while size sorting does occur on these screes (Chapter 13), the local variation in the size of sample boulders prevents the occurrence of significant areal bias of the kind discussed in the examples (a) and (b) above. Any bias which is introduced into the calculations by the size of the sample sites will probably be distributed randomly over the scree.

Table 7.3 summarizes the relationships between sample boulder area and the measured volume of accumulation. The variations are an interesting reflection of the dominant processes. The sites dominated by avalanche activity in 1969 and 1970 (S.V.,T.C., S. II) show statistically

TABLE 7.2: CORRELATION COEFFICIENTS FOR REGRESSIONS OF THE HEIGHT OF THE SAMPLE BOULDERS ABOVE THE BASE OF THE SCREE AGAINST BOULDER AREA, S.E. is in sq. m.

	1968-1969				1969-1970			
Site	N	R	R^2	S.E.	N	R	R^2	S.E.
S.V.	44	.0039	0.0002	0.5197	As for 1968-1969			
T.C.	100	.2560**	0.0655	0.4808	255	.0202	0.0040	0.3799
S. II	155	.0140	0.0020	0.4918	237	.0568	0.0032	0.4499

TABLE 7.3: CORRELATION COEFFICIENTS FOR REGRESSIONS OF BOULDER AREA AGAINST LOG_{10} VOLUME OF ACCUMULATION, S.E. in units of $\log_{10}$ volume

	1968-1969				1969-1970			
Site	N	R	R^2	S.E.	N	R	R^2	S.E.
S.V.	58	.4025***	0.1620	1.4693	57	.2594*	0.0673	1.5354
T.C.	164	.3436***	0.1181	1.1878	309	.0729	0.0053	1.3180
S. II	155	.2000**	0.0400	1.3018	237	.4570***	0.2088	0.8856
Pall.	103	.1116	0.0125	0.5945	123	.0919	0.0084	0.4991
E.V.S.	137	.0088	0.0001	0.9191	136	-.1233	0.0150	0.7518
Ent.	36	-.1784	0.0318	0.7339	36	-.2077	0.0431	0.7652
O.N.	55	.4150***	0.1722	0.6291	55	.4479***	0.2006	0.6234

*Significant at the 95% level.

**Significant at the 99% level.

***Significant at the 99.5% level.

NOTE: S.V. = Strike Valley; T.C. - Tumblin' Creek; S. II = Surprise II; Pall. = Palliser, E.V.S. = Eastern Valley Side; Ent. = Entrance; O.N. = Old Nip.

significant relationships between boulder area and the volume of deposition with the exception of Tumblin' Creek in 1970. It is interesting to note that the highest correlation is at Surprise II (1970) where the deposition was almost entirely associated with an even spread of debris from a series of large slab avalanches. The deposits at Tumblin' Creek in 1970 included a number of fairly large boulders (2000 cc+) scattered throughout the avalanche debris which produce results not unlike the distribution pattern (a). Although some of these regressions are statistically significant, the scatter of points, high standard errors and low percentage explanation (r^2) indicate that other, probably more significant, variables (such as the position of the sample site on the slope) influence the volume of deposition.

The sites with little deposition show no relationship between the volume of deposition and the surface area of the sample boulders, probably because between 50-80% of the sites have no accumulation. The significant relationships of Old Nip (1969 and 1970) largely reflect the influence of one very large boulder (see Chapter 8).

When a correction is made for the differences in area by dividing the volume of accumulation by the surface area of the sampled boulder, the resulting correlations are as shown in Table 7.4. All the positive correlation coefficients are reduced except for Tumblin' Creek (1970) and the negative ones are increased slightly. Four of the regressions remain significant, usually at a lower level of significance and one of the negative correlations becomes significant at the 95% level. These results indicate that the correction for boulder area does not appear to produce any marked reversals of the area-volume of accumulation

TABLE 7.4: CORRELATION COEFFICIENTS FOR REGRESSIONS OF BOULDER AREA AGAINST LOG_{10} "CORRECTED" VOLUME

	1968-1969				1969-1970			
Site	N	R	R^2	S.E.	N	R	R^2	S.E.
S.V.	58	0.3329***	0.1128	1.5483	57	0.1405	0.0197	1.6052
T.C.	164	0.2064*	0.0426	1.3331	309	0.0792	0.0063	1.4532
S.II	155	0.0101	0.0001	1.4850	237	0.1747**	0.0305	0.9827
Pall.	103	0.0098	0.0001	0.7120	123	0.0802	0.0064	0.5553
E.V.S.	137	-0.0507	0.0026	1.1327	136	-0.1615	0.0261	0.9649
Ent.	36	-0.2547	0.0649	0.9488	36	-0.2441	0.0596	1.0085
O.N.	55	0.2298*	0.0528	0.7182	55	0.1670	0.0279	0.8528

*Significant at the 95% level.
**Significant at the 99% level.
***Significant at the 99.5% level.

NOTE: See note on Table 7.2.

relationship as might be expected if the correction produced a number of "inflated" values. Although some of the relationships remain statistically significant, the "percentage explanation" is so low that it can usually be ignored as an important effect on the volume of accumulation.

Conclusion

The dominance of avalanches as the major depositional process on most of the screes sampled in Surprise makes it more reasonable to assume that fresh debris accumulation is spread over certain areas of the scree rather than being located at a series of discrete points. Thus, since the volume of debris accumulation is partially dependent upon the area sampled, this figure must be corrected for differences in the size of the sample site. To standardize results, the volume of accumulation is given in cubic centimetres per square metre of sampled area (cc/m^2). In cases where large boulders rest on relatively small sample sites, this may produce "inflated" values but results of this type are not very common and may be averaged out over a period of years.

CHAPTER 8

RESULTS OF THE MEASUREMENT OF DEBRIS ACCUMULATION

During August 1968, polyethelene squares and sample boulder sites were set up at seven different screes in Surprise. These sites were selected on morphological criteria and on the basis of the observations of the previous spring so as to give a wide range of scree types, both in terms of their form and dominant processes. Debris accumulation was measured annually for these sites from 1969 to 1972 and the major sampling dates are given in Table 8.1. Also, in the first two years, a photographic record was kept of the extent and character of the ablating snow cover and its debris content. A similar, less comprehensive photographic record is available for some of the sites in 1968 and provides a qualitative assessment of deposition for the 1967-68 winter to add to the four years of detailed measurement.

In this chapter, the results for each site will be examined separately, taking the sites in alphabetical order. The complete results are tabulated in Appendix 2. For convenience, the annual accumulation figures will be referred to by the year of measurement, e.g. accumulation in the period August 1970-August 1971 is referred to as the 1971 data. A more general discussion of these results and the relative merits and weaknesses of the techniques employed will follow in Chapter 9.

TABLE 8.1: TIMETABLE OF DATA COLLECTION FOR THE ACCUMULATION STUDY, 1968-1972

Site	Date Set Up	Major Dates of Sampling[1] 1969	1970	1971	1972
Eastern Valley Side	10 Aug/68	24 July	18 July	21 Aug	21 Aug
Entrance	16 Aug/68	16,17 June	2 July	20 Aug	18 Aug
Old Nip	14 Aug/68 30 Sept/69	17 July	30 June	21 Aug	21 Aug
Palliser	18 Aug/68 27 Sept/69	23 May 6 June	24 June	20 Aug	20 Aug
Strike Valley	11 Aug/68	16,17 July	11 July 13 Aug	13 Aug	20 Aug
Surprise II	9,13,19 Aug/68 28 Sept/69	9,10,18, 19 July	1,13,19,July 14,22 Aug	15,16 Aug	22 Aug
Tumblin' Creek	17 Aug/68 23 Sept/69	June-July	May-June	12-15 July, 14,22 Aug	19,20 Aug

[1]These are the major dates of sampling. At certain screes, samples were taken later as snowpatches melted or lake levels permitted. Tumblin' Creek, being nearest to basecamp and having the largest number of sites, was visited frequently and all the dates could not be listed.

THE EASTERN VALLEY SIDE

South of Paintbrush Creek, the form of the eastern valley side is controlled by a 20-30 m thick bed of well jointed limestone dipping westwards at 40-50^0. This forms large dipslope slabs on the upper third of the slope which are dissected by funnel shaped gullies cut into the underlying shales, but pinching out as they cross the slabs (see Figures 2.2 and 2.4). The lower, mainly vegetated, slope has a cover of scree, clitter and other debris and gully sections show up to 10 m of fossil scree in some locations. Although the gully heads and slabs provide excellent source areas for avalanches and the lower slopes are scarred by numerous avalanche tracks, obvious avalanche deposits are not common. The only distinct constructional form is the Eastern Valley Side (E.V.S.) site, although several other poorly vegetated fans and small accumulations of boulders also occur on the lower slopes.

The E.V.S. site is a poorly developed avalanche boulder tongue of the "roadbank" type, with plan irregularities caused by the topography of the depositional area (Figures 8.1 and 8.2). The depositional tongue is approximately 150 m long and 35 m wide at the base and convexes upwards in cross profile with a slightly steeper slope on the southern side. It is composed of platy slabs of limestone and the deposit is probably not more than 1.5-2 m thick. The source of the avalanches is an area of slabs between two gullies 400-500 m upslope.

Experimental Design

A network of 138 sample boulders was set up in August 1968, following a zig-zag series of transverse profiles on the lower 100-125 m of

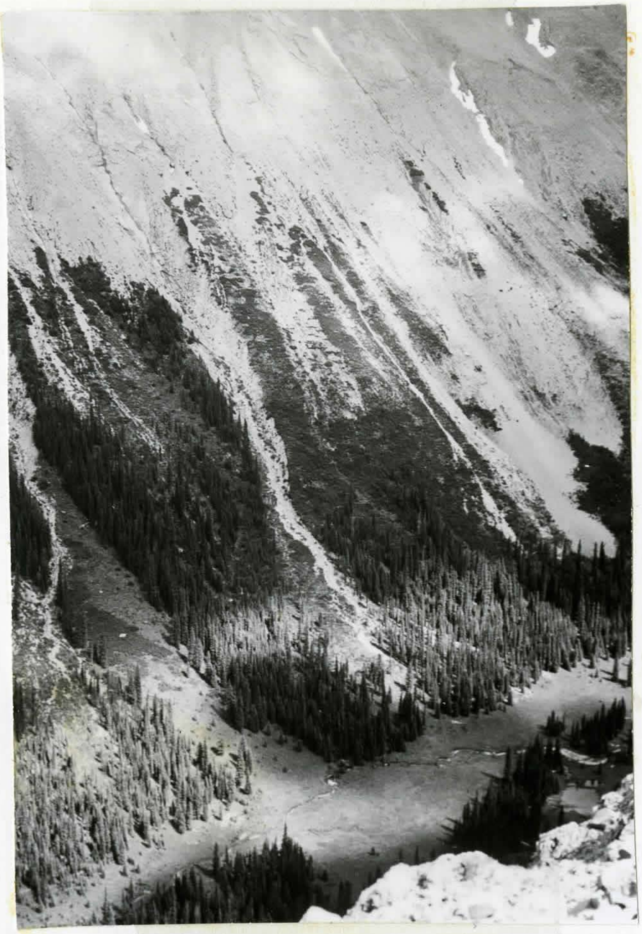


Figure 8.1

The Eastern Valley Side scree seen from the Palliser Bench. The sites (centre right) extend approximately to the large patch of vegetation at the left of the narrowest part of the track. Squares A1-A3 were situated in the gully in the centre of the photograph.

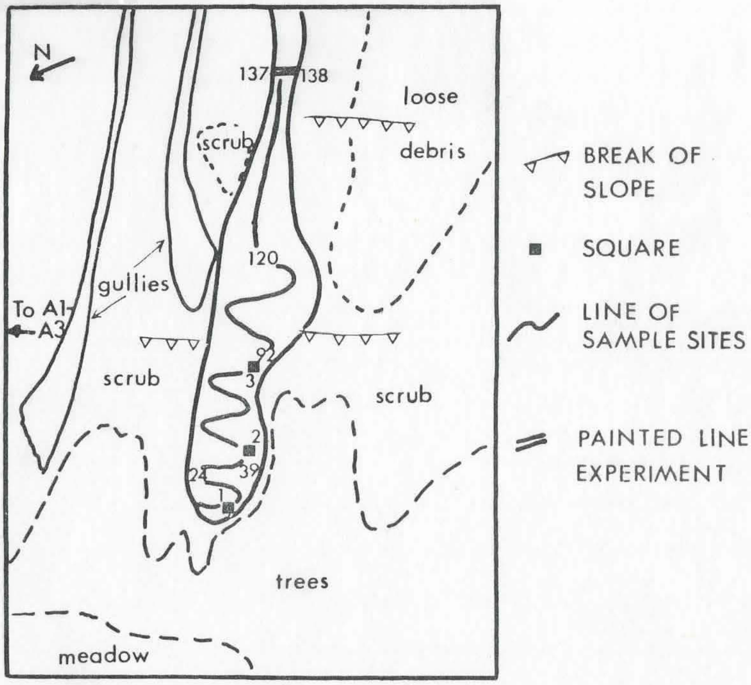


Figure 8.2 Plan sketch of the Eastern Valley Side site

the tongue. The highest 18 boulders form an upslope profile linking the lower sites to the painted line of stones discussed in Chapter 6. Three squares (S1-S3) were set up on the lower part of the tongue and also in a gully about 200 m further north (A1-A3). The general position of these sites is shown in Figure 8.2.

Results (Table 8.2)

General Observations

When it was first visited in June 1968, the site was covered by the remains of a large, fairly clean deposit of avalanche snow with scattered rock fragments. Similar deposits were seen in the two subsequent years, but the site was snow free when visited in 1971 and 1972.

1969 and 1970

Deposition was very slight in these two years (Table 8.2). Allowing for small differences in statistics due to measurement problems in 1969 (see below), the results are very similar; in both years, over 80% of the sample boulders had no significant deposition. The larger number of sites in the less than 0.0 and 0.0-0.5 classes ($\log_{10}$ units, see Table 8.2) in 1969 probably reflect inefficient or hasty cleaning in the previous year rather than fresh deposition. Similar differences occur at all sites between the 1969 and 1970 figures and it is probably more accurate to combine these two classes with the "no accumulation" class to obtain comparable results for the two years.

This site also is more affected by creep and sliding than any of the others, due to the platy elongate shape of the debris. Because of this, sample boulder surfaces are often flush or raised only a few

TABLE 8.2: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE SITES AT THE EASTERN VALLEY SIDE SITE

Class Limits[1]	Sample Boulders (%) 1969	1970	1971	1972	Mean[2]	Sample Squares (%) 1969	1970
No accumulation	71.5	82.4	27.7	81.0	21.2	75.0	100.0
Less than 0.0	3.7	0	0	0.8	2.9	0	0
0.0 - 0.5	4.4	0.7	0.8	1.6	3.6	0	0
0.5 - 1.0	1.5	1.5	3.2	0	4.4	0	0
1.0 - 1.5	1.5	1.5	7.9	3.2	7.3	0	0
1.5 - 2.0	2.2	2.2	7.1	0.8	8.8	0	0
2.0 - 2.5	2.9	2.9	6.3	2.4	12.4	25.0	0
2.5 - 3.0	5.1	3.4	11.9	1.6	10.2	0	0
3.0 - 3.5	2.9	2.9	7.1	3.2	12.4	0	0
3.5 - 4.0	3.7	1.5	9.5	2.4	13.1	0	0
4.0 - 4.5	0.7	0.7	15.1	2.4	2.2	0	0
4.5 - 5.0	0	0	1.6	0.8	1.5	0	0
5.0 - 5.5	0	0	1.6	0	0	0	0
Number of Sites	137	136	126	126	137	4	3
Mean accumulation[3]	0.23	0.18	3.98	0.63	1.14	-	-

[1]The class divisions are accumulation in cubic centimetres per square metre expressed in logarithmic units (base 10). Sites with accumulations of less than 1.0 cc/m^2 are divided into two classes: those with accumulation ("less than 0.0") and those without. To simplify calculations involving the logarithms of the volume of accumulation, all accumulation values of less than 1.0 cc/m^2 were considered to be 1.0 cc/m^2, i.e. a logarithm of 0.0.

[2]The mean figure is the total debris accumulation over the period of record divided by the area sampled in that period. In the great majority of cases, the mean is for a three or four year period (see Table 9.2).

[3]This figure is the total accumulation at the site divided by the total area sampled. It is expressed in units of millimetre thickness per square metre (i.e. 1000 cc/m^2 is equivalent to a thickness of 1.0 mm/m^2).

centimetres above the general surface and therefore debris can arrive on their surface by sliding or creep. Movements of this type were the most frequent activity on the painted line site at the top of the sampled area (see Chapter 6). Many of the fragments on the sample boulders in 1969 only slightly overlapped the upslope side of the site and, although some were obviously new, it is possible that they could have been missed on the initial cleaning. Such debris was removed in 1969 and in 1970 the sample sites were differentiated on the basis of the position and character of debris into creep and non-creep. The results were as follows:

TABLE 8.3: DIFFERENTIATION OF THE CREEP COMPONENT OF ACCUMULATION AT THE EASTERN VALLEY SIDE SITE IN 1970

		Accumulation Log_{10} (cc/m^2)								
Class	No Accumulation	Less Than 0.0	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	Total
Possibly creep	112	1	1	2	0	1	4	2	1	12
Not creep		1	1	0	3	3	1	2	1	12

These figures indicate that, in 1970, only about 9% of the sites had accumulation which, from its sedimentological characteristics, could be considered to have been deposited by avalanches.

The squares (S1-S3) showed no accumulation in either year and perished badly in the 1969-70 winter. Two of the squares in the gully (A1-A3) were destroyed in 1968-69 and the deposition on the remaining square was mainly fines washed onto the snow during snowmelt. None of the squares were reset.

1971

In 1971 the surface of the cone was considerably modified by avalanche activity. One or more avalanches covered the whole cone, extending 40-50 m into the trees and over 72% of the sites recorded debris (53% were greater than 100 cc/m^2). Most of the debris free sites were near the base of the tongue and maximum deposition occurred in the middle and upper parts of the sampled area. Many sites were covered with a layer of debris three or four particles thick. Most of this debris was the result of avalanche erosion of the upper part of the cone; 10 of the top 18 sample sites were moved downslope or buried and the line at the top of the sampled area was almost completely obliterated and its painted debris scattered downslope. Maximum displacements were of the order of 70-80 m.

1972

Most of the tongue had little deposition (only 3 of the basal 79 sites had debris) but avalanche deposits comparable to those of 1970 covered a small area in the middle of the upper part of the cone. This suggests that avalanche erosion also occurred in 1972 but was much more limited in extent.

Conclusions

This site was subject to avalanche activity in each of the five years, although the geomorphic effects of these avalanches varied considerably. The years 1969, 1970, 1972 and probably also 1968 showed very little deposition, whilst debris movement in 1971 was about ten times the total of the previous two years. These data classically illustrate the magnitude-frequency problem in the estimation of process rates from short-term records. The 1971 and, in part, the 1972 data show that the avalanche modification at this site is similar to the other avalanche dominated sites, although the occurrence of significant modification is less frequent. Unfortunately, the necessary winter field observations are not available to indicate why extensive erosion and deposition only occurred in one of the five years; 1971 is the median year in terms of total snowfall (Table 2.2) and it seems likely that it was a combination of a particular set of avalanche conditions with depth of snow cover which produced this activity. However, from the available data, it is impossible to try and estimate the recurrence interval of this event.

ENTRANCE SCREES

The Entrance Screes occur below a vertical cliff flanking the northern side of the entrance to Surprise (Figure 8.3). The cliff cuts through the dipslope at right angles to the strike and increases in height and complexity eastwards as a greater thickness of the Banff Formation outcrops below the Pekisko Limestone and several small thrusts cause repetition of the succession. The accumulation measurement sites are at the western end of the scree (Figure 8.4) where the cliff is only 20-50 m high and composed of Pekisko Limestone. In this area, the screes are basically straight with a few small rockfall cones.

Experimental Design

This is the smallest site examined and the sample sites were set up in two separate areas. The first group of ten sample boulders and two

Figure 8.3 The Entrance Screes looking north from Big Bend Mountain. Medicine Lake is visible on the left and the Hoodoo Valley Screes on the extreme right. Several small thrusts can be seen in the cliff which is capped by a major morainic ridge. 25th July 1970.

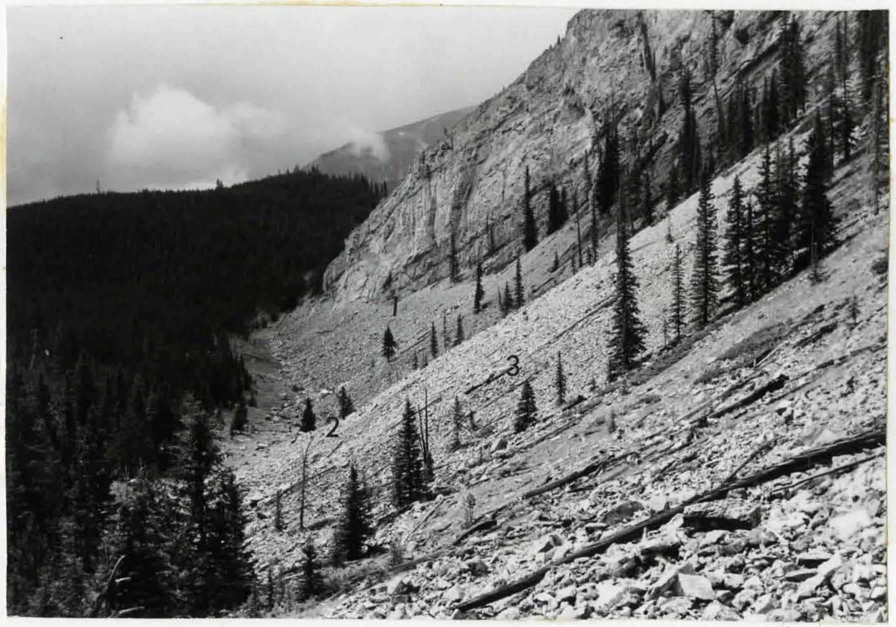


Figure 8.4 The sampled area of the Entrance Screes. The figure 1 marks the area of the upper sites and the lower sites follow a profile from 2 to 3. The sedimentological samples were taken from the small cone beyond area 1. 29th June 1970.

squares are within 5 m of the cliff near the apex of a small cone (Area 1, Figure 8.4). The remaining 28 sample boulders and a square were set up on a larger cone further east (Area 2, Figure 8.4); the square and sample boulders 11-21 are at the base of this cone and the remainder extend obliquely up its lower half.

Results (Table 8.4)

This site has never been seen under its spring snow cover since the low elevation and southerly aspect produce a very early melt. The sample sites will be treated as two distinct groups, since their position markedly influences the amount and character of deposition.

The Upper Sites

One of the sites was never relocated and another is excluded because of creep onto its surface. Nearly all of the remaining eight had small amounts of deposition in each of the four years. The greatest amount of deposition was in 1970 but there is no consistent pattern of variation between individual sites. The relatively low values for these sites are, in part, due to their small area and the overhanging nature of the lowest part of the cliff in some places. The two squares (set on the cone near its apex) collected much more debris, including a boulder of 1760 cc. All of this accumulation is rockfall from the cliff during the six months or so when the site is snow covered.

The Lower Sites

These had very little accumulation. Half the sites were covered by small amounts of avalanche debris in 1971 but, allowing for poor

TABLE 8.4: SUMMARY STATISTICS FOR THE ACCUMULATION ON SAMPLE SITES AT THE ENTRANCE SCREES

(A) AT THE TOP OF THE SCREE

Class Limits	1969	1970	1971	1972	Mean
No accumulation	25.0	0	0	12.5	0
Less than 0.0	12.5	0	0	0	0
0.0 - 0.5	0	0	0	0	0
0.5 - 1.0	0	0	37.5	12.5	0
1.0 - 1.5	12.5	25.0	25.0	37.5	12.5
1.5 - 2.0	12.5	12.5	12.5	0	25.0
2.0 - 2.5	12.5	25.0	12.5	37.5	37.5
2.5 - 3.0	25.0	25.0	12.5	0	25.0
3.0 - 3.5	0	12.5	0	0	0
Number	8	8	8	8	8
Mean accumulation	0.218	0.337	0.108	0.080	0.186

(B) ON THE LOWER PART OF THE SCREE / (C) SQUARES

Class Limits	(B) 1969	(B) 1970	(B) 1971	(B) 1972	(B) Mean	(C) 1969
No accumulation	64.3	96.4	50.0	89.2	28.6	33.3
Less than 0.0	7.1	0	0	0	21.4	0
0.0 - 0.5	7.1	0	3.6	3.6	7.1	0
0.5 - 1.0	7.1	0	7.1	0	10.7	0
1.0 - 1.5	3.6	0	10.7	3.6	7.1	0
1.5 - 2.0	7.1	0	14.3	0	7.1	0
2.0 - 2.5	0	0	3.6	3.6	10.1	33.3
2.5 - 3.0	0	0	3.6	0	3.6	0
3.0 - 3.5	0	3.6	7.1	0	3.6	33.3
3.5 - 4.0	3.6	0	0	0	0	0
Number	28	28	28	28	28	3
Mean accumulation	0.054	0.006	0.157	0.006	0.055	0.62

cleaning in 1968, only four (1969), one (1970) and two (1972) sites had significant deposition in the other three years. These were isolated fragments except for three of the 1969 sites which could also have been avalanche since many small fragments were involved. The differences in means between the years is not significant since it merely reflects the size of the largest individual boulder in that year.

Conclusions

With the exception of 1971, the pattern of deposition at this site indicates a fairly inactive scree with small amounts of rockfall accumulation. This conclusion is supported by other lines of evidence such as the thick lichen cover on many of the boulders and the absence of observed rockfalls during the investigations at this site. The avalanche in 1971 was probably a small slide redistributing the snow on the scree since there are no obvious source areas in the cliffs.

THE PALLISER CONE AND ADJACENT AREAS

These screes lie below the complex scar which was the source area for the rockslide which blocks the northern end of Surprise. The rockslide consisted of several distinct lithological units which become stratigraphically lower to the south and east and broke away cleanly, sliding on the bedding plane surfaces. Since these dip at 40-50^{0} to the west, the landslide scar looks like an irregular giant stairway lying on its side (Figure 8.5); each tread is the bedding plane surface of the top of a formation and the riser is the breakaway scar of the higher formation and is succeeded, in turn, by a similar tread. This very neat

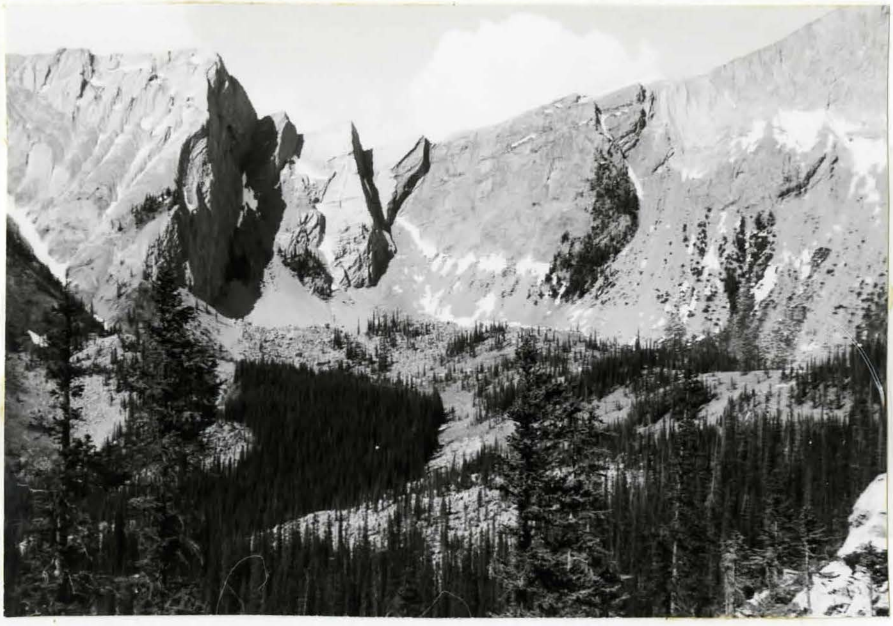


Figure 8.5 The Palliser-Scree No. 1-Isosceles area, 29th May 1969. For details, see Figure 8.6.

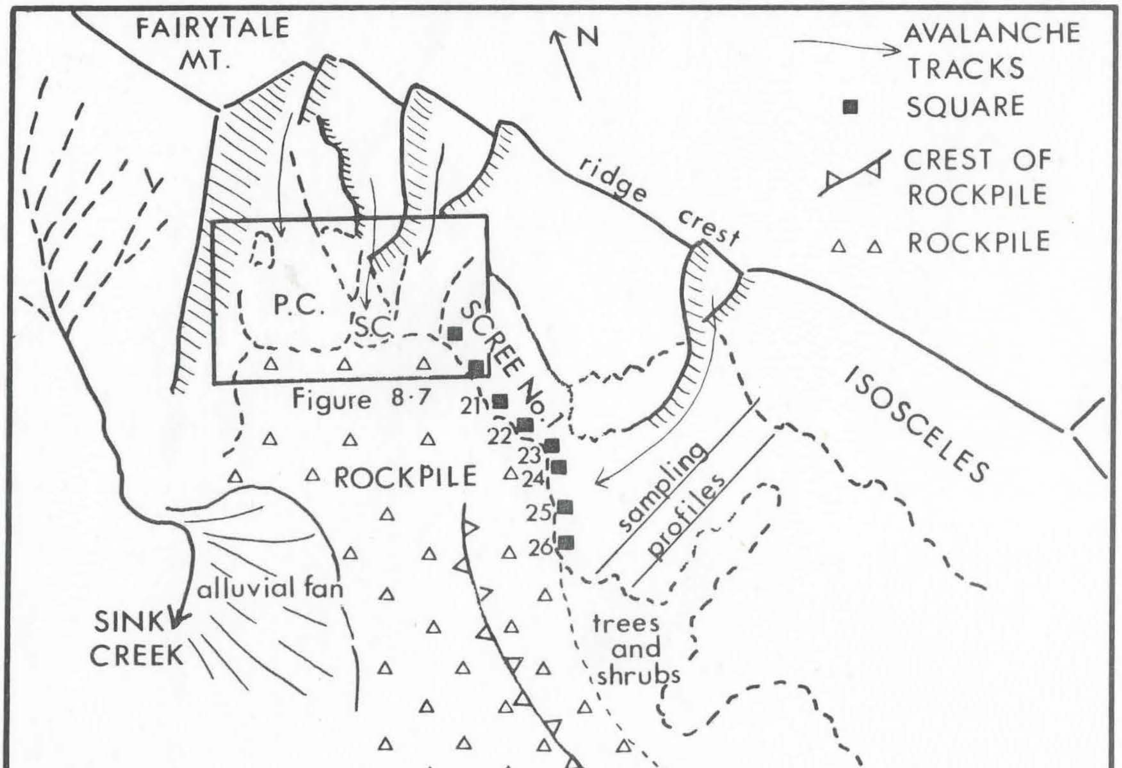


Figure 8.6 Plan sketch of the Palliser-Isosceles area

arrangement provides a series of simple single lithology screes.

The screes composed of Palliser debris comprise two small straight screes flanking a large and small cone which originate in the rockslide scar (Palliser Cone and Small Cone, Figures 8.5 and 8.6). Both cones appear to be favourable sites for avalanche activity because of the large collection areas at their heads. East of the Small Cone, the straight scree is flanked by a scree consisting of large slabs from the muddy limestone forming a triangular wedge in the cliffs (Figure 8.5) underlying the Palliser. After 50-75 m, this scree grades southwards into Scree No. 1 and further south this is replaced by the muddy limestone and siltstone debris from Isosceles (Figure 8.6). Both Scree No. 1 and Isosceles are dominantly rockfall screes except for the avalanche track at their junction (Figure 8.6).

Experimental Design

A transect of 108 sample boulders was set up in 1968 starting at the western end of the Palliser Cone and continuing eastwards approximately to the junction of the slabby limestone with Scree No. 1. This was supplemented in 1969 by a further 22 sample boulders, numbered 110-130. The approximate location of these sites is shown diagrammatically in Figure 8.7. A series of 22 squares was set up in 1968 as two major transects; the higher transect follows the approximate line of a goat trail about a quarter of the way up the Palliser Cone and onto the Small Cone. The other follows the line of marked boulders but extends beyond it across the base of Scree No. 1 (Squares 19-24) to below the avalanche track at the junction with Isosceles (Squares 25 and 26, Figure 8.6). In

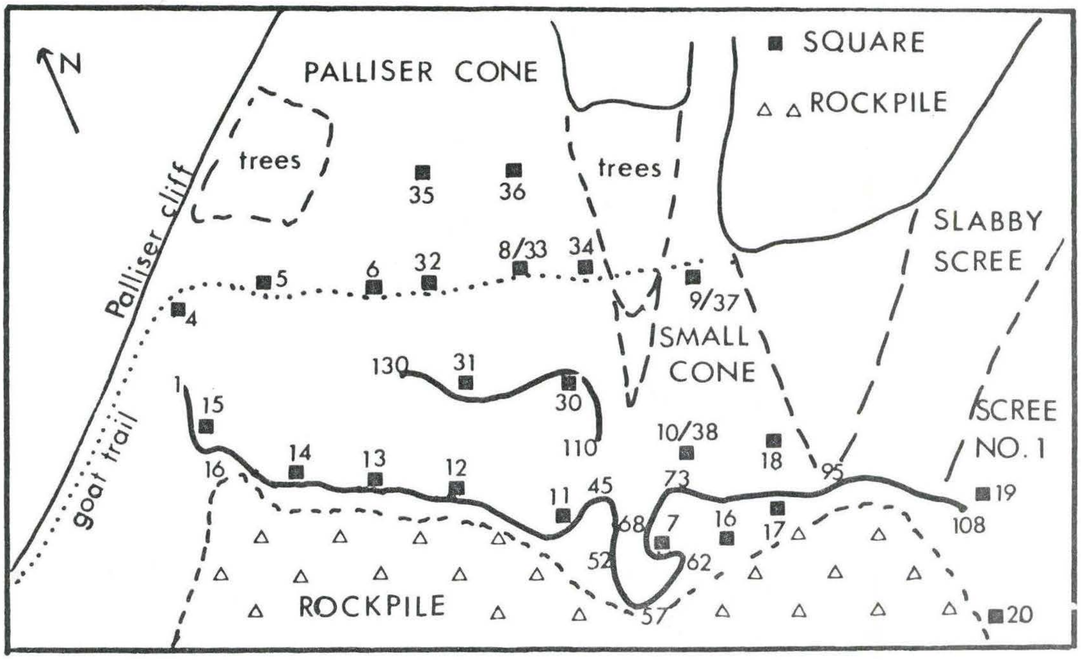


Figure 8.7 Plan sketch of the sites on the Palliser Cone

1969, nine squares were added to the network, two on the Small Cone (37, 38; replacing squares 9 and 10) and seven on the Palliser Cone, arranged symmetrically about 30 m on either side of the goat trail (see Figure 8.7).

Results (Table 8.5)

Like the Entrance Screes, this site has never been seen under complete spring snow cover, although residual snow patches were seen at the base of the screes in May 1969.

1969

All the sample boulders were relocated but, due to excessive surface weathering, four of the sites were not used. Over 89% of the boulders had less than 10 cm^3/m^2 of accumulation and, allowing for poor cleaning, probably at least 82% had no significant accumulation. Small amounts of accumulation (less than 20 cm^3/m^2) occurred in the runnel on the west side of the Palliser Cone (boulders 1-6, square 4). The largest accumulations were a rockfall boulder on the Palliser Cone and two sites connected with the avalanche on the Small Cone (69 and 70).

The squares on the lower transect of the Palliser Cone showed negligible accumulation but the higher sites showed more activity. Squares 4 and 6 both had debris, half the markers of square 8 were removed and a large boulder was deposited on square 5. Both the latter results appeared to be the result of rockfall as fresh bumpholes were found adjacent to square 8, together with a large bruised boulder (0.15 m^3).

On the Small Cone, square 9 was completely demolished and squares 10 and 7 partially destroyed. Their marker boulders were scattered

TABLE 8.5: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE SITES AT THE PALLISER-ISOSCELES SITE

(A) SAMPLE BOULDERS

Class Limits	1969	1970	1971	1972	Mean*
No accumulation	71.5	91.1	61.0	66.9	36.8
Less than 0.0	4.9	2.4	0	2.4	4.0
0.0 - 0.5	5.8	0.8	3.3	4.0	7.2
0.5 - 1.0	6.8	2.4	4.9	2.4	5.6
1.0 - 1.5	2.9	0.8	5.7	0.8	10.4
1.5 - 2.0	1.0	0.8	8.1	7.3	8.0
2.0 - 2.5	1.0	0.8	3.3	4.8	9.6
2.5 - 3.0	0	0	3.3	4.0	7.2
3.0 - 3.5	0	0	6.5	3.2	5.6
3.5 - 4.0	0	0.8	3.3	0.8	1.6
4.0 - 4.5	1.0	0	0.8	1.6	3.2
4.5 - 5.0	1.0	0	0	0.8	0.8
5.0 - 5.5	0	0	0	0.8	0
Number of Sites	103	123	123	124	125
Mean accumulation (includes squares)	0.534 (0.750)*	0.121	0.906	1.388	0.608 (0.668)*

(B) SAMPLE SQUARES

Class Limits	1969	1970	1971	1972	Mean*
No accumulation	38.1	59.3	25.0	0	23.1
Less than 0.0	9.5	0	0	0	10.0
0.0 - 0.5	19.0	3.7	0	0	6.7
0.5 - 1.0	0	7.4	0	0	0
1.0 - 1.5	0	0	0	50.0	3.3
1.5 - 2.0	9.5	11.1	12.5	0	10.0
2.0 - 2.5	14.3	11.1	12.5	0	6.7
2.5 - 3.0	0	3.7	25.0	0	16.5
3.0 - 3.5	4.8	3.7	0	50.0	16.5
3.5 - 4.0	4.8	0	12.5	0	6.7
4.0 - 4.5	0	0	12.5	0	0
Number of Sites	21	27	8	2	30

*Includes August 1969.

downslope and the observed displacements of the boulders recovered were measured with a tape (Figure 8.8). The original site of square 9 was not located and measurements were made from the highest paint spots on the scree. Although several fresh bumpholes were found in this area, the total destruction of square 9 and the manner of the downslope displacement of its boulders, without regard to their size (Figure 8.9), suggest erosion by a snow avalanche moving down the cone. The debris on squares 7 and 10 indicate the probable downslope limit of this deposition.

Only two of the squares in the Scree No. 1-Isosceles area recorded any debris; square 21 had a single rockfall boulder (550 cm^3) and square 26 was covered with many small fragments from an avalanche starting in the slabs between Scree No. 1 and Isosceles. Remnants of this avalanche snow persisted until late May.

August 5-6, 1969

The freak storm which deposited 13 inches of snow at camp on the 5th August resulted in considerable rockfall and snow avalanche activity, particularly in the Scree No. 1-Isosceles section. Several avalanches were observed in the Palliser crags on the 6th and photographs taken on the 8th (Figure 10.4) show clean avalanche deposits extending almost to the base of both the Palliser and Small Cones. A small dirty avalanche extended down the east side of the Palliser Cone almost to the goat trail and deposited a thin brown veneer of fines and rock chips derived from higher up the cone.

The greatest amount of avalanche activity was observed on Scree No. 1. By the afternoon of the 6th, most of the snow had already gone from

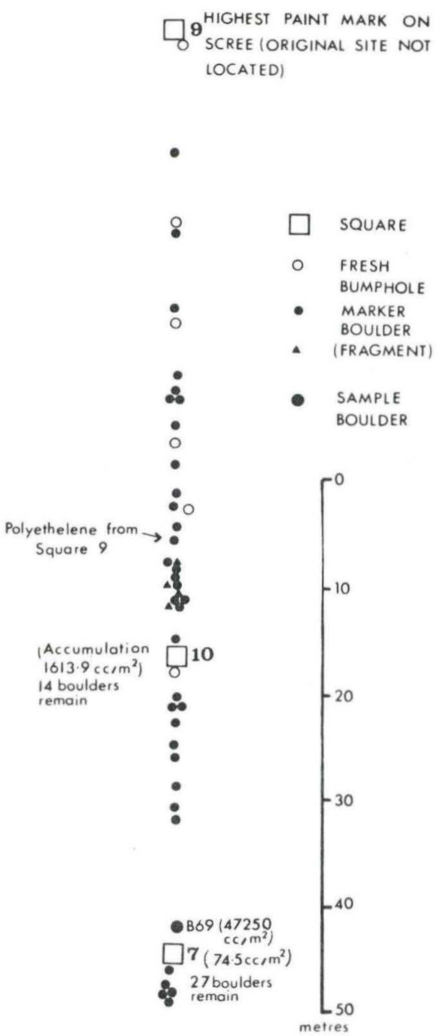


Figure 8.8 Displacement of boulders from squares 7,9 and 10 on the Small Cone in 1969

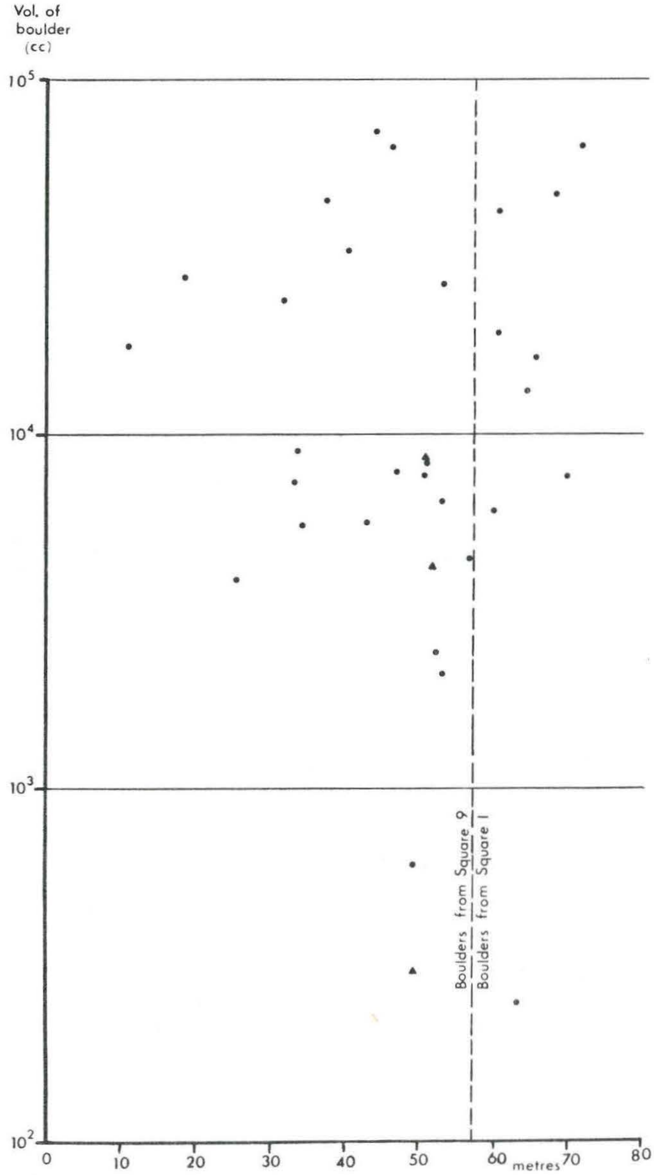


Figure 8.9 Relationship between boulder volume and downslope displacement from squares 9 and 10 Small Cone,1969

the lower slabs, although frequent avalanches from upper slopes were observed (see Chapter 5), carrying debris up to 100 m down the scree. In a number of places, the avalanches had denuded the upper scree slopes of snow which was swept to the base of the scree or onto the rockpile. Elsewhere, debris from the slabs covered the snow on the upper parts of the scree. Snow slabs breaking away and falling down snow-free cliffs were observed to trigger multiple rockfalls which preceded them down the face onto the scree.

When the site was examined on August 8th, the cliffs and upper parts of the scree were completely snow-free, although considerable amounts of avalanche snow still covered the lower slopes. The majority of the avalanche deposits were fairly clean snow, although several dirty avalanches also occurred. Most of the debris was fairly fine (less than 10 cm^3) although it ranged considerably from coarse debris (over 100 cm^3) to silt and clay with considerable local variation. Several samples taken from these deposits on August 10th are discussed in Chapter 14. It was apparent from the debris on the snow that the avalanches had, in places, eroded the surface of the scree and the character of the avalanche deposit simply reflects the nature of the scree at that point. Some of the avalanches deposited only fines and vegetation fragments (including two small trees). At one location near the base of the slope, the avalanche had scoured a four metre wide, corrugated track in the wet snow without affecting the underlying scree.

The sample sites were examined on August 24 when only a few small snowpatches remained. Despite being covered by avalanche snow, no deposition occurred on squares 21-24. The debris on squares 19 and 20 and boulders 100-108 was all eroded from Scree No. 1 and the wide range given by these samples indicates the considerable variation in deposition over a small area (Table 8.6).

TABLE 8.6: DEPOSITION IN THE SCREE NO. 1-ISOSCELES AREA, AUGUST 1969

Site	Area (m^2)	Volume (cc)	Corrected Volume (cc/m^2)
B100	0.2500	733.9	2935.6
B101	0.2200	221.4	959.5
B102	0.2200	97.3	442.3
B103	0.3075	169.5	551.2
B104	0.4000	15.3	38.2
B105	0.2500	107.8	431.2
B106	0.1200	7779.8	64831.7
B107	0.2500	8.7	35.2
B108	0.2400	66.8	280.7
SQ 19	2.3226	10390.9	4473.8
SQ 20	2.3226	20646.3	8889.8
SQ 21,22, 23,24	2.3226	0	0
SQ 25	2.3226	7179.8	3091.4
SQ 26	2.3226	4055.4	1746.2

Comparable amounts of debris were recorded from squares 25 and 26 at the foot of the Scree No. 1-Isosceles avalanche track. Square 25 was partially destroyed and eight of its marker boulders (one was not found) moved an average of 7.3 m (maximum 8.2 m) downslope and were deposited in a very restricted area. The avalanche debris continued beyond the limits of the scree onto the Rockpile. This result is interesting, since it indicates that avalanche erosion is not restricted to the upper parts of the scree slope and may even occur at its base if conditions are suitable.

1970

Over 96% of the boulders had less than 10 cm^3/m^2 accumulation and about 93% could be considered to be zero. Two of the "old" boulders had possible rockfall debris with single fragments of 3844 and 134 cm^3, whilst small amounts of possible avalanche debris occurred on boulders 1-3 and squares 4 and 15. This debris could have been deposited following the August storm, since the boulders were not checked after that event. The boulders set up in 1969 showed similar results, although one of them was missing and another was excluded because of the possibility it had not been cleaned properly.

Most of the 1968 squares which had not been reset with thicker polyethelene in September 1969 perished along the original fold of the material, although it was still possible to use them. The upper four new squares on the Palliser Cone all had several rock fragments, except for square 33 which stopped a rockfall boulder (0.026 m^3) but the lower squares (30, 31) and those on the Small Cone showed no deposition. Square 25 had a single large boulder and square 26, although it had no debris on its surface, was hit by a rockfall boulder which tore the polyethelene and continued about 40 m downslope into the Rockpile.

1971

In contrast to the previous two years, 1971's results demonstrated considerable avalanche activity in three main areas. The greatest effects were seen in the area between the two cones and on the Small Cone. In the basal area, boulders 52-86 all had debris except for boulder 72 and boulder 64 (which was carried downslope). Square 37, near the apex of the Small Cone, was completely destroyed and its marker boulders scattered over the main depositional area near the base of the slope (boulders 79-85 and 52-58), further downslope than the deposition in 1969. The characteristics of the deposits indicated that they were eroded from the surface of the Small Cone and the basal third of the Palliser Cone.

The second area was at the highest sites on the Palliser Cone, about one third of the way up. Squares 33, 35 and part of square 36 were destroyed and their marker boulders scattered up to 50 m downslope beyond squares 30-32. However, except for square 31, none of the sites in this area (squares 30, 32, boulders 124-130) showed any deposition and it is therefore possible that the avalanche was a fairly clean one which may have been separate from the one down the east side of the cone. Another avalanche deposited small amounts of debris in the runnel on the west side of the cone (boulders 1-10). Most of the remaining sites had no debris and, except for squares 20 and 25, all the old squares had either perished or not been replaced.

1972

The results were similar to 1971, except that a more limited area was affected by avalanches. There were two main depositional areas, at the base of the Small Cone (boulders 65-85) and in the runnel west of the Palliser Cone (boulders 1-11). Only one square (20) remained intact, although a large rockfall boulder rested on the marker boulders of square 30, giving a minimum estimate for that site.

Conclusions

This site has been affected by strongly localized avalanche activity during the period of observation. This activity was most marked on the Small Cone with avalanche erosion of squares and other surface debris in the middle and upper parts of the cone in three of the four years. The position of the main depositional area on the lower slopes also varied from year to year and only reached the area of sample boulders in 1971 and 1972. Avalanche activity also affected the upper transect of squares on the Palliser Cone in 1970 and 1971 and small quantities of avalanche debris were deposited in the runnel west of the Palliser Cone in each of the four years.

Apart from this localized avalanche activity, there was very little deposition. The Palliser site has the greatest number of sample sites (41.2%) with a mean accumulation of less than 1 cc/m^2 over the four year period (Table 8.5) and 64% of the sites have less than 30 cc/m^2. This appears largely due to their position; most of these sites are around the base of the Palliser Cone and the avalanche activity shown by the upper transect of squares did not extend to the base of the cone, except at its margins. The choice of this particular experimental design was controlled by the lack of suitable boulder sites higher up the slope and therefore a more appropriate sampling network should include numerous squares higher up the slope.

The results indicate considerably more deposition on the sample site network in 1971 and 1972 than in the two earlier years, reflecting the greater amount of avalanche deposition. The zone of avalanche deposition in 1969 was upslope of the sample sites and therefore the results are more akin to 1970; the higher mean for 1969 merely reflects the occurrence of two large boulders. When the Small Cone sites are considered separately, the average accumulation over the four year period is

2.41 mm/m^2/year which is comparable to other sites with heavy avalanche deposition (E.V.S. 1970, Strike Valley, Tumblin' Creek).

The observations of August 1969 at Scree No. 1 throw an interesting light on the geomorphic consequences of infrequent climatic events. Snowfalls of that magnitude are rarely followed by three hot (65-80^0 F) cloudless days which caused rapid melting and ideal conditions for avalanching. Prior to the storm, Scree No. 1 had been selected and sampled as a typical straight rockfall dominated scree (see Section III). During that sampling, evidence of former avalanche activity was rarely encountered and the marked change in the appearance of the scree surface after the avalanching confirmed the earlier interpretation that avalanching was rare at this site. For most of those sites listed in Table 8.6, the avalanche deposition was the only deposition on the site over the four year period.

THE OLD NIP SITES

The Old Nip Screes occur below massive vertical cliffs of Mississippian Limestones 200-300 m high (Figure 8.10). Both the cliff and screes are straight in plan, except for a large cone (Old Nip Cone) below a small re-entrant in the cliff. A major avalanche track and associated avalanche boulder tongue occur on the northern flank of this coarse rockfall cone. A second, wider avalanche track occurs in a partially vegetated area of the scree 200 m south of the cone. There are several areas of diffuse avalanche deposition in this latter area at the base of the scree.

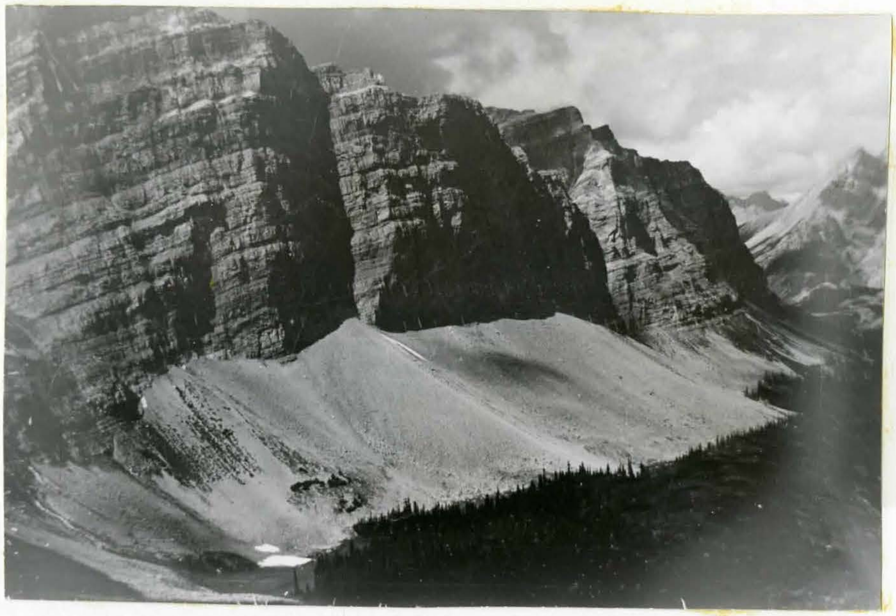


Figure 8.10 The Old Nip Screes from Strike Valley, August 1968. The cliffs are 350-450 m high. Note the remnant snowpatches on the north side of the cone and the area south of squares 3 and 4. The main avalanche track on the cone may be picked out by its lighter colour.

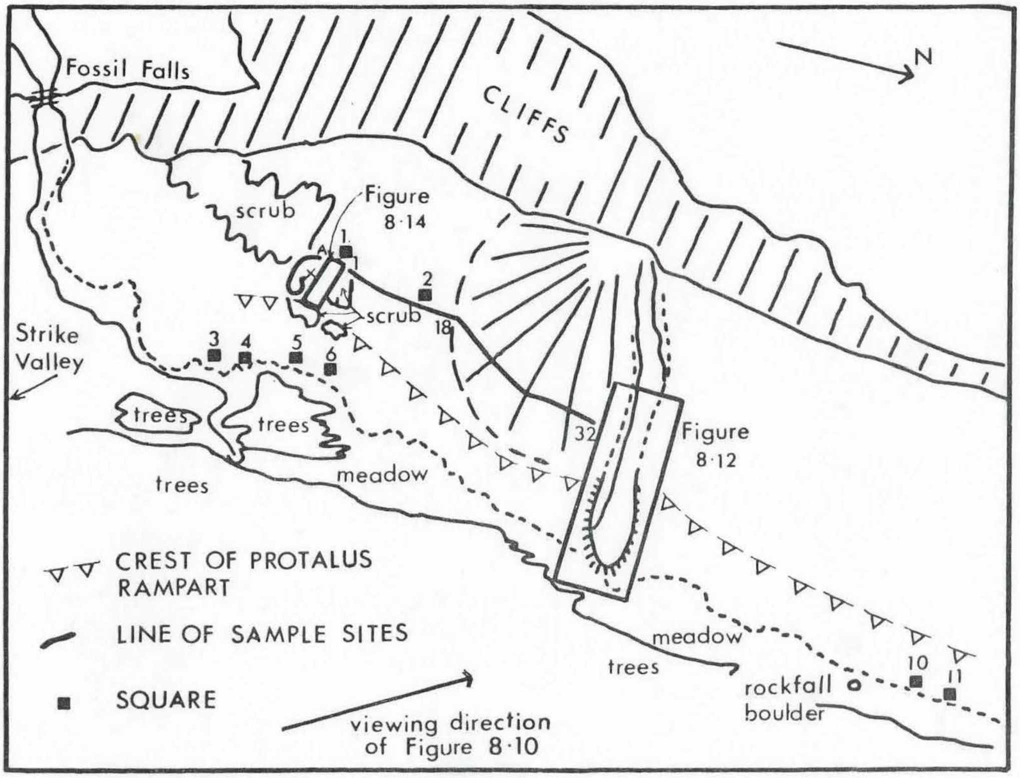


Figure 8.11 Plan sketch of the Old Nip area

Experimental Design

Two sets of sample boulders were set up at this site. The first, labelled A-X, were laid out in the vegetation free section of the southern avalanche track above the break of slope of the protalus rampart (see Figures 8.10, 8.11 and Chapter 15). A second transect, numbered 1-32, began at a large boulder on the edge of this track and, continuing at this height, crossed to the main cone (1-18) and contoured around it to the avalanche track on the northern side (19-32). This transect is about 200 m from the apex of the cone, i.e. about one quarter of the way up it.

The lettered boulders at this site are much smaller than the numbered ones; only three have an area greater than 0.5 m^2 and eleven are less than 0.15 m^2. This was unavoidable due to the lack of larger boulders in this avalanche track and leads to slightly higher values for the areally adjusted accumulation at this site due to the difference in the relationship between the size of debris and sampled area.

Eleven squares were also set in 1968; two on the numbered transect, seven in the terminal zones of the avalanche tracks and another two 300-400 m north of the cone close to the site of a major rockfall (Figure 8.11; also, see Chapter 4). Another seven squares were added to the three on the avalanche boulder tongue after the first year's results (Figure 8.12).

Results

The results from this site may best be examined in two groups, the avalanche boulder tongue and the remaining sites.

The Avalanche Boulder Tongue (Table 8.7)

This is a "roadbank" tongue and is shown in detail in Figures 8.12 and 8.13. The terminal area may be divided into two parts; the main tongue, which is about 2 m high, has well-defined edges and is flat in cross profile, and a more diffuse area with an almost continuous, thin veneer of avalanche deposits covering the vegetation. This latter area will be termed the avalanche apron.

General Observations

Large avalanches covered the lower parts of the tongue and apron in each of the first four years of observation. The tongue was covered with avalanche snow on the first visit (18th June 1968) and snowpatches remained at the apex and base until August (Figure 8.10). In 1969 the rockfall cone was bare of snow by May 16, apart from a small drift on the northern side parallel to the avalanche track. The upper part of the track had been stripped of snow and the basal area covered with several feet of avalanche snow. A wide trail of debris in the snow below this bare patch indicated that the upper part of the track had been eroded by the avalanche and the blocky slabs of snow showed it was a slab avalanche. A similar distribution of snow cover was seen in 1970 except that the upper and middle parts of the track still had a partial snow cover on May 28th and the avalanche extended 30-40 m beyond the apron. In both 1969 and 1970, an arcuate drift remained at the top of the avalanche track until July. No observations were made of the snow cover in 1971 or 1972.

These observations of snow cover have yielded considerable information about the character of avalanche activity at this site. The persistance of the drift north of the apex of the cone in 1969, 1970 and 1971

TABLE 8.7: RESULTS FROM THE SAMPLE SQUARES ON THE AVALANCHE BOULDER TONGUE AT OLD NIP

(A) ACCUMULATION

Site	1969	1970	1971	1972	Mean	Years
Square 7	593.2	0.3	snow covered	3854.4[1]	1112.0	4
Square 8	15799.9	12171.0	1944.1	0.0	7478.7	4
Square 9	2529.9	1618.4	2167.5	0.0	1579.0	4
Square 15	not set	1.6	destroyed	not set	1.6	1
Square 16	" "	destroyed	3008.6	96.2	1525.0	2
Square 17	" "	5.3	844.6	2.0	240.5	3
Square 18	" "	0.0	1507.5	not set	753.7	2
Square 19	" "	destroyed	2773.8	" "	2773.8	1
Square 20	" "	182.9	1222.7	18.6	471.2	3
Square 21	" "	1298.3	destroyed	not set	1298.3	1
Mean	6.31	1.91	1.92 (2.17)	0.02 (0.02)	2.18	

(B) EROSION OF MARKER BOULDERS

Site	1969	1970	1971	1972
Square 7	0	0	-	0
Square 8	0	14(22)	0	0
Square 9	0	0	0	0
Square 15	n.s.	18(26)	22(23)	n.s.
Square 16	n.s.	25(26)	1(25)	0
Square 17	n.s.	0	0	0
Square 18	n.s.	0	3(21)	n.s.
Square 19	n.s.	13(29)	16(23)	n.s.
Square 20	n.s.	10(19)	2(20)	0
Square 21	n.s.	0	23(23)	n.s.

NOTE: The numbers in brackets in the lower table are the original number of marker boulders; the other figure is the number of marker boulders lost from the site. The numbers in brackets in the upper table are the means when Square 7 is included in the calculations.

[1]This is a two year total. However, it is obvious from the 1972 results that it was deposited in 1971.

suggests that the avalanches do not begin at the apex but further north, below the straight section of cliff. Furthermore, since there is no accumulation area in the cliffs (they are vertical), the avalanching snow must be derived from the snow cover on the scree itself and the pronounced concentration of avalanche activity suggests that their location is controlled by some distinctive feature of the site. It is therefore suggested that these avalanches are triggered by cornice falls onto an unstable snow cover on the scree since, given similar conditions, cornices tend to develop in the same position at the top of the cliff in successive years. The exact nature of the avalanches would then depend upon the characteristics of the slope's snow cover; the available evidence suggests some of these may be slab avalanches where the fracture zone is at the base of the snowpack, leading to the erosion and incorporation of the underlying scree.

<u>1969</u>

All three squares in the basal area were covered with avalanche debris, the largest volume being on the tongue itself (square 8). The material deposited on that site was considerably coarser than that on square 9 and had obviously been eroded from higher up the tongue.

<u>1970</u>

The enlarged network of sites showed both erosion and deposition on the tongue and throws an interesting light on the processes involved in its development. Five of the seven squares on the tongue had over half their marker boulders eroded and moved downslope (Figure 8.12). The two exceptions were square 18, on the edge of the avalanche track, and square 21 which is the highest site and in the middle of the track (where most of the erosion took place). The most probable explanation of this anomaly is that the avalanche did not extend to the base of the snow cover at this point; it is highly unlikely that the avalanche was initiated below square 21.

The movement patterns of the displaced marker boulders (Figure 8.12) show few of them were swept beyond the limits of the tongue and many were deposited, with the intact polyethelene from square 16, on the steep slope marking the edge of the tongue. Square 7, just beyond this edge, showed no significant deposition even though marker boulders from square 15 were recovered less than 5 m upslope. This suggests that the relatively smooth, flat upper surface of the tongue is basically erosional in origin and debris incorporated into snow avalanches is redistributed downslope or deposited on the steep frontal zone of the tongue. Erosion occurred even at the base of the tongue (square 8 was only held in place by its surface debris) whilst the avalanche apron area showed purely depositional activity and merely indicates the extent of the largest avalanches and the most probable direction of future growth of the tongue. This overall pattern shows marked similarities to deposition at a delta front.

1971

A similar picture of erosion and deposition occurred in 1971 (Figure 8.13). Squares 15 and 21 were destroyed and 19 and 20 so badly damaged that they were not reset. The erosional and depositional zones were higher than in 1970 on the centre of the tongue, although some of the boulders eroded from square 19 in 1970 were moved further downslope in 1971. The debris from square 15 was deposited at the edge of the tongue extending slightly beyond the 1970 position over the site of square 7. This site was snow covered during sampling and obviously marked the zone

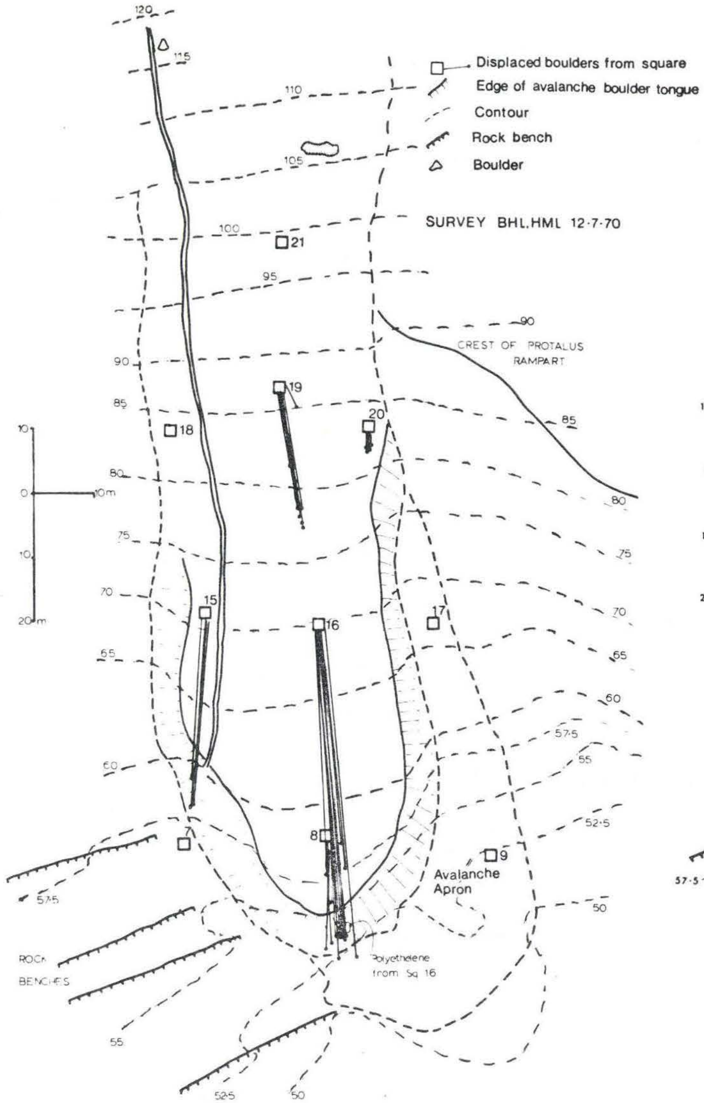


Figure 8.12 Displacement of marker boulders at Old Nip in 1970

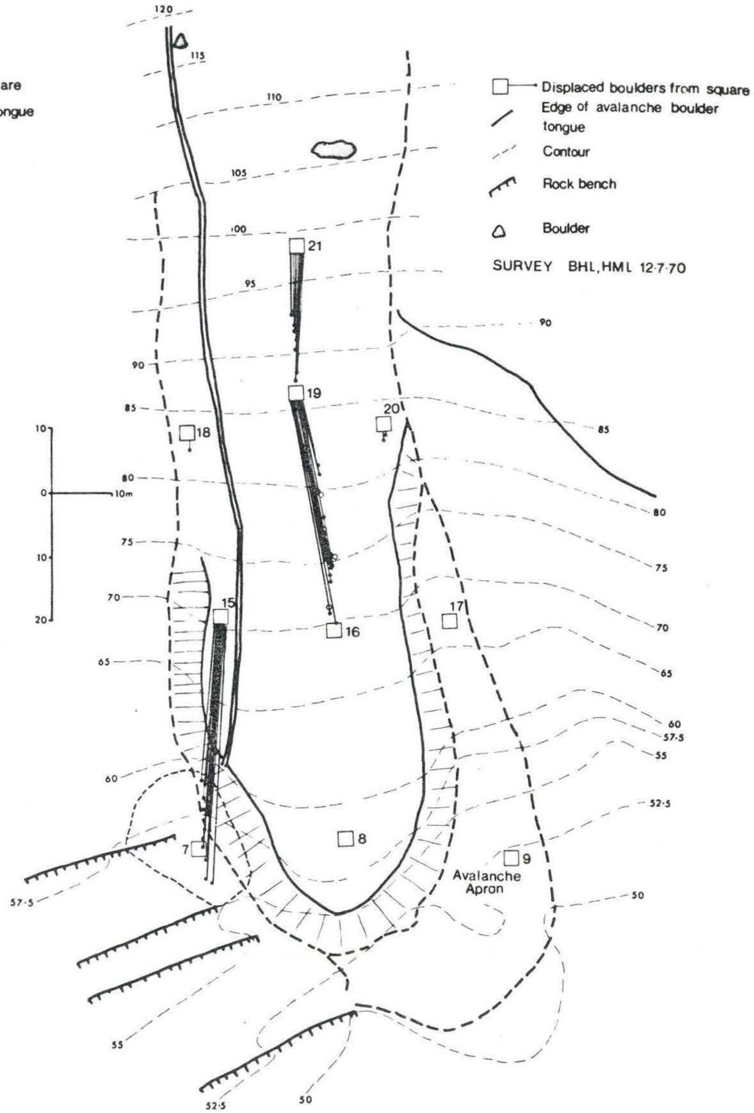


Figure 8.13 Displacement of marker boulders at Old Nip in 1971

of maximum accumulation of avalanche snow. The deposition on the basal sites was relatively smaller than in previous years, indicating that the maximum debris deposition was probably further upslope than in either 1969 or 1970.

1972

Apart from several fragments on squares 16 and 20, there was no deposition or erosion at these sample squares in 1972. In view of these results, it therefore seems reasonable to assume that the two year total (1970-1972) recorded for square 7 was all deposited in 1971.

Conclusions

This site is the simplest avalanche boulder tongue examined in detail. From the results, it is clear that the form is the result of continued interaction with avalanche erosion refashioning the deposits of earlier avalanches and building out the avalanche boulder tongue. The position of the erosional and depositional zones fluctuates and overlaps from year to year, but the long-term pattern would appear to be the eventual downslope transfer of loose surface debris over (or from) the surface of the tongue to its edge where it is incorporated into the prograding front or spread thinly over the avalanche apron. In the two earliest years (1969 and 1970), the heaviest deposition occurred near the base of the tongue and it would be interesting to set up sites on the front to see whether the deposition is much greater there as the initial results suggest.

The amounts of deposition on these squares is comparable with other avalanche sites in Surprise; the average over the four year period is

2177 cc/m^2/year. However, this debris lacks the larger boulders (5,000 cc and over) found at those sites. This is due to their earlier removal or burial by avalanche activity at this site (see Chapter 14).

The Remaining Sites (Table 8.8)

Avalanche activity also occurred at these sites but it is more diffuse and irregular, both spatially and temporally. Remnant snowpatches of avalanche snow were seen in 1968 (Figure 8.10) and two dirty avalanches were examined in 1969, one on each side of the lettered boulder transect. With the exception of square 5 in 1969, all the squares along the base of the scree (squares 3, 4, 5, 6, 10 and 11, Figure 8.11) showed no significant deposition during the period of study.

1969

Both sets of boulder sites showed very little accumulation, except for one boulder in each series; if these are excluded, the mean accumulation becomes 1.57 cc/m^2 and 1.47 cc/m^2 respectively for the numbered and lettered sites. Avalanche deposition did occur on both sides of the lettered sites, missing most of them. A dirty avalanche completely demolished square 1, covered boulder 1 (area 1.8 m^2) with an average thickness of 1.6 cm of debris and scattered similar debris over the slope as far as square 5 (908 cc/m^2). The debris is very similar to that immediately upslope of boulder 1, indicating considerable redistribution of the surface material--in fact, the remnant of polyethelene at the original site of square 1 was so heavily covered that it was not located until late in the season. Marker boulders from this square (Figure 8.14) were carried almost to the crest of the protalus rampart and, like the Palliser example (Figure 8.9),

TABLE 8.8: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE SITES AT OLD NIP

(A) SITES A-X

Class Limits	Sample Boulders 1969	1970	1971	1972	Mean
No accumulation	79.2	54.2	16.7	62.5	16.7
Less than 0.0	8.3	4.2	0	0	0
0.0 - 0.5	0	4.2	0	0	12.5
0.5 - 1.0	4.2	12.5	16.7	0	4.2
1.0 - 1.5	0	0	4.2	16.7	4.2
1.5 - 2.0	4.2	12.5	0	8.3	8.3
2.0 - 2.5	0	4.2	8.3	4.2	16.7
2.5 - 3.0	0	4.2	16.7	4.2	20.8
3.0 - 3.5	4.2	4.2	20.8	4.2	4.2
3.5 - 4.0	0	0	4.2	0	8.3
4.0 - 4.5	0	0	8.3	0	0
4.5 - 5.0	0	0	0	0	4.2
5.0 - 5.5	0	0	4.2	0	0
Number of Sites	24	24	24	24	24
Mean accumulation	0.04	0.05	3.08	0.14	0.83

(B) SITES 1-32 / (C) SQUARES (EXCLUDING A.B.T.)

Class Limits	(B) 1969	(B) 1970	(B) 1971	(B) 1972	(B) Mean	(C) 1969	(C) 1970	(C) 1971	(C) 1972	(C) Mean
No accumulation	67.7	64.5	45.1	74.2	22.5	42.9	71.4	100.0	100.0	28.6
Less than 0.0	9.7	3.2	3.2	6.5	9.7	28.6	14.3	0	0	42.9
0.0 - 0.5	9.7	3.2	0	6.5	19.3	0	0	0	0	0
0.5 - 1.0	9.7	6.5	12.9	3.2	3.2	0	0	0	0	0
1.0 - 1.5	0	16.2	3.2	0	6.5	0	0	0	0	0
1.5 - 2.0	0	3.2	3.2	0	6.5	0	0	0	0	14.3
2.0 - 2.5	0	0	3.2	3.2	0	14.3	14.3	0	0	14.3
2.5 - 3.0	0	3.2	6.5	0	0	14.3	0	0	0	0
3.0 - 3.5	0	0	0	0	9.7					
3.5 - 4.0	0	0	6.5	0	19.3					
4.0 - 4.5	3.2	0	12.9	6.5	3.2					
4.5 - 5.0	0	0	0	0	0					
5.0 - 5.5	0	0	3.2	0	0					
Number of Sites	31	31	31	31	31	7	7	2	1	7
Mean accumulation	1.40	0.04	4.07	0.56	1.52	0.007	0.001	0	0	0.003

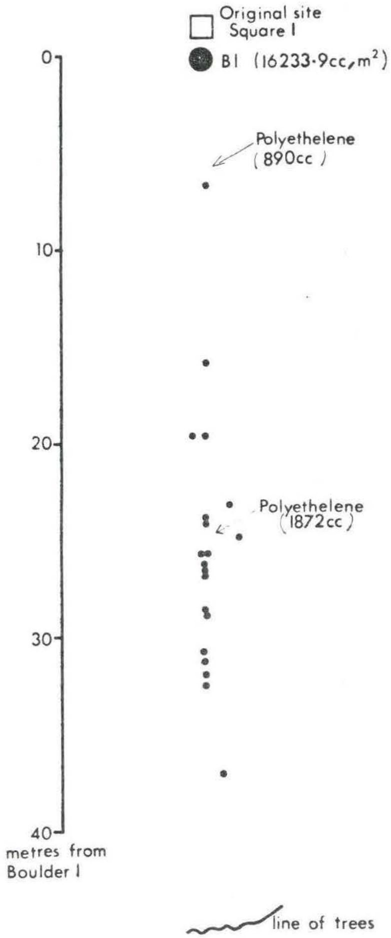


Figure 8.14 Displacement of marker boulders from square 1, Old Nip ,1969

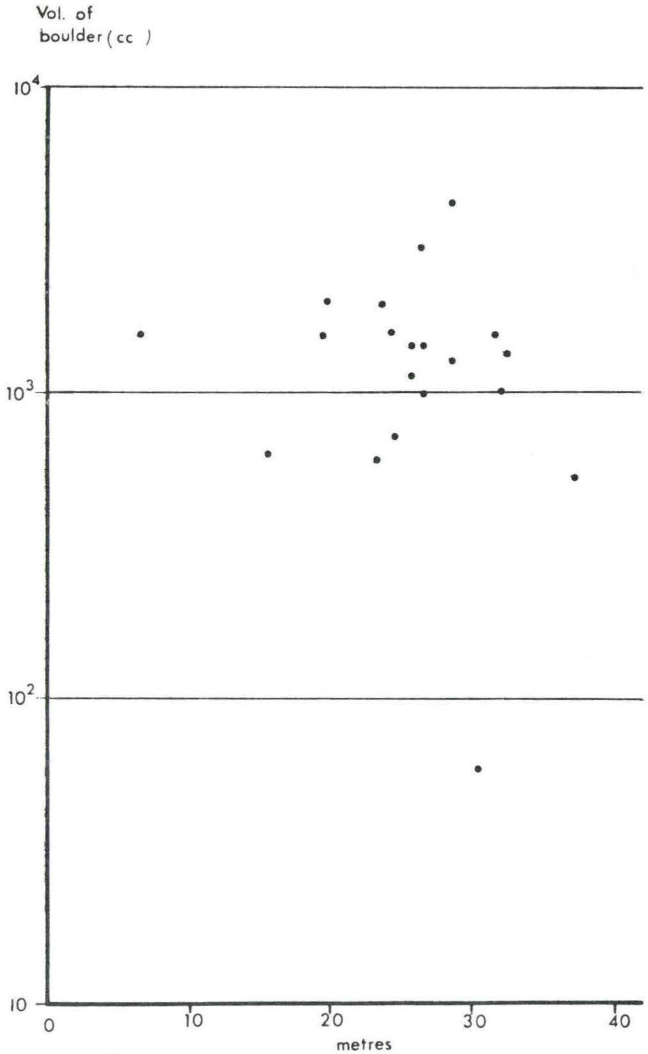


Figure 8.15 Relationship between boulder volume and downslope displacement from square 1,Old Nip,1969

there is no relationship between boulder size and distance travelled (Figure 8.15). Boulder 2 was overturned by this avalanche and small amounts of deposition also occurred on square 2.

1970

Small amounts of avalanche debris were scattered over the lettered sites, boulders 1-13 (mainly boulder 1) and square 2. All the remaining sites showed no significant accumulation except for four on the cone which are adjacent to the sedimentological sample sites (see Section III) and probably the result of human disturbance.

1971

This year showed the greatest depositional activity since both sites had considerable avalanche deposition. Numerous small to medium sized fragments were deposited on the lettered sites and only four had no debris. Most of this material appeared to have been eroded from higher up the slope. By way of contrast, deposition on the numbered sites was mainly on boulders 14-22, situated near the edge of the cone. The average accumulation on these sites was 18753.7 cc/m^2, consisting mainly of one or two large fragments on each boulder. The variety of lithologies involved, the range of grain size present and the areal spread of the accumulation all indicate that this is an avalanche rather than a rockfall deposit, its coarse nature reflecting the characteristics of the scree further upslope. Scattered avalanche deposits also occurred on boulders 1, 6, 9 and 10 but the deposits on boulders 25-28 were all single fragments which, from their position, are interpreted as rockfall fragments.

Square 2 perished during the preceding winter and was not reset.

1972

About one third of the lettered boulders (mainly those at the upper end of the site) showed avalanche deposition as did boulder 1. The only other significant deposition was two single rockfall boulders, one with shattered fragments, on the cone (boulders 23 and 26).

Conclusions

These data demonstrate the great local variability in the character and intensity of depositional processes over a small transect across a scree. Generally, the results confirm inferences about dominant processes made initially from the surface characteristics of the scree. Avalanche activity ranges from localized intense erosion to insignificance (on the cone) and the nature and volume of deposition varies markedly with conditions and individual avalanches from year to year. The results from the cone also suggest that much greater areas need to be sampled to obtain meaningful estimates of rockfall activity.

STRIKE VALLEY

The two massive limestone cliffs of the western side of Surprise are separated by a bench or valley developed on the Banff Shales, except for a short distance between Old Nip and Surprise II where the shales merely form a gentler slope in the combined cliff. Strike Valley is the small valley on the northern side of this "col" and extends obliquely down dip to Old Nip, excavating the line of the limestone-shale junction. The eastern slope of the valley is a clitter and bedrock slope developed mainly on the lowest shale beds; the western slope is a straight scree below an almost vertical cliff of Mississippian Limestones 200-400 m high.

The Strike Valley site is at the head of the valley. A shallow embayment occurs in the cliffs just north of the col and is the source of an avalanche track which runs to the base of the screes and then continues down the axis of the valley. The detail of the upper part of the site is shown in Figure 8.16. Several avalanche boulder tongues of the "roadbank" type also occur further north along the screes (see Figure 15.5) and are probably similar in origin to the example at Old Nip. Most of the rest of the scree is a coarse rockfall scree, although there is a wide protalus rampart developed at the base of the scree near Fossil Falls (see Figure 8.18).

Experimental Design

A series of 63 sample boulders was set up in 1968, beginning on the col. Since the col sites showed no deposition and were not visible from the survey point, they are not shown in Figure 8.17. The higher transect of sample sites (14-35) traverses the avalanche track to an area of coarse material (boulder 35, Figure 8.16), then continues downslope, re-entering the avalanche track at the base of the scree (42) and continuing thence down valley along the debris-covered valley floor.

Results

The sites may be subdivided into two main areas, those on the col and the main part of the site. With the exception of one small fragment, there was no deposition on sites 1-13 (Table 8.9) and the rest of this

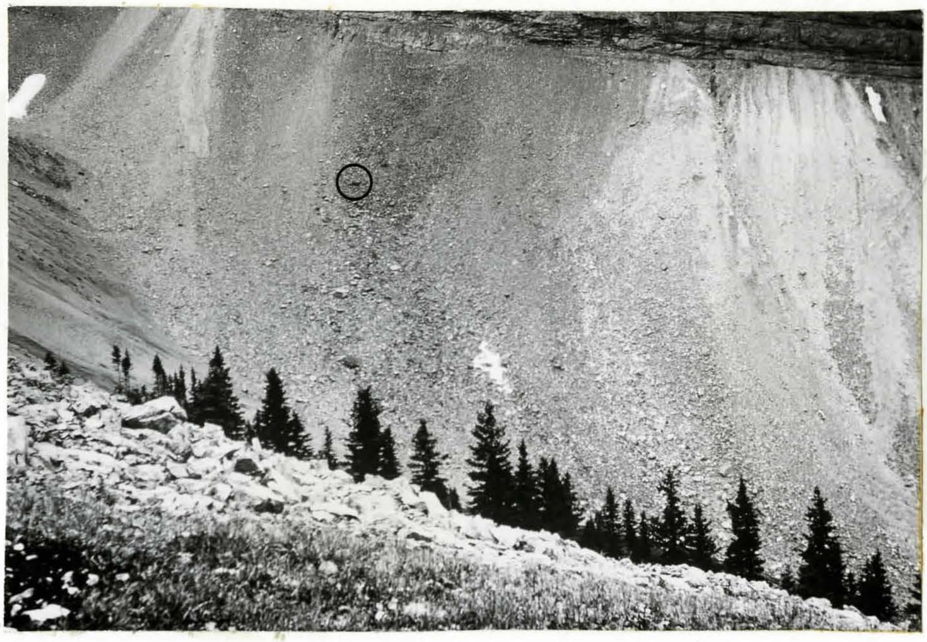


Figure 8.16 The Strike Valley site from the Palliser Bench. The lighter colour of the avalanche track is clearly visible to the left of boulder 35 (circled) and the white area to the right is debris from the massive rockfall described in Table 4.5. The lowest sites (42-63) are not visible.

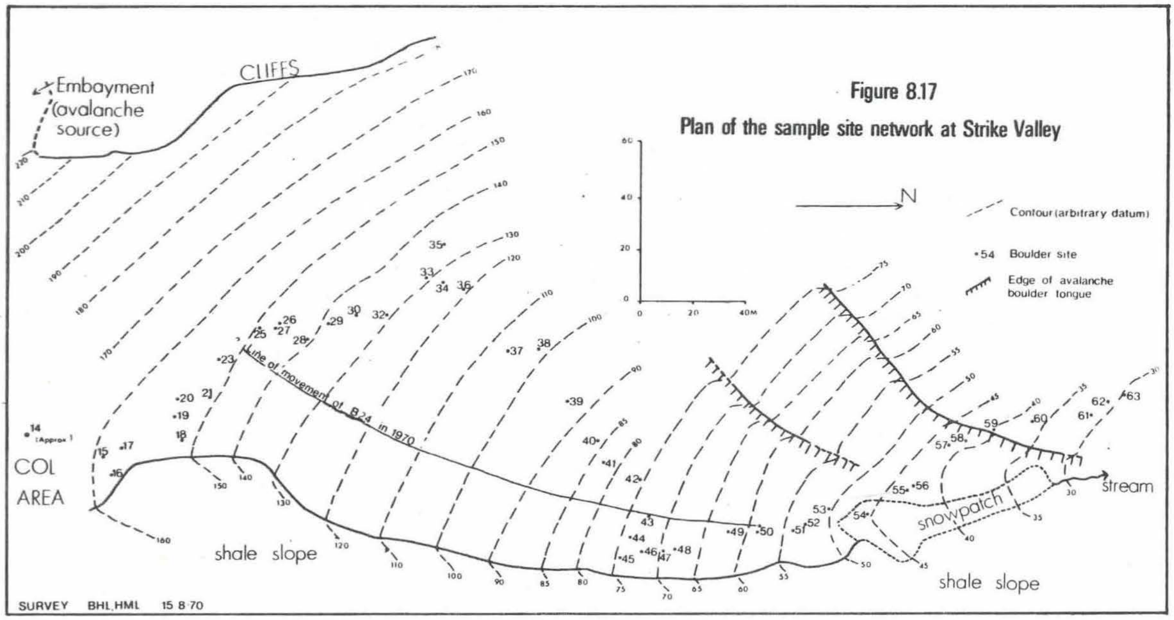


Figure 8.17
Plan of the sample site network at Strike Valley

TABLE 8.9: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE BOULDERS AT THE STRIKE VALLEY SITE

(A) ON THE COL

Class Limits	1969	1970	1971	1972	Mean
No accumulation	100.0	92.3	100.0	100.0	92.3
Less than 0.0	0	0	0	0	0
0.0 - 0.5	0	0	0	0	7.7
0.5 - 1.0	0	7.7	0	0	0
Number of Sites	13	13	13	13	13
Mean Accumulation	0.0	0.0007	0.0	0.0	0.0001

(B) REMAINDER

Class Limits	1969	1970	1971	1972	Mean
No accumulation	22.1	6.9	19.6	34.8	0
Less than 0.0	11.0	0	4.4	4.4	4.2
0.0 - 0.5	4.4	6.9	4.4	13.0	4.2
0.5 - 1.0	4.4	4.5	13.0	13.0	0
1.0 - 1.5	8.9	9.2	4.4	13.0	2.1
1.5 - 2.0	6.7	2.3	10.9	6.5	12.5
2.0 - 2.5	6.7	16.0	8.7	4.4	10.4
2.5 - 3.0	6.7	9.2	10.9	0	12.5
3.0 - 3.5	2.2	22.9	13.0	4.4	18.8
3.5 - 4.0	15.4	2.3	6.5	2.2	29.1
4.0 - 4.5	6.6	16.0	2.2	4.4	4.2
4.5 - 5.0	4.4	4.5	0	0	0
5.0 - 5.5	0	0	0	0	2.1
5.5 - 6.0	0	0	0	0	0
6.0 - 6.5	0	0	2.2	0	0
Number of Sites	45	44	46	46	48
Mean Accumulation	3.94	4.64	29.44 (1.44)	0.66	19.84 (2.64)

NOTE: The means in brackets exclude accumulation from boulder 52 in 1971.

discussion is limited to sites 14-63. Spatial variations in the depositional patterns for each year are shown in Figure 8.20 and sites may be located by reference to Figure 8.17. Boulder 14 was not visible from the survey point and does not appear on these diagrams.

General Observations

Avalanche deposits were observed at this site in the first four years. In 1968 a large dirty avalanche extended down the main track to about sites 50-54 eroding the scree in the middle section of the track (Figure 8-18). Three smaller dirty avalanches also occurred below the main cliffs. Avalanching in 1969 occurred between May 31st and June 8th (photograph from camp) during a spell of very hot weather, but the deposits were not examined since the site was not revisited until most of the snow had melted. The site was not examined after the storm on the 5th August 1969; photographs from camp on the 8th show a large number of clean avalanches along the Strike Valley Screes, but not extending much beyond sites 20-25. Because of the shorter field seasons in 1970, 1971 and 1972 this site was not examined under a complete snow cover in those years. However, large snowpatch remnants from avalanches were examined in 1970 and 1971.

1969

Avalanche deposition was extensive on the upper transect of sites (particularly boulders 19-25) and extended to boulder 53 in the lower part of the avalanche track (Figure 8.20). However, except for large single boulders on sites 45 and 48, deposition in this lower area was small compared with the almost total debris cover of several of the higher sites. On the downslope profile, only sites 34, 37 and 38 recorded

Figure 8.18 Strike Valley from Old Nip, 18 June 1968. A large dirty avalanche occupies the main track at the sampling site extending down to approximately sites 50-54. Several other small dirty avalanches can be seen below the cliffs. The snow free area of scree is the area of protalus rampart or proscree lobe (see Chapter 15).

Figure 8.19 Avalanche debris on snow, Strike Valley, 11th July 1970. This is the coarsest avalanche debris seen in Surprise. Note the size of the debris and the relative lack of small material.

large amounts of debris, in each case a single large boulder which may have been either rockfall or avalanche in origin. Avalanche erosion also occurred since boulder 31 was moved 20 m downslope and boulder 21 was never found.

1970

When this site was first visited on July 11th, the lower part of the track, from 50 m upslope of boulder 42, was covered with a distinctive deposit of avalanche snow. The area above boulder 52 (about 2,000 m^2) had a scattered cover of boulders (Figure 8.19) with a minimum estimated total volume of 10-15 m^3. The largest boulder was about 1.5 m^3 and there were at least another 100 greater than about 0.02 m^3, i.e. of comparable size to the largest boulders recorded on sites elsewhere in Surprise. This avalanche carried a similar amount of debris to the one at Tumblin' Creek in 1968, although they are quite different in character. The Tumblin' Creek avalanche (see Figure 8.39 and Luckman, 1971, Figure 4) was very dirty whereas this avalanche snow contained little fine debris (Figure 8.19). One of the larger boulders in the deposit was sample boulder 24 (1.5 x 0.6 x 0.4 m, about 0.27 m^3) which had been moved 150 m downslope. This, together with the distinctive character of the deposit, suggests that the avalanche debris was entrained near the upper line of sample sites where there are few surface fines.

Below site 52, the avalanche contained smaller amounts of debris and little debris occurred on the remnant snowpatch on August 15th (Figure 8.17). A similar snowpatch occurred in 1971 and on August 22nd, 1966 (Figure 2.2) and, since all the other screes are snowfree on that photograph, it would appear that major avalanches are fairly common at this site.

Almost all the sample sites seem to have been covered by this avalanche which extended down valley well beyond the lowest sites. The heaviest concentration of deposition was again on the upper transect (sites 23-33, slightly further north than in 1969) and only three sites had no accumulation (15, 16 and 17 which are on the margin of the track). The lower sites showed moderate (100-1000 cc/m^2), although variable deposition with occasional higher values where one of the larger boulders seen on the avalanche snow ablated onto the site (47, 50, 59 and possibly 63). The sites on the downslope profile showed little deposition, except for 35 and 37 which had single large boulders.

<u>1971</u>

On August 11th, a long thin snowpatch, similar to that of the previous year (Figure 8.17), covered the environs of the stream for 80-100 m downstream of boulder 53. At least 10 m^3 of debris was scattered over its surface (1000-1500 m^2) including two boulders of 1.5 m^3. Most of this debris was concentrated in an area of 400 m^2 close to the upper end of the snowpatch. However, since a number of the boulders were freshly bruised and of similar lithology, it is possible that some of this debris is rockfall, either on top of, or incorporated into, the avalanche deposit.

Apart from this snowpatch, the pattern of deposition is similar to that in 1969, except that the lower sites (45-52) have slightly more debris and the upper sites (14-32) slightly less than that year. There was negligible deposition on the downslope profile and boulder 44 was either overturned or moved. Boulder 52 was almost covered by a boulder of 1.03 m^3 (Figure 9.1) which, because of its size, was cleaned and used

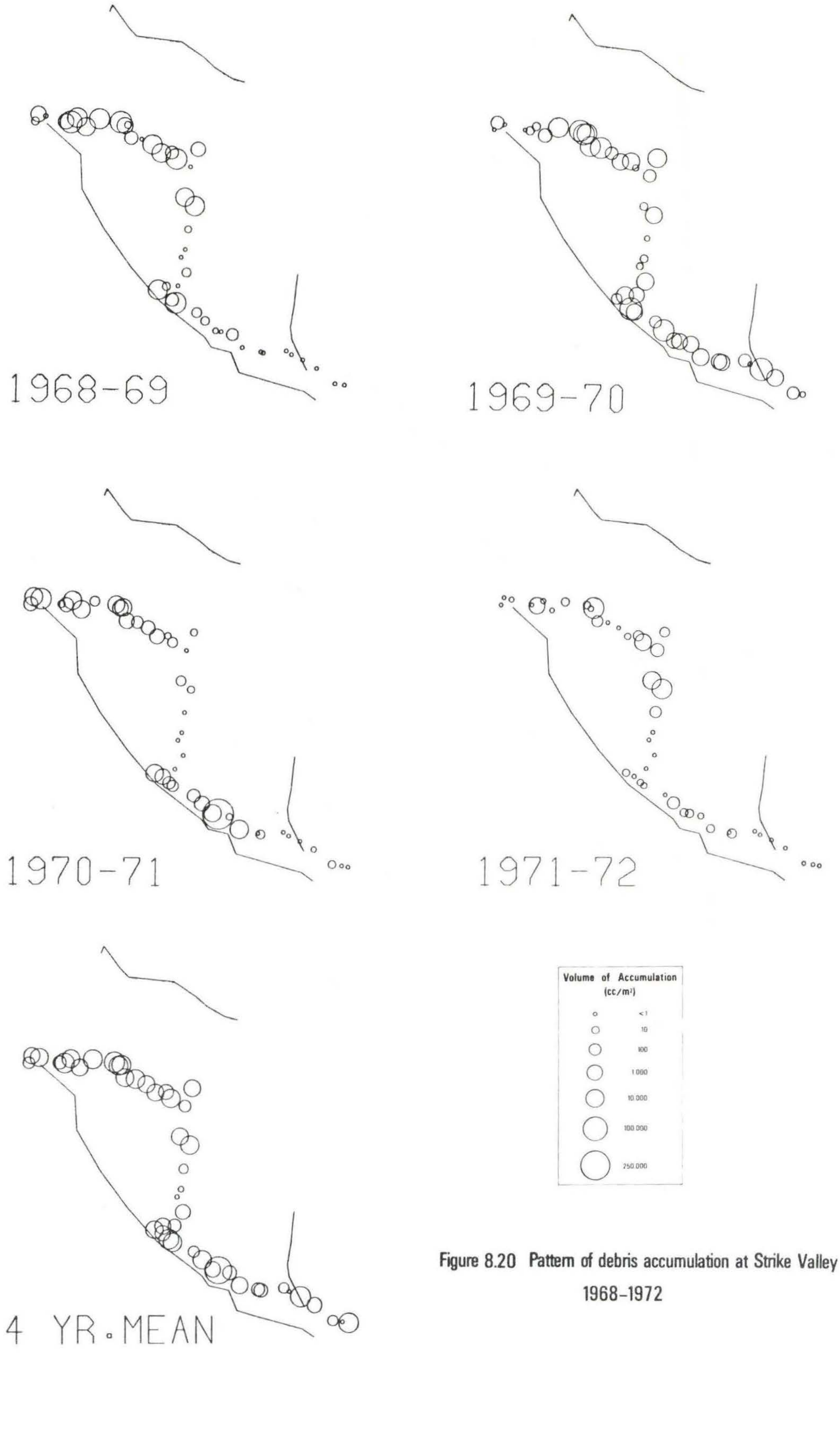


Figure 8.20 Pattern of debris accumulation at Strike Valley 1968-1972

in subsequent years as a sample site. The inclusion of this boulder causes the unusually high mean annual accumulation figure for this scree site.

Despite the snowpatch evidence, there was negligible deposition down valley of boulder 54. Possibly these sites were not covered by the main part of the avalanche since they are 30-40 m from the stream (Figure 8.17) and were all snowfree on August 11th.

1972

Deposition on the sample sites in 1972 was almost an order of magnitude less than the preceding three years. Nearly 80% of the sites had less than 30 cc/m^3 deposition and the greatest accumulation was on sites 34-39, possibly as a result of a small avalanche. Scattered deposition as far as boulder 56 indicates that the avalanche in the main track carried little debris. A possible explanation of this might be the greater depth of snow cover on the screes preventing significant avalanche erosion.

Summary and Conclusions

This site may be divided into three main areas; the col (sites 1-13) with negligible deposition, the downslope profile (sites 33-42) with sporadic deposition and the avalanche track (see Figure 8.20, mean accumulation). The latter area showed considerable accumulation in three of the four years of measurement and avalanche activity in all five years of study. The intensive deposition is linked with avalanche erosion of the scree in the higher parts of the track and the position of the depositional zone varies from year to year, depending upon the size and characteristics of the avalanche. Over the four year period, 91% of the

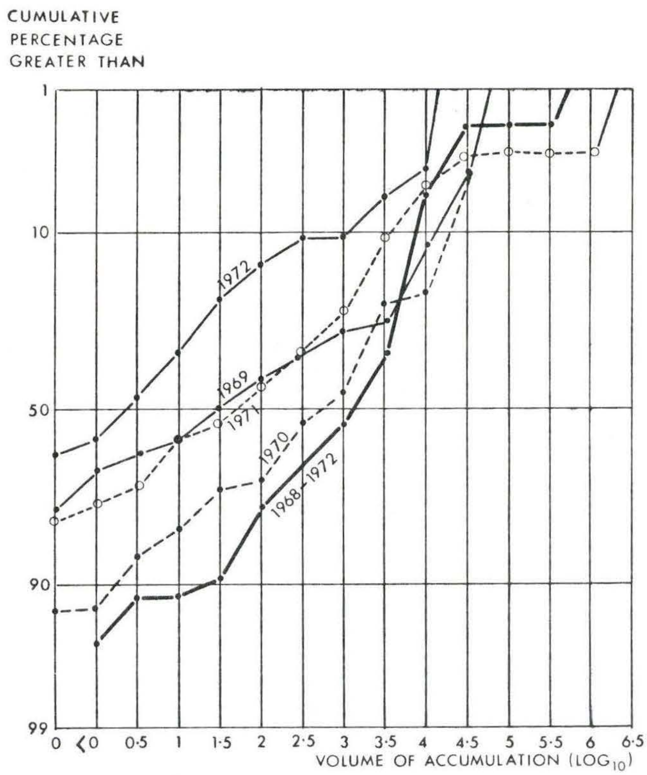


Figure 8.21 Cumulative frequency curves for volume of accumulation on sample boulders at Strike Valley

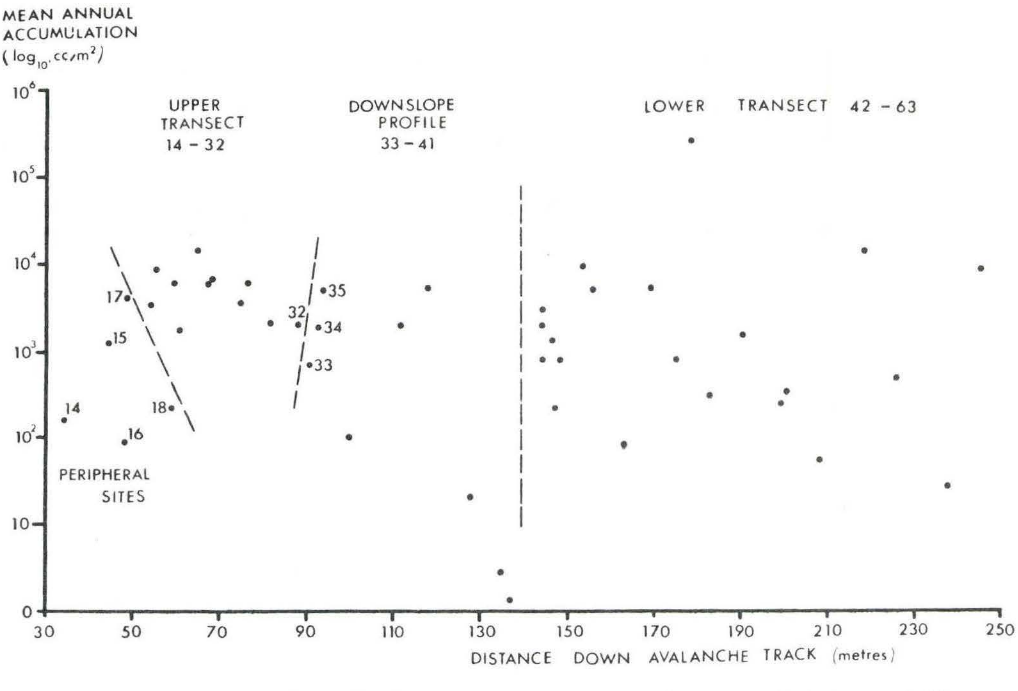


Figure 8.22 Relationship between mean annual accumulation and distance down the avalanche track at the Strike Valley site

sites (14-63, see Table 8.9) averaged more than 10 cc/m^2/year and over half of them exceeded 1000 cc/m^2/year. Comparing the individual years (Figure 8.21), 1970 showed the greatest overall deposition on the sample sites followed by 1969. However, the largest boulder deposited in 1971 was so big that this year has the largest mean, although the remaining sites only average 1440.0 cc/m^2. Deposition in 1972 was much less than the other years.

There were also differences in the character of deposition within the avalanche track. Figure 8.22 is a crude plot of the volume of accumulation (four year mean) against distance along the avalanche track (measured from an arbitrary point near the cliff). Despite the lack of sample sites in the middle of the track, it can be seen that apart from the sites on the edge of the track (14-18, 32-34), deposition is uniformly heavy on the upper transect but much more variable (and generally less) at the lower sites. This is true both for the mean and for individual years and reflects differences in the character and frequency of deposition in each area. Over the four year period, avalanche deposits at the upper sites have typically consisted of a large number of moderate to small fragments in contrast to the scattered large boulders and smaller fragments found in the lower part of the track (Figure 8.19). This contrast mirrors differences in the characteristics of the surface scree of the upper slopes and it appears that the avalanches were picking up debris from different parts of the slope and depositing it in the same relative position further downslope.

The large boulders deposited on the lower sites also emphasize the danger of inferring process from the characteristics of a single site.

Unless there is no evidence of avalanching from snow cover observations or sample sites in the adjacent area, such sites cannot be unambiguously identified as rockfall.

SURPRISE II

Surprise II lies in a blind strike valley, 120-150 m deep, between a ridge of steeply dipping Palliser Limestone and the cliffs of the eastern face of Opal Mountain (see Figure 2.5). Apart from the two cirques above the lake, the cliff is straight in plan, 100-600 m high and slopes at between 50 and 70^{o}. The Mississippian Limestones of the lower part of the cliff are repeated by thrust faulting above a bench developed on the Triassic Shales. Several broad, shallow avalanche chutes occur in the upper part of this cliff but do not extend below the shale bench. Many of the dirty avalanches at this site contain considerable amounts of shale debris which is obviously derived originally from this bench area.

The screes are also basically straight with several poorly developed multiprocess cones. The Surprise II site is associated with three of these cones and lies below the highest part of the cliff between the lake and a well developed protalus rampart. Figure 8.23 is a composite view of the site (also, see Luckman, 1971, Figure 5).

Experimental Design (Figure 8.24)

The initial sample network was a line of sample boulders along the base of the scree (1-51, 111-160) and in a profile up it (52-103) with a few additional sites near the apex of cone D. In 1969, a second transect

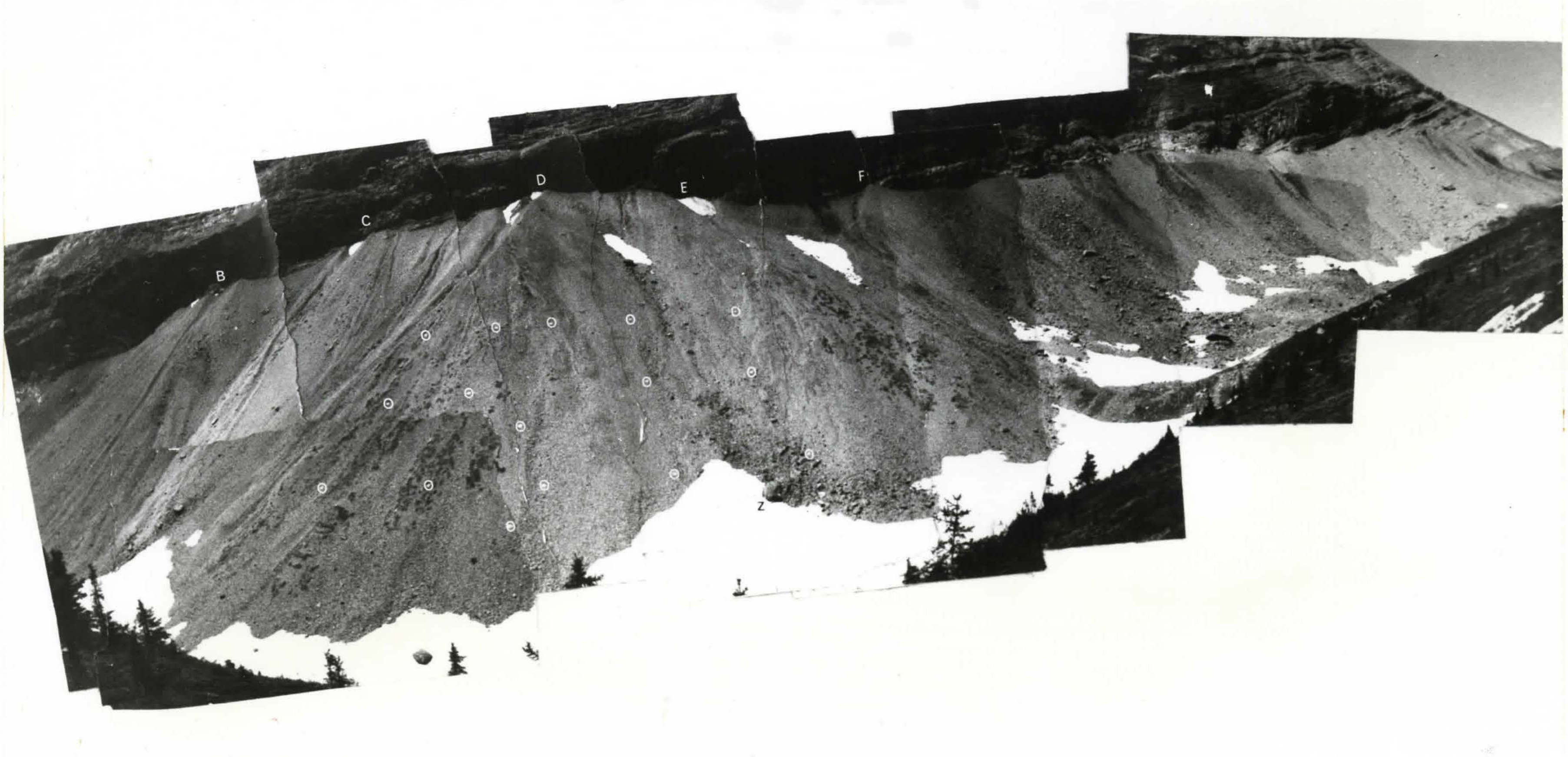
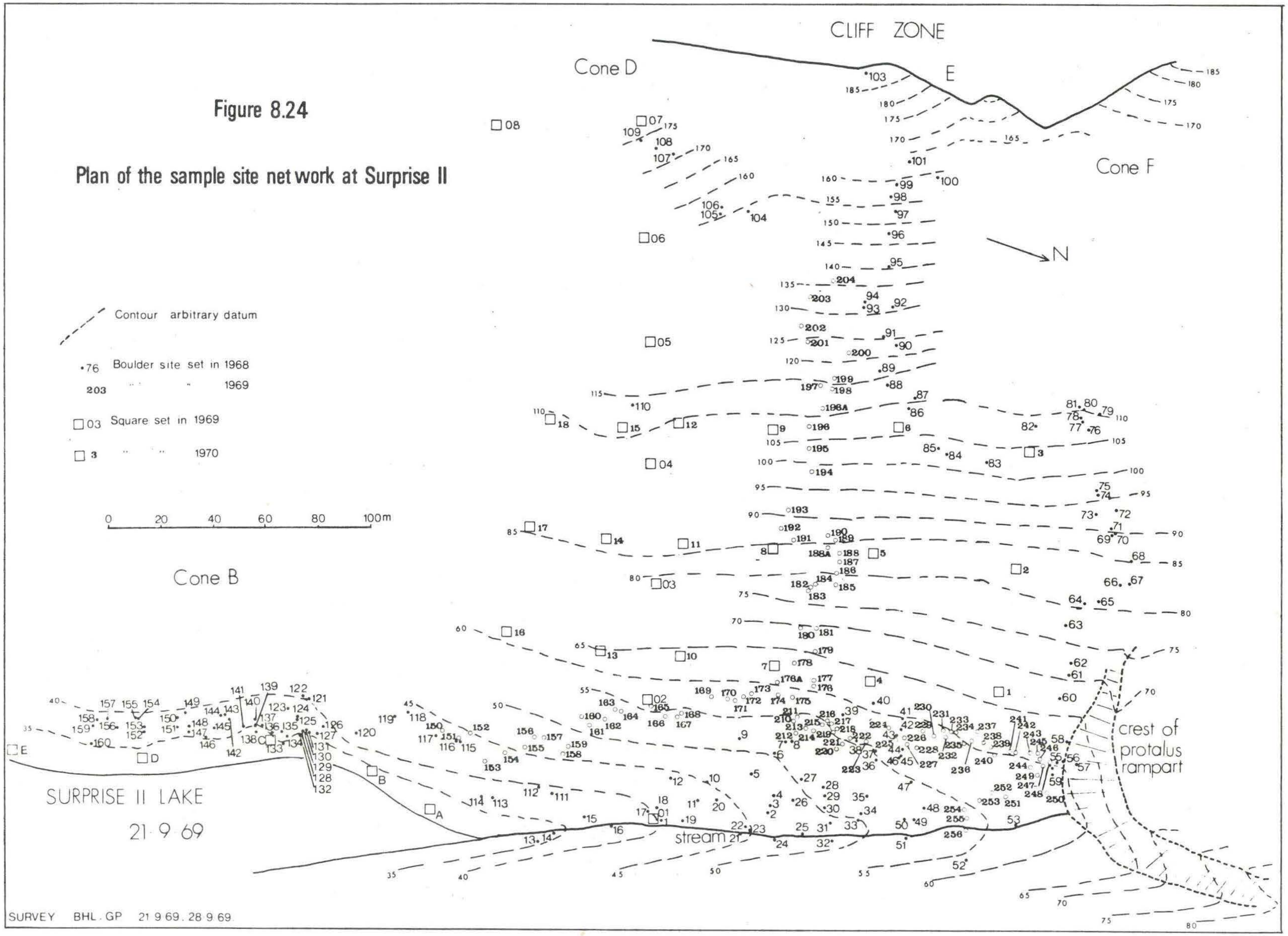


Figure 8.23 Panoramic view of the Surprise II site. Most of the lowest part of the scree is still covered with a great thickness of avalanche snow but the network of sample squares is clearly visible except for squares 1-3. The two squares in the centre which are out of line are old squares 2 and 3. The feature at Z is a large boulder adjacent to boulder 39. Note the protalus rampart sticking through the snow (right). 19th July 1970.

Figure 8.24

Plan of the sample site net work at Surprise II



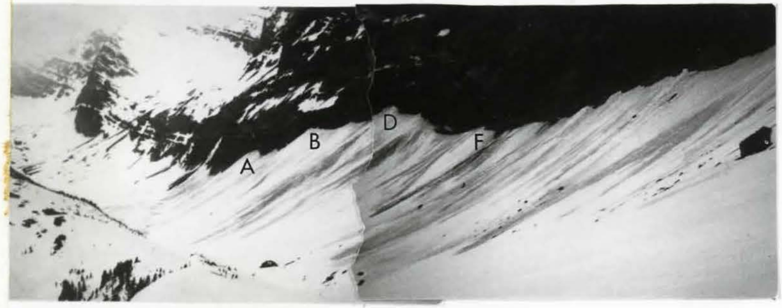
was laid out parallel to and upslope of the first (N150-174, N210-256), together with a second profile (N175-204) following the coarse area of boulders between cones D and E. The idiosyncrasies of this design largely reflect the presence of suitable sites away from the base of the scree and the high rockfall hazard near the top of the slope; it is a compromise between what was possible and what would have been desirable.

In 1968, a profile of seven squares, approximately 45 m apart, was laid out up the centre of the largest cone (cone D). An extra site was set 50 m south of the top site, both sites being 30 m from the cliff base. Another nine squares were set along the line of sample boulders at the base of the slope. The higher sites on the profile were badly damaged by avalanches in the following winter and not reset. To replace them, a network of 18 squares was set up in 1969 on the middle parts of cones D and E above the upper transect of boulders. This network consisted of three rows, 45 m apart, and six columns spaced at intervals of 45, 30, 30, 30 and 30 m (north to south).

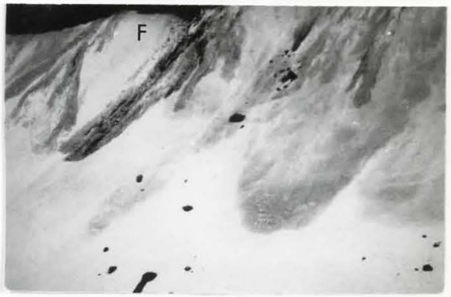
Results

General Observations

The variations in the pattern and character of avalanche activity in the first three years are shown in Figures 8.25-8.27. However, it must be remembered that these figures only give a very general picture; early avalanche deposits may be covered by later snow and, since debris becomes progressively concentrated at the surface as melt continues, differences in the photographic tone of the deposits do not necessarily reflect differences in debris content (compare, for example, the relevant



A



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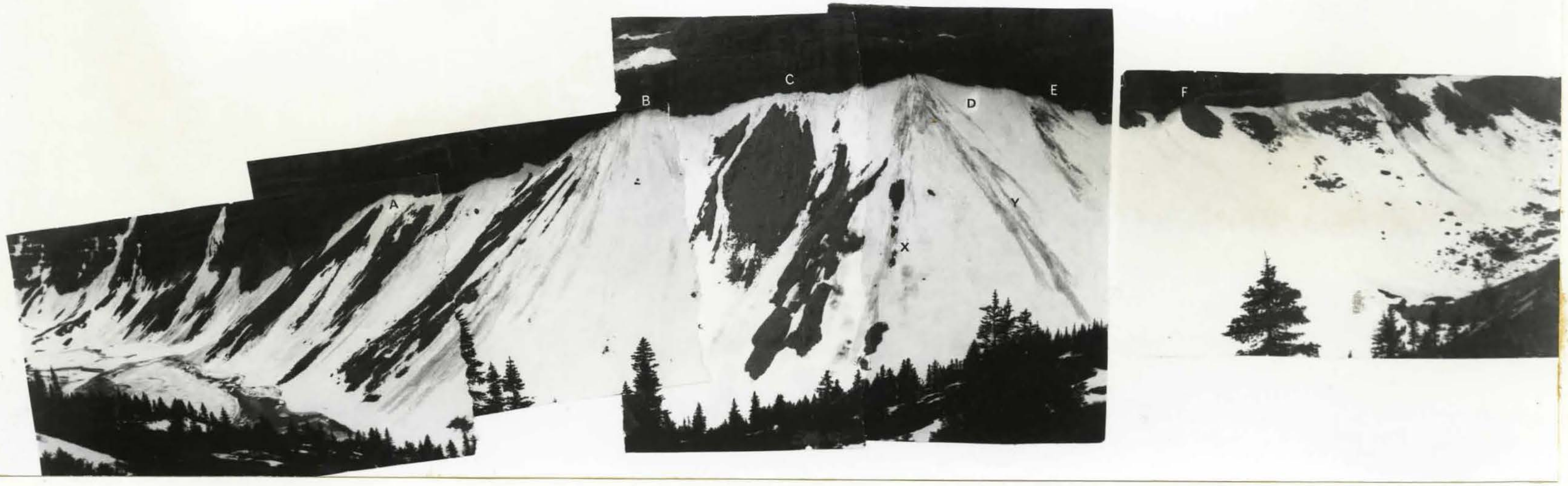

Figure 8.25 (A and B, above) The Surprise II site, 16th June 1968. Viewed from the north these two photographs show the large amount of avalanche deposition in 1968 (also, see Luckman, 1971, Figure 5).
Figure 8.26 (below) The Surprise II site, 2nd June 1969. Note the differences in the amount and pattern of avalanching compared with Figure 8.25. The avalanche at Y is also shown (at a later date) in Luckman, 1971, Figure 6).

part of Figure 8.26 with Luckman, 1971, Figure 6 or the insets A and B of Figure 8.27 with the main figure).

Large numbers of avalanches were observed in the cliffs on June 9th, 1968 (Figure 5.2) and their effects are clearly visible on Figure 8.25 (also, see Luckman, 1971, Figure 5). The upper and middle sections of most of the cones were covered by several types of dirty avalanche and the widespread debris cover on the snow suggests more deposition occurred in 1968 than in any of the succeeding years. The avalanche snow remained at the base of the slopes until well into August, especially at the base of cone C and near the protalus rampart.

In 1969 most of the avalanches were long and narrow, covering a much smaller area than in 1968. Four visits were made to the site during the melt season on May 16th and 26th, June 2nd (Figure 8.26) and 9th. Only two new avalanches could be identified in this period, the avalanche at Y and a shallow slab avalanche on the flanks of cone D. Both occurred between May 16th and 26th. The major avalanche affecting the sites in the protalus area (Figure 8.28) is not visible on any of these photographs; either it occurred between June 9th and July 9th or it was buried by later snow.

These observations suggest that most of these avalanches took place while the scree was still snow-covered and originated in the cliffs. Although many small streams flowed onto the snow-covered slope, most rapidly melted their way to the scree below and slush avalanches were restricted to a small area near the apex of the cones. Most of the snow had disappeared by July 9th, a month earlier than in 1968.

There were numerous deposits of clean avalanche snow at this site

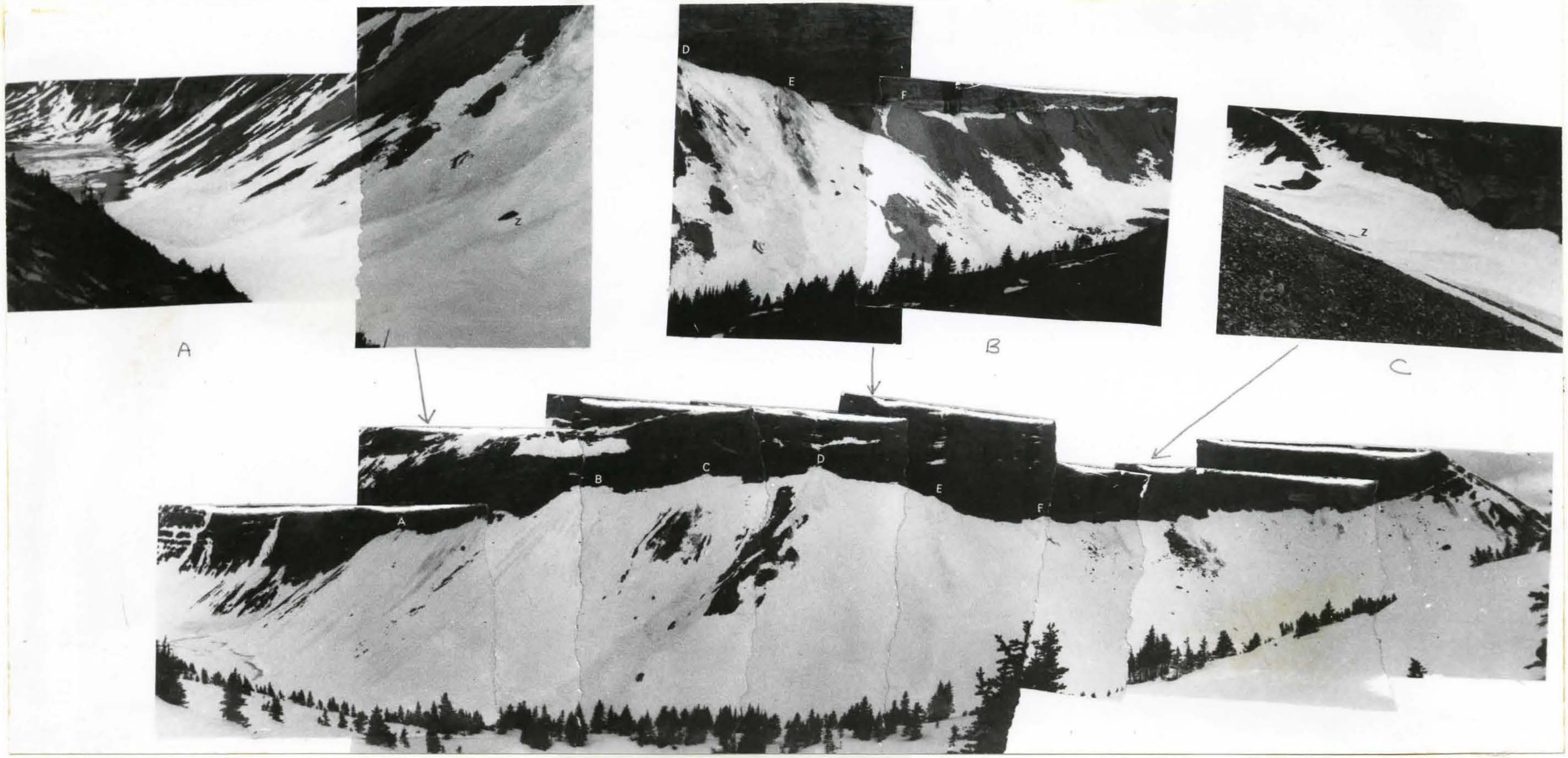

Figure 8.27 The Surprise II site, May-June 1970. The large mosaic was taken on the 18th May and the three others (A, B and C) on the 18th June. The outline of the main avalanches can be discerned by differences in tone in the earlier photograph, including a slab avalanche which has bared the flank of cone D. The surface concentration of ablated debris produces the darker colour in the upper photographs. The crest of the protalus rampart is just visible in inset C. The ridge is 8-10 m high at this point indicating the great depth of avalanche snow at the base of the scree.

on August 9th, following the storm of August 5th, 1969. Only seven sites showed fresh debris when they were checked on September 21st. Most of these were close to the cliff and except for a boulder of 0.02 m^3 (on boulder 95) none of them exceeded 200 cm/m^2. These results were combined with the earlier totals since a few sites could not be cleaned prior to the avalanche due to their snow cover.

The pattern of deposition in 1970 was quite different to those of the two previous years. Although there were some linear dirty avalanches, most of the scree was covered by a few large avalanches carrying only small amounts of debris. Small snow scarps near the cliff and "clasts" (rectangular blocks showing stratification) in the avalanche snow indicate at least one major slab avalanche on cone D. However, the even spread of the larger avalanches and the subdued ridge at their base (Figure 8.27, inset C) suggests they consisted of fairly wet snow whilst the character of their deposits (see below) is more typical of an avalanche sweeping loose debris from the cliff. Detailed examination of the photograph reproduced as Figure 8.27 indicates that the slab avalanche is later than the other major avalanches. In some parts of the basal area of the scree, the hard packed avalanche snow was 6 to 8 m deep and, although the summer was one of the hottest and driest on record, several of the sample sites were still covered by 1 to 2 m of snow on August 22nd.

Only isolated patches of the snow cover remained when the site was visited in 1971 and 1972. These were mainly at the apices of cones and yielded no information about the overall characteristics or extent of avalanches in these years.

The detailed accumulation data are presented in Figures 8.28 and

8.29 which show the spatial distribution of deposition and the relationship between the volume of accumulation and the distance from the cliff for each year. They also show the mean annual accumulation which is calculated by dividing the total accumulation by the number of years of observation and correcting for sample site area. These data include the results from those sites which could not be measured in every year because of late-lying snow cover, high water levels, etc.

1969

Nearly 70% of the sites recorded deposition (Table 8.10), although there was considerable variation between the different parts of the site. Deposition was most variable in the basal area and depended upon the position of the terminal zone of avalanches and their debris content. Almost half (51) of the 108 sites in this area had no accumulation. There were two main areas of avalanche deposition, near the protalus rampart (see below) and along the base of cone C (boulders 118-138) where a debris-covered snowpatch remained until early September and two boulders were moved by avalanches. Scattered deposition also occurred on some of the higher sites near the base of cone D (boulders 38-50, squares 1-3).

A large dirty avalanche deposited considerable debris near the protalus rampart (boulders 51-75). Contrary to the overall trend (see Figure 8.29), these sites show a direct relationship between the volume of deposition and distance from the cliff. When allowance is made for the sites which are peripheral to the main depositional area or affected by other avalanches (see Luckman, 1971, p. 105 and Figure 8[1]), the

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[1]The estimates of volume given in this paper are not corrected for particle shape. However, the general relationships are not altered

TABLE 8.10: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE SITES AT SURPRISE II

(A) SAMPLE BOULDERS

Class Limits	1969	1970	1971	1972	Mean
No accumulation	22.6	7.7	31.8	45.7	2.3
Less than 0.0	9.7	1.3	3.3	6.0	2.3
0.0 - 0.5	7.1	2.1	8.9	2.6	2.7
0.5 - 1.0	4.5	8.1	13.2	2.1	7.7
1.0 - 1.5	11.0	11.5	11.2	4.7	20.7
1.5 - 2.0	5.8	26.0	10.7	9.8	14.9
2.0 - 2.5	7.1	20.0	5.1	7.7	17.6
2.5 - 3.0	12.3	11.5	6.1	8.1	13.8
3.0 - 3.5	10.3	6.4	2.3	7.3	9.6
3.5 - 4.0	5.2	3.8	3.7	3.8	4.2
4.0 - 4.5	1.3	1.3	1.4	2.1	3.1
4.5 - 5.0	1.3	0.4	1.9	0	0.8
5.0 - 5.5	1.9	0	0	0	0.4
Number of Sites	155	235	214	234	261
Mean accumulation (includes squares)	2.08	0.97	0.94	0.58	0.98

(B) SAMPLE SQUARES

Class Limits	1969	1970	1971	1972	Mean
No accumulation	26.7	0	0	15.0	3.0
Less than 0.0	0	3.8	0	5.0	0
0.0 - 0.5	6.7	7.7	5.0	0	3.0
0.5 - 1.0	6.7	7.7	5.0	0	6.1
1.0 - 1.5	20.0	15.4	10.0	10.0	12.1
1.5 - 2.0	6.7	23.1	20.0	25.0	9.1
2.0 - 2.5	0	23.1	25.0	15.0	27.3
2.5 - 3.0	6.7	11.5	25.0	20.0	18.2
3.0 - 3.5	6.7	0	5.0	10.0	12.1
3.5 - 4.0	20.0	7.7	5.0	0	9.1
Number of Sites	15	26	20	20	33

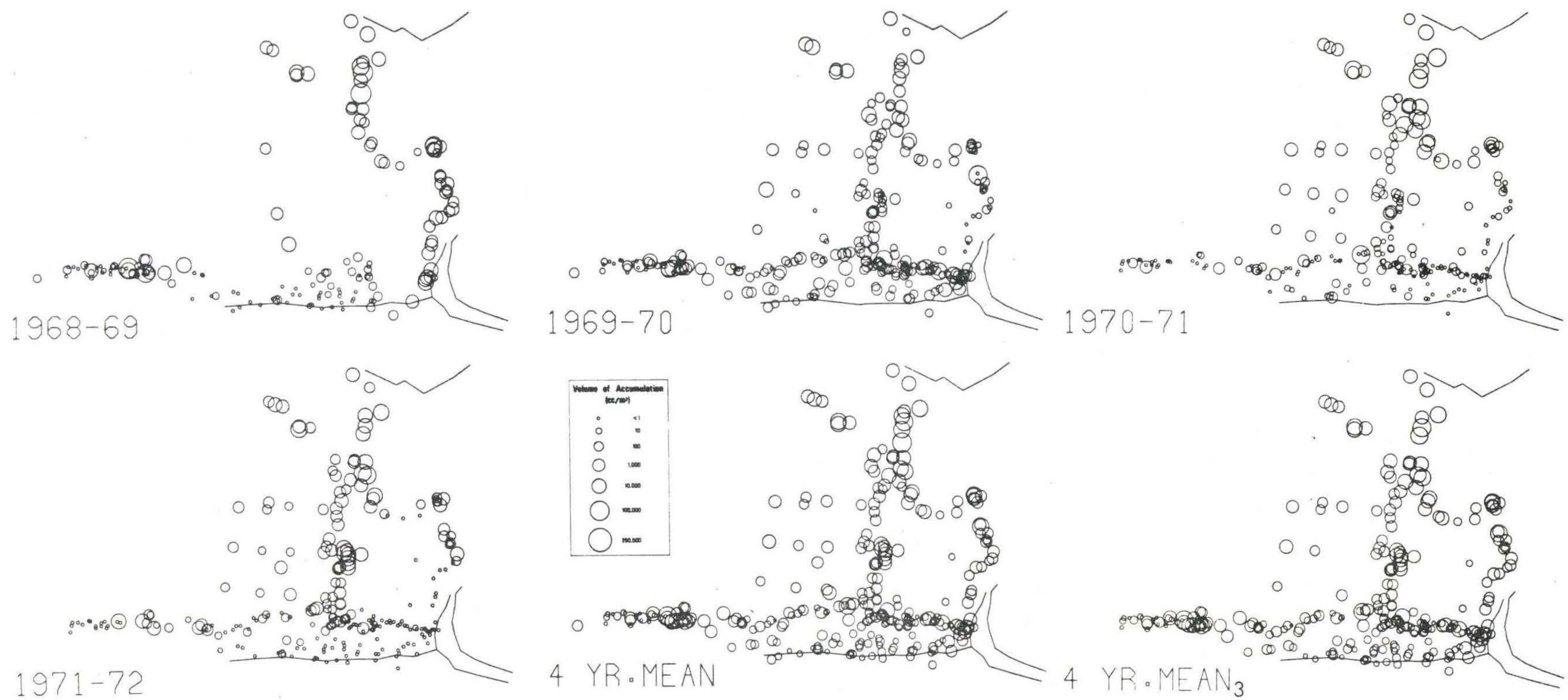

Figure 8.28 Pattern of debris accumulation at Surprise II,1968-1972

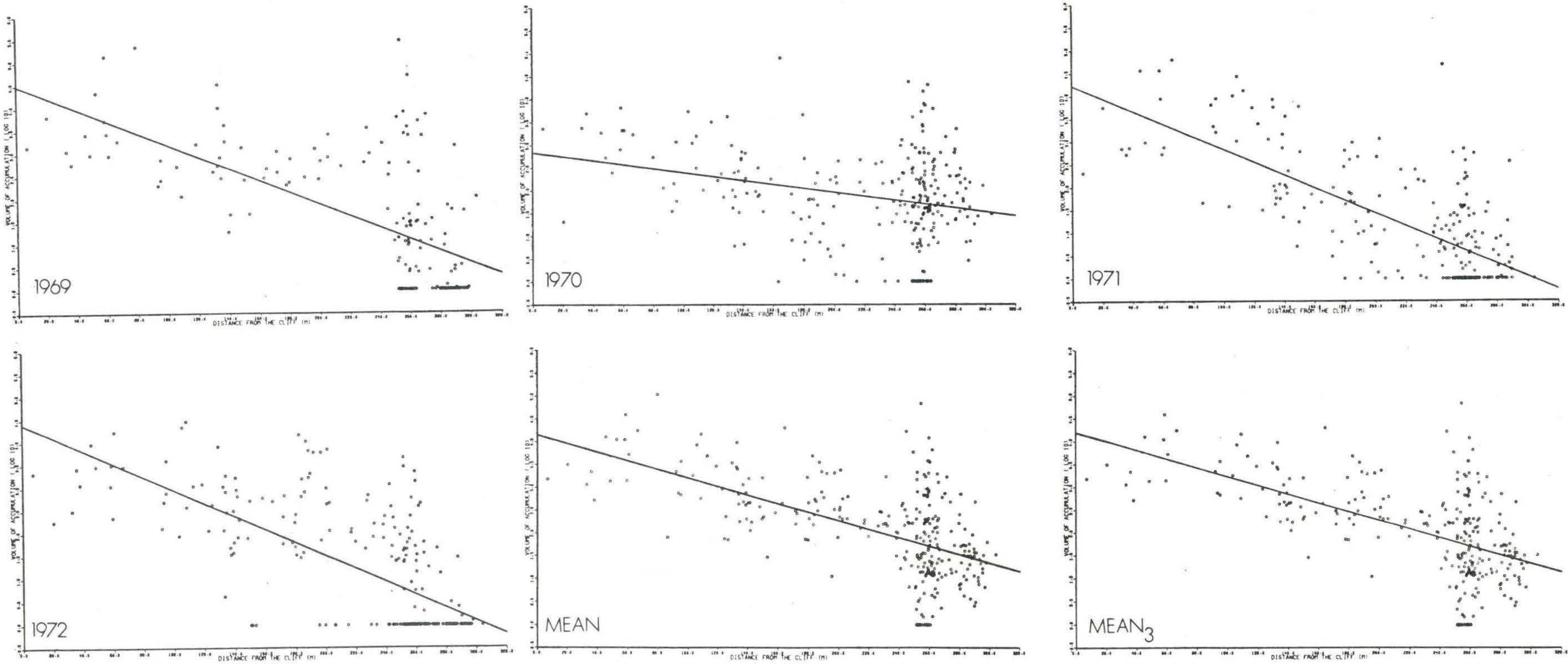

Figure 8.29 Relationship between volume of accumulation and distance from the cliff at Surprise II

correlation coefficient between deposition ($\log_{10}$) and distance from the cliff is 0.7537. It is, however, possible that this result is merely a random effect. A sample metre quadrat on the coarsest section of a heavily debris-covered snowpatch, 10-15 m south of boulder 60, yielded an estimated volume of 70,000 cc/m^2 (about 15 times greater than the largest figure of the sample sites). The great lateral variability shown by this estimate is typical of avalanche deposits and underlines the problems of extrapolation from a small number of sample sites.

The sites on the upper slopes (82-110) show a poorly marked trend of increasing deposition towards the cliff. This is due to the presence of debris from small avalanches and rockfalls which do not travel far down the slope. However, if the three largest values are excluded (two are single large boulders, the other has a very small sampling area) the slope of the regression line becomes almost zero. This result is a reflection of sample design rather than the absence of deposition close to the cliff. The only boulder site within 20 m of the cliff (103, 102 was lost) is small and has a steep surface slope. However, evidence from late lying snowpatches (e.g. Figures 8.30 and 8.31) indicates there is considerable deposition in this area, especially on the apices of cones.

The profile of squares was covered by avalanche X (Figure 8.25; also, see Luckman, 1971, Figure 6) and the upper squares destroyed (Table 8.11). Sixty-three marker boulders from these squares were found near the sites of squares 3 and 4 and another (probably from square 8) 50 m

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by the volume conversion (compare Figure 8a with the relevant portion of Figure 8.29) and the correlation coefficients are similar.

Figure 8.30 (right) Avalanche and rockfall debris at the apex of Cone D, Surprise II. The upper edge of the dirtier snow-bank has been melted by the stream which descends the cliff at this point. The snow cliff is about 2 m high.
13th July 1970.

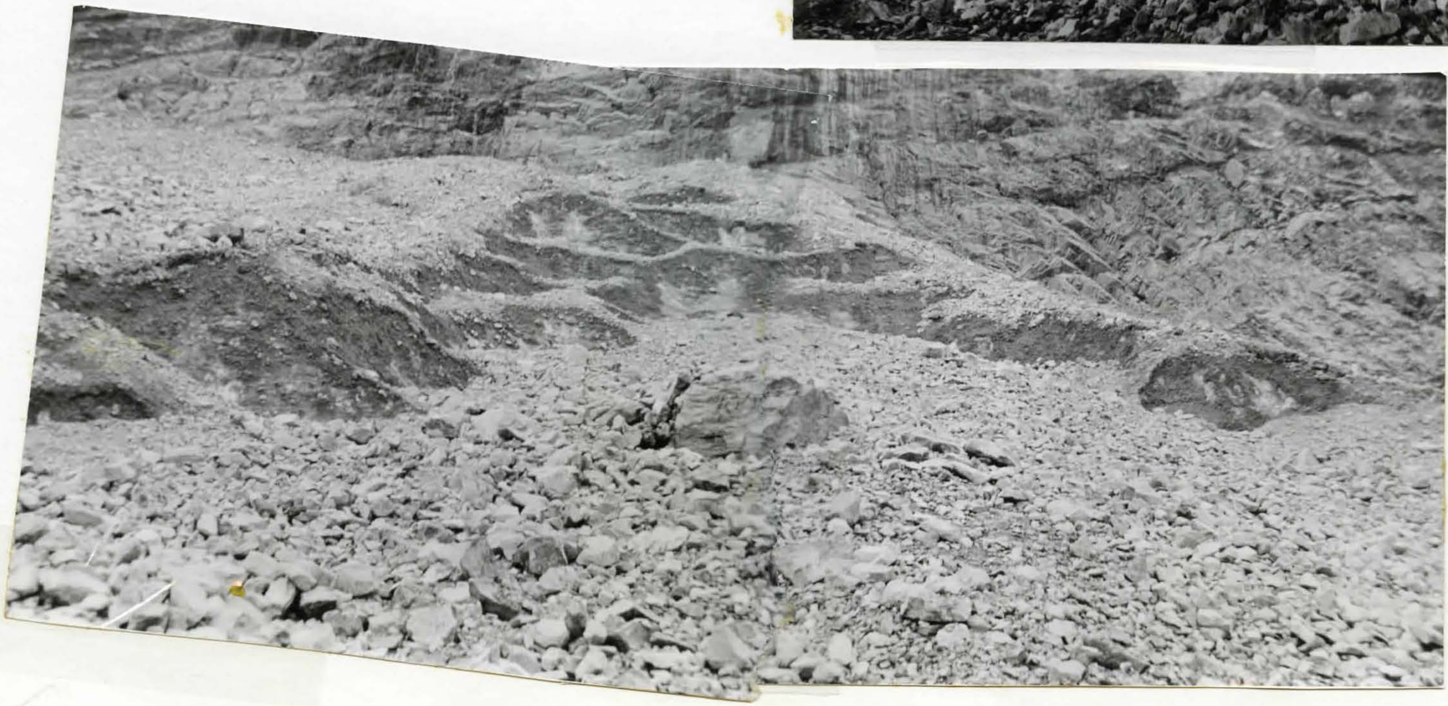


Figure 8.31 (left) Ablating remnants of the dirty avalanche at the top of Cone E, Surprise II. The buried snow cliff is 1.5-2.0 m high and the deposit extends back over 40 m to the cliff. The larger boulder in the fore-ground is boulder 100 which is about 1 m high. 16th August 1971.

further south (Figure 8.32). The original number of marker boulders on these squares was not recorded but allowing an average of 25 per square, 76 were recovered (including those remaining on squares 6 and 7) of the 100 on the main profile. The areal concentration and pattern of these boulders suggests they were all eroded and deposited by the same avalanche.

TABLE 8:11: RESULTS FROM THE PROFILE OF SAMPLE SQUARES AT SURPRISE II IN 1969

Square	Distance From Cliff (m)	Area Sampled (m^2)	Boulders Remaining	Deposition (cc/m^2)
1	288	2.32	all	55.3
2	232	2.32	31	3480.4
3	200	2.32	29	673.5
4	154 (est.)	0.22	0	820.0 (approx.)
5	110 (est.)	-	0	no trace
6	70-80 (est.)	0.60	8	675.0 (approx.)
7	30	-	5	no polyethelene
8	30	1.15	about half	6640.0 (approx.)

NOTE: Distance estimates are made from available survey data and field notes.

Two lines, each 2 to 3 cm wide and 10 to 15 m long, were painted on the scree surface near square 8 and boulder 110 in August 1968. By July 1969, the upper line had almost completely disappeared except where it was painted on large boulders and only 4 m of the lower line remained. The rest of this line, together with the anchor boulder (0.3 m^3) had completely disappeared and numerous fragments, marked with red or green paint, were found scattered over the area of avalanche deposition (Figure 8.32).

1970

The most striking feature of these results is that 69% of all the sample boulders and 73.1% of the squares received between 10 and 1000 cc/m^2 of debris (the corresponding figures for 1969 are 36.2% and 33.3%). This uniform spread of debris is also shown by the fact that only 21 sites (9.0%) had less than 1.0 cc/m^2 of debris. Thirteen of these sites are in the area close to the lake (138-160) which was not affected by the main avalanches but received deposition from cone B. Two other sites were at the toe of a calving snow cliff (134, 133) and thus never received ablating debris and another four were in the protalus area (60, 61, 63 and 75) at the other edge of the main avalanches.

With the exception of these two areas, the rest of the lower part of the scree was covered by two or possibly three large dirty avalanches which deposited an even spread of fines, small rock fragments and occasional larger boulders. Almost all the sites had some debris and the major source of variation between the sites was the presence or absence of one of the larger fragments distributed randomly throughout the depositional area. This inference is supported by observations on the ablating snow during sampling and the thorough mixing of debris, its general calibre and fresh appearance (see Figure 9.1) all suggest it is mainly derived from the cliff zone. The deposition of material eroded from the scree occurred mainly in the terminal zone of the slab avalanche at the base of cones C (boulders 135, 136, square C) and D (see Figure 8.33).

There was also some rockfall deposition in this lower area. Two

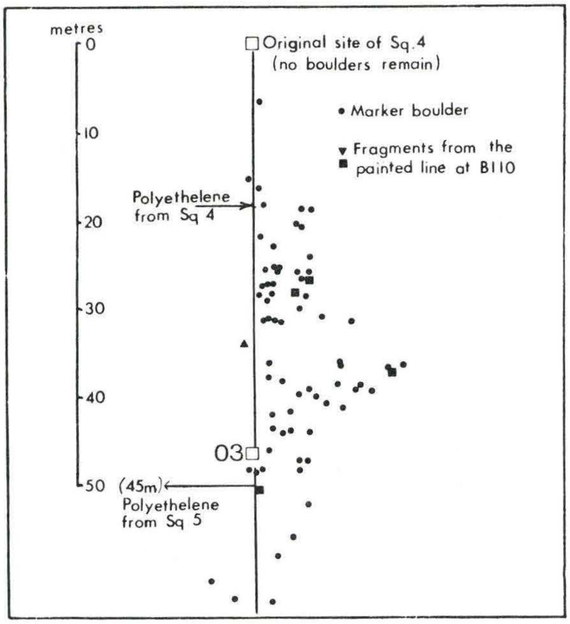


Figure 8.32 Displaced marker boulders from squares 4–7, Surprise II 1969

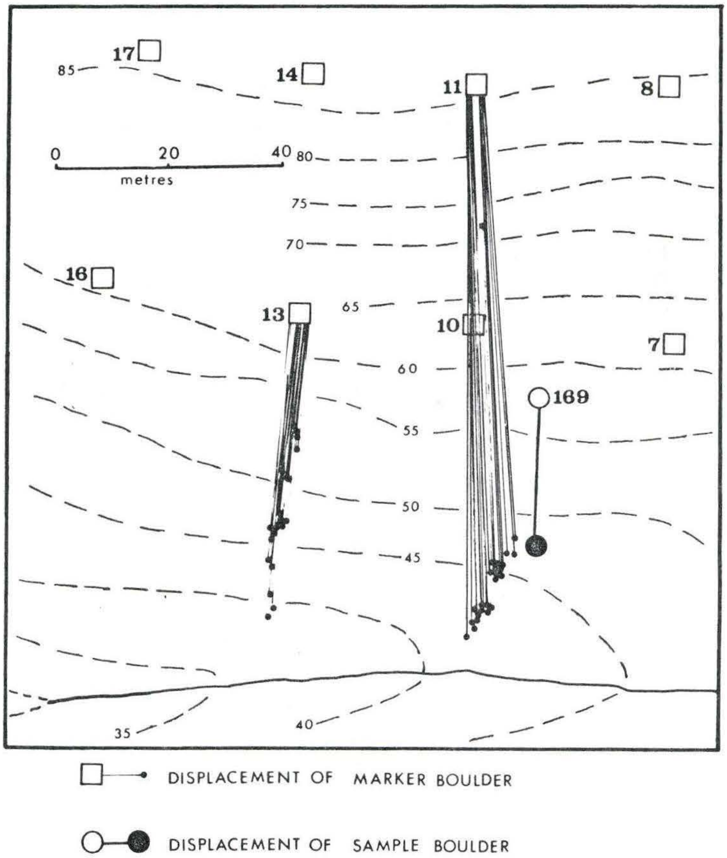


Figure 8.33 Movement of marker boulders from squares at Surprise II in 1970

freshly bruised boulders were found on snow near boulder 171 (0.05 m^3) and boulder 245 (0.2 m^3) whilst the large boulders on sites 39 (0.028 m^3), 74 (0.022 m^3) and 239 (0.005 m^3) probably arrived in a similar manner.

Figure 8.29 indicates that there is, however, a greater tendency for the upper sites on the slope to have more high values of accumulation. If the basal sites are excluded, the sites in the upper 235 m of the scree (61-110, N178-204 and the upper two lines of squares) show a general trend towards increasing deposition upslope (correlation coefficient -0.5047, n = 93). This trend is more marked in the older sites (61-110, correlation coefficient -0.6958, n = 49) which were affected by smaller dirty avalanches on cones D and E (see Figure 8.26). The newer sites (N178-204) were mainly in the area covered by the main avalanches.

The results from the squares are similar to the results from the boulder sites in the same area. Five of the new squares were damaged and two completely destroyed (Table 8.12). Squares 15 and 17 each lost marker boulders from one side of the square and square 1 lost the markers from the top, most of which merely rolled to the base of the square. The nature of the damage to these three squares suggests either that the markers were initially unstable or were dislodged by rockfall impact.

All the displaced marker boulders from the destroyed squares were recovered, mainly due to the concentrated depositional pattern (Figure 8.33). The polyethelene of square 11 was also found intact, with only a few small tears and anchored by some of its marker boulders. These two squares were both within the area affected by the slab avalanche which was most probably the erosional agent since all the other squares (although covered by the large dirty avalanches) were unscathed. However, even within the track of the slab avalanche, erosion was discontinuous since the avalanche carried the boulders of square 11 directly over square 10 before depositing them at the base of the slope.

TABLE 8.12: RESULTS FROM THE NEW SQUARES AT SURPRISE II in 1970

Number	Marker Boulders Original	Lost	Recovered	Deposition (cc/m^2)	Comments
1	25	3	0	29.7	No search for boulders
2	26	0	-	5.1	
3	22	0	-	80.8	
4	21	0	-	19.4	
5	21	0	-	242.4	
6	23	0	-	159.6	
7	23	0	-	140.5	
8	27	0	-	64.2	
9	26	2	2	88.0	Boulders just below square
10	22	0	-	40.9	
11	22	22	22	-	Totally destroyed
12	24	0	-	474.6	
13	21	20	20	-	Totally destroyed
14	21	0	-	26.0	
15	21	5	0	185.4	No search for boulders
16	25	0	-	94.8	
17	23	6	0	4571.5	No search for boulders
18	23	0	-	512.8	

1971

Although the mean annual accumulation figures for 1970 and 1971 are almost identical (Table 8.10), the depositional patterns are quite different. In 1971 over 70% of the sites had less than 100 cc/m^2 deposition, half of these having less than 1 cc/m^2. Nearly all the latter group are in the two basal traverses where deposition was sporadic and light; apart from the single large boulder (0.01 m^3) on boulder N171 none of the basal sites had more than 1000 cc/m^2 accumulation. These results, together with observations on vestigal snowpatches, indicate that those avalanches which reached the basal area were fairly clean and carried few large boulders.

The network of squares and lower parts of the profiles showed a similar range of deposition, although most of the sites (except those near the protalus area) had some accumulation. The main area of deposition was in the upper half of the slope where many of the boulders were almost covered with avalanche deposits. The remains of two avalanches were clearly visible near the apex of cone E. One of them was so dirty that the main form was preserved by differential ablation and formed a debris-covered snowbank 1.0-1.5 m high with many of the characteristics of dead ice topography (Figure 8.31). The debris cover on this snow was 10-20 cm thick and consisted of a heterogeneous mixture of debris with a lot of fine material and an estimated solid volume of 15-30 m^3. The nature and position of this deposit clearly indicate that it is a primary input of fresh debris to the scree from the cliffs.

Several of the upper sites were covered by this deposit (boulders 93-97, 100), others were outside its limits (99,101,103) resulting in rapid lateral contrasts in the volume of deposition. In the same area, boulder 98 was moved about 30 m downslope and boulder 95 disappeared and may have been buried. Similar volumes of deposition extend down to boulders 80 and N199, although this deposition may be from a different source.

The overall pattern of deposition for 1971 clearly shows a strong inverse relationship between deposition ($\log_{10}$) and distance from the cliff (correlation coefficient -0.7288, n = 233, Figure 8.29) due to the absence of heavy avalanche deposition at the base of the slope. Also, except for the two boulder sites at the top of the slope, there is no direct evidence of erosion on the scree since all the squares were intact.

1972

There was less deposition in 1972 than in any of the previous four years. Over half the sites had less than 1.0 cc/m^2 accumulation. Most of these were in the two basal transects where over 75% (122/161) had no accumulation. Avalanches reached the basal area in two places, on the lowest flanks of cone D (boulders 6-12, N210-217) and at the base of cone C (boulders 115-143, N150-153 and squares B and C). Although sites 128-142 were water-covered in 1971, most of the deposition measured on these sites in 1972 is thought to be from the latter year.

The main depositional area covered the upper and middle parts of the profiles extending downslope to boulder N175. The debris cover on several of these sites is similar to that observed on the dirty avalanche in 1971 and the similar (although smaller) debris-covered snowpatch at the top of the slope in 1972 was probably a remnant from the previous year covered with additional fresh debris.

A smaller avalanche affected the most northerly sites (boulders 65-82) with freshly ablated fine debris extending upslope from boulder 80. This was the only deposition in this area of the scree, even including squares 1-3. The other squares on the lower flanks of cones D and E all had small to moderate amounts of deposition (29-1707 cc/m^2). All were unaffected by erosion, although the polyethelene from square 4 had been eaten.

The overall correlation between deposition ($\log_{10}$) and distance from the cliff is similar to 1971 (correlation coefficient -0.6956, n = 253), but a brief inspection of Figure 8.29 indicates this is largely because of the large number of sites with no accumulation at the base of the slope. When these basal sites are excluded, the overall relationship is weaker reflecting the transport of more material further down the slope in 1972 (correlation coefficient -0.4108, n = 99).

Summary and Conclusions

The Surprise II site is the largest and most complex of the screes studied, both in terms of the variety of processes and scree form. The sample sites extended over a wide area, particularly at the base of the screes, and there was great variation in the observed pattern, amount and character of avalanche activity (Figures 8.25 to 8.27). Most of the avalanches were wet snow avalanches from the cliffs, although a few slab avalanches were seen on the screes themselves.

During the four year period, fewer than 5% of the sites (12/261) recorded less than 1.0 cc/m^2 deposition. Most of the these (9) came from the same area, the transect along the lake shore on cone B (boulders 145-157). The relatively low mean accumulation figures (vis à vis other avalanche dominated sites in Surprise) reflect the large percentage of basal sites and the lower volumes of avalanche erosion noted at this site.

Since many of the observed avalanches did not reach the lowest slopes, the basal sampling bias considerably reduces the overall mean. Depositional values for the upper half of the slope are much larger (Table 8.13) and comparable with means from other avalanche sites. The apparent reversal of this pattern in 1970 and, to a lesser extent, in 1969, is due to the presence of several large rockfall boulders in the lower part of the scree.

Apart from 1968, the greatest amount of deposition occurred in 1969 when a major avalanche extended into the protalus area. In 1970, deposition was extensive but light (except for a few rockfalls) and consisted mainly of small amounts of debris swept from the cliffs. The last two years (1971 and 1972) saw little accumulation in the basal zone and deposition was concentrated on the upper sites, particularly in 1971. The least amount of deposition occurred in 1972.

Over the four year period, there is an inverse logarithmic relationship between the mean volume of accumulation and distance from the cliff, similar to that seen in the individual years (Figure 8.29). In the basal areas, deposition is sporadic, depending upon the location and debris content of the avalanche termini. Only one area, at the base of cone C (boulders 114-136, squares B and C), received marked deposition in more than one year. This great variability produces a very wide scatter of points for accumulation in the basal areas and lower slopes. An analysis of variance performed on the results from the network of squares on the lower slopes of cone D indicated an absence of any overall spatial trends in the mean accumulation over the three year period (Table 8.14).

TABLE 8.13: SUMMARY ACCUMULATION DATA FOR SURPRISE II BY ZONES

AREA SAMPLED (m^2)

Distance from the Cliff	1969	1970	1971	1972	Total
0 - 50 m	5.50	5.50	5.98	5.98	23.92
50 - 100 m	4.17	4.36	4.11	4.03	16.64
100 - 150 m	5.72	21.48	21.21	21.21	69.80
Subtotal, upper half of the scree	15.39	31.34	31.30	31.22	110.36
150 - 245 m	10.80	49.42	51.56	47.90	160.04
245 - 304 m (Basal transects)	80.73	79.90	55.77	71.55	350.66
TOTAL	106.92	160.66	138.63	150.67	621.06

VOLUME OF ACCUMULATION (mm/year thickness or $cc/m^2 \times 10^{-3}$)

Distance from the Cliff	1969	1970	1971	1972	Mean
0 - 50 m	1.37	1.88	4.67	2.07	2.44
50 - 100 m	13.51	0.82	9.08	1.40	6.17
100 - 150 m	5.50	0.41	2.08	1.76	1.74
Subtotal, upper half of the scree	6.20	0.72	3.49	1.77	2.56
150 - 245 m	1.37	0.78	0.40	0.57	0.63
245 - 304 m (Basal transects)	1.39	1.18	0.002	0.007	0.63
TOTAL	2.08	0.97	0.94	0.58	0.98

NOTE: The four year totals and means include those sites which were missed during any season (due to snow cover, etc.) and sampled the following year.

Sites Used:		
	0- 50	boulders 99-103, 107-109
	50-100	boulders 92-98, 104-106, N203-204
	100-150	boulders 76-91, 110, N195-202; squares 6, 9, 12, 15, 18
	150-245	boulders 60-75, N171-N194; squares 02, 03, 1-5, 7, 8, 10, 11, 13, 14, 16, 17
	245-304	all remaining sites

TABLE 8.14: RESULTS OF AN ANALYSIS OF VARIANCE TEST ON THE THREE YEAR MEAN ACCUMULATION VALUES FOR THE NETWORK OF SQUARES AT SURPRISE II

Source of Variation	D.o.F.	Sum of Squares	Mean Square	F	F_{95}
Between columns	5	9101267.49	1820253.50	2.28	3.11
Among rows	2	4105193.76	2052596.88	2.57	3.88
Error	12	9572139.51	797678.69	-	-
TOTAL	17	22778600.76			

Higher up the slopes, avalanche deposition is more consistent and involves larger amounts of debris. Despite the scatter of points, there is a general increase in deposition upslope except for the topmost sites (Figure 8.29, Table 8.13). However, snowbank deposits indicate that maximum deposition (avalanches and rockfall) occurs close to the cliff and this decrease probably reflects the relatively small size and steep surface slopes of available sample boulders in this area.

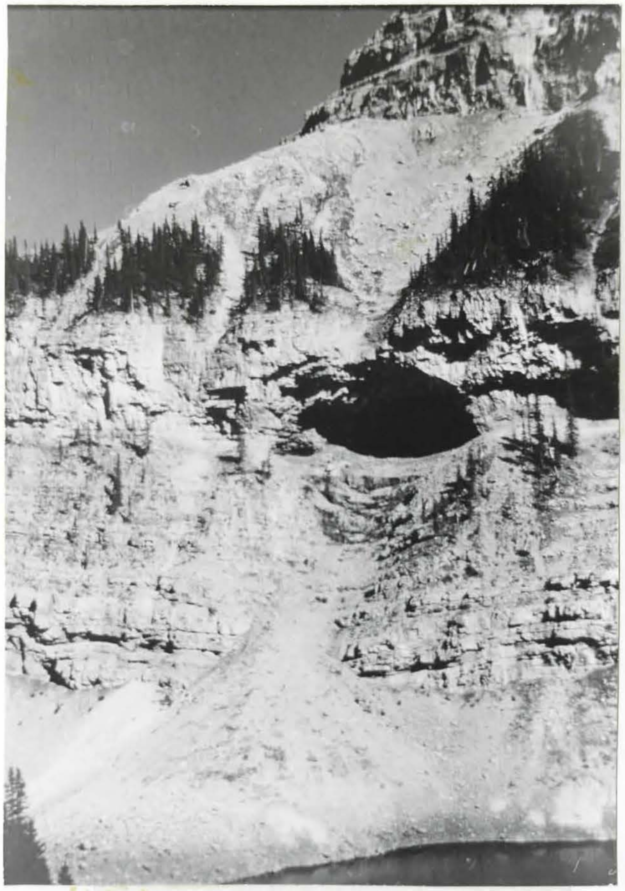
Avalanche erosion was only observed in the first two years, associated with the networks of squares. The erosional zone in 1970 was at approximately the same height as the deposition in the previous year, indicating an overlapping pattern similar to those seen elsewhere. The limited extent of avalanche erosion observed may be a function of the small number of sites in the erosional zones but inventory observations indicate avalanche erosion of the scree is not as frequent at this site and much of the avalanche debris is transported onto the screes from the cliffs (e.g. 1970, 1971).

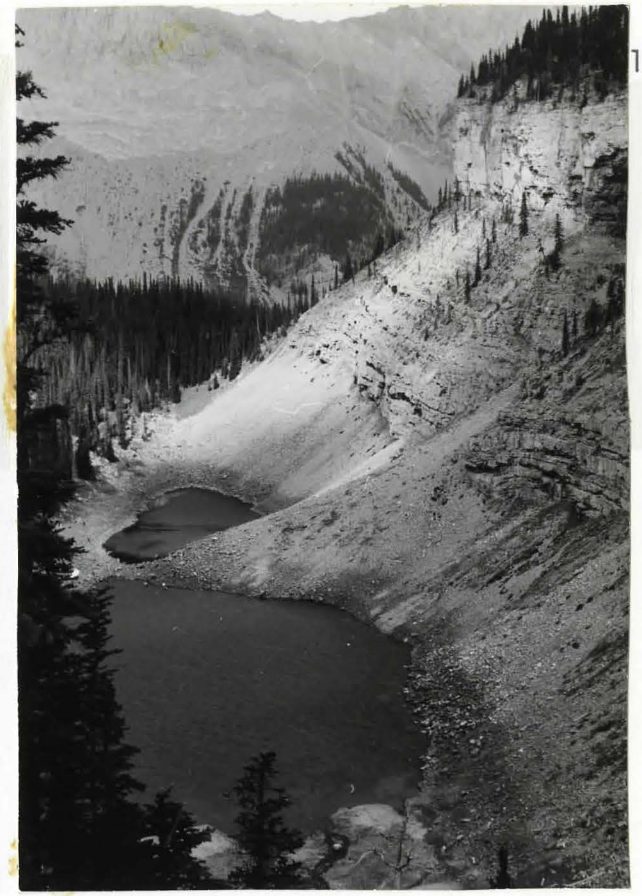
The lack of concentrated avalanche activity in well defined tracks on the scree accounts for the absence of well developed avalanche forms at this site. Avalanche activity is too diffuse and variable in position to produce avalanche tongues like that at Old Nip. However, it is possible to distinguish several areas of "smooth" stable scree surface which end in breaks of slope 1.0-1.5 m high, running obliquely across the slope. The deposition from square 11 in 1970 follows the base of one of these features (Figure 8.33) which is probably a poorly developed roadbank tongue. Such incipient tongues may be easily distinguished from the areas of predominantly avalanche deposition which resemble the avalanche apron area at Old Nip and are characterized by many "balanced boulders" and marked surficial instability.

TUMBLIN' CREEK

Lake Helen is flanked on two sides by screes from massive cliffs of Mississippian Limestones and on the third by the rockslide which impounds the lake. These cliffs have been eroded into a series of vertical faces and more gently sloping benches (Figures 8.35 and 8.36). The major cliffs are formed by the Pekisko and parts of the Turner Valley Formations; smaller cliffs occur in the limestones of the upper part of the Banff Formation, just above the screes (Figure 8.34).

The main site at Tumblin' Creek is a large avalanche cone which divides Lake Helen into two parts when the lake level is low (Figures 8.34 and 8.35). The cone is situated below a long avalanche chute (Figure 8.34) which begins above the Turner Valley cliff and has cut a wide rounded gully across the debris strewn bench above the Pekisko cliff. At the head of the throat of the cone is a large frost pocket related to a spring at the Pekisko-Banff junction. This area and the small benches





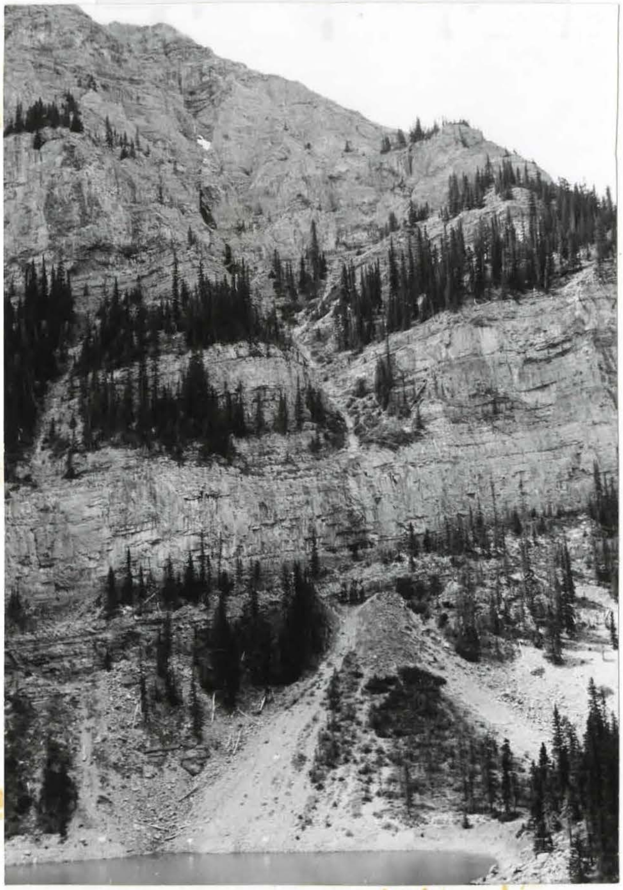


Figure 8.34 (above, left)
The Tumblin' Creek Cone from the west. The avalanche track begins above the Turner Valley cliff (top) and continues down the debris covered chute and over the Pekisko cliff. Note the large frost pocket at the base of the cliff and the smaller chute to the left. August 1971.

Figure 8.35 (above, right)
The Tumblin' Creek Cone from the south. The vertical cliff is the Pekisko limestone underlain by the upper part of the Banff Formation. The Tumblin' Creek delta is in the foreground. 4th August 1969.

Figure 8.36 (left)
The cone on the west side of Lake Helen. The cone is below a major avalanche chute and has avalanche tracks on each flank. The squares are, from left to right, old 10, 11, 12 and 20 (above).
22nd June 1970.

of Banff Limestones provide another major source of debris near the top of the cone. A small chute feeds the subsidiary cone on the north side of the main cone (Figure 8.34) and, although other small chutes occur, the remaining screes on the east side of the lake are basically straight.

On the west side of the lake, the partially vegetated screes are dominated by another large avalanche cone (Figure 8.36) situated below a major chute. Although this cone has considerable avalanche activity, relatively little debris is carried onto the cone and the vegetation limits erosion to two "runs" on the flanks of the cone. Further north (right on Figure 8.36), opposite the rockpile, are a series of coarse rockfall screes and beyond the limits of the valley the main cliffs of Mamma Mountain and Big Bend Mountain both have several well developed chutes and small avalanche cones.

Experimental Design

In 1968 a traverse of 167 sample boulders was set up around the lake with two additional profiles on the flanks of the main cone. Twelve squares were also set up, 8 on the cone (Figure 8.38) and 4 on the other side of the lake (see Figure 8.36). An additional 172 boulder sites were set up in September 1969 on the main cone, filling in gaps in the sampling network and adding a basal traverse. Another 11 squares were also set up, 10 of them on the cone (Figure 8.38). These additional sites give the cone an almost complete cover of sample sites except for a small central area where there are no available boulders.

Six lines of marked boulders were also set up in the throat of the cone in September 1969 in an attempt to obtain better estimates of

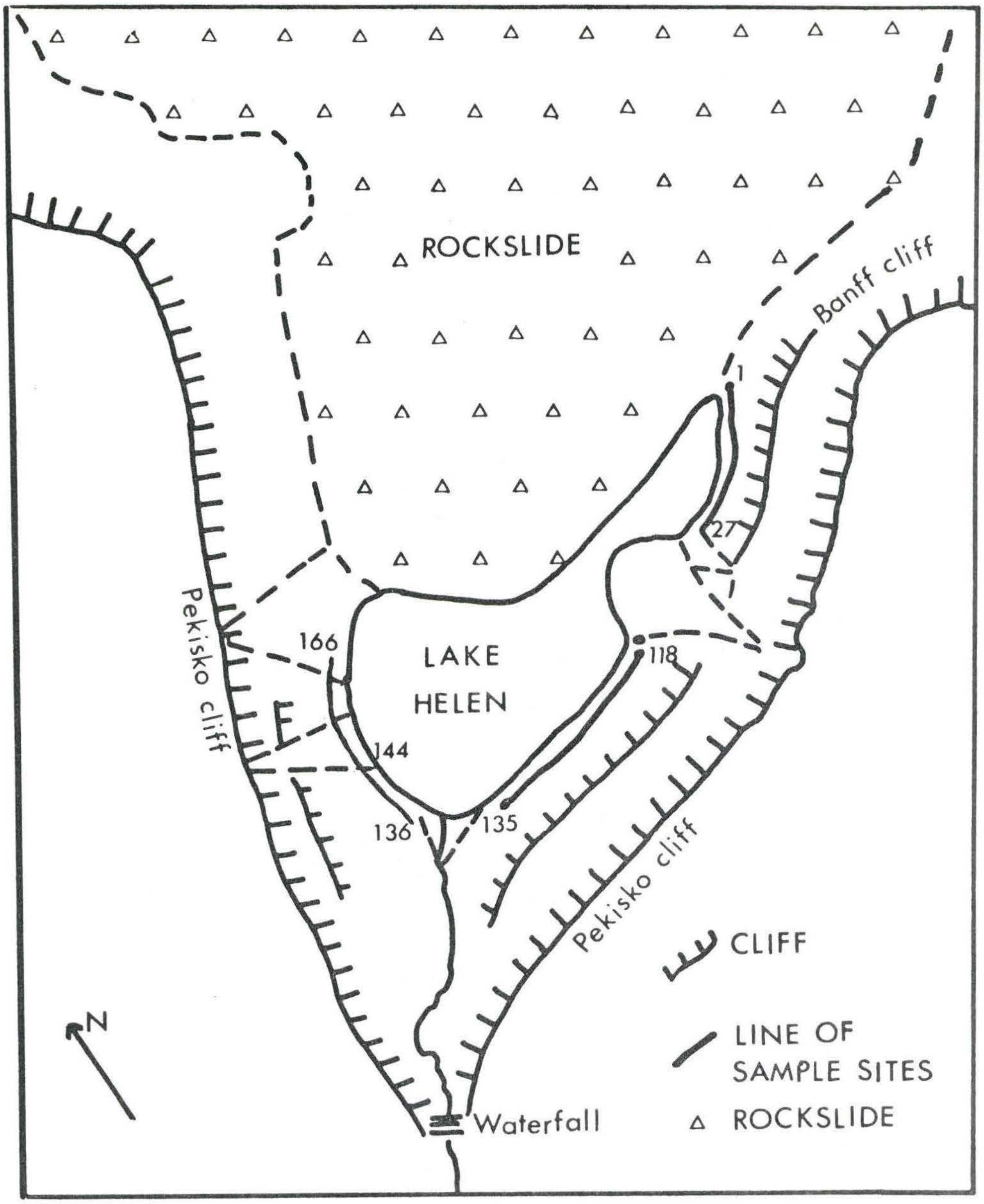


Figure 8.37 Plan sketch of the Tumblin' Creek site

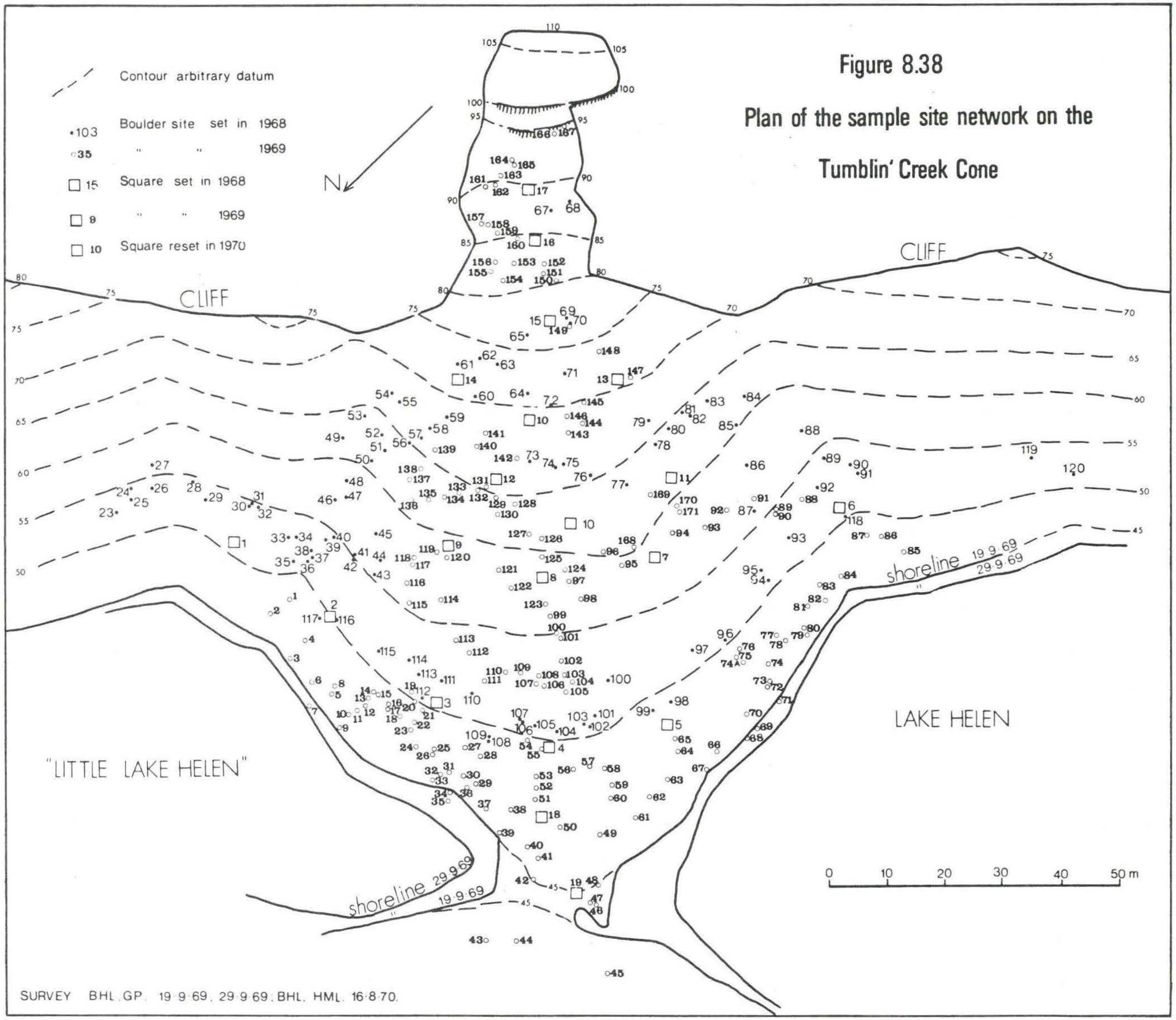


Figure 8.38

Plan of the sample site network on the Tumblin' Creek Cone

the erosion in that area. The boulders were set 0.5-1.0 m apart with paint marks on each of their major faces, a different symbol being used for each line. The position of these lines is shown in Figure 8.46.

Results

Unfortunately, the fluctuating lake levels at this site have prevented sampling of the lowest transects on the cone in 1971 and 1972, although it was possible to estimate volume on some of the underwater sites in the first year. Otherwise, apart from the destruction and movement of sample boulders and squares by avalanches on the cone this site has yielded excellent results. For descriptive convenience, this site may be treated as two distinct parts, the large avalanche cone (Tumblin' Creek Cone) and the remaining area.

The sites on the cone comprise boulders 28-88, 93-117, N1-N84, N88-N171 and squares 1-19 (see Figure 8.38). Although sites 28-32 are on the small cone, they are included with the main cone because that area was affected by avalanches running down the flanks of the main cone. Boulders 89-92 and N85-N87 lie on the straight scree and are not affected by deposition from the cone.

The Tumblin' Creek Cone

General Observations

This site is the most active of all the screes studied in Surprise and shows a wide range of intense erosional and depositional activity. When first visited on June 9th, 1968, the cone was partially covered with the remnants of a large dirty avalanche (Figure 8.39) which had covered the cone above the 45 m "contour" (Figure 8.38). This avalanche was

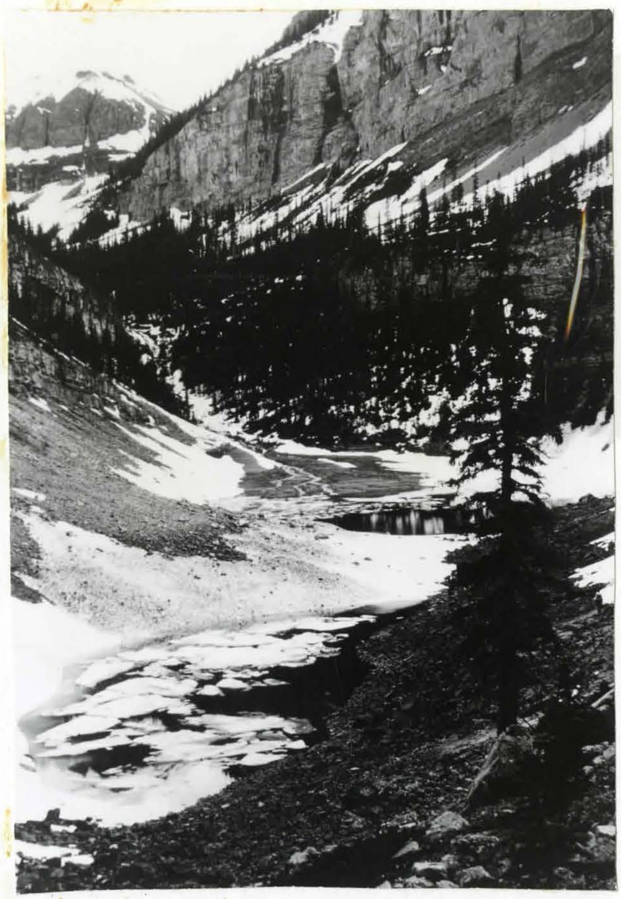


Figure 8.39 The Tumblin' Creek Cone, 9th June 1968. A large dirty avalanche covers the lower part of the cone (centre, left).

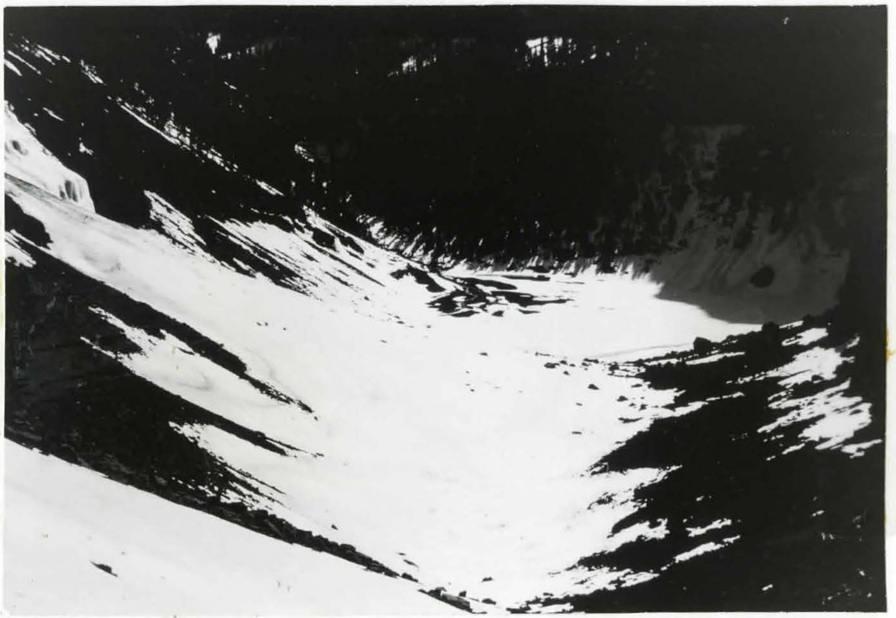


Figure 8.40 The Tumblin' Creek Cone, 10th May 1969. A small amount of avalanche deposition is visible near the apex of the cone and on the northern margin. Several dirty avalanches can be seen in the shadow on the other side of the lake which is just beginning to fill.

extremely dirty with debris ranging from fines to large boulders (see Luckman, 1971, Figure 4) and, although no estimate was made at the time, the photographic material suggests the remnant contained at least 10-20 m^3 of debris. Most of the debris could have been derived from the chute above the cliff or from erosion of the scree.

There was very little evidence of avalanche activity on the cone in the spring of 1969 (Figure 8.40). Most of the deposition was confined to the higher part of the cone, although a small avalanche containing fines ran part way down the runnel on the north side of the cone (Figure 8.40). Two small mudflows from the Banff benches had moved debris onto the snow- and ice-covered carapace at the top of the slope and some of the ablating debris in this area had also been redistributed by small slushflows (maximum displacement 3 m).

Little avalanche activity occurred at this site following the storm in August 1969. The site was visited on the 8th August and only eight sites had fresh debris, seven of them near the top of the cone (62, 64, 69-72). These data are combined with the 1969 data.

In 1970, the whole cone was covered by an extensive avalanche which spread 50-100 m beyond the shoreline (on Figure 8.38) over the summer lake bed and also extended up the slope almost to the trees opposite the cone (Figure 8.41). This avalanche eroded a lot of material from the cone and debris was spread throughout its deposits, particularly in the area close to the two boulder transects. Considerable deposition also took place on the lake floor, beyond the sampled area.

A second avalanche, or possibly two avalanches, travelled down the depression between the main cone and the smaller cone to the north,

Figure 8.41 The Tumblin' Creek Cone, 24th May 1970. Although the snow in the photograph is slightly overexposed, debris from the large avalanche can be traced over the whole area of the cone. Note the avalanches on the far side of the lake (also, see Figure 8.49).

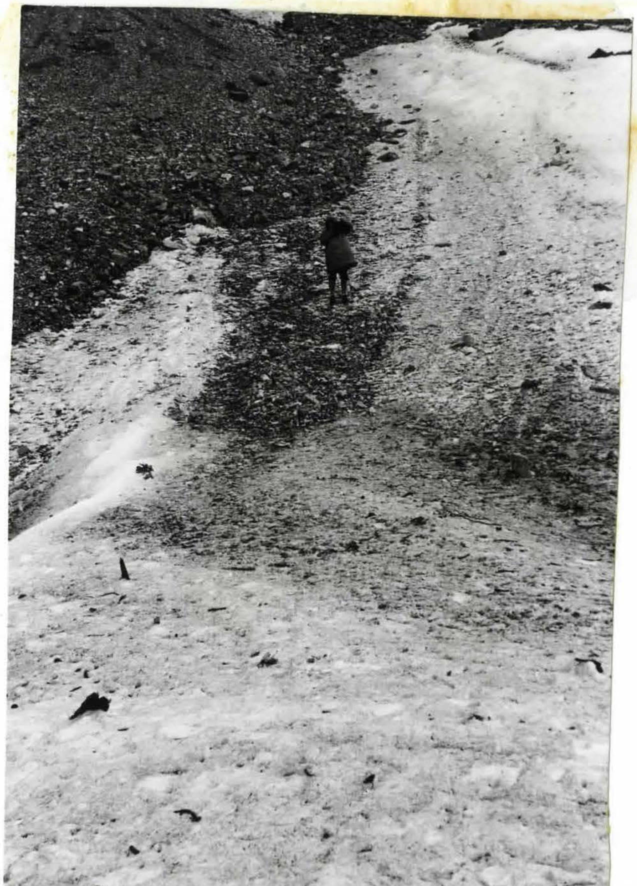


Figure 8.42 Detail of the avalanche debris on the north flank of the Tumblin' Creek Cone in 1970. The debris in the foreground is from the main avalanche, the heavier cover may be from a smaller avalanche. Square 1 is just off the photograph to the left of and at the same height as the figure. 29th May.

eroding the scree surface (Figure 8.42). This material was deposited on some of the sample sites and the collapsed ice cover of "Little Lake Helen". As the lake filled up with snowmelt, several icefloes were created which carried this debris back and forth across the lake before they melted and dumped their load. This avalanche eroded at least 2-3 m^3 of material from the higher parts of the scree.

No observations were made of the spring snow cover in 1971 or 1972.

Annual Accumulation Patterns

The detailed accumulation patterns for all four years are shown in Figures 8.43 and 8.44. Since many sites yielded debris on only one or two years (because of avalanche erosion and high lake levels in 1971 and 1972), two sets of means are shown in those figures and in Table 8.15. The first is the mean accumulation regardless of the number of years of record; the second (mean 3) uses only those sites with accumulation measurements for three years or more, to avoid undue emphasis on individual year's results in certain parts of the scree. The apex referred to in Figure 8.44 is an arbitrarily defined point on the low cliff in the centre of the cone on the "100 m" contour (Figure 8.38).

1969

This year showed the least amount of accumulation, most of which was concentrated on the sample sites on the upper part of the cone and in the runnel on its northern side. The avalanche extended beyond the higher sites but did not reach the lower transect (50-55 m "contour", see Figure 8.45). Only three of these lower sites have significant accumulation (boulders 44, 47 and 107) in the form of single large boulders possibly of rockfall origin. Because of the concentration of debris

TABLE 8.15: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE SITES ON THE TUMBLIN' CREEK CONE

(A) SAMPLE BOULDERS

Class Limits	1969	1970	1971	1972	Mean	Mean (3)
No accumulation	29.5	8.4	14.3	38.6	3.4	1.3
Less than 0.0	2.4	0.4	0.6	1.3	0.4	0
0.0 - 0.5	7.1	1.6	1.7	7.2	0.4	0.7
0.5 - 1.0	9.5	3.4	6.3	7.8	2.1	1.3
1.0 - 1.5	3.6	7.0	10.9	7.8	6.7	4.6
1.5 - 2.0	13.1	10.1	8.0	1.3	7.1	5.2
2.0 - 2.5	4.8	15.3	10.3	7.8	12.2	11.0
2.5 - 3.0	7.1	12.7	12.6	5.9	13.9	16.2
3.0 - 3.5	5.9	15.7	10.9	4.6	18.5	21.4
3.5 - 4.0	8.3	11.9	10.9	6.5	16.0	16.2
4.0 - 4.5	4.8	7.1	6.9	5.2	17.1	20.1
4.5 - 5.0	3.6	6.3	5.1	5.9	2.1	2.0
5.0 - 5.5	0	0.4	1.7	0	0	0
Number of Sites	84	236	175	153	238	154
Mean accumulation (includes squares)	2.53	5.70	7.62	5.38	5.61	6.06

(B) SAMPLE SQUARES

Class Limits	1969	1970	1971	1972	Mean	Mean (3)
No accumulation	0	0	12.5	0	0	0
Less than 0.0	0	0	0	0	0	0
0.0 - 0.5	14.3	0	0	16.7	0	0
0.5 - 1.0	57.2	0	0	50.0	0	0
1.0 - 1.5	0	11.7	12.5	0	5.3	0
1.5 - 2.0	14.3	5.9	25.0	33.3	15.8	20.0
2.0 - 2.5	0	11.7	0	0	15.8	20.0
2.5 - 3.0	0	23.4	0	0	21.1	0
3.0 - 3.5	14.3	11.7	12.5	0	10.5	20.0
3.5 - 4.0	0	17.6	12.5	0	26.3	20.0
4.0 - 4.5	0	11.7	25.0	0	5.3	20.0
4.5 - 5.0	0	5.9	12.5	0	0	0
Number of Sites	7	17	8	6	19	5

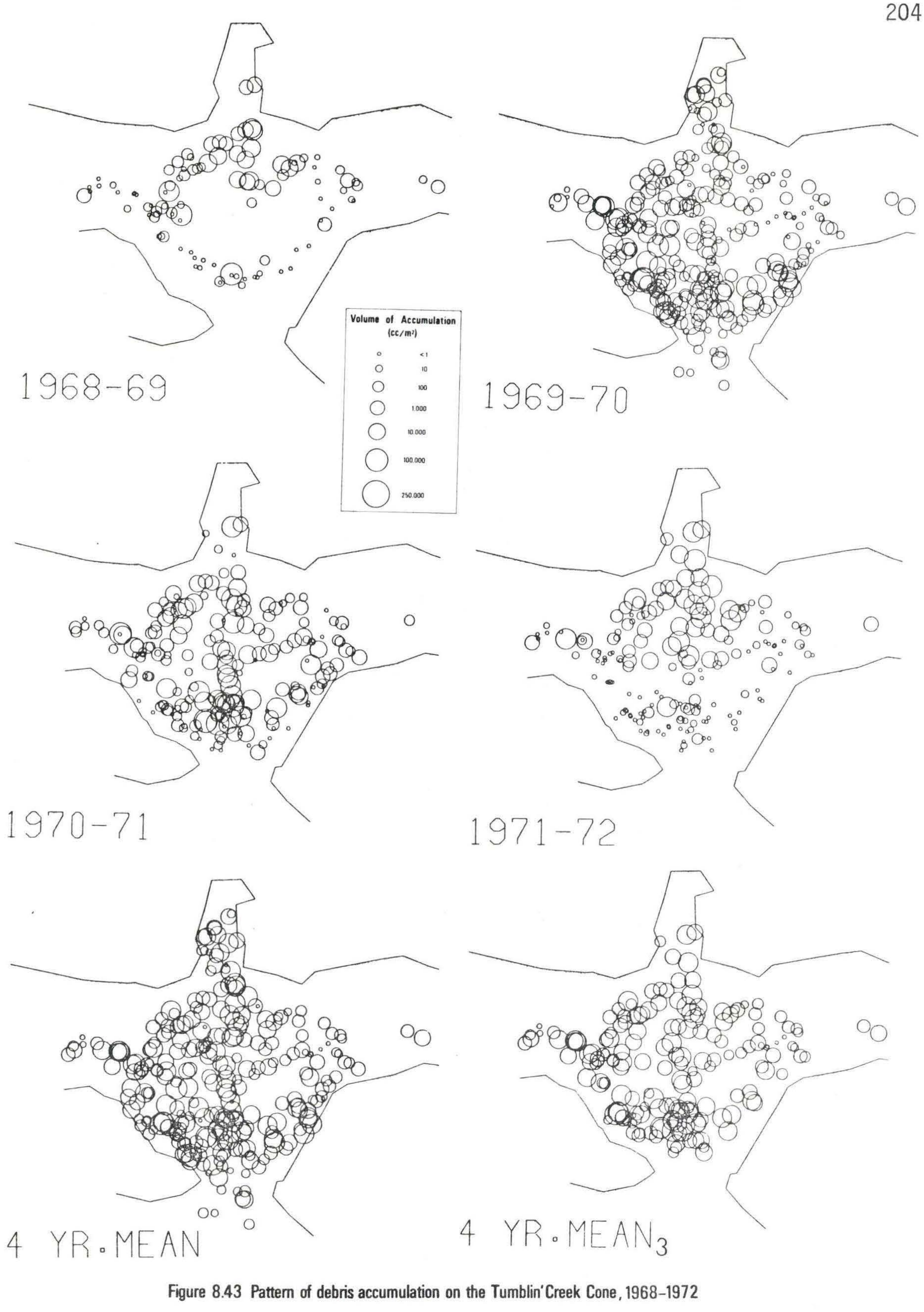


Figure 8.43 Pattern of debris accumulation on the Tumblin' Creek Cone, 1968-1972

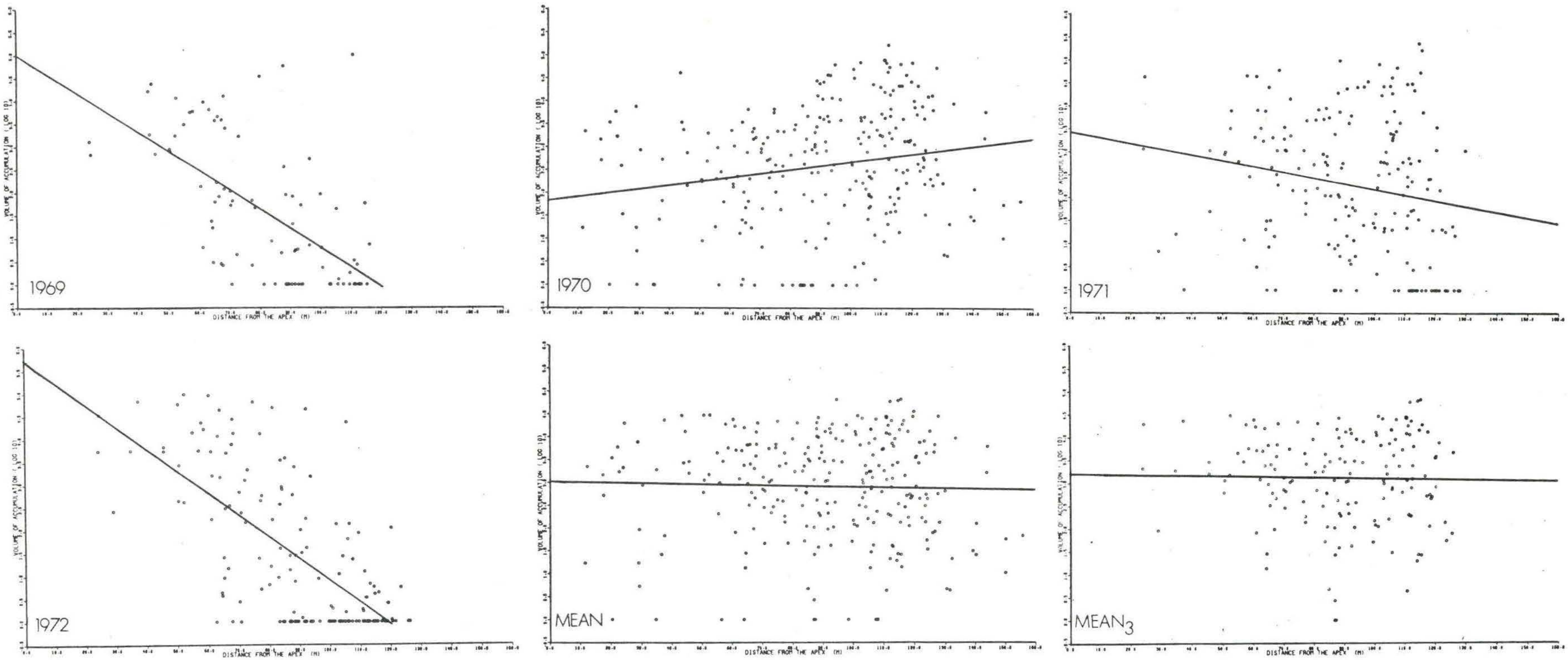


Figure 8.44 Relationship between the volume of debris accumulation and distance from the apex of the Tumblin' Creek Cone

at the top of the cone, these results show a general trend of increasing deposition upslope (Figure 8.44, correlation coefficient -0.6187, n = 91). If the obvious rockfall debris is excluded, the correlation increases to -0.7165 (n = 88).

A limited amount of erosion also occurred near the apex of the cone as the upper two squares were partially damaged and one of the sample boulders was moved about 40 m downslope (Figure 8.45). In the light of the deposition on the lower transect, it would appear that these marker boulders show the approximate limit of avalanche activity and, because of the lack of sample sites in this area, total deposition is probably underestimated for the cone as a whole.

1970

In 1970 the whole cone was covered by at least one major avalanche (Figure 8.41) which eroded the surface of the cone and resulted in widespread, heavy deposition extending well beyond the lowest line of sample sites. Over 42% of the sites (boulders and squares) recorded more than 1000 cc/m^2 and less than 8% had no accumulation (Table 8.15). Most of the latter were on the southern flank of the cone (boulders 78, 95, N84, N88-96), peripheral to the main avalanche. Elsewhere, the character and amount of accumulation measured was comparable with the debris observed on the ablating snow (see Figure 9.1) including a number of large boulders (up to 0.2 m^3) in the area of the lower transect. For example, square 4 received almost 150,000 cc of debris (Figure 9.2). Considerable amounts of finer debris were also found in the avalanche deposits including balls of soil of up to 1000 cc eroded from higher up the slope. Several of the boulders near the base of the small cone were almost completely covered by debris from the small avalanche in that area (Figures 8.42 and 9.1).

These results show no clear relationship between the volume of accumulation and the distance from the apex of the cone (Figure 8.44). However, there is a weak tendency for the largest values to be on the lower slopes and the correlation coefficient (0.1936, n = 253) is statistically significant (at greater than the 99% level!). This relationship merely reflects the greater frequency of large boulders on the sample sites in this area.

Evidence from the movement of sample sites indicates that most of the avalanche debris was eroded from the middle and lower parts of the cone. Four squares in this area were badly damaged (Table 8.16) and eleven sample boulders were moved downslope (four were not recovered). In addition, the wooden sampling square left on the upper part of the scree in 1969 (when the sampling programme was abandoned because of snow) was smashed by the avalanche and scattered over the scree. The movement patterns shown by these displaced markers are shown in Figure 8.46. Although the results from square 10 and the wooden square dominate this figure, it is clear that the erosion occurred as a broad swath down the middle of the cone and that boulders or other obstacles were swept off this central area to the lower parts of the cone and over the lake bed (e.g. the marker boulders lost from square 5).

Higher up the cone, however, there was little erosion of the upper squares or sample sites and few boulders were displaced from the painted lines. Since these usually involved single boulders and few moved more than 10 m (Table 8.17), most of this movement could be attributed to rockfall impact or the initial instability of the sites. Thus, it would

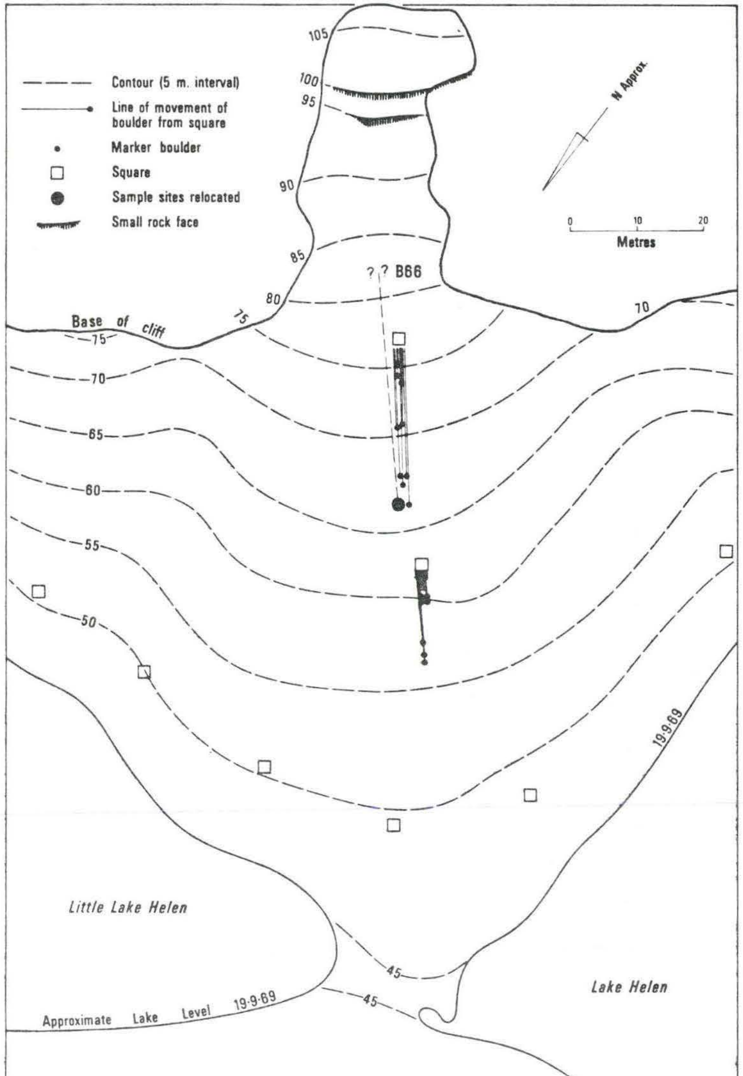


Figure 8.45: Displacement of Marker Boulders from Sample Squares in 1969

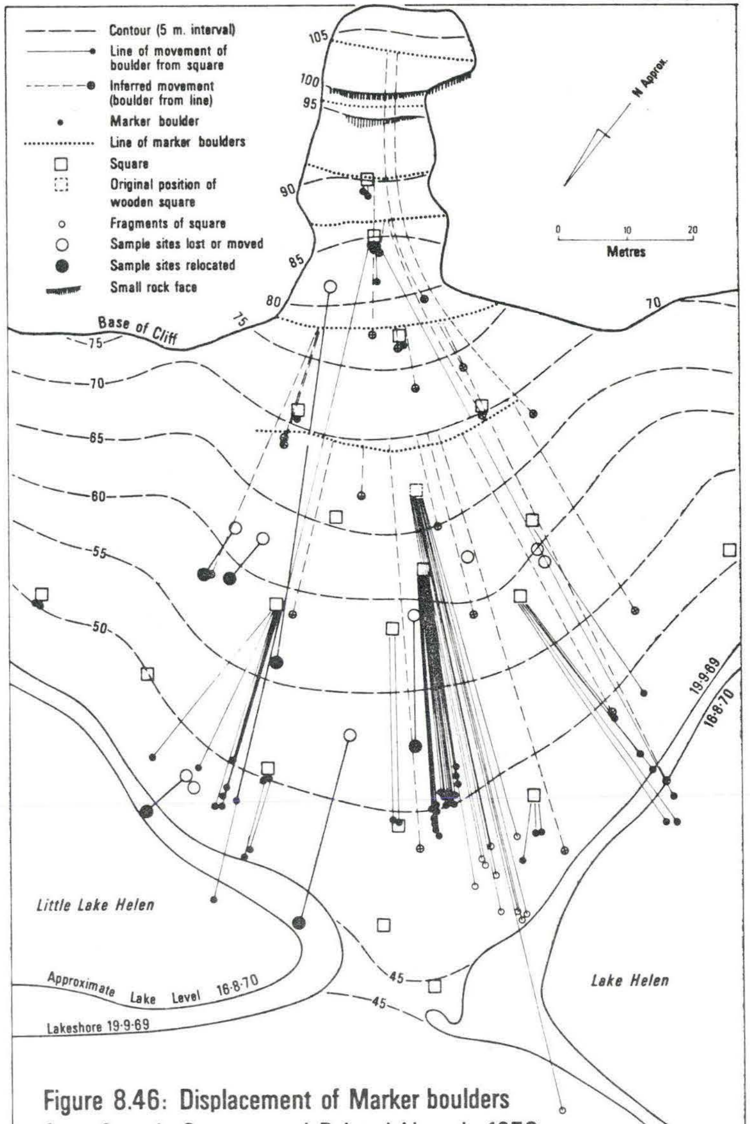


Figure 8.46: Displacement of Marker boulders from Sample Squares and Painted Lines in 1970

TABLE 8.16: SUMMARY DATA FOR THE SQUARES ON THE TUMBLIN' CREEK CONE IN 1970

Square	Area (m^2)	Deposition (cm^3/m^2)	Marker Boulders Original	Remaining	Recovered	Lost	Comments
1	2.32	10924.0	22	20	2	0	
2	2.32	417.9	19	19	-	0	
3	2.32	20345.5	25	17	5	3	
4.	2.32	64479.4	23	23	-	0	
5	-	-	30	4	3	23	polyethelene intact but useless
6	2.32	21.9	25	25	-	0	
7	2.32	1514.5	24	6	8	10	polyethelene held in place by debris
8	2.32	2102.0	22	20	2	0	
9	2.32	806.2	21	11	4	6	
10	-	-	23	0	19	4	totally destroyed
11	2.32	412.3	22	21	1	0	
12	2.32	45.4	23	23	-	0	
13	2.32	974.2	22	22	-	0	
14	2.32	204.6	23	22	1	0	
15	2.32	3431.5	25	24	1	0	
16	2.32	7536.7	21	13	6	2	
17	2.32	3423.3	20	18	2	0	
18	1.16	259.0	17	17	-	0	
19	1.16	25.4	17	17	-	0	

TABLE 8.17: DISPLACEMENT OF BOULDERS FROM THE SIX LINES ON THE TUMBLIN' CREEK CONE, 1969-1971

Line	Boulders Set	Period of Measurement	Remaining on Line[1]	< 2m	Movement < 10 m	> 10 m	Lost[2]
1	29	1969-70	15	5	4	2	3
		1970-71	16		2	7	4
2	29	1969-70	25	3	0	0	1
		1970-71	16		4	1	8
3	31	1969-70	21	6	0	1	3
		1970-71	12		2	12	5
4	30	1969-70	26	3	0	1	0
		1970-71	6		1	20	3
5	40	1969-70	31	2	4	4	0
		1970-71	3		1	35	1
6	50	1969-70	39	3	1	7	0
		1970-71	5		0	36	9

NOTE: The lines were not reset in 1970. The results should be examined in conjunction with Figure 8.48 which illustrates the spatial pattern of deposition in 1971. The data in the table are grouped for convenience in comparison of the two years.

[1] Columns 1 and 2 are combined for the 1970-1971 results because of the difficulty of relocating the original lines.

[2] These boulders could be buried, underwater or may have lost their identification marks.

appear that the throat of the cone was protected from avalanche erosion, probably by a carapace of ice or ice-crusted snow. Such a carapace was observed in both 1969 and 1970, nourished by meltwater from the spring and stream at the head of the cone. The time needed for the development of such a feature plus the fluid nature of the avalanche snow suggest the avalanche was a large wet snow spring avalanche from the area above the Pekisko cliffs.

1971

The sample site network was badly damaged by avalanche erosion in the upper and middle part of the cone. The 11 squares above the basal traverse were all destroyed; samples were taken from the polyethelene remnants at two sites but in five cases there was no trace of the original site of the square (Table 8.18). The ten highest sample boulders were either moved downslope or lost and only five of the top twenty-two sites remained (two were eroded in 1970, another in 1969). Marked erosion also occurred in the area of finer surface debris in the south central part of the cone (boulders N129, N131-4, N140-41; boulders N135, N137 and N139 were moved in 1970). In addition, the three lowest lines of painted boulders were demolished and only a few scattered boulders remained (Table 8.17). The upper two lines and the southern half of line 3 were much less affected and probably protected from erosion by a small ice carapace, since the avalanche must have occupied the whole width of the throat of the cone.

Over 300 boulders with various markings were recovered from the surface of the cone. Some of these are shown in Figures 8.47 and 8.48 which graphically portray the form and extent of the main depositional

TABLE 8.18: SUMMARY DATA FOR THE SQUARES ON THE TUMBLIN ' CREEK CONE IN 1971

Square	Area (m^2)	Deposition (cc/m^2)	Marker Boulders Original	Remaining	Recovered	Lost	Comments
1	2.32	25.8	22	22	-	-	
2	2.32	45.8	19	19	-	-	
3	2.32	117.0	22	22	-	-	
4	2.32	7476.4	22	22	-	-	
5	2.32	688.3	20	15	5	0	top of sq. moved
6	2.32	95.6	24	24	-	-	
7	1.56	5704.3	22	6	11	5	remnant of square
8	1.86	19793.4	23	8	12	3	remnant of square
9	-	-	20	4	7	9	totally destroyed
10	-	-	20	0	10	10	no trace
11	-	-	22	1	15	6	totally destroyed
12	-	-	23	0	10	13	no trace
13	-	-	23	0	21	2	no trace
14	-	-	22	0	17	5	no trace
15	-	-	23	1	21	1	totally destroyed
16	-	-	20	0	7	13	no trace
17	-	-	20	8	5	7	totally destroyed
18	1.16	0(est.)	17	17	-	-	underwater
19	1.16	not seen	-	-	-	-	underwater

NOTE: The area given is the area sampled. All squares except 18 and 19 were originally 2.32 m^2.

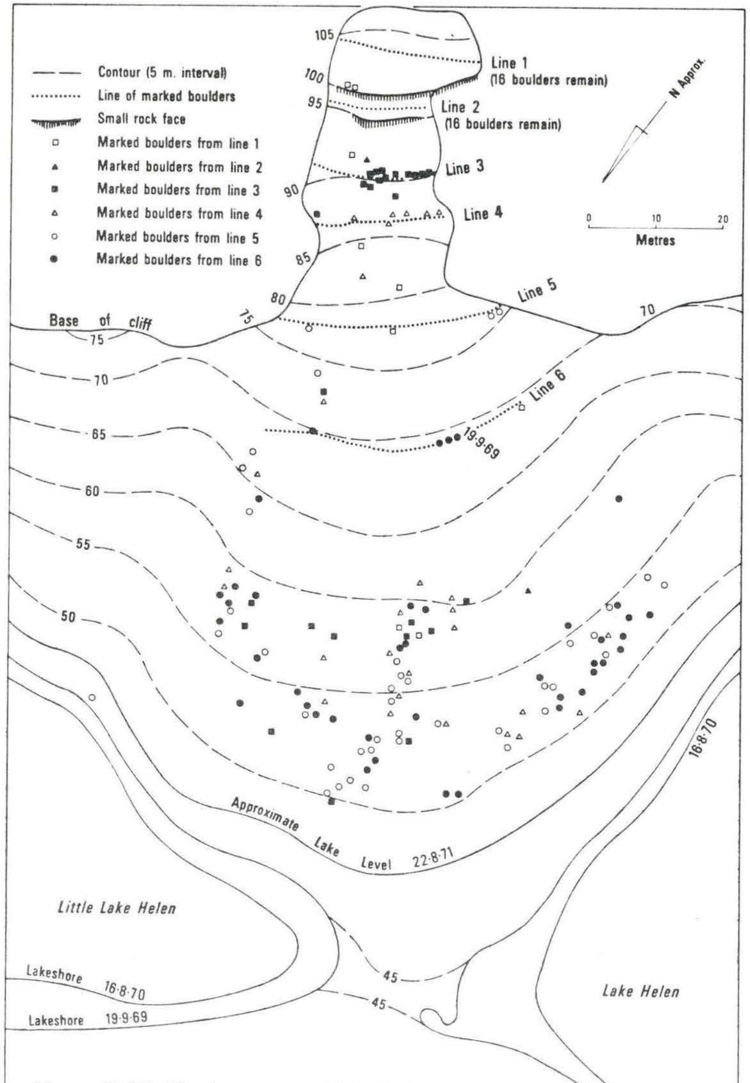


Figure 8.47: Displacement of Marked Boulders from Painted Lines in 1971

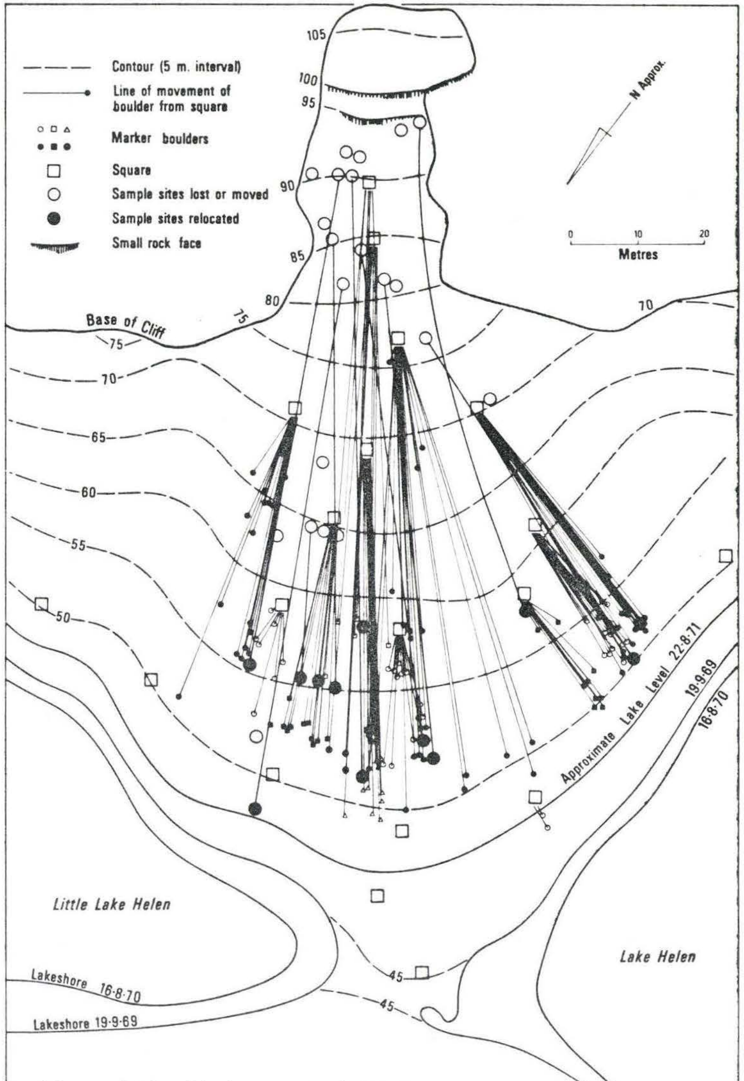


Figure 8.48: Displacement of Marker Boulders from Sample Squares in 1971

zone. The pattern of both diagrams suggests a single large avalanche covering the whole cone, except for the runnel on the northern flank (see Figure 8.48). Although the lake level was high throughout the sampling period, the lack of boulders recovered from below the 50 m "contour" suggests that this was the limit of deposition (see the discussion below). Most of the boulders which were not recovered were probably buried or broken.

Deposition was very heavy and is comparable to 1970, except for a higher mean value (Table 8.15) which reflects the presence of several large boulders. About 15% of the sites had less than 1 cc/m^2 deposition, mainly on the lowest sampled transect around the cone. Deposition extended below the lake level at one locality on the southern flank of the cone (boulders N81-87) where debris accumulation was estimated for those sites which were visible. This depositional pattern mirrors that of the marker boulders, even to the relatively small amounts (500-600 cc/m^2) in the northern runnel (boulders 35-48), although a separate small avalanche appears to have occurred on the small cone (boulders 31-34). Away from this peripheral area, considerable deposition occurred on the main cone, although the amounts recorded from adjacent sites often varied considerably due to local fluctuations in the size and concentration of debris.

From Figure 8.44, it is apparent that there is no clear relationship between the volume of accumulation and the distance from the apex of the cone. The weak negative correlation coefficient (-0.1896, n = 183, significant at the 99% level) is mainly due to those basal sites with no accumulation and the great scatter of data points suggests, as the 1970 results did, that there is no general simple relationship.

Although the site was not examined in the spring of 1971, there are strong similarities between the observed depositional pattern in 1971 and the distribution of avalanche debris in 1968 (Figure 8.39). Also, the erosional and depositional zones in 1971 overlap those of 1969 and 1970.

1972

Apart from the larger network of sites, the accumulation pattern in 1972 was very similar to that observed in 1969 (Figure 8.43), although larger volumes of debris were involved. The heaviest deposition was concentrated on those sites below the throat of the cone (boulders 64-80, N126-153) many of which were almost completely covered with debris. Many of the marker boulders moved in 1971 were partially buried under larger boulders and several large boulders of a white, freshly-broken, crystalline limestone were scattered over this area. At least five of these boulders were greater than 0.1 m^3 and together they comprised a minimum of 1.5-2.0 m^3 of debris which was probably a fresh rockfall onto the scree or avalanche snow.

There was only sporadic deposition below the 55 m "contour" and almost 40% of the sampled sites on the cone had less than 1 cc/m^2 accumulation. Most of these sites were in the basal area where another 53 sites were underwater and not sampled. This strongly contrasted depositional pattern produced a marked inverse relationship between the volume of accumulation and distance from the apex of the cone (correlation coefficient = -0.6840, n = 159) similar to that seen in 1969 (Figure 8.44).

Since none of the squares, lines or sample boulders destroyed in 1971 were reset, there was little direct evidence available to indicate whether erosion took place on the upper part of the cone. Boulder 73 was moved 6 m downslope from the apex of the cone and boulders N100 and N114 both disappeared. Little trace remained of any of the six lines and, although no attempt was made to trace the boulders moved, this suggests that the avalanche acquired some of its load from the throat of the cone. This was supplemented by some rockfall material from above the Pekisko cliff.

Summary and Conclusions

This cone is an avalanche boulder tongue of the "fan" type (Rapp, 1959) and the results over the five year period have contributed a great deal to the understanding of the importance of avalanche erosion and redeposition in the genesis of these forms. Because the small area studied is entirely within one major avalanche track, the major process-sediment-form linkages are considerably simplified (as compared with, for example, Surprise II) except for the addition of an unmeasurable rockfall component.

There has been considerable variation in the amount and extent of avalanche erosion and deposition at this site. The greatest activity occurred in 1968, 1970 and 1971 when there was marked avalanche erosion on the cone and heavy deposition over the sampled area, extending down onto the lake bed in 1970. In 1969 and 1972, erosion was more limited and deposition confined to the upper and middle parts of the cone.

In successive years, the erosional and depositional zones overlap (Table 8.19), producing the progressive downslope redistribution of the surface material. Debris swept off the higher and central areas is deposited towards the edges (or base) of the track to be subsequently moved again by larger avalanches. The upper slopes are constantly replenished with fresh debris swept onto the cone by avalanches from the higher avalanche chute and the benches and cliffs flanking the throat of the cone. Thus, the upper slopes are not completely stripped of coarse debris (as is the tongue at Old Nip) but have a highly mobile transitory veneer of coarse debris--as witnessed by the frequent erosion of smaller sample boulders from this part of the cone. The provision of abundant debris from the area above the Pekisko cliff also accounts for the relatively large size and well developed nature of this cone.

TABLE 8.19: APPROXIMATE EXTENT OF THE EROSIONAL AND DEPOSITIONAL ZONES ON THE TUMBLIN' CREEK CONE 1968-1972

Year	Erosional Zone	Lower Limit of Deposition
1968	?	45-55 m
1969	85?-60 m	55-60 m
1970	70-45 m	lake bed
1971	90-55 m	50-45 m
1972	above 70 m?	55-60 m

NOTE: The numbers refer to the "contour" lines shown on the various diagrams.

This constant reworking of debris involves the transport of considerable volumes of material. Unlike the other sample sites in Surprise, the small size, intensive sampling network and homogeneous character of this site suggest that it is possible to extrapolate these results to the whole cone. Thus, assuming deposition on these sites is representative of the whole cone (an assumption supported by snow inventory observations in 1969 and 1970), the extrapolation of the mean accumulation for all sampled sites to the area covered by those sites yields annual volumes of 14, 45, 49 and 35 m^3 (Table 8.20). These crude approximations are not unreasonable when compared to inventory type estimates of up to 20 m^3 for individual avalanches at other sites. As might be expected from their location, they are considerably greater than the annual figures quoted by Rapp (10-15 m^3/year) since avalanche activity in Kärkevagge is not very intense (Rapp, 1960, p. 133), but the volume of debris carried by these avalanches is comparable with the less frequent, large slush avalanches seen in Kärkevagge.

TABLE 8.20: APPROXIMATE VOLUME OF DEBRIS CARRIED BY AVALANCHES ON THE TUMBLIN' CREEK CONE 1969-1972

Year	Area Covered With Sample Sites (Approx. m^2)	Mean Accumulation (mm Thickness)	Debris Moved (m^3)
1969	5500	2.53	13.9
1970	8000	5.70	45.6
1971	6500	7.62	49.5
1972	6500	5.38	35.0

NOTE: The mean accumulation is the total volume measured/total area sampled in each year.

The data show no relationship between mean accumulation on sample sites and their distance from the apex of the cone, regardless of whether all sites ($r = -0.0293$, $n = 257$) or only those with at least three years observations ($r = -0.0263$, $n = 159$) are used (Figures 8.43 and 8.44). The strong negative correlation noted in two of the four years appears to be a function of the position of the terminal zone of the avalanche rather than any depositional gradient within the avalanche itself. A similar relationship may be seen at Surprise II in 1970.

The Remaining Sites

These sites may be considered in three distinct groups differentiated by their locations (Figure 8.37 and Table 8.21). The first group (boulders 1-27) are on the straight coarse scree between the northern end of Lake Helen and the Tumblin' Creek Cone. Deposition in this area was very light with almost half the sites averaging less than 1.0 cc/m^2/year. Several of the sites in this area are flush with the scree surface and recorded deposition in most years (boulders 10, 20, 21 and 23). The remaining deposition was from small avalanches with little debris content (boulders 7-12, 1969; 20-27, 1971; 2-8, 1972) and occasional small rockfalls.

The second group (Table 8.21B) is also basically a coarse straight rockfall scree, running from the cone to the delta (Figure 8.37). However, small dirty avalanches were noted in this area in 1969 and 1970 (Figure 8.49), although they contained little debris. The area adjacent to the cone received avalanche deposition in all four years (boulders 88-92, 118-121, N85-87, see Figure 8.43). The greatest accumulation was from a series of rockfalls to a very restricted area. Boulder 125 was smashed in 1970 and individual boulders of 0.016 m^3 (boulder 127, 1970), 0.01 m^3 (124, 1971), 0.02 m^3 (128,1972) and 0.05 m^3 (129, 1972) were deposited in this area from 1970-1972, giving rise to the higher mean values shown in Table 8.21B.

The sites on the western side of the lake are the most active of these groups. Several well marked avalanche tracks cross the line of

TABLE 8.21: SUMMARY STATISTICS OF THE ACCUMULATION ON SAMPLE SITES AT TUMBLIN' CREEK EXCLUSIVE OF THOSE ON THE CONE

(A) SAMPLE BOULDERS 1-27

Class Limits	1969	1970	1971	1972	Mean
No accumulation	37.0	63.0	72.0	44.0	18.5
Less than 0.0	11.1	3.7	0	8.0	0
0.0 - 0.5	11.1	7.4	4.0	8.0	18.5
0.5 - 1.0	11.1	7.4	0	12.0	12.2
1.0 - 1.5	14.8	0	4.0	12.0	7.4
1.5 - 2.0	3.7	7.4	4.0	0	7.4
2.0 - 2.5	3.7	0	8.0	4.0	3.7
2.5 - 3.0	7.4	3.7	4.0	4.0	7.4
3.0 - 3.5	0	0	0	4.0	11.1
3.5 - 4.0	0	7.4	0	4.0	3.7
4.0 - 4.5	0	0	4.0	0	0
Number of Sites	27	27	25	25	27
Mean Accumulation	0.07	0.33	0.26	0.15	0.20

(B) SAMPLE BOULDERS 88-91, 119-135, N85-87

Class Limits	1969	1970	1971	1972	Mean
No accumulation	50.0	27.2	38.0	47.3	20.0
Less than 0.0	4.5	0	0	0	0
0.0 - 0.5	4.5	0	4.7	0	4.0
0.5 - 1.0	9.1	13.6	4.7	0	8.0
1.0 - 1.5	18.2	9.1	9.5	15.8	8.0
1.5 - 2.0	4.5	9.1	19.1	5.3	8.0
2.0 - 2.5	0	9.1	0	5.3	12.0
2.5 - 3.0	9.1	13.6	14.2	5.3	16.0
3.0 - 3.5	0	4.5	4.7	5.3	8.0
3.5 - 4.0	0	4.5	4.7	0	0
4.0 - 4.5	0	0	0	0	4.0
4.5 - 5.0	0	4.5	0	5.3	12.0
5.0 - 5.5	0	4.5	0	0	0
5.5 - 6.0	0	0	0	10.5	0
Number of Sites	22	22	21	19	25
Mean Accumulation	0.09	3.20	1.71	12.04	3.79

(Cont'd)

TABLE 8.21 (Cont'd)

(C) SAMPLE BOULDERS 136-166

Class Limits	1969	1970	1971	1972	Mean
No accumulation	32.3	37.5	68.1	63.6	19.4
Less than 0.0	3.2	0	4.5	0	6.5
0.0 - 0.5	9.7	0	4.5	0	6.5
0.5 - 1.0	9.7	8.3	4.5	4.5	0
1.0 - 1.5	9.7	0	4.5	4.5	16.1
1.5 - 2.0	12.9	25.0	4.5	9.1	12.9
2.0 - 2.5	6.4	8.3	9.1	4.5	12.9
2.5 - 3.0	9.7	8.3	0	9.1	12.9
3.0 - 3.5	3.2	4.2	0	4.5	6.5
3.5 - 4.0	0	8.3	0	0	6.5
4.0 - 4.5	3.2	0	0	0	0
Number of Sites	31	24	22	22	31
Mean Accumulation	0.32	0.31	0.03	0.12	0.35

(D) SAMPLE SQUARES

Number	1969	1970	1971	
Old Square 9	destroyed			
Old Square 10	295.6		2308.9 (two years)	
Old Square 11	0.0	0.0	perished	
Old Square 12	868.6	1297.9	224.1	perished
Square 20	not set	97.0		

Figure 8.49 Avalanches on the eastern and western shores of Lake Helen, 24th May 1970. The large avalanche in the foreground covers the main cone. The snow free area (top, left) is the Tumblin' Creek delta.

sample sites and avalanches were observed in this area in 1968, 1969 and 1970 (see Figure 8.49). In 1969, a narrow dirty avalanche, similar to that in Figure 8.42, eroded some 3-4 m^3 of scree and, just missing square 10, obliterated several of the small former shorelines in that area. Similar avalanches occurred between here and the delta in both 1969 and 1970 and the southern flanks of the large avalanche cone (Figure 8.36) were affected by a slab avalanche in 1969 and a large wet snow avalanche in 1970 (Figure 8.49). Most of the deposition was recorded in these two years (Table 8.21C and D), principally near old square 10 (boulders 141-152) and old square 12 (boulders 163-166, see Figure 8.36). There were small amounts of avalanche accumulation in both 1971 and 1972.

Although avalanche activity is common on both sides of the lake, the accumulation data indicate much smaller amounts of debris are transported by the avalanches on the western side. The western screes have a much greater vegetation cover and a smaller input of debris from above the Pekisko cliff and the debris is generally smaller in size than that on the Tumblin' Creek Cone. The development of a vegetation cover has protected the underlying scree from avalanche erosion and many avalanches in this area merely carry twigs, leaves and broken branches. However, where avalanching has removed or inhibited vegetation, debris transport and scree erosion is comparable with similar sites on the main cone (e.g. the avalanche by old square 10 in 1969 and Figure 8.42).

It is also interesting to note that avalanche activity and its effects are not synchronous around the lake. Although both sides had large avalanches in 1970, avalanche erosion was very important only on the Tumblin' Creek Cone in 1971 and was more important (and lower) on the western cone in 1969. This example merely indicates the variability between different avalanche tracks in the same year, both in the amount of avalanche activity and its geomorphic consequences.

Conclusion

Like the Old Nip sites, the remaining sites around Lake Helen showed a variable mix of rockfall and avalanche activity, although deposition was generally light. The eastern sites are dominantly coarse rockfall screes and several rockfalls were recorded, although small amounts of avalanche deposition also occurred. The vegetation cover restricts avalanche erosion to a few narrow tracks on the west side of the lake and, except for one small avalanche, deposition was much less than on the Tumblin' Creek Cone.

CHAPTER 9

DISCUSSION OF THE RESULTS OF THE ACCUMULATION MEASUREMENTS AND THEIR WIDER IMPLICATIONS

The initial aims in setting up large numbers of polyethelene squares and sample boulders were experimental and geomorphic. The sampling networks were designed to examine whether deposition was common at the base of the slope and to try and locate other major depositional zones by the use of selected profiles and transects on the higher slopes. Since the methods were experimental, it was also necessary to establish whether such sites were a practical and reliable way to collect data on the amount, distribution and character of deposition on screes and whether they might also provide information on the dominant geomorphic processes involved in that deposition. For this reason, the experimental sites chosen covered a wide range of scree sizes and types.

Within the limits of these aims, the methods have been remarkably successful. The sites have provided a great amount of data on the volume and nature of deposition in four consecutive years for comparison with more general observations over a five year period. The movement of painted boulders at several sites has furnished considerable information about the character and extent of avalanche erosion on scree slopes. This information, in conjunction with the longer term effects discussed in the following sections, has provided a better understanding of the role of avalanches in scree slope modification.

However, although these data are unique in the amount and nature of the detail they provide, there are major constraints on the wider inferences which may be drawn from it because of the limited aims of the original design. Many of the sample site networks were laid down without an adequate foreknowledge of the detailed lateral variations in dominant processes at the site. Using the evidence derived from this study, a much greater potential yield of information would be possible employing the same techniques with more suitable sampling designs. Within this chapter, these constraints will be discussed, firstly by an assessment of the techniques used and secondly by a summary of the results and a consideration of some of their broader implications.

SAMPLE BOULDERS AND SQUARES

Sample boulders are easily set up and involve no cost or transport of materials to the site. They are robust and require little attention after the initial cleaning. Over the four year period, only 8.7% of the sites were removed, mainly at two sites (Tumblin' Creek Cone and Eastern Valley Side, see Table 9.1) where the boulders involved were relatively small and avalanche erosion was severe. Apart from these sites, the vast majority of the remainder yielded results for the whole three or four year period (Table 9.2). Sites which were temporarily unavailable due to snow or water cover in one year could be examined in the following year, except for the lowest transect at Tumblin' Creek which was water-covered in both 1971 and 1972.

TABLE 9.1: SUMMARY STATISTICS FOR SAMPLE BOULDER SITES LOST, BY SCREE, 1968-1972

Site	Number Set	Lost	Moved	Under Snow	Under Water	Paint Lost	Reject	Lost/ Moved Prev.	2 Yr. Total	Number Sampled
1969										
Eastern Valley Side	138	0	0	0	0	1	0	-	-	137
Entrance	38	1	0	0	0	0	1	-	-	36
Old Nip	56	0	1	0	0	0	0	-	-	55
Palliser	108	0	0	0	0	0	5	-	-	103
Strike Valley	63	4	0	1	0	0	0	-	-	58
Surprise II	160	2	2	0	0	0	1	-	-	155
Tumblin' Creek Cone	85	0	1	0	0	0	0	-	-	84
Tumblin' Creek (rest)	82	2	0	0	0	0	0	-	-	80
TOTAL 1969	730	9	4	1	0	1	7	-	-	708
1970										
Eastern Valley Side	138	0	0	0	0	0	1	1	0	136
Entrance	38	0	0	0	0	0	1	1	0	36
Old Nip	56	0	0	0	0	0	0	1	0	55
Palliser	130	1	0	0	0	0	5	0	1	123
Strike Valley	63	1	1	0	0	0	0	1	3	57
Surprise II	265	2	1	23	0	0	0	4	0	235
Tumblin' Creek Cone	254	9	5	0	0	3	1	1	0	235
Tumblin' Creek (rest)	85	1	1	0	5	0	2	2	0	74
TOTAL 1970	1029	14	8	23	5	3	10	11	4	951
1971										
Eastern Valley Side	138	6	5	0	0	0	0	1	0	126
Entrance	38	0	0	0	0	0	1	1	0	36
Old Nip	56	0	0	0	0	0	0	1	0	55
Palliser	130	0	1	0	0	0	5	1	0	123
Strike Valley	63	1	0	0	0	0	0	3	0	59
Surprise II	265	2	1	4	17	0	2	6	19	214
Tumblin' Creek Cone	254	13	14	0	33	0	0	18	0	175
Tumblin' Creek (rest)	85	0	0	0	14	0	1	1	0	68
TOTAL 1971	1029	22	21	4	64	0	9	32	19	856
1972										
Eastern Valley Side	138	0	0	0	0	0	0	11	1	126
Entrance	38	0	0	0	0	0	1	1	0	36
Old Nip	56	0	0	0	0	0	0	1	0	55
Palliser	130	0	0	0	0	0	4	2	0	124
Strike Valley	63	0	0	0	0	0	0	4	0	59
Surprise II	265	1	0	3	0	0	0	9	18	234
Tumblin' Creek Cone	254	2	1	0	51	0	0	46	1	153
Tumblin' Creek (rest)	85	1	1	0	1	0	1	5	10	66
TOTAL 1972	1029	4	2	3	52	0	6	79	30	853
FOUR YEAR MEAN	1029	-	-	-	-	-	-	-	-	993

TABLE 9.2: NUMBER OF YEARS OF OBSERVATION ON SAMPLE BOULDERS AND SAMPLE SQUARES

Site	Number of Years of Record 0	1	2	3	4	Total Set
(A) BOULDERS SET IN 1968						
Eastern Valley Side	1	0	10	1	126	138
Entrance	2	0	0	0	36	38
Palliser	4	0	1	1	102	108
Old Nip	1	0	0	0	55	56
Strike Valley	2	1	1	0	59	63
Surprise II	3	1	5	0	151	160
Tumblin' Creek Cone	1	2	3	1	78	85
Tumblin' Creek (rest)	2	3	2	3	72	82
TOTAL	16	7	22	6	679	730
(B) BOULDERS SET IN 1970						
Palliser	1	0	0	21		22
Surprise II	1	2	1	101		105
Tumblin' Creek Cone	15	56	24	74		169
Tumblin' Creek (rest)	0	0	0	3		3
TOTAL	17	58	25	199		299
GRAND TOTAL	33	65	47	205	679	1029
(C) SQUARES SET IN 1968						
Eastern Valley Side	0	3	3	0	0	6
Entrance	0	3	0	0	0	3
Palliser	2	3	16	1	1	23
Old Nip	1	0	5	1	4	11
Surprise II	2	4	4	0	7	17
Tumblin' Creek Cone	0	1	2	0	5	8
Tumblin' Creek (rest)	1	0	1	2	0	4
TOTAL	6	14	31	4	17	72
(D) SQUARES SET IN 1970						
Palliser	0	3	5	1		9
Old Nip	0	3	2	2		7
Surprise II	0	0	3	15		18
Tumblin' Creek Cone	0	8	3	0		11
Tumblin' Creek (rest)	0	1	0	0		1
TOTAL	0	15	13	18		46
GRAND TOTAL	6	29	44	22	17	118

The major problem with sample boulders is that they are not uniform. There are differences in the size, surface slope, surface texture and height of the sampled area above the adjacent scree which may all influence the results, although it has been shown (Chapter 7) that these factors do not introduce any consistent bias into the results from Surprise. The size and position of the sample sites is partially controlled by the availability of suitable boulders and, since these are not equally distributed over the slope, this produces a bias towards the areas of larger boulders, usually at the base of the scree.

Polyethelene squares are also relatively cheap and easily transported, providing standardized sample areas of any reasonable size. Although they are more likely to be damaged by rockfalls or avalanche action and need more attention and resetting, they are surprisingly strong. Ripping was not a major problem and only involved the loss of small amounts of fines during sampling at a few sites. However, after two or three year's exposure to sunlight, the polyethelene perishes and is easily blown away if not replaced. The large reduction in the number of squares sampled in 1971 and 1972 (Table 9.3) is due to the abandonment of many such sites in 1970 and 1971 plus the non-replacement of squares destroyed by avalanches in 1971.

Squares may be set up anywhere on the scree except amongst very coarse debris and therefore standard statistical designs may be employed from which statistically valid inferences could be made to the whole scree. However, due to their greater vulnerability to avalanche erosion and the fact that squares are needed on the upper slopes where avalanche erosion has often removed suitable boulder sites, it is difficult to

TABLE 9.3: SUMMARY STATISTICS OF SAMPLE SQUARES LOST IN SURPRISE, 1968-1972

Site	Original Number	Under Snow	Under Water	2 Yr. Total	Destroyed			Not Reset	Number Sampled
					Aval.	Animals	Wind		
1969									
Eastern Valley Side	6					1	1		4
Entrance	3								3
Old Nip	11				1				10
Palliser	23				2				21
Surprise II	17				2				15
Tumblin' Creek Cone	8						1		7
Tumblin' Creek (rest)	4						1		3
TOTAL 1969	72	0	0	-	5	1	3	-	63
1970									
Eastern Valley Side	6							3	3
Entrance	3							3	0
Old Nip	18				2			1	15
Palliser	32						2	3	27
Surprise II	35	1			2		1	5	26
Tumblin' Creek Cone	19				2				17
Tumblin' Creek (rest)	5		1				1	1	2
TOTAL 1970	118	1	1	0	6	0	4	16	90
1971									
Eastern Valley Side	6							6	0
Entrance	3							3	0
Old Nip	18	1			2		5	1	9
Palliser	32				3		16	5	8
Surprise II	35		5	1			4	5	20
Tumblin' Creek Cone	19		1		9				9
Tumblin' Creek (rest)	5			1			1	2	1
TOTAL 1971	118	1	6	2	14		26	22	47
1972									
Eastern Valley Side	6							6	0
Entrance	3							3	0
Old Nip	18			1			3	8	6
Palliser	32						6	24	2
Surprise II	35			4		1	1	9	20
Tumblin' Creek Cone	19		2					11	6
Tumblin' Creek (rest)	5						2	3	0
TOTAL 1972	118	0	2	5	0	1	12	64	34
FOUR YEAR MEAN	118	-	-	-	-	-	-	-	112

NOTES: Sites sampled include all those which were partially damaged by avalanches. The sites "destroyed" had no debris accumulation at all in that year. Nearly all of those destroyed by "wind" are due to the perishing of the polyethelene cover with age, rather than loosing the entire polyethelene.

maintain such sampling networks over the whole scree since the upper sites may be lost (e.g. Tumblin' Creek Cone, 1971) or the carefully planned design modified by the loss of one or two sites (e.g. Surprise II, 1970).

The relatively short life of the squares in Table 9.2 reflects this, plus the progressive abandonment of squares as they perished (e.g. Palliser, E.V.S.). This suggests that the greatest potential use for squares is in depositional areas, although much useful information about avalanche erosion may be acquired from their destruction.

The Comparability of the Results from Boulders and Squares

The operational procedures and measurement problems are similar for both methods and were discussed in Chapter 7. The range and character of the samples taken are illustrated in Figures 9.1 and 9.2 and summary statistics given in Tables 9.4 and 9.5.

These accumulation measurements are spot samples of the total amount of debris deposited on the snow and may be compared using cumulative frequency curves. Differences between these curves were tested for several sets of aggregate data, using the Kolmogorov-Smirnoff two sample test (Table 9.6). Despite some divergence in the curves which may be attributable to differences in the spatial pattern and number of sample boulders and squares at and between individual sites, only one pair of curves showed a significant difference between the two distributions. This difference is due to the different number of sites with no accumulation; there is no significant difference between the methods when this group is excluded from the calculations (Table 9.6). Since the bulk of

Figure 9.1 Examples of debris accumulation on sample boulder sites. TOP, LEFT: old boulder 101, Tumblin' Creek, 27th May 1970. Most of the debris visible except the three largest boulders are resting on the snow. The circled boulders are marker boulders from a square further upslope. BOTTOM, LEFT: boulder 194, Surprise II, 13th July 1970. This debris is typical of the fine rock debris carried to the base of the scree by the large avalanches from the cliffs in 1970. CENTRE: old boulder 32, Tumblin' Creek, 27th May 1970. The site is almost totally covered by debris eroded from the scree (photograph courtesy of S. B. McCann). TOP, RIGHT: boulder 136, Surprise II, 14th August 1970. This boulder was outside the zone affected by the avalanches from the cliffs. BOTTOM, RIGHT: boulder 52, Strike Valley, 13th August 1971. The site is at the lower end of the measuring device and the large boulder resting on its surface is approximately 1.03 m^3. The shale slope and col area can be seen in the background.

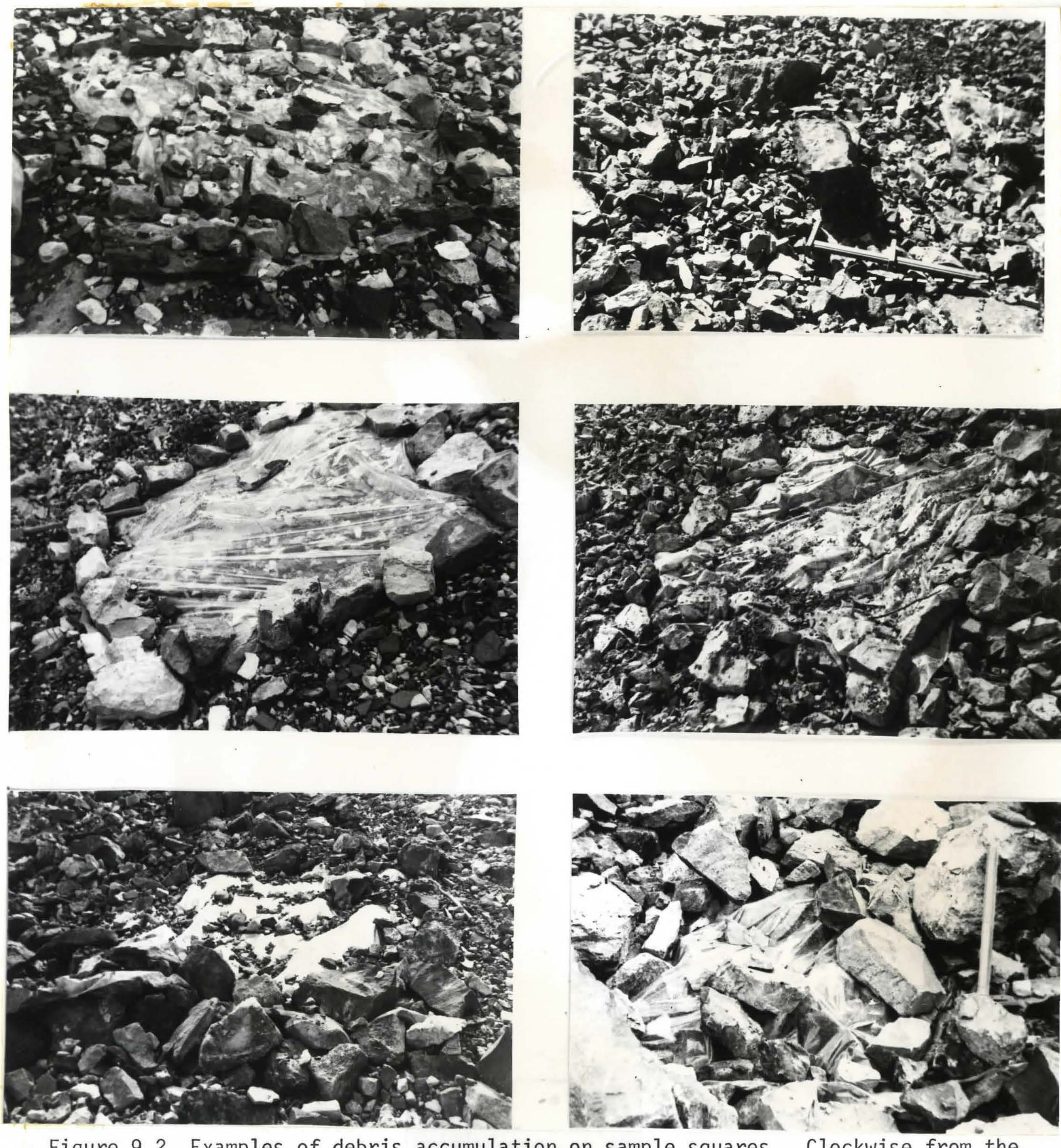


Figure 9.2 Examples of debris accumulation on sample squares. Clockwise from the top right: Square 8, Tumblin' Creek, 14th August 1971. Although nearly all the marker boulders have been lost, the polyethelene is more or less intact below a thick cover of debris. Square 20, Tumblin' Creek, 22nd June 1970. The fines, dead leaves and twigs are typical of avalanche debris from a vegetated area. Square 4, Tumblin' Creek, 14th June 1970. This was the coarsest deposit recorded on a square amounting to approximately 150,000 cm^3. The right edge of the square is marked by the ruler. Square 1, Tumblin' Creek, 25th May 1970. Finer material eroded from higher up the scree. Note the chaotic appearance of the scree and the many balanced boulders. Square 12, Surprise II, 14th August 1970. Most of the debris has rolled to the base of the square. Square 17, Surprise II, 18th June 1970. Although one side of the square has been removed, the polyethelene is intact. The knife is about 20 cm long.

TABLE 9.4: SUMMARY STATISTICS FOR DEPOSITION ON SAMPLE BOULDER SITES, 1968-1972

Volume (cc/m²)	1969	1970	1971	1972	Mean
No accumulation	49.3	38.7	34.8	56.0	13.7
Less than 0.0	6.6	1.1	1.4	3.0	2.9
0.0 - 0.5	5.9	1.9	3.9	4.1	4.4
0.5 - 1.0	5.7	4.9	8.3	4.1	5.1
1.0 - 1.5	5.9	6.2	8.5	5.5	10.9
1.5 - 2.0	5.2	11.0	8.5	5.0	10.0
2.0 - 2.5	3.8	10.7	6.3	5.9	12.8
2.5 - 3.0	6.2	8.0	8.3	4.7	11.7
3.0 - 3.5	4.0	7.5	6.4	4.3	11.5
3.5 - 4.0	4.0	4.9	5.7	3.0	9.4
4.0 - 4.5	1.8	2.9	5.1	2.7	6.0
4.5 - 5.0	1.1	2.0	1.8	1.3	1.4
5.0 - 5.5	0.4	0.2	0.8	0.4	0.2
5.5 - 6.0	0	0	0	0	0
6.0 - 6.5	0	0	0.1	0	0
Number of Sites Sampled	708	951	856	853	996

TABLE 9.5: SUMMARY STATISTICS FOR DEPOSITION ON SAMPLE SQUARES, 1968-1972

Volume (cc/m²)	1969	1970	1971	1972	Mean	Mean*
No accumulation	33.3	28.6	8.7	17.1	15.2	13.3
Less than 0.0	4.8	3.3	0	8.6	5.4	7.2
0.0 - 0.5	9.5	4.4	2.2	2.9	3.6	3.6
0.5 - 1.0	7.9	5.6	2.2	11.4	1.8	2.4
1.0 - 1.5	4.8	6.7	6.5	8.6	5.4	6.0
1.5 - 2.0	6.3	12.1	15.2	22.9	9.8	10.8
2.0 - 2.5	9.5	14.3	15.2	8.6	15.2	14.5
2.5 - 3.0	6.3	8.9	19.6	11.4	17.9	20.5
3.0 - 3.5	9.5	6.7	17.4	8.6	15.2	12.0
3.5 - 4.0	6.3	5.6	8.7	0	9.8	8.4
4.0 - 4.5	1.6	3.3	4.4	0	0.9	1.2
4.5 - 5.0	0	1.1	0	0	0	0
Number of Squares Sampled	63	91	46	35	112	83

*This mean is for those sites with more than one year of record.

the sample sites at Surprise II and Tumblin' Creek were affected by only one or two avalanches in 1970, producing a fairly uniform distribution of debris, the closeness of the distribution curves at these sites provides a convincing example of the compatibility of the estimates.

TABLE 9.6: RESULTS OF THE KOLMOGOROV-SMIRNOFF TEST FOR DIFFERENCES IN THE CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE VOLUME OF ACCUMULATION ON SAMPLE BOULDERS AND SQUARES IN SELECTED YEARS

	Data Used	Chi-Squared	Significance
1968-69	All sample sites	7.33	95%
1968-69	All sample sites with accumulation	1.80	n.s.
1969-70	All sample sites	3.39	n.s.
1969-70	All sample sites on the Tumblin' Creek Cone	1.90	n.s.
1969-70	All sites at Surprise II	0.56	n.s.
1968-72	All sample sites (mean)	2.08	n.s.
1968-72	All sample sites at the Palliser site	5.03	n.s.
1968-72	All sample sites on the Tumblin' Creek Cone	3.91	n.s.
1968-72	All sample sites at Surprise II	2.19	n.s.

NOTE: Data from 1971 and 1972 were not tested because of the selective abandonment of squares in that period.

Critical values of chi-squared 95% 5.99
99% 9.21

Despite the general similarity, all the examples show a larger percentage of boulder sites in the tails of the distributions (Figure 9.3). This may be attributed to differences in the size of the sampled areas. Most of the sample boulders are about 10-30% of the area of the squares (Figure 7.1) and since avalanche debris is usually scattered irregularily throughout the snow, the probability of trapping debris is a function of

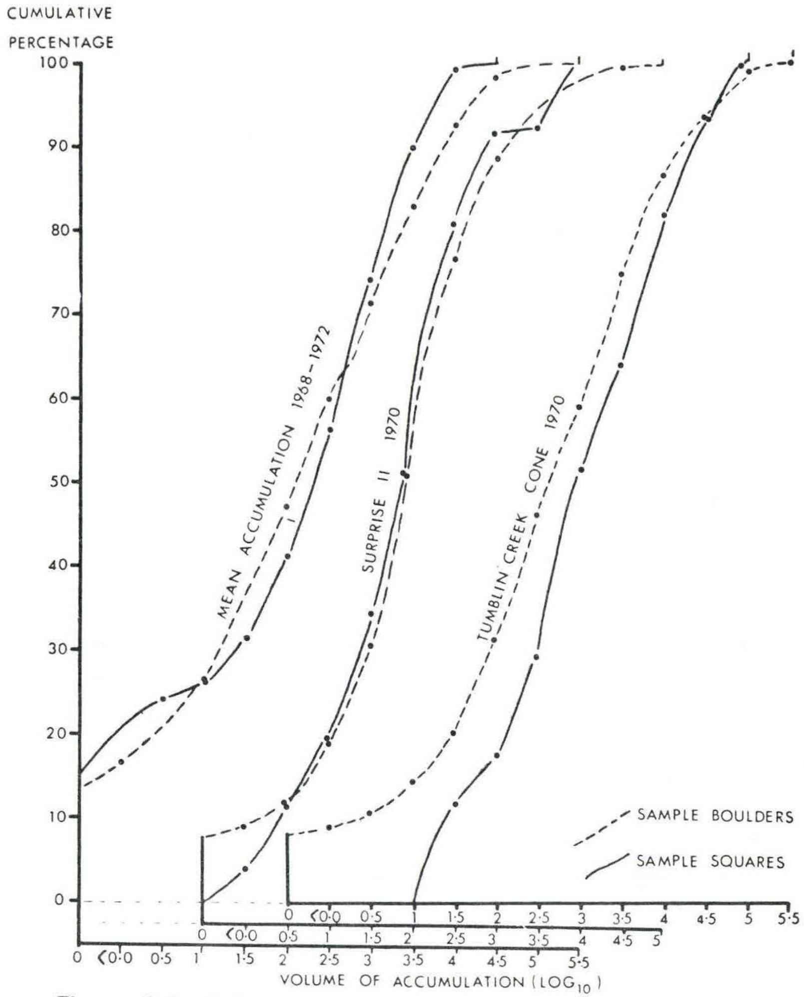


Figure 9.3 Selected cumulative frequency curves comparing accumulation on sample boulders and sample squares

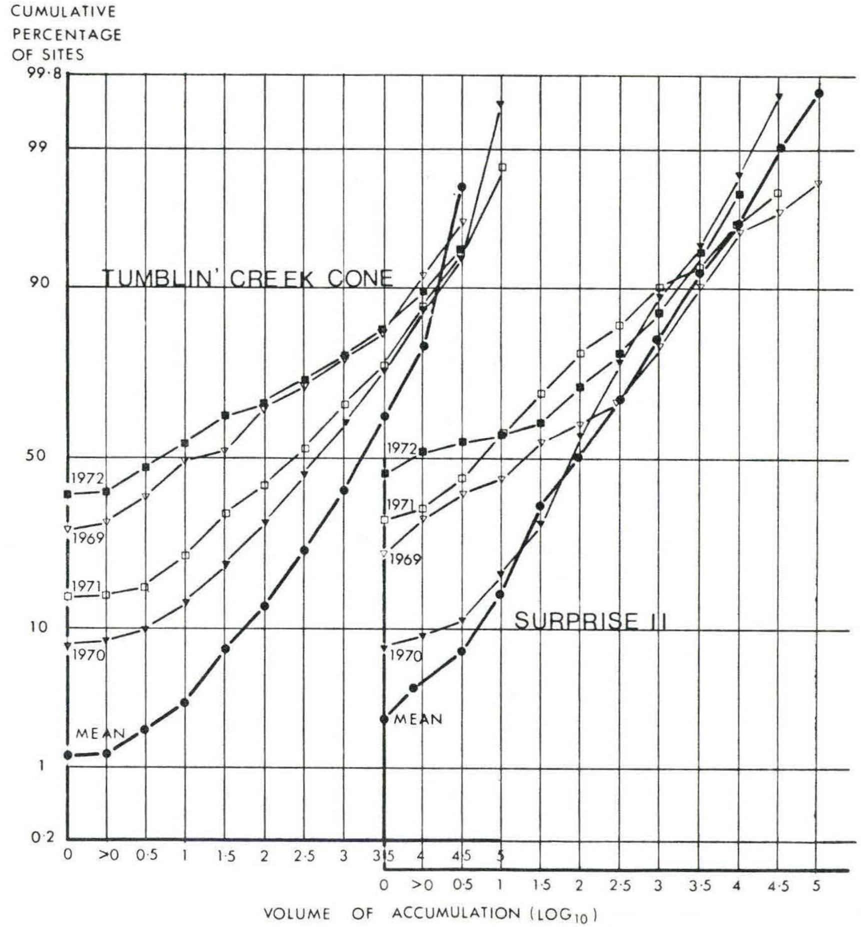


Figure 9.4 Cumulative frequency plots of the volume of accumulation on sample sites at Surprise II and on the Tumblin' Creek Cone

quadrat size as well as position on the slope. The squares are therefore more likely to have some debris than the smaller sample boulders where the distribution is discontinuous.[1] At the opposite extreme, the highest accumulation values occur when a large boulder ablates onto a small sample site and the necessary correction for area produces a very large figure. This accounts for the small number of extreme values at the upper end of the distribution for sample boulders.

These small differences reflect the more general problem of the small size of the sample sites relative to the area of scree and the characteristic spatial variability of rockfall and avalanche deposition. The problem is further compounded by the fact that some of the debris sampled approached the size of the sample site (Figure 9.1) and therefore produces anomalously high values and the great variability of these spot sample estimates can make it difficult to see the overall pattern of deposition. The easiest way to overcome this might be to rely only on squares of 10-50 m^2 or more in area. However, this would involve a considerable increase in the expenditure of time and effort, both to maintain and to measure debris accumulation on such sites. Despite their higher variance, reasonable estimates might also be achieved by increasing the number of boulder sites in suitable areas in view of the similarity of the results obtained. Boulder sites are also much easier to set up and maintain than squares and need only be supplemented in areas where suitable sites are lacking.

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[1]The anomalous reversal of this situation in the four year mean in Figure 9.3 is due to the fact that probability of accumulation at a site also increases with the number of years of record. Most of the squares with no accumulation have only two years record; the majority of the boulders have three or four years of record.

An examination of the cumulative frequency distributions for those sites where the majority of the boulders received deposition suggests that the distribution of volumes of accumulation approaches a log-normal form. When these results are plotted on probability paper (Figure 9.4; also, see Figure 8.21), they show reasonable approximations to straight lines except in the tails where measurement and sampling problems occur. Although these are not statistically random samples, this suggests that for sites dominated by avalanche deposition, as these examples are, the frequency distribution of the accumulation of debris is composed of two elements which may be treated separately:

(a) sites with no accumulation.--the number of these is a function of the distribution and character of deposition and its relationship to the position of the sampling network;

(b) sites with accumulation.--accumulation follows a log-normal distribution with the mean and standard deviation reflecting the amount and character of deposition (compare, for example, Surprise II and the Tumblin' Creek Cone in 1970). This distribution follows the log-normal distribution of particle sizes on the slope itself (see Section III).

The Limitations of the Accumulation Data

In the first year of measurement, a number of sites recorded small amounts of debris (less than 5 cc) which were obviously the result of poor cleaning in the initial setting up of the sites. These sites are reflected in the relatively large number of sites with accumulation of less than 10 cc/m^2 in 1969. Apart from this debris, almost all the accumulation measured was derived from an ablating snow cover. The raised boulder surfaces prevented accumulation by creep or rockfall (when the site was snow-free) except for small fragments thrown up in the wake of rockfall boulders. Very few sites showed any accumulation in the summer period, except as a result of the avalanches in August 1969.

Therefore, the measured accumulation is a minimum figure and refers only to the period when the scree is snow covered, i.e. a period of five to nine months, depending upon the height and aspect of the scree and the position of the site on the slope. While this covers the winter, spring and early summer rockfall and avalanche activity, it does not include any deposition in the late summer to early winter period when rockfall and possibly avalanches may be important. Only the squares, which are flush with the surface, may record deposition in all seasons.

Both techniques are excellent for the examination of avalanche deposition but considerably underestimate the amount of rockfall. Rockfalls are rarely recorded when the scree is snow-free and, apart from sites close to the cliff base (e.g. Entrance Screes, upper sites at Surprise II), the probability of sampling a rockfall is very limited due to their small size relative to the area sampled. Rockfall can probably best be measured using an inventory method or by covering large areas of scree with a marker surface on which deposition can be recorded (e.g. Gray, 1972). Rockfall deposits may only rarely be clearly differentiated from avalanche debris on the sample sites. Inventory observations have shown that large boulders may be incorporated in fairly clean avalanche deposits (Figure 8.19) and therefore only when adjacent sites have no trace of avalanche deposition can large boulders be certainly identified as rockfalls.

The destruction of squares and sample boulders on several scree slopes indicates that a considerable proportion of the avalanche debris may be eroded from the scree slopes above the sample site. Such debris can only be differentiated from material derived from the cliff in exceptional cases (e.g. Surprise II, 1970; Tumblin' Creek Cone, small avalanche, 1970). Without marking the whole scree surface, it is impossible to tell what proportion of the deposited material is fresh input from the cliffs and how much is merely redistribution of surface scree. Therefore, these accumulation measurements cannot be used to make inferences about the rates of retreat of the cliff (as, for example, Rapp, 1960 and Gray, 1972, have done).

Finally, these results are only valid within the limits of the sample design. In most cases, the sampled area is limited to only a part of the scree (e.g. Palliser, Entrance Screes) and the considerable lateral variations in deposition seen on the snow (e.g. Figures 8.25-8.27) suggest it would be unwise to extrapolate beyond the sampled area. The results can only validly be considered as unique transects or profiles which may or may not be representative of the site as a whole except for the avalanche boulder tongue at Tumblin' Creek where the sampling network is more detailed.

DISCUSSION OF THE RESULTS

Rockfall

The methods of data collection are heavily biased towards recording avalanche deposition and it is therefore difficult to assess the relative importance of rockfall activity. Inventory observations indicate that rockfalls occur at all sites with significant variations in the amount and character of this activity between the different sites (Chapter 4). However, since few of the sampled screes have unambiguous rockfall accumulation, differences of this type cannot be picked up from the accumulation data. In fact, since it is impossible to differentiate rockfall and avalanche debris where they occur together, the bulk of such deposition has to be considered of avalanche or mixed origin and therefore rockfall amounts are underestimated in basal areas. The results from sites where rockfall may be an important contribution show either "inflated" values or very little accumulation (Table 9.7, classes C and D) because of the nature of the deposition. This does not mean, however, that rockfall is unimportant in the development of these screes; most of them are formed mainly of rockfall material and therefore it seems more likely that the methods of measurement, the area sampled and the amounts of deposition are inadequate to yield reasonable results over a short time period for comparison with the more obvious effects of avalanching.

Snow Avalanches

The four or five years' observations at each scree clearly demonstrate the great importance of avalanche activity as a major agent of debris supply and movement on screes. All seven screes were influenced by avalanches in at least one year with effects ranging from scattered deposition to intense erosion, and provide many graphic examples of the forms of avalanche activity discussed in Chapter 5.

Although avalanches provide important inputs of debris at several sites (e.g. Surprise II, Tumblin' Creek Cone), the results have strongly emphasized their role as a queueing process, eroding surface scree material and transferring it further downslope (Eastern Valley Side, Tumblin' Creek Cone, Strike Valley, Small Cone, etc.). This facet of avalanche activity has not previously been considered in studies of alpine scree slope development. The present observations indicate that debris shift is probably the most important effect of avalanches on scree slopes. The results of this activity correspond closely to the model for talus slope development by slush avalanching put forward by Caine (1969), although the mechanism involved is quite different.

The observations in Surprise indicate there are considerable fluctuations in the nature and position of erosional and depositional zones on any particular scree from year to year. The net result of this overlap is the stripping of loose debris from the upper slopes which become bare unless replenished by fresh inputs from the cliff zone. The eroded debris is swept downslope to the edge or, more usually, the base of the avalanche track. Where avalanche activity is concentrated in a narrow track distinctive depositional landforms, avalanche boulder tongues, are built up in the lower part of the track and subsequently modified by further erosional trimming of their upper surfaces by larger avalanches.

Since avalanches were the major agent of deposition in the sample sites, any grouping of the screes on the basis of the amount of deposition is essentially an indication of the amount of avalanche activity, although there is an unknown rockfall component in all the results. The heaviest deposition occurred at those sites where considerable erosion and redeposition of surface scree occurred in most years (most of Group A, Table 9.7). Comparable rates of deposition occurred in individual years at

TABLE 9.7: MEAN ACCUMULATION (MM/YEAR) ON SAMPLE SITES AT THE SAMPLED SCREES IN SURPRISE

Area	1969	1970	1971	1972	Mean
(A) Sites with marked avalanche erosion/deposition in most years					
Tumblin' Creek Cone	2.53	5.70	7.62	5.38	5.61
Strike Valley (14-63)	3.94	4.64	29.44	0.66	9.49
Strike Valley (exclude B52, 1971)			(1.44)		(2.64)
Surprise II (upper half)	6.20	0.72	3.49	1.77	2.56
Palliser (Small Cone area)	1.16	0.00	1.66	6.47	2.41
Old Nip (Av. B.T.)	6.31	1.91	2.17	0.02	2.18
Surprise II (150-245 m)	1.37	0.78	0.40	0.57	0.63
(B) Sites with marked avalanche activity in one or two years					
Old Nip (1-32)	1.40	0.04	4.07	0.56	1.52
Palliser (upper squares)	-	0.25	3.12	2.88	1.49
Eastern Valley Side	0.23	0.18	3.98	0.63	1.14
Scree No. 1-Isosceles	2.46	0.04	0	0.02	0.99
Old Nip (A-X)	0.04	0.05	3.08	0.14	0.83
Surprise II (basal area)	1.39	1.18	0.002	0.007	0.63
(C) Sites dominated by rockfall					
Tumblin' Creek (118-135)	0.09	3.20	1.71	12.04	3.79
Entrance (cliff area)	0.71	0.34	0.11	0.08	0.44
Entrance (exclude squares)	(0.23)				(0.19)
(D) Sites with small amounts of avalanche or rockfall deposition					
Tumblin' Creek (136-166)	0.32	0.31	0.03	0.12	0.35
Tumblin' Creek (1-27)	0.07	0.33	0.26	0.15	0.20
Palliser (basal transect)	0.09	0.12	0.006	0.09	0.08
Entrance (lower slopes)	0.05	0.006	0.16	0.006	0.05
Old Nip (squares not on A.B.T.)	0.007	0.001	0	0	0.003
Strike Valley (1-13, on the col)	0	0.007	0	0	0.001
(E) Mixed Sites					
Surprise II (all sites)	2.08	0.97	0.91	0.58	0.98
Palliser (all sites)	0.75	0.12	0.91	1.39	0.67

other sites where avalanche erosion was less frequent (Table 9.7, Group B). Lower rates of deposition occur where avalanche activity was mainly depositional, more localized or involved mainly clean snow (e.g. Eastern Valley Side, 1969, 1970) with isolated rockfall deposition (Group D, Table 9.7).

The figures in Table 9.7 can only be treated as crude approximations of the amounts of deposition due to the various types of activity. They indicate that screes with marked avalanche erosion may receive accumulation of between 1-8 mm/year over most of their lower and middle slopes (e.g. Tumblin' Creek, 1970, 1971) within the avalanche tracks. Extrapolating the results from the Tumblin' Creek Cone, this would involve a maximum of 144 m^3 of debris shift over the four year period. At other sites, the volumes involved would probably be much less, although inventory estimates for individual avalanches range up to 10-20 m^3 at several sites. The majority of screes, however, are far less active than this and possibly the mixed sites and Groups C and D (Table 9.7) are more typical of the majority of screes in Surprise.

These variations in activity between sites may be explained in terms of the geomorphic setting of individual sites (see discussion in Chapter 3). The amount of avalanche modification is a function of the frequency of avalanches, their characteristics and the concentration of that activity. Thus, the best developed avalanche tongues occur at Old Nip and the Tumblin' Creek Cone where avalanche activity is strongly localized and there is a plentiful supply of loose material. Where avalanche tracks are more variable (e.g. Surprise II), these effects are not as easily observed since avalanche activity is not concentrated into one track.

As well as the variation between sites, there is also a wide range in the character and extent of the geomorphic effects of avalanches at any site from year to year. These variations do not show any apparent synchroneity from site to site, except possibly for 1972 (Table 9.8). There is also no apparent relationship between the amount of winter snowfall, number of avalanches and their geomorphic effects. The two snowiest winters (1967-68 and 1971-72) produced completely different results at the four sites for which observations are available and similar contrasts may be seen between 1968-69 and 1969-70 which had almost identical amounts of winter snowfall (Table 9.7; also, see Table 2.2). It, therefore, appears that local conditions of snow accumulation, avalanche hazard and snow conditions in the track at the time of avalanching are more important controls of the amount of geomorphic activity accomplished by avalanches than any regional year to year variation in winter snowfall conditions.

Observations of the disposition and character of avalanche snow suggest that several different types of avalanche may have significant geomorphic effects. Erosion of the scree may be accomplished by both slab avalanches triggered in the snow cover of the scree (e.g. Old Nip) and wet snow spring avalanches from accumulation areas in the cliffs. The extent of the erosion depends upon the characteristics of the avalanche and the snow cover of the scree; it may affect the whole track (e.g. Tumblin' Creek Cone, 1970) or only a small part of it (e.g. the slab avalanche, Surprise II, 1970). The assessment of the detailed relationships between different combinations of avalanche types and snow cover

TABLE 9.8: QUALITATIVE RANKING OF THE RELATIVE AMOUNTS OF GEOMORPHIC ACTIVITY CARRIED OUT BY AVALANCHES AT EACH OF THE SCREES STUDIED IN SURPRISE BETWEEN 1967 AND 1972

Site	1968	1969	1970	1971	1972	Comments
Eastern Valley Side	3	4=	4=	1	2	
Entrance (cliffs)	No data	(1)	(2)	(3)	(4)	Rockfall only
Entrance (lower slopes)	No data	2	3=	1	3=	
Palliser	No data	3	4	1	2	
Old Nip (A.B.T.)	No data	2=	1	2=	4	
Old Nip (rest)	No data	2	4	1	3	
Scree No. 1-Isosceles	2	1	3	No	data	(includes Aug.1969)
Strike Valley	3=	2	1	3=	5	
Surprise II	1	2	3=	3=	5	
Tumblin' Creek Cone	1=	4	2	1=	3	
Tumblin' Creek (1-27)	No data	3(4)	4(1)	1(2)	2(3)	
Tumblin' Creek (118-135)	No data	3=(4)	1(2)	2(3)	3=(1)	
Tumblin' Creek (136-166)	No data	1=	1=	4	3	

NOTE: The ranks in brackets refer to relative amounts of activity when the inclusion of rockfall results in a change in ranking.

and their geomorphic effects requires many more field observations of the effects of individual avalanches.

The Relationship Between Deposition and Distance from the Cliffs

The results of the accumulation on the sample sites may be plotted against the distance from the cliff or the apex of the cone (Figures 8.22, 8.29 and 8.44) and compared with other observed patterns expressed in this manner. Caine (1969) made two sets of measurements of this type to provide the data for his slush avalanche model. All the debris was taken from 100 m^2 quadrats of snow, one set of samples indicating a winter rockfall situation (decreasing deposition away from the cliff) and two other profiles, taken after "slush avalanching", which showed increased deposition downslope as far as the lower end of the deposit which was part way up the slope (see Caine, 1969, Figure 2). The values given for rockfall are small (maximum 61 cm^3/m^2) whilst the figures given for avalanche deposition are comparable with those measured in Surprise. The extremely high correlation coefficients obtained by Caine (as compared with the results from Surprise) would seem to be a function of the small number of points used and the use of a linear scale. More recently, Gardner (1970) has published some observations made on burlap mats on slopes in the Lake Louise District. However, in view of the variability of the data from Surprise, it would seem pointless to attempt to draw any meaningful conclusions from 17 sites on 9 different talus slopes.

Gray (1971, 1972) has recorded the accumulation of debris on two strips of fish netting, 3 and 8 m wide, placed down the centre of two cones in the Yukon. These results are shown in Figure 9.5 and it can be

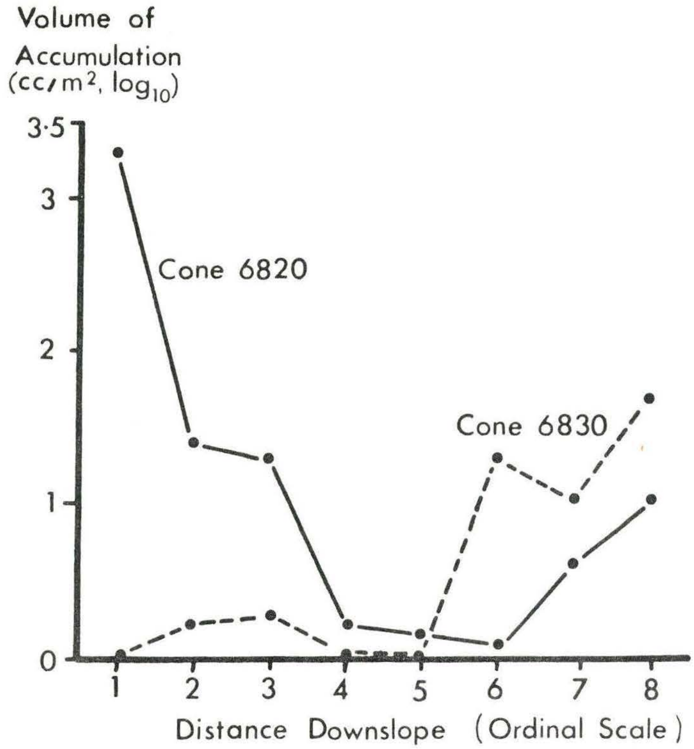


Figure 9.5 Debris accumulation on two cones in the Ogilvie Mountains, Yukon Territory (J.T.Gray, private comm. 1970)

seen that maxima occur both at the top and the base of the slope. These cones seem to be mainly affected by rockfall activity and, making a few simple assumptions, the pattern of deposition can be described by two theoretical curves.

(a) If one assumes that the distance travelled is a function of size and that the distribution of the sizes of the rockfalls is log-normal or exponential (see Chapter 4), this curve will show an exponential or log-normal decrease downslope.

(b) Making the same assumptions, the mean size of rockfall will increase either log-normally or exponentially downslope.

It can be seen that the combination of these curves gives a magnitude-frequency spectrum which, when observed for a short period of time, might produce maxima at either or both ends of the scree. It is not, therefore, anomalous to get large values for accumulation at the base of the slope in the short-term because these probably represent low frequency events involving one or two large boulders.

Most of the results from Surprise show either a logarithmic increase of deposition towards the cliff or no strongly marked relationship (Table 9.9). Only two examples, the protalus area avalanche at Surprise II in 1969 and the Tumblin' Creek Cone in 1970, show increasing deposition downslope and the weak relationship of the latter is largely due to scattered large boulders in the lower part of the track. The common relationship of increasing deposition towards the cliff is especially marked at Surprise II where many of the avalanches are small and avalanche and rockfall deposition is most common on the upper and middle slopes. This relationship is visible even in 1970 (Figure 8.29) when

TABLE 9.9: REGRESSION EQUATIONS OF THE VOLUME OF ACCUMULATION (LOG_{10}) AGAINST DISTANCE FROM THE TOP OF THE SLOPE (m)

Site	Year	A	B	R	S.E.	N
Surprise II	1969	4.495	-0.0130	-.6466*	1.120	163
"	1970	2.839	-0.0044	-.2847*	0.951	260
"	1971	4.229	-0.0140	-.7288*	0.857	233
"	1972	4.404	-0.0143	-.6956*	0.964	253
"	Mean	4.159	-0.0094	-.5884*	0.836	287
"	Mean(3)	4.188	-0.0095	-.5936*	0.823	271
Tumblin' Creek Cone	1969	5.015	-0.0424	-.6187*	1.181	91
"	1970	1.838	-0.0084	.1936*	1.271	253
"	1971	3.436	-0.0124	-.1896*	1.459	184
"	1972	5.729	-0.0484	-.6840*	1.176	159
"	Mean	3.013	-0.0011	-.0293	1.128	257
"	Mean(3)	3.208	-0.0012	-.0263	0.997	159

NOTE: A, B = coefficients of the regression equations
R = correlation coefficient
S.E. = standard error
N = number of observations
Mean(3) = the mean accumulation for those sites with at least three year's observations

*Significant at the 99% level.

most of the lower slopes were covered by a light scatter of debris from two large avalanches. A similarly strong inverse relationship between deposition and distance from the cliff occurred at the Tumblin' Creek Cone in the two years when the avalanche terminated high on the cone (Figure 8.44).

Where an avalanche covered the whole length of the slope, there was no consistent pattern of deposition throughout the track (e.g. Tumblin' Creek Cone, 1970, 1971; lower slopes Surprise II, 1970; also, see Figure 8.22). The overall trend usually reflects the range of deposition in the lower part of the track rather than greater amounts in one area than the other (see Figures 8.49, 8.22). Nearly all the largest boulders measured have been found in the lower parts of such sites. Heavy deposition on the upper sites is more usually a thick cover of smaller debris.

The long-term implications of these depositional relationships are difficult to generalize since the lack of data on the amounts of erosion prohibit any attempt to draw up a sediment budget for the slope as a whole. Obviously, where little fresh debris is arriving on the slope, there is a net debris loss from the upper slopes until the exposure of more cohesive finer material retards further erosion (e.g. Old Nip, A.B.T.). However, where there are large inputs of fresh debris (e.g. Tumblin' Creek Cone), the picture is less clear. The lower part of the slope is obviously being built out but it is impossible to say whether the upper slope is undergoing net deposition or erosion. It may even be an equilibrium form acting essentially as a transport surface and temporary store of debris. At Surprise II, the major role of avalanches appears to be depositional, acting as an input process and producing greater accumulation on the upper slopes. However, avalanche erosion also occurs at this site and, since few suitable sample sites occur in the upper areas which are susceptible to erosion, it is possible that much of this material could also be redistributed downslope by erosion.

Thus, these short-term results indicate no consistent relationship between deposition and distance from the cliff. Depositional maxima may occur on either the upper or lower parts of the slope, depending upon the extent and character of avalanche and rockfall activity. Similarly, no obvious relationship was observed between deposition and distance within individual avalanches.

Magnitude-Frequency Considerations

No other data are available to estimate where these five years of observation might lie within the magnitude-frequency spectrum of annual depositional events on these screes. Furthermore, since the geomorphic activity of avalanches is not correlated with the number and size of avalanches or the amounts of snow (Chapter 5), the spectrum cannot be extrapolated from other data. The character of the screes and surrounding areas suggest that this activity is in no way unusual and that similar, more extensive, activity has occurred in the recent past. The only exception to this is the avalanche deposition on Scree No. 1 resulting from the storm of August 5-6th, 1969; sedimentological evidence from that site indicates that avalanching is a rare occurrence. From the character of the material composing the present scree, it is also obvious that the period of observation is too short to cover the full range of rockfall activity.

A major lesson obtained from these year by year observations has been the folly of predicting next year's results as the basis of previous years' observations, e.g. Eastern Valley Side or Small Cone, 1971; Strike Valley and Old Nip (A.B.T.), 1972. Therefore, while it is possible to produce crude magnitude-frequency groupings of sites, such as those in Table 9.7, such groupings must be subject to constant revision with the continuing input of fresh data over a much longer period of time. The only comparable data to Surprise is from Rapp's study in Kärkevagge (Rapp, 1960); while individual avalanches carry similar volumes of material to those described by Rapp (1-15 m^3), several of the sites in Surprise have more concentrated erosion and deposition than the slopes in Kärkevagge.

CONCLUSION

These results have demonstrated that the methods employed can yield a great deal of information about erosion and deposition on scree slopes, particularly by snow avalanches. They also show there is considerable variation in the pattern, character and intensity of rockfall and avalanche activity from one area of scree to another and also from year to year. Avalanche activity is of more limited occurrence on scree slopes but is able to move a greater volume of material than rockfalls and may considerably modify the surface of the scree. However, these results may overemphasize the relative importance of avalanches as compared with rockfalls because several of the sites studied are areas of intense avalanche activity and the accumulation measurements record only small amounts of rockfall.

The results are only for a five year period and much longer periods of observation and measurement are needed before the true range and significance of the processes can be fully understood. Nevertheless, by associating the implications of these short-term results with observations of the present character of the screes, it is possible to make inferences about the processes which have produced the screes. In the next two sections of the thesis, these characteristics will be examined in detail, firstly by an examination of the sedimentary characteristics of several screes and secondly by a discussion of scree form.

SECTION III

THE SEDIMENTARY CHARACTERISTICS OF THE SURFACE MATERIAL ON SCREE SLOPES

Chapter 10: Previous Sedimentological Work on Screes and an Outline of the Present Study

Chapter 11: Particle Size and Shape

Chapter 12: The Characteristics of the Sampled Distributions

Chapter 13: The Variation of Grain Size Over the Scree Slope

Chapter 14: Avalanche Deposits

CHAPTER 10

PREVIOUS SEDIMENTOLOGICAL WORK ON SCREES AND AN OUTLINE OF THE PRESENT STUDY

The materials which form a scree are a primary sedimentary deposit and usually consist of freshly weathered rock fragments. The characteristics of such deposits may therefore be described by the methods commonly used in sedimentology. An examination of these characteristics and their spatial variations can complement our understanding of the processes involved in their formation by adding a temporal dimension to the studies of process discussed in Section II. The nature and variation of some of these sedimentary parameters, notably grain size, were studied in detail on four major screes in Surprise and additional observations made on three other screes. This section presents the results of these investigations and a discussion of their wider significance in the understanding of scree slope development.

PREVIOUS WORK

Although a reasonable number of observations of particle size or downslope sorting of material on scree slopes are recorded in the literature, the majority of them are qualitative in nature (e.g. Miner, 1934; Rapp, 1960a; Andrews, 1961; van Burkalow, 1945 and references therein). Almost all the sedimentological literature dealing with material greater than sand size refers to fluvial, fluvio-glacial or marine gravels (e.g. Folk and Ward, 1957, Dobkins and Folk, 1970). Recently, more measured data have become available for screes, although they are still widely scattered throughout the geomorphological and geological literature.

Some of the earliest observations are those of Cailleux (1947) which mainly deal with slope angle and orientation data. Hamelin (1958) and Daveau (1958) studied debris cones under Cailleux's direction in the French Alps, concentrating on the measurement of size, shape and orientation of the surface material. Neither author found a simple relationship between position on the slope and mean long axis size for the samples each took on their respective cones. No details of sample size or measurement procedure are given.

Using an elegant analysis of variance design, Griffiths (1959) found no selective sorting on samples taken from a scree in Pennsylvania and concluded that the greatest source of variation was between individual fragments. This result is not very surprising when it is realized that the sample was taken from an area of approximately 25 x 75 feet at the base of the scree and involved a total of only 84 rock fragments. Griffiths also discusses the shape of the fragments as measured by their axial ratios.

The most detailed sampling of scree material was carried out by Caine (1967) in a study of coarse dolerite screes in Tasmania. Twenty-three spot samples of 100 boulders were taken and the measurements of a, b and c axes combined, using a theoretical shape factor, to give the normal diameter of the particle (see Appendix 3). The debris is considerably coarser than that encountered in Surprise, the mean sizes ranging from -8.24 ø to -9.31 ø (the derivation of phi (ø) units is discussed later in this chapter). All the samples are moderately well sorted (using Folk's 1961 classification), coarsely skewed and mesokurtic or slightly leptokurtic. Although there is a tendency for particle size to increase downslope, no statistically significant trends were present in the data. Caine also studied the fabric of the scree and found little preferred orientation in the deposits, although there was a slight downslope dip on many of the particles.

Recently, Thornes (1971) has published some size, shape and orientation data for a number of different types of scree slopes in Iceland as an illustration of his discussion of the effects of scree "environments" (input-output relationships, see Chapter 3) on the attributes of the scree. Size is measured as the logarithm (base 10) of the longest axis and the fragments are similar in size to those encountered in Surprise. A variety of downslope size grading patterns were observed and related to the different "environments" of the screes.

The most important contribution to date, and also the most recent, is the work of Gardner in the Canadian Rockies (Gardner, 1971; also, see 1968a). Gardner collected data on debris size, orientation and roundness for samples from 20 different slopes in the Lake Louise area. The size data were measured as nominal diameter computed from triaxial observations, without a shape or volume correction, for 25 stones at each site. A logarithmic transformation (base 10) was used to normalize the data. Depending upon the size of the scree between 3 and 10 evenly spaced samples were taken along a profile up the centre of each scree studied.

The observations from a total of 117 sites were grouped together and yielded a correlation coefficient of -0.71 for the relationship between size and distance from the base of the cliff. On individual slopes, the sorting gradients varied considerably and local reversals of the logarithmic pattern of downslope sorting were observed. Gardner also considers the surface material at any one point on the slope to be "unsorted" and maintains that no sharp distinctions can be made between the dominant processes on slopes and particle morphology.

The only available sedimentary data on avalanche boulder tongues are a series of histograms of samples taken from longitudinal and cross profiles of the Galena Creek Tongue by Potter (1968). These measurements are the intermediate (b) axis of the fragments and several orientation diagrams are also given. Similar orientation diagrams occur in Rapp (1959).

These published data may be supplemented by material from several unpublished sources, but, like the published material, there is considerable variation in the quality of the data, the attributes measured and the sampling procedures adopted. During 1967, several investigations were carried out on scree slopes in Baffin Island (Ryder, 1968; Compton, 1968; Stock, 1968). Compton measured 50 particles at 15 sites which are plotted as histograms of intermediate diameter in millimetres. All three screes studied showed a downslope increase in grain size but the untransformed measurements make comparison with the Surprise data difficult. All the samples are highly skewed but show better sorting towards the top of the scree. A study of point samples of the larger boulders on the scree showed a similar relationship, although the sorting gradient is more irregular and several reversals of grading occur (Table 5, p. 48).

Stock (1968) made triaxial measurements of 24 or 48 fragments at 24 sites on four screes. From these data, he developed an empirical relationship between the number of fragments within a metre square and the mean size of the intermediate axis of the debris within the square. This was used to estimate mean size for a number of sites for which more detailed measurements were not available. He also examined the relationship between the five largest boulders at a site and the mean size to see if this measure could be used as an estimate of mean size. A good relationship was found on three of the four screes but this method did not give good results where there were relatively few large boulders amongst much smaller debris and he concluded that the photographic size estimates were better.

Photographic size estimates and measured data are presented for two screes to illustrate the variability of size over the slope (Stock, 1968, Figure 10) and indicate that the variations in grain size are not regular and may trend obliquely across the scree. All of the measured samples showed a marked downslope increase in grain size and significant differences in the size distribution at the top and base of the screes. The measured samples are compared on the basis of intermediate diameter in either phi or millimetre units. All of the distributions are positively skewed and no distinctive patterns of kurtosis variation were observed in the data.

The surface and profile characteristics of a series of debris slopes containing permafrost have recently been described by Bones (1971).

Triaxial size and weight data were collected for six samples of 50 fragments arranged in a 2 x 3 analysis of variance design on 27 screes. Phi transformations of the a axis measurements were used for the analysis of variance tests on each scree and in all cases except one the differences between the rows (position on the slope) were greater than the differences between the columns, although only 15 out of the 27 sites showed a statistically significant downslope arrangement of the material. However, since none of the measurements of mean size, sorting, skewness or kurtosis are given in the thesis (only the analysis of variance tables), it is not possible to compare the characteristics of these data with other available work. Bones also examined the orientation of the scree debris using the photographic technique developed by Caine (1969b) and concluded that a random fabric is the most common.

AIMS OF THE PRESENT STUDY

From the foregoing summary, it is apparent that there is very little available information about the sedimentary characteristics of scree deposits. The sedimentary studies carried out in Surprise were made, therefore, with the express purpose of obtaining further information about these characteristics, particularly grain size. Interest was focussed on both the characteristics of the size distribution at selected points on the scree surface and the amount and nature of the spatial variations of its parameters over the whole area of the scree. More specifically the aims were:

(a) to examine the nature of size sorting at sample points;

(b) to examine variations in the parameters of size sorting over the scree, e.g. mean size, sorting, skewness, etc. to see if any significant patterns occurred;

(c) to attempt to pinpoint the major levels of variation by replicating samples at a site to examine local variability;

(d) to examine the relative magnitude of downslope size sorting of fragments and the amount of lateral variation over the area of the scree;

(e) to examine whether any linkages could be found between sedimentary characteristics and the dominant depositional processes on the respective scree slopes; and

(f) to examine the size and shape characteristics of scree particles.

No attempt was made in the present study to study scree fabric; it is difficult to determine and measure the long axis of scree particles without removing them and disturbing the remaining fragments. Also, in many cases, the longest axis cannot be unambiguously identified from photographs where the particles are not elongate or are partially buried (see Figures 13.6-13.10).

The Choice of Sites

Five major sites were selected for detailed study: Scree No. 1, Isosceles, the Palliser Cone, Old Nip and the Tumblin' Creek Cone. Since all these sites were also used in the accumulation studies, their general characteristics have been described in Chapter 8 and are summarized in Table 10.1. A more detailed description will be given in a later section of this chapter dealing with sample design at each site. The sampling programme at Tumblin' Creek was abandoned after only one day as a result of the heavy snowfall which terminated the field season on October 1969. Additional sedimentological data are also available from sampling experiments at the Entrance Screes and Surprise II.

TABLE 10.1: SUMMARY CHARACTERISTICS OF THE SITES EXAMINED IN SURPRISE

Site	Rockwall	Scree	Major Process	Geology
Scree No. 1	Straight	Straight	Rockfall	Sandy limestone
Isosceles	Straight	Straight	Rockfall	Limey mudstone
Palliser	Tilted cliff and bench	Cone	Avalanche	Massive limestone
Old Nip Cone	Straight	Cone	Rockfall	Massive limestone
Old Nip (A.B.T.)	Straight	Modified Cone	Avalanche	Massive limestone
Tumblin' Creek	Bench and chute	Cone	Avalanche	Massive limestone
Entrance	Straight	Cone	Rockfall	Massive limestone
Surprise II	Straight with gullies	Straight with cones	Multi-process	Limestones and shales

The choice of sites was governed by geomorphic, statistical and logistical considerations; their careful selection enabled several major sources of variation to be controlled by reducing the number of variables to be considered at each site. The simple form is necessary to match the assumptions of the statistical design with the geomorphic realities of the extent of the deposit and its source. In practice, this means that the screes are either simple straight screes beneath straight cliffs (Scree No. 1, Isosceles) or single cones (Palliser, Old Nip). This simplicity of form is linked to a simplicity of process. Although all screes are affected by several processes, it is desirable that the sites should be dominated by one process so that possible sediment-process relationships may be more easily recognized. Thus, obvious multiprocess screes were avoided and the sites were selected to try and show the operation of only one major process.

Since lithology is one of the major controls of the size and shape of debris fragments, it is important, both from a sedimentological and statistical viewpoint, to eliminate this source of variation from the observations. Debris shape variations are particularly important in rockfalls since they control the nature of movement over the scree surface (see Chapter 4). In classical sedimentological studies, this problem has been overcome by restricting observations to a particular part of the deposit (e.g. quartz grains, Griffins, 1967, p. 66) or to individual lithologies (e.g. Sneed and Folk, 1957). In the present context, this means finding a single lithology scree and making the assumption that the fragments of any one lithology are relatively homogeneous in shape or have a consistent size-shape relationship. Fortunately, the screes of the Palliser-Isosceles area are ideal in this respect because the characteristics of the cliffs provide a series of simple single lithology screes side by side. However, this control had to be relaxed in the case of the two major avalanche screes (Old Nip, Tumblin' Creek) which are composed of a variety of Mississippian limestones. However, these lithologies do not appear to show great variability in their size and shape characteristics and neither site has any shale debris. The shale debris was the only one which was consistently different in the sampling at Surprise II (see Chapter 11 and Gardner, 1968a).

Sampling Design

The sampling design used followed an analysis of variance model (ANOVA) with replicate samples for each site; slight modifications had to be made to the sampling network at some scree sites due to local terrain or vegetation conditions. A series of radial or parallel profiles were measured using a tape and Brunton compass and an equal number of samples taken from each profile. The same points were used for sampling on all the profiles and their position was determined in the following manner. The length of the scree was first established by taping and the scree divided into three equal zones. Each of these zones was further subdivided into equal parts and, using a table of random numbers, a sample site was selected in each part. Each zone contained at least two samples and the total number of samples on a profile ranged from seven to ten, depending upon the length of the scree. The largest number of sites was located in the lowest zone, since it seemed likely from Gardner's results (1968a, 1971) that the pattern of downslope size sorting would be logarithmic.

(i) Scree No. 1

Scree No. 1 was chosen as an example of simple, straight rockfall scree. It lies beneath a dipslope cliff of approximately 45-50^{0} on which the only irregularities are a few narrow joint-controlled ledges (Figure 10.1). The scree itself merges into the partially vegetated rockslide debris at its base and the zone of mixture was excluded from

Figure 10.1 Scree No. 1 from the base of the Palliser Cone. The light coloured finer scree on the left (adjacent to the large slabs) is the Small Cone. The top of the Isosceles scree is visible on the right and the large boulders (5-8 m plus) in the foreground are part of the Rockpile. 4th August 1969. (compare with Figure 10.4).

the sampled area. Although there are low shrubs and a few stunted trees on the upper parts of the slope, they did not cause any major sampling problems except that profile 3 had to be removed 12 m to the north to avoid one such area. Four parallel profiles were surveyed with seven sites on each profile and the full design is shown on Figure 10.2. The two lowest sites on profiles 3 and 4 were moved upslope slightly to avoid rockslide debris.

The assumption of a simple rockfall dominated scree was challenged by the avalanche activity at this site following the storm of August 5th, 1969 (see Chapters 8 and 14). However, the sampling of this site had been completed prior to the storm and the difference in the surface characteristics of the scree after that event suggests that such avalanche modification is rare. Few examples of "avalanche boulders" were found during sampling and the results from the polyethelene squares at the foot of the scree support this conclusion--at least for the period 1968-1971 (see Chapter 8).

(ii) Isosceles

The Isosceles scree is adjacent to Scree No. 1 but is much longer and composed of a different rock type. Two parallel sample profiles were taken about 18 m apart, with nine sites on each profile (Figure 10.3). The location of the profiles was selected to avoid the avalanche track at the junction with Scree No. 1 and also to miss the more heavily covered areas of shrubs and willows on the main scree (see Figures 8.5 and 8.6). In the upper 50 m of the slope, the scree is merely a thin veneer of rock debris overlying bedrock or a layer of indurated fines.

Due to an error in the initial calculation of the length of the

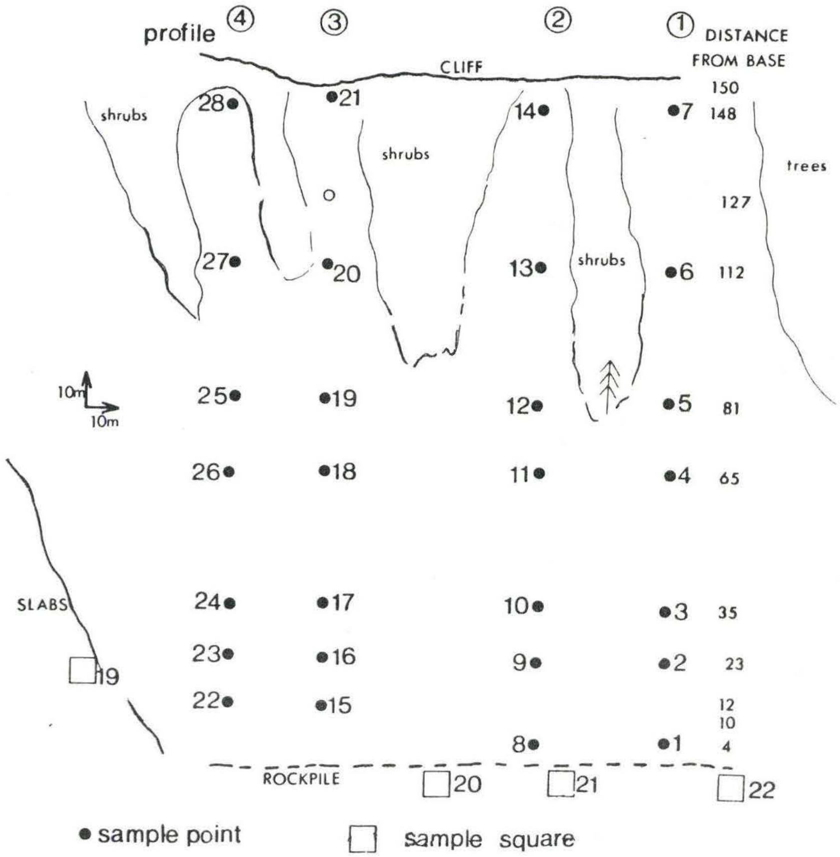


Figure 10.2 Sampling sites on Scree No.1

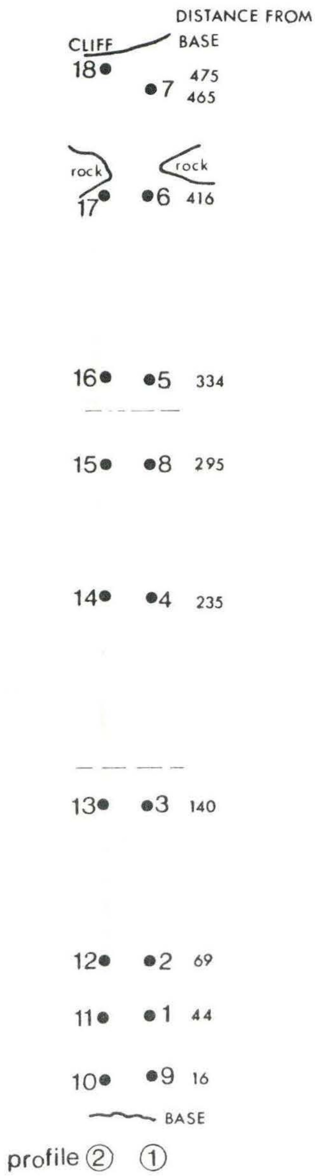


Figure 10.3 Sampling sites on the Isosceles site

scree, two additional pairs of sites (8-10 and 15) were added to the sample design after the first profile had been set up.

(iii) The Palliser Cone

This large cone is fed by the cliffs and sloping benches of the rockslide scar (Figure 10.4). The basal scree and rockslide debris were differentiated on their size, degree of weathering and the presence or absence of rillenkarren (no rillenkarren were noted on scree materials). Sampling was concentrated in the lower third of the scree because of the avalanche erosion, lack of sorting and vegetation cover on the upper parts of the cone. Thus, each of the three zones (upper, middle and lower) were sampled separately with the number of sites in each zone decreasing upslope, partially in response to the cone shape. This complex design is shown in Figure 10.5. The selection of profiles in the upper two sections was largely governed by the absence of a thick vegetation cover. Originally, a sixth profile was planned in the lowest zone (see Figure 10.5) but was abandoned since this area at the edge of the cone is a collecting area for coarse debris from the small scree to the west as well as for debris swept off the cone.

Although rockfalls are the obvious form of debris accretion, very few were observed during work at this site, probably due to the massive nature of the cliffs and the lack of secondary rockfalls. The main process today appears to be avalanche modification and the main avalanche tracks can clearly be seen on Figure 10.4, taken four days after the storm of August 5th 1969.

(iv) Old Nip

This site is a large rockfall cone (Figure 10.6) below a small

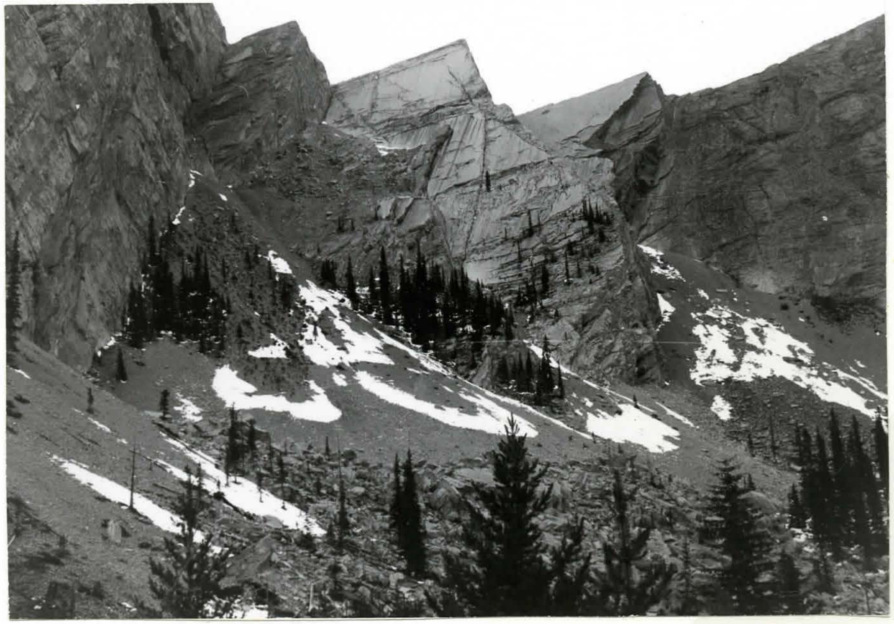


Figure 10.4 The Palliser Cone and environs, 8th August, 1969. The extent of the snow avalanches is clearly seen on the Palliser and Small Cones. The goat trail can be picked out as a very faint white line. Rockpile debris is in the foreground.

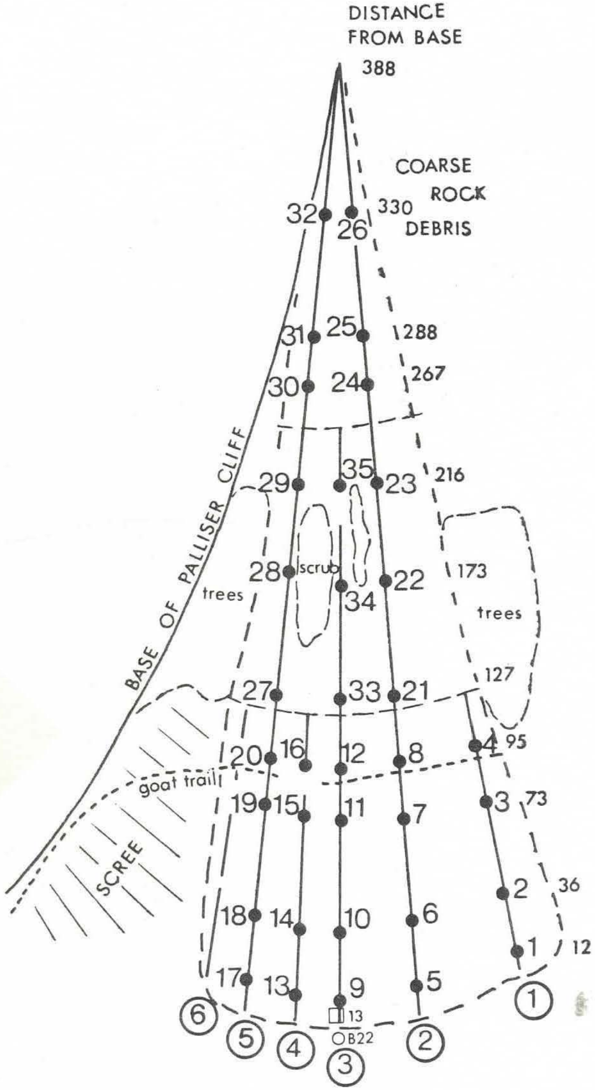


Figure 10.5 Sampling sites on the Palliser Cone

re-entrant in a straight, vertical cliff and its general setting has been discussed in Chapter 8. Strongly localized avalanche erosion on the northern flank of the cone has produced an avalanche boulder tongue (Figure 10.7) and the juxtaposition of these two areas (rockfall cone and avalanche modified flank) is an ideal experimental situation for the comparison of the two types of scree. Two sample profiles, each with eight sample sites, were established in each area (see Figure 10.8). The profiles on the tongue followed the avalanche track and continued to the apex of the cone. These profiles avoided the problem of sampling in the gullies and their associated levees. The avalanche boulder tongue extends well beyond the limit of active rockfall scree which is bordered by a zone of older, larger blocks of more weathered debris, often associated with considerable amounts of fines. This zone also exhibits a marked break of slope in some places and is thought to be an old protalus rampart. Sampling of the rockfall cone did not include this material and therefore the two sets of profiles are of different lengths. Due to an underestimate of the length of the slope, an extra site was added to the top of the rockfall profiles.

(v) Tumblin' Creek

Although it was not possible to complete sampling at this site, four samples were taken on a profile up the middle of the cone. The topmost site was 74 m from the base of the cone (about half way) and the others are 13, 35 and 56 m respectively. A full description of this site can be found in Chapter 8.

(vi) Entrance Screes

During July 1969, a small rockfall cone at the western end of the

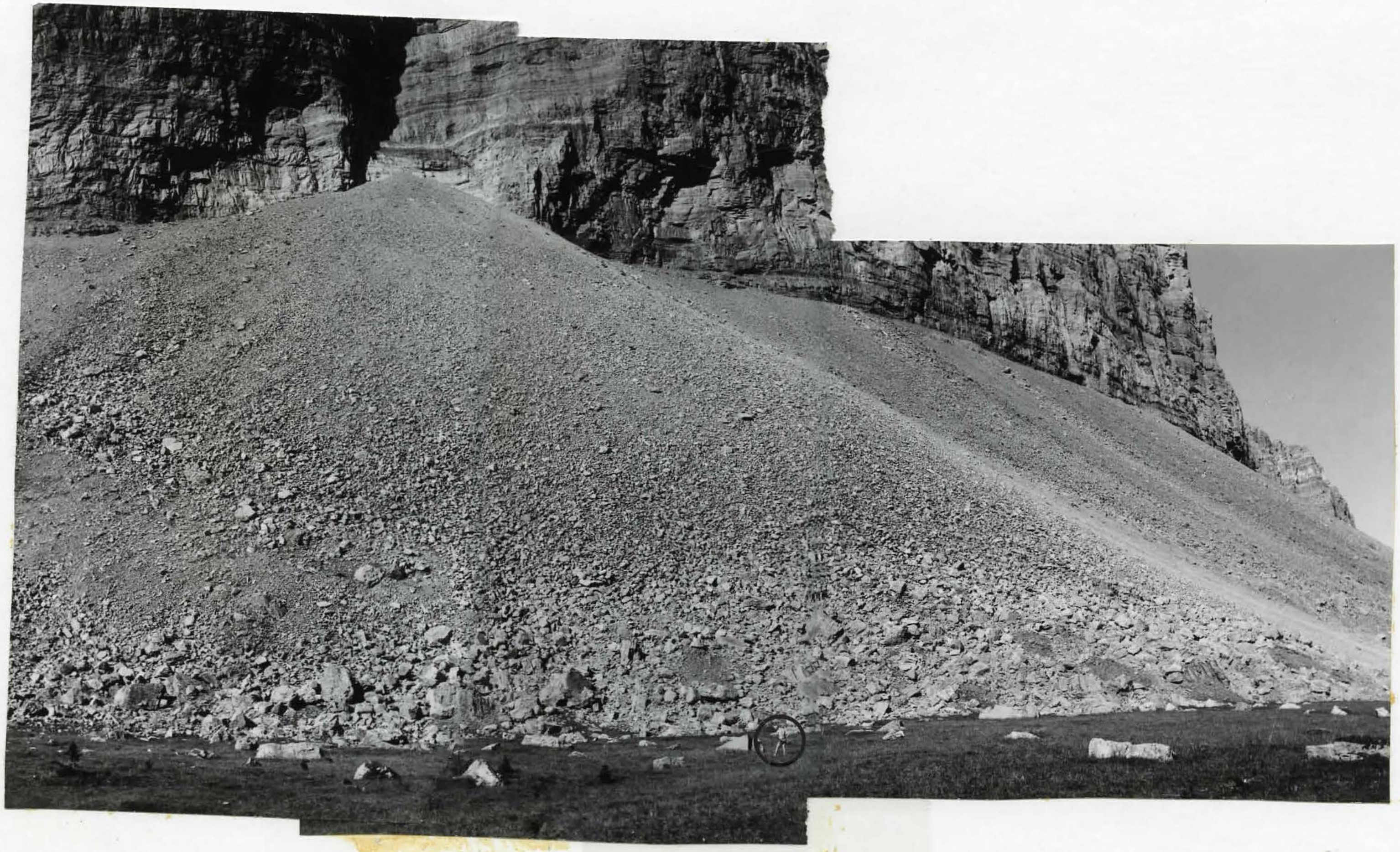


Figure 10.6 The Old Nip Cone from the southeast. The lower limit of present rockfall activity is clearly visible with the older, larger weathered debris below. The avalanche track is visible as the light coloured area to the right. 9th September 1969.

Figure 10.7 The Avalanche Boulder Tongue at Old Nip. (Also, see Figure 11, Appendix 5).

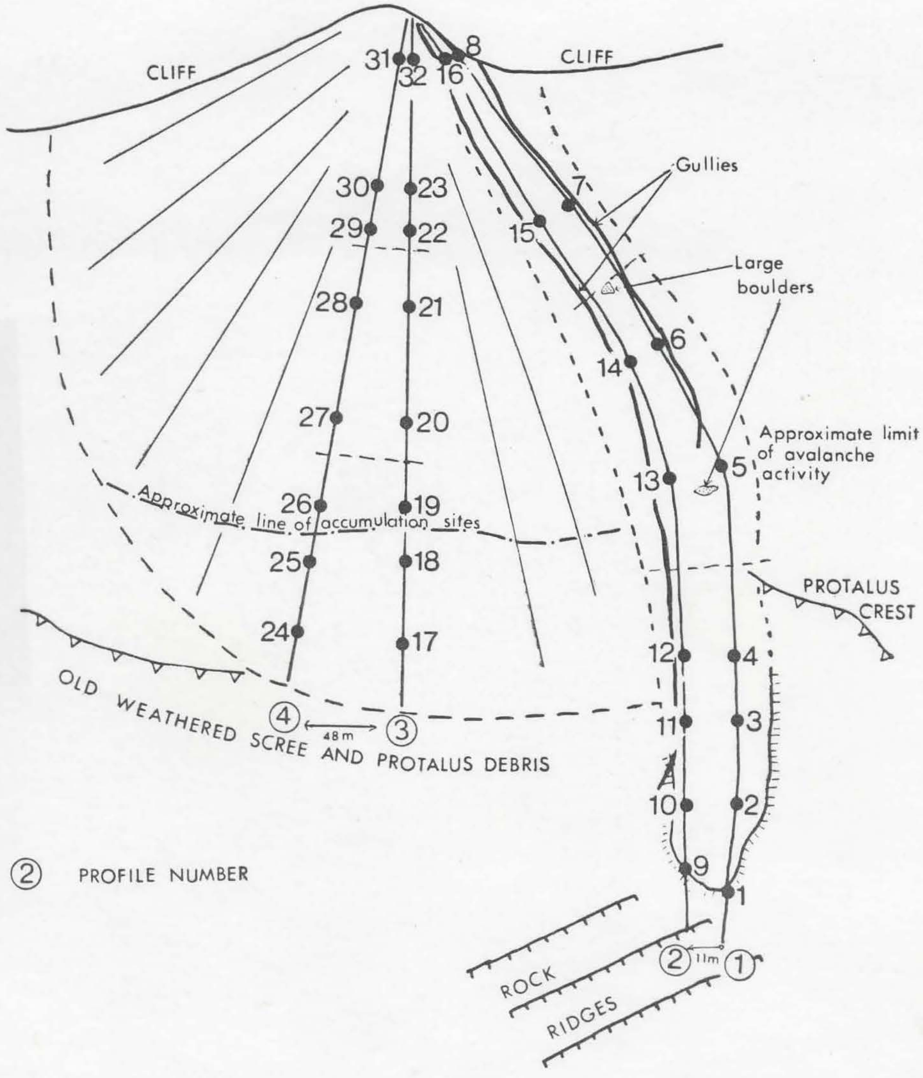


Figure 10.8 Sampling sites at Old Nip

cliffs was used as an experimental site for sampling techniques. Four sites were sampled by two methods at 3, 11, 22 and 30 m from the base of a 33 m long profile up the centre of the cone. The straight cliffs of Rundle Limestone are only about 15-25 m high at this point (see Figure 8.4, left of point A).

(vii) Surprise II

An earlier experiment, in 1968, involved the measurement of 12 samples of 50 particles on a profile up the largest cone at Surprise II. Sampling was by the grid method (see below) and the three axes of each stone were recorded, together with verbal descriptions of lithology and shape. The line of profile is identical to the line of squares set up in that year (see Chapter 8 for a description of the site). The position of the sites is given in Table 10.2.

TABLE 10.2: SEDIMENTOLOGICAL SAMPLING SITES AT SURPRISE II, 1968

Site Number	1	2	3	4	5	6	6A	7	8	9	10	10A	Apex of Cone
Distance from Base	0	50	150	250	350	450	450	550	650	750	850	850	1025

NOTE: All measurements were made in feet.

Sampling Methods

Rationale

Purposeful sampling requires a full understanding of the statistical population under examination before valid inferences can be made from the results. With many forms of geological data, the total population of a variate is not readily available or equally accessible and therefore the target population towards which sampling is directed is an "available" rather than the total population (see discussion in Griffiths, 1967, p. 14). In this study, the target population is defined as the surface layer of material on a particular scree slope; although sampling at depth is possible in some places on these screes where fines are at the surface, the absence of sections and the amount of work involved in digging pits makes such a programme impracticable in Surprise.

A variety of sampling techniques has been used in past studies of scree sediments. The two most common have been sampling using a 10 cm grid on a metre square (e.g. Bones, 1971) or random sampling along a line measured or paced across the scree at the same elevation as the sample point (e.g. Gardner, 1968a; Compton, 1968). Neither of these methods by itself was considered suitable for the aims of the present study. The surface material on scree slopes shows considerable, and often abrupt, lateral variations in size. Line sampling over 50 or 100 feet integrates such differences and since the examination of this variability was one of the purposes of the study, intensive sampling of a relatively small area provides more realistic results. In practice, the area sampled in this study varies considerably in size, since it is linked to the size of the debris (it is 20 fragments wide) but the same relative proportions are retained over the whole sample area. In some cases, major variations still occurred within the sampled area and resulted in bimodal sample populations.

Sampling from a grid pattern produces a consistent bias towards the larger fragments in a mixed population because the probability of selection of any individual is proportional to its surface area in the sampling plane. The selection of randomly chosen individuals along a line of traverse removes this bias since every fragment in the area traversed has an equal chance of selection. However, because of the necessity to limit the sample to a small area and also maintain a consistent sampling method over the scree, five traverses were used rather than one long one. This still retains a slight bias towards the larger fragments since they may be intersected by more than one of the sample lines and therefore may have a greater probability (up to five times in extreme cases) of being selected. In practice, however, this probability was rarely more than twice normal and where the debris was less than about 10-15 cms long, it was negligible. To test these two methods, a small sample project was carried out on the Entrance Screes in June 1969 and six sites were measured by both methods. In all cases, about half the fragments were common to both methods (although the figure decreases as the material gets smaller) but the mean size of the grid samples was consistently higher than the line samples (Table 10.3). On the basis of these results, the latter method was adopted for the sampling programme.

As a result of the trials at Surprise II in 1968 and the comments of Griffiths (1967, pp. 66-69 and p. 345), it would appear that a sample of 50 fragments would be adequate for the present study. However, should the variability of the deposits have been greater than was anticipated, it would have been possible to combine the replicate samples at each site and double the sample size.

TABLE 10.3: MEAN SIZE (NOMINAL DIAMETER) OF DEBRIS IN THE SAMPLING EXPERIMENT AT THE ENTRANCE SCREES

Site	Common to Both Samples	Lines Method mm	Lines Method ø	Grid Method mm	Grid Method ø
2R	30	100.7	-6.28	103.3	-6.33
2L	27	92.4	-6.05	99.8	-6.33
3R	27	83.1	-6.17	90.5	-6.33
3L	25	82.9	-6.07	90.7	-6.31
4R	24	61.7	-5.72	67.9	-5.91
4L	17	46.2	-5.39	52.1	-5.57

Sampling Procedure

Samples were collected during the surveying of profiles by the use of a wooden sampling frame divided into decimetre squares by string (Figure 10.9). This square was 1.2 m long rather than 1 m so that the 1 m^2 area to be sampled could be clearly seen when the square was in place. Two samples of fifty stones were taken, one on each side of the sample point as determined by the survey. For each sample, ten stones were chosen at random from the first twenty stones intersected by each of five parallel lines running across the square. One line was taken opposite the sample point (the mid point of the side) and the other four were randomly selected within each of four equal subdivisions of the square (Zones 1-4, Figure 10.9). Triaxial measurements were taken on each rock fragment and converted to a nominal diameter type of measure. Full details of this procedure are given in Appendix 3.

When it was not possible to sample 20 boulders on a single line within the confines of the square, the line was extended until the

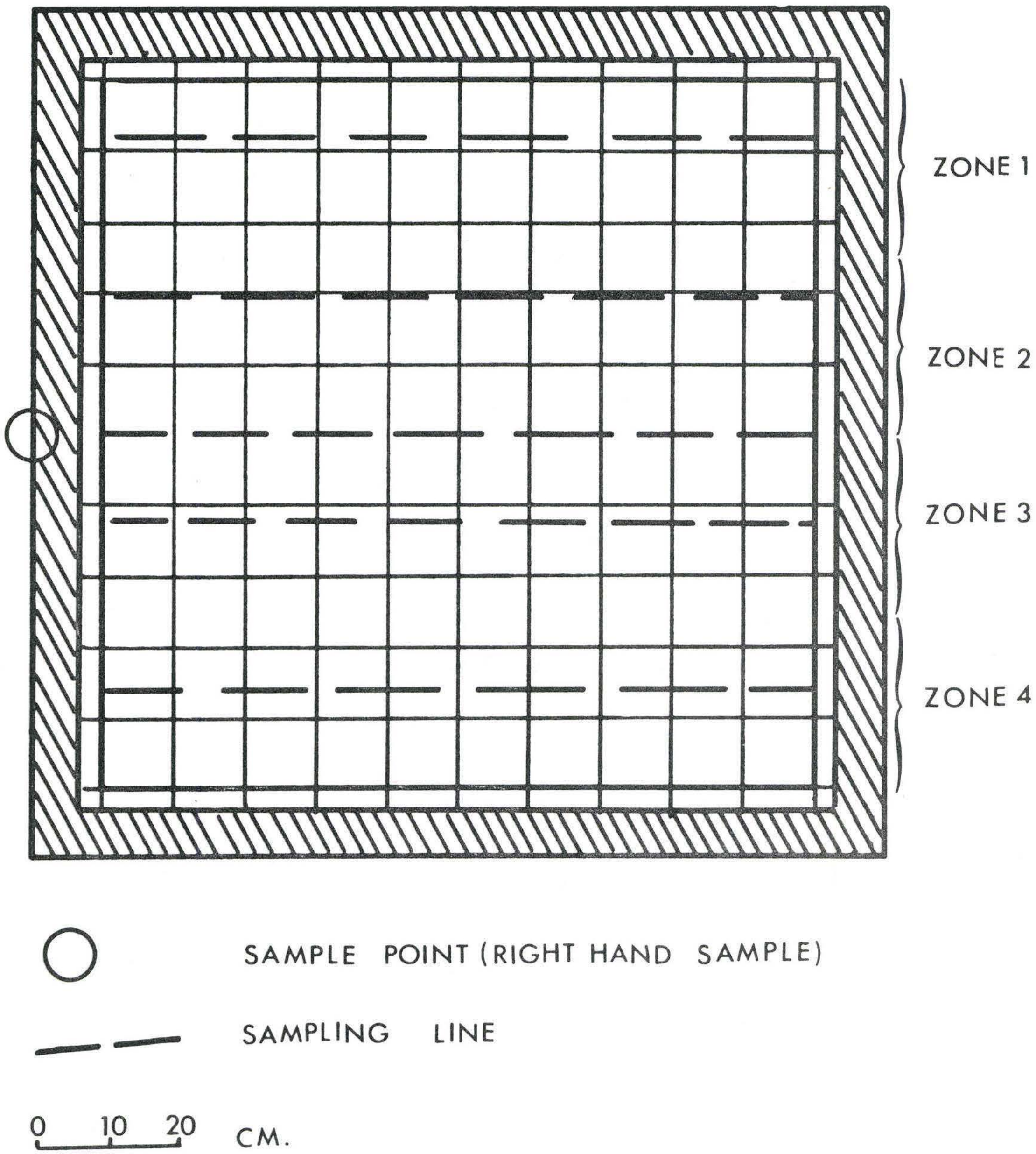


Figure 10.9 Sketch of the sampling square

requisite number of fragments had been sampled. Sampling was without replacement so that no stones were sampled twice; in exceptional cases, where the same large boulder was measured in both samples at a site, it was only included in one of the two samples (chosen randomly) and an additional observation was taken. Where considerable local variations in grain size occurred, additional samples of 50 stones were taken from selected locations to illustrate this variability. These sites are numbered 13EX, 25EX, etc. following the number of the original sample point.

At each site, either five or ten measurements of the angle of slope were taken (depending upon the grain size of the sampled area) using a 60 cm long rod laid across the surface. The five largest boulders within the area sampled were also recorded together with the largest visible boulder within five metres of the sample point (on the appropriate side). In an attempt to assess the importance of avalanching, an estimate of the percentage of larger boulders with avalanche debris was made for a sample of 25 boulders. The site was also photographed and these photographs are reproduced as Figures 13.6-13.10.

CHAPTER 11

PARTICLE SIZE AND SHAPE

Before examining the variation of sedimentological characteristics at individual sites, it is important to try and establish the magnitude of possible differences between the fragments on different screes resulting from variables not specifically included in the sample design. The most important of these is the geology of the cliffs since the bedding, jointing and other weaknesses in the parent material control the available size range and basic shapes of the scree particles. The purpose of this chapter is to examine the magnitude of such differences. Since most of the screes are composed of a single rock type, these differences may be discussed on a scree by scree basis.

GEOLOGICAL CHARACTERISTICS OF THE SCREE DEBRIS

(a) Palliser Cone

The Palliser Limestone is a fine, dark grey, massive, unfossiliferous, dolomitic limestone which weathers to a light grey colour. Initially, the limestone breaks down into large resistant blocks such as those which characterize the rockslide debris. However, in some localities, physical weathering has disintegrated such blocks into large numbers of relatively small (10-100 mm, a axis), irregular fragments often showing a hackly fracture. Fragments on the scree have very few clear bedding plane or joint faces. The fragments are multi-faceted, almost subrounded in form and difficult to place clearly in the shape classes. Individual faces are rough and show little sign of weathering.

(b) Scree No. 1

This scree is fed by a formation stratigraphically below the Palliser within the upper part of the Sassenach Formation (Mountjoy, 1964). This is a medium grey to brown silty limestone or siltstone with a few sandy partings and breaks down into fairly regularly-shaped blocky slabs. Between this formation and the Palliser is a similar bed with more sandy partings which breaks down into huge slabs (see Figure 10.1).

(c) Isosceles

The lower part of the Sassenach Formation and the underlying Mount Hawk Formation are composed of calcareous silty mudstones and argillaceous limestones. These break down to the irregular bladed fragments which form the scree at Isosceles. These fragments are generally smaller than those produced by other lithologies and often have arcuate fracture planes.

(d) Entrance Screes

This small cone is fed from a cliff of Pekisko (Mississippian) Limestone. This is a massive, echinoidal limestone or dolomitized limestone (MacQueen, 1966) and fragments tend to be large and blocky.

(e) Old Nip, Tumblin' Creek and Surprise II

These three screes are all multiple lithology screes. Their principal components are Mississippian limestones and dolomites which are either massive or well bedded and break down to similar blocky material. The underlying Banff Formation (shales and limestone) contributes to the scree at Tumblin' Creek, yielding platier blocks. At Surprise II, Triassic shales and quartzite are thrust into the cliff and the shales form very distinctive small tabular or platy fragments easily recognizable by their brown colour.

PARTICLE SIZE

The Measurement of Size

Triaxial measurements were made in the field using a 60 cm long caliper-like device graduated in millimetres. These measurements were converted firstly to volume, using a crude shape correction factor, and then to a nominal diameter type measure which is defined as the side of a cube of equal volume to the particle. The problems associated with the measurement of size are discussed at length in Appendix 3. All linear measurements of debris size given in this thesis refer to this nominal diameter figure unless otherwise specified.

The use of a standard measurement and sampling procedure led to certain difficulties at a small number of sites where the surface material was too small to be accurately measured by the techniques used. At such sites, there is a measurement cut-off where the a axis is less than about 5-10 mm (1-4 mm nominal diameter or 0.0 to -2.0 ø) and the mean grain size of these sites is probably overestimated. This cut-off simulates a natural occurrence elsewhere on the scree where the smaller particles fall or are washed down into the voids between the larger ones leaving a "lag concentrate" type of deposit at the surface. The only places where this sampling problem arises are where the loose coarser material has been stripped from the surface and finer material is exposed or where finer material near the top of the scree is associated with soil and plant development. Since errors of this type only affect a small number of sites (two at Old Nip and two on the Palliser Cone), it was considered better to maintain a standardized measurement and accept these inaccuracies rather than trying to compare the results from two completely different measurement techniques.

Phi Units

Measurements of size given in this thesis are in one of two basic scales, millimetres or phi (ø) units, and unless otherwise specified refer to nominal diameter measurements as defined in Appendix 3. Phi units are a logarithmic transform of millimetres following a scale devised by Krumbein (1938; also, see Griffiths, 1967, pp. 75-77) for grain size distributions. The scale is based on logarithms to base 2 in such a way that $x = 2^{-\phi}$ where x is a measurement in millimetres. The zero point on the scale is set at 1.0 mm and, since the majority of sediments studied on this scale are smaller than this, they are conventionally shown as positive numbers. Thus, scree fragments, usually being larger than 1 mm in size, are represented by negative numbers on the phi scale, e.g. 8 mm = -3.0 ø, 256 mm = -8.0 ø, etc. Therefore, it is important to remember that the smaller the phi value, the larger the size. The value of this transformation and its relevance to the measurement of scree fragments is discussed in Chapter 12.

The Size Distribution of the Sampled Debris

The sample sites on each scree provide a stratified random sample of all possible sites on that area of scree. However, because individual fragments were not chosen randomly over the whole scree but from spatially associated groups (i.e. sample squares), the sum total of the observations is not a random sample (in the strict statistical sense) of the surface fragments covering the whole scree and therefore statistical inferences cannot be made from these data to the population as a whole. Nevertheless, the total sampled populations from each site may be validly compared as samples of the surface material on each scree.

Figure 11.1 shows histograms of the particle size distributions at each of the major screes sampled. Since the detailed sampling design was not the same at all sites and to compensate for the areal bias in those designs, not all the measured data for each site were used. Certain sites were excluded (on a random basis) so that, for the straight screes, there were an equal number of sites in each of the three zones and, on the cones, the number of sites in each zone approximated the ratio of 5:3:1 (lower:middle:upper). In this way, within the limitations of the sampling method, a reasonable approximation of the true size distribution of the surface debris may be achieved. Summary statistical parameters of these distributions are shown in Table 11.1.

Considerable variation in the size of the sampled populations is evident from Figure 11.1. Modal values are in the range of -3 to -7 ϕ, within the gravel to coarse gravel range of most classifications of sediments (e.g. Griffiths, 1967, p. 76). Extreme sampled values range from -0.06 (next smallest -0.44 ϕ) to -9.45 ϕ and although larger

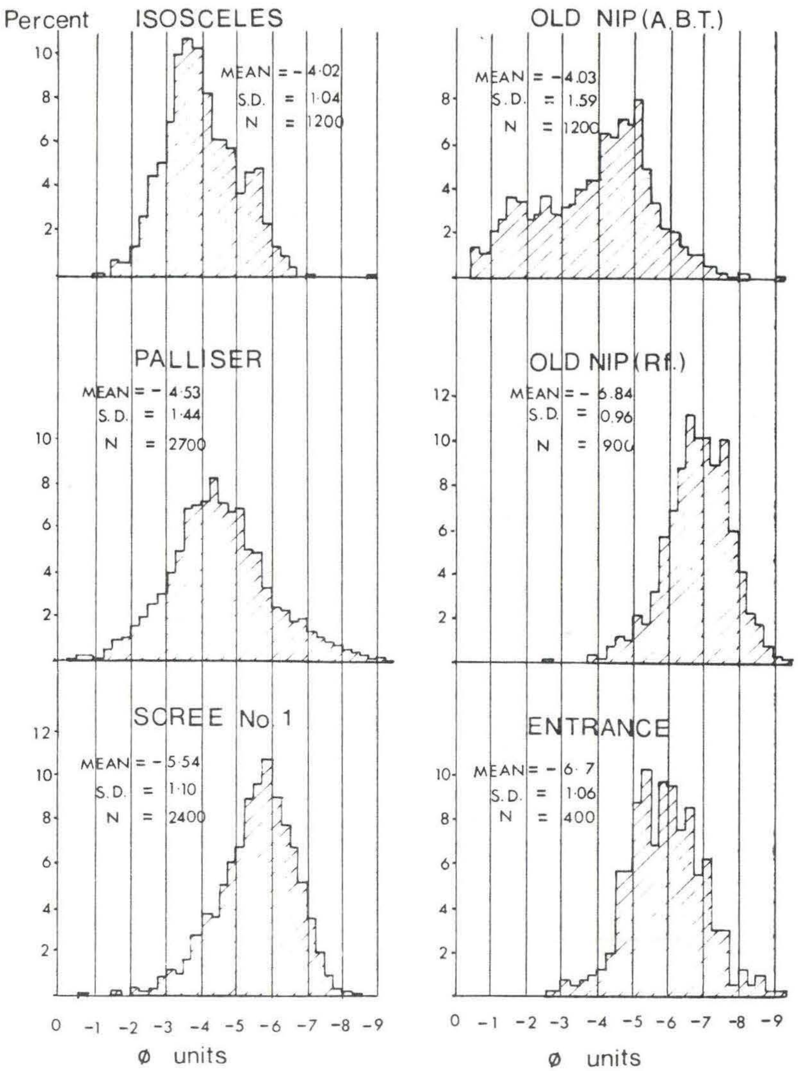


Figure 11.1 Particle size distributions of the major screes sampled in Surprise

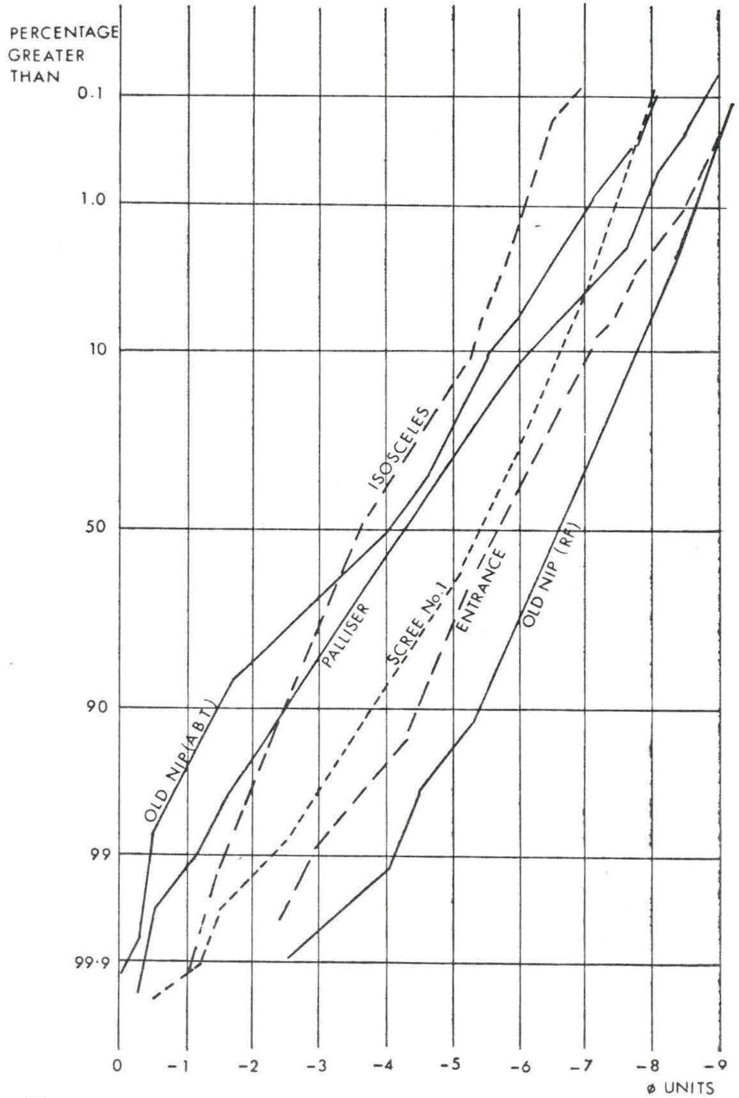


Figure 11.2 Cumulative percentage plots of samples from individual screes (probability paper)

boulders are present on the scree (Table 11.1), they rarely exceed -12.0 ø. This rapid coarse cut-off is a function of the size of block which can fall without fragmentation and the logarithmic nature of the phi scale. As the phi value gets smaller, a much larger size range occurs in successive classes and, for example, boulders with nominal diameters of -9, -10, -11, -12.18 and -13.29 ø would have volumes of 0.13, 1.07, 8.29, 100 and 1000 m^3 respectively.

TABLE 11.1: SOME SEDIMENTARY STATISTICS FOR THE TOTAL OBSERVATIONS AT EACH SCREE (PHI UNITS, NOMINAL DIAMETER)

Variable	Scree No. 1	Palliser	Isosceles	Old Nip (R)	Old Nip (A.B.T.)
Approximate true mean size	-5.54	-4.53	-4.02	-6.84	-4.03
Standard deviation	1.10	1.44	1.04	0.96	1.59
Number in sample	2400	2700	1200	900	1200
Mean of all observations	-5.64	-4.58	-4.15	-6.34	-4.23
Standard deviation	1.10	1.37	1.09	1.10	1.57
Fragments sampled	2800	3500	1800	1600	1600
Smallest fragment	-0.55	-0.44	-0.58	-1.67	-0.06
Largest fragment sampled	-8.45	-9.32	-8.83	-9.46	-9.23
Largest boulder within 5 m of sample points	-8.65	-11.25	-8.83	-10.66	-10.96

Except for the avalanche site at Old Nip (ONAV) and Isosceles, all possible pairs of mean values are significantly different at the

99% level. Again, with the exception of ONAV, all samples approach a log-normal (phi-normal) distribution and approximate straight line plots on probability paper (Figure 11.2). These differences in particle size and distribution reflect both lithological variables and the resorting of available material by various scree slope processes. This is clearly shown at Old Nip where both sites have similar geology but markedly different grain size distributions have resulted from the action of different processes (Figures 11.1 and 11.2). The rockfall cone is both the coarsest and the best sorted of the screes sampled; it is a typical lag deposit with a small tail of fines. Grain size distribution on the avalanche cone is almost bimodal, probably reflecting the finer material exposed by avalanche stripping. The lack of coarse material is probably due to its burial beneath the finer material swept from further upslope (see Chapter 13).

Differences in the remaining sites can probably be more confidently ascribed to geological causes, although avalanche activity on the Palliser Cone may have significantly affected the characteristics of that site. This site is unusual in that the distribution has very long tails at both ends, with a bias towards the coarser tail. This probably reflects the two stages in the breakdown of this material, firstly to large blocks and then to much smaller fragments. The other two screes in this area, Isosceles and Scree No. 1, both lack really coarse particles. Their less massive bedding generally results in smaller c axis sizes which decreases overall size (see discussion below). Isosceles has the smallest modal values of any of the screes (-3 to -4 ø) and Scree No. 1 is considerably larger. The absence of a fine tail to the distribution of samples from Isosceles is probably due to a measurement cut-off (as is that at ONAV) rather than a "lag" effect.

The Pekisko Limestone at the Entrance Screes is one of the components of the scree at Old Nip (rockfall cone) and, although slightly smaller in size, has very similar characteristics. Because of the small number of samples at this site, it was not possible to apply the correction for a cone to these data and therefore the mean size of the debris (for the whole cone) is probably underestimated.

The Relationship of Nominal Diameter to A Axis Length

The data of Table 11.1 and associated figures are given in terms of nominal diameter and, since this measure is unique to this thesis, it is important to relate it to some standard measure for comparative purposes. Thus, for each sample site of 50 stones, the difference was calculated between the mean a axis length and the nominal diameter in phi units. These results are tabulated in Table 11.2 and on the basis of this, it can be seen that nominal diameter values are, on the average, 0.8-1.25 ø units less than the a axis length. The differences between these mean figures can be interpreted as a result of differences in

TABLE 11.2: DIFFERENCE BETWEEN MEAN A AXIS SIZE AND NOMINAL DIAMETER IN PHI UNITS

Site	Mean	S.D.	Maximum	Minimum
Isosceles	1.23	0.089	1.45	0.92
Scree No. 1	0.89	0.061	1.06	0.79
Palliser	0.85	0.059	1.01	0.74
Old Nip	0.85	0.063	1.09	0.70

shape of the "average" fragment. Isosceles, with the most bladed fragments, has the largest difference, whilst the two massive limestones are similar with the smallest values. Scree No. 1 is slightly less thickly bedded and is significantly different from these two at the 99% level.

When the amount of reduction is plotted against a axis size (for example, Figure 11.3), there is a general inverse relationship between the amount of reduction and the a axis mean size (Table 11.3).

TABLE 11.3: CORRELATIONS BETWEEN MEAN A AXIS SIZE AND THE DIFFERENCE BETWEEN A AXIS AND NOMINAL DIAMETER (PHI UNITS)

Site	N	R	R^2	S.E.	Significance
Scree No. 1	61	-0.630	0.40	0.039	99.9%
Isosceles	43	-0.738	0.54	0.075	"
Palliser	79	-0.389	0.15	0.318	"
Old Nip	82	-0.676	0.46	0.574	"

This reflects the changing relationships between the axes with increasing size and is more fully discussed in the following section. It also indicates the difficulty of considering size independently of shape as there are general relationships between them.

PARTICLE SHAPE

One of the major variables affecting the nature of downslope movement of particles is particle shape. However, three dimensional shape is difficult to define simply. The empirical shape classes derived in Appendix 3 permit only a crude estimate of change in overall shape of the particles. Thus, in spite of problems in their meaning and

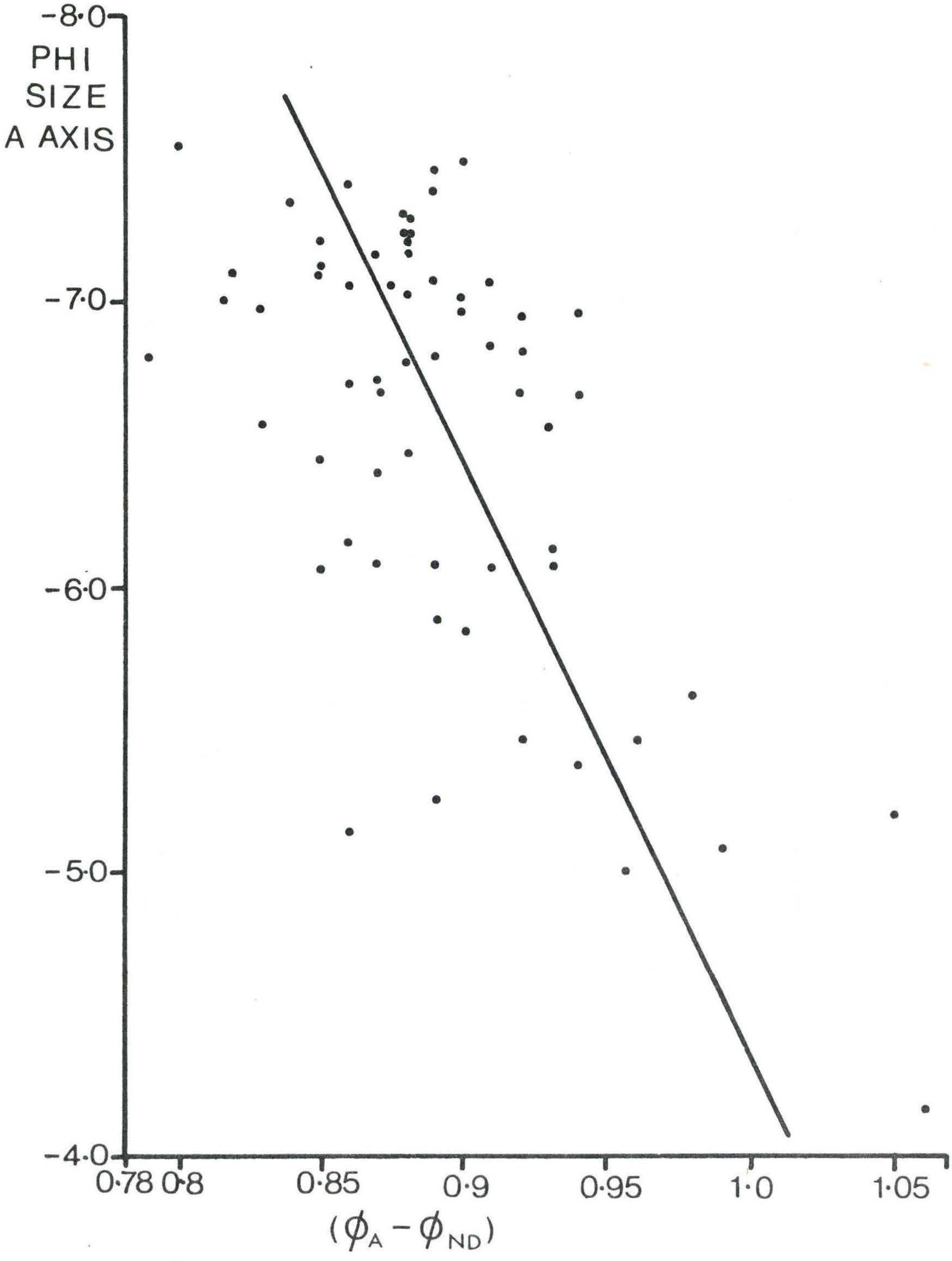


Figure 11.3 Relationship between a axis and nominal diameter (in phi units) for the means of sample sites on Scree No.1

interpretation, axial shape ratios provide the best way to define variations of particle shape over the scree. Within this section, the character and variability of the shape of the sampled particles will be discussed in an attempt to (i) examine variations in shape between lithologies and (ii) to examine the variation of shape with size.

Observed Shape Data

Table 11.4 shows the percentage of each of the five shape classes (Appendix 3) used for nominal diameter coversions for the major scree sites in the order in which the measurements were taken. Although there are obvious variations between the sites, the two most consistent trends were for a decrease in the number of fragments of class 5 (6 sides) and increases in classes 3 and 4 (6-2/3, 6-3/4) as the measurements progressed. This represents operator "drift" as the season progressed and, while it is assumed that such drift is not significant at individual sites, these trends must invalidate any firm statistical comparisons

TABLE 11.4: PERCENTAGE OF FRAGMENTS IN EACH SHAPE CLASS AT THE VARIOUS SAMPLE SITES

Site	Shape Classes 1	2	3	4	5	"% Blocky"
Scree No. 1	12.43	43.05	0.16	11.90	31.02	42.92
Palliser	25.57	39.11	0.66	10.71	23.87	34.56
Old Nip (AV)	20.69	43.06	1.50	14.81	19.94	34.75
Old Nip (RF)	11.50	20.56	6.00	43.75	10.19	53.94
Old Nip (EX)*	18.47	42.00	4.12	24.35	11.06	35.41
Isosceles	21.25	31.16	6.19	28.88	12.51	41.39

*Only 15% of these sites are from the rockfall cone.

based on these data, hence the use of axial ratios to examine particle shape.

Despite this, several trends are visible even within these data. The most obvious difference is between the sites at Old Nip where, since the lithologies are the same, the differences in the proportions of the shape classes must represent differences due to size-shape relationships (the size ranges are significantly different) or some linkage between particle shape and process. It is also notable that the coarser screes (Old Nip Cone and Scree No. 1) have much smaller percentages of shape class 1 (four sides) and a tendency, especially at Old Nip, for the material to be 'blockier'. These observations suggest that the smaller particles tend towards a more irregular shape (classes 1 and 2) while the larger debris tends to be more regular. Data from profiles on Scree No. 1 support this, since individual sites with the largest numbers of observations of class 1 are those at the top of the scree where the material is smallest. These trends are more clearly visible in the axial data and are discussed in detail below.

Axial Ratios of Shape

Numerous axial ratios have been used by geologists and geomorphologists as indices of particle shape, roundness and sphericity (King, 1966, p. 291; Griffiths, 1967, Chapter 8). These range from single axial ratios (a/b, c/a, etc.) to complex relationships such as the Krumbein sphericity ($\sqrt[3]{\frac{bc}{a^2}}$) or the oblate prolate index 10 $\frac{\left(\frac{a-b}{a-c} - .50\right)}{c/a}$ (Dobkins and Folk, 1970). Within this particular study, no attempt was made to measure the roundness or sphericity of scree particles as they were all demonstrably angular. Apart from the simple axial ratios, only two more complex measures were used:

(a) a modified Cailleux flatness index (a+b)/2c (King, 1966, p. 291). This is a measure of the "flatness" or platyness of the particle.

(b) the parameter (a-b)/(a-c) which is one of the two axes of the Folk Triangle (Sneed and Folk, 1957, p. 123) for the classification of particle shapes. This measures the relationship of all three axes such that if the b axis is truly intermediate in size between the other two, the index has a value of 0.5.

All axial measurements given within this section are ratios between axes measured in millimetres. Since phi unit measurements are logarithmic transforms, relationships between them are power functions and the linear measures correspond more clearly to an intuitive notion of shape. Two examples illustrate this point:

(i) When one axis is double the length of the other, the phi axial ratio is size dependent, e.g.

Sample	a(ø)	b(ø)	Ratio	a(mm)	b(mm)	Ratio
1	-2.0	-1.0	2.0	4	2	2.0
2	-4.0	-3.0	1.33	16	8	2.0
3	-7.0	-6.0	1.17	128	64	2.0
4	-11.0	-10.0	1.10	2048	1024	2.0

(ii) When the phi ratio of the axes is constant, the length of the axes is geometrically related and the "shape" changes, e.g.

Sample	a(ø)	b(ø)	Ratio	a(mm)	b(mm)	Ratio
1	-2.0	-1.0	2.0	4	2	2.0
2	-6.0	-3.0	2.0	64	8	8.0
3	-8.0	-4.0	2.0	256	16	16.0
4	-10.0	-5.0	2.0	1024	32	32.0

Two major sources of particle shape variation were examined; those resulting from lithological differences and those resulting from variations in size.

Variation of Shape Between the Lithologies

The axial shape ratio data are summarized in Table 11.5.

TABLE 11.5: MEAN AXIAL RATIOS FOR THE SEDIMENTOLOGICAL DATA AT EACH SAMPLE SCREE

Site	N	a/b	b/a	a/c	b/c	Folk	Cailleux
Isosceles	2150	1.808	0.619	4.782	2.841	0.534	3.811
Old Nip	4100	1.464	0.723	2.506	1.744	0.523	2.125
Palliser	3850	1.448	0.727	2.468	1.738	0.521	2.103
Scree No. 1	3050	1.485	0.712	2.758	1.909	0.505	2.333
Surprise II (shale)	239	1.568	0.678	6.188	4.081	0.444	5.134
Old Nip (AV)	1600	1.488	0.714	2.669	1.826	0.523	2.248
Old Nip (RF)	1600	1.450	0.729	2.315	1.624	0.530	1.967

NOTE: The latter two samples for Old Nip are subsamples of the whole.

Throughout this table, only one (a/b ratio) of the comparisons of means between Old Nip and the Palliser Cone is significantly different at the 95% level. All other pairs of sites are significantly different (99% level, using a t test) with the exception of several of the Folk ratios (Isosceles/Palliser, Palliser/Scree No. 1, Old Nip/Isosceles). These results indicate that there are significant differences in axial ratio shapes between the lithologies at all sites except the Palliser Cone and Old Nip, although the Folk parameter is the least suited to such differentiation. However, these differences are not solely the results of differences in lithology. When the two parts of the Old Nip site are considered separately, there are significant differences between them. Since their geology is similar, this difference must be related to changes in shape associated with changes in size.

To investigate this relationship more fully, the original data were reorganized on the basis of the nominal diameter in phi units and axial ratios calculated for each size group. The number of observations in each size class are shown in Table 11.6 and the means of those classes with more than 25 observations are plotted in Figures 11.4-11.10. These clearly indicate relationships between the axial ratios and both size and lithology. The relative importance of these effects may be tested by the analysis of variance (ANOVA) with a single entry in each cell. The results of these tests are shown in Table 11.7.

TABLE 11.6: NUMBER OF OBSERVATIONS IN EACH CLASS USED FOR THE CALCULATIONS OF AXIAL SHAPE RATIOS

	Size Range (Phi Units)									
Site	0	-1	-2	-3	-4	-5	-6	-7	-8	-9
Isosceles	2	31	258	731	607	439	80	1	1	0
Scree No. 1	1	10	45	178	498	1072	988	250	8	0
Old Nip	33	183	256	500	839	1007	772	410	93	7
Palliser	17	95	329	923	1224	846	324	140	45	7

The data were first tested using the four major lithologies over the -2 to -6 ø range. This range was selected to exclude those classes where one or more of the lithologies had a very small sample size

TABLE 11.7: ANALYSIS OF VARIANCE RESULTS FOR THE AXIAL RATIOS OVER THE SIZE RANGE OF -2 TO -6 ø (FIRST TWO COLUMNS) AND -1 TO -8 ø (PALLISER AND OLD NIP)

Ratio	Source	D.o.F.	MS	F	D.o.f.	MS	F	D.o.f.	MS	F
a/b	Mean	1	48.1306		1	32.7111		1	33.7271	
	Lithology	3	0.1153	67.82***	2	0.0062	15.50**	1	0.0021	3.00 n.s.
	Size	4	0.0077	4.41*	4	0.0027	6.25*	7	0.0053	7.55**
	Residual	12	0.0017		8	0.0004		7	0.0007	
a/c	Mean	1	198.0785		1	107.8647		1	105.8081	
	Lithology	3	4.6149	14.09***	2	0.4230	18.43**	1	0.0156	0.58 n.s.
	Size	4	1.3966	4.28*	4	0.3613	15.87***	7	0.6034	22.59***
	Residual	12	0.3281		8	0.0229		7	0.0267	
b/c	Mean	1	86.8587		1	52.1212		1	52.6495	
	Lithology	3	0.9991	9.34**	2	0.0888	22.77***	1	0.0004	0.08 n.s.
	Size	4	0.4843	4.52*	4	0.1180	30.28***	7	0.2149	46.95***
	Residual	12	0.1070		8	0.0039		7	0.0047	
Cailleux Flatness	Mean	1	137.4400		1	78.1676		1	77.5897	
	Lithology	3	2.4281	12.63***	2	0.2017	32.02***	1	0.0002	0.67 n.s.
	Size	4	0.8978	4.63*	4	0.2267	36.98***	7	0.3850	53.47***
	Residual	12	0.1939		8	0.0063		7	0.0072	
Folk	Mean	1	5.3986		1	3.9753		1	4.1871	
	Lithology	3	0.0006	1.10 n.s.	2	0.0002	0.4 n.s.	1	0.0002	0.03 n.s.
	Size	4	0.0012	2.40 n.s.	4	0.0004	0.8 n.s.	7	0.0015	5.00*
	Residual	12	0.0005		8	0.0005		7	0.0003	
			ALL SITES			PALLISER, OLD NIP AND SCREE NO. 1			PALLISER AND OLD NIP	

*Significant at the 95% level.

**Significant at the 99% level.

***Significant at the 99.9% level.

D.o.F. = Degrees of Freedom

(Table 11.6). The results in Table 11.7 show that, with the exception of the Folk parameter, all the sites show significant variations in axial ratios both between lithologies and between sizes. The generally much higher levels of significance attached to variations in lithology indicate that it is the more important cause of variation in the ratio means. When the Palliser and Old Nip sites are considered separately over the -1 to -8 ø size range, there are no significant differences between the two lithologies (as might be expected from Table 11.5) but all the axial ratios vary significantly with size. With the addition of Scree No. 1 and a reduction again to the -2 to -6 ø range, significant effects are found due to lithology and size except for the Folk parameter. This would seem to indicate that,as well as Isosceles, the debris on Scree No. 1 is also significantly different in shape from the other two over this size range.

These differences may be more clearly shown by a discussion of the individual axial measures.

a/b Ratio (Figure 11.4)

This ratio or its inverse, the b/a ratio, is probably the most commonly used in sedimentological studies. It tends to be very stable over many rock types with b/a ratios ranging from 0.608-0.729 (Griffiths, 1967, pp. 122-124). All of the sampled lithological groups fall within this range (Table 11.5) with Isosceles having the most distinctly bladed fragments. The shales (not shown in Figure 11.4) and Scree No. 1 are slightly more bladed than the debris at Palliser and Old Nip. The size-shape relationships show a tendency towards decreasing a/b ratios with increasing size which is most marked for Isosceles. The few points which differ markedly from this trend (Old Nip, 0 ø; Isosceles, -1 ø; Palliser, -8 ø) are all estimates based on relatively small samples (Table 11.6). Many of the adjacent means plotted on the lowest three lines in Figure 11.4 are not significantly different (t test), although significant differences do occur between the more distant points on these lines.

<u>a/c Ratio (Figure 11.5)</u>

The smallest axis of a rock fragment is usually controlled by the thickness of the bedding planes, except where the particles are small chips and bedding characteristics are not as important. Because of this control, the size and range of the c axis values are closely linked to the lithological characteristics of the rock and therefore the a/c or c/a ratio differentiates rock types most clearly, especially in sedimentary rocks where large variations in bedding characteristics may occur. The c axis is therefore a far more important cause of variation of axial shape measures than the other two axes.

Figure 11.6 illustrates some of these effects. It is constructed on the same basis as Figure 11.5, except that the size classes used are based on the a or c axis rather than nominal diameter. The plots on the basis of a axis size (Figure 11.6A) show only a weak tendency (Isosceles is a little stronger) for a decreasing a/c ratio with increasing a axis size. However, there is a very strong inverse relationship between the a/c ratio and c axis size (Figure 11.6B).

Two main groups of variables appear to influence these relationships. The first group is related to the calculation and measurement of the ratios. The a axis measurements are truncated more than the other

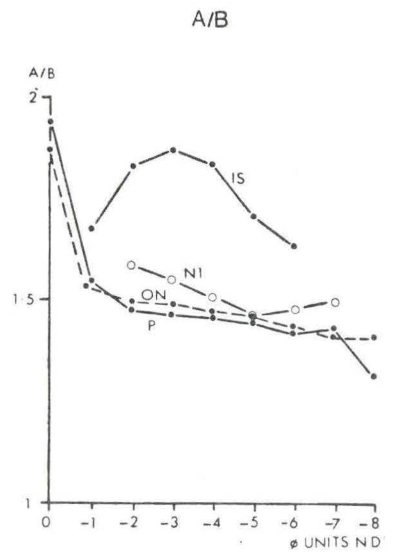


Figure 11.4 Relationship between phi size and a/b ratio

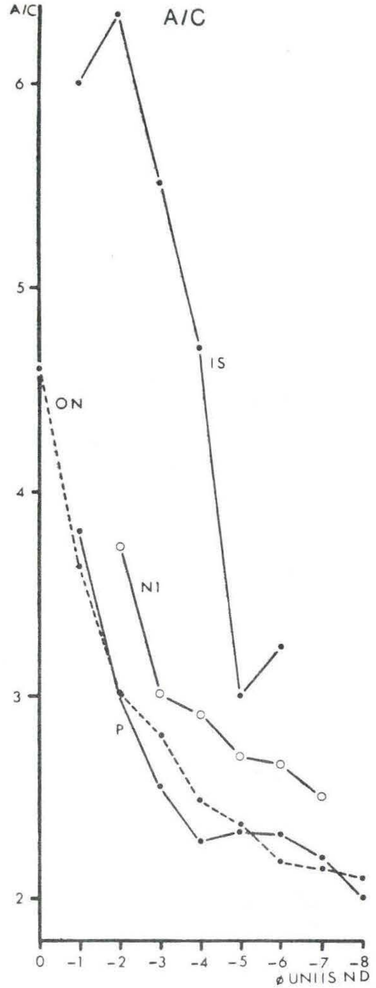


Figure 11.5 Relationship between phi size and a/c ratio

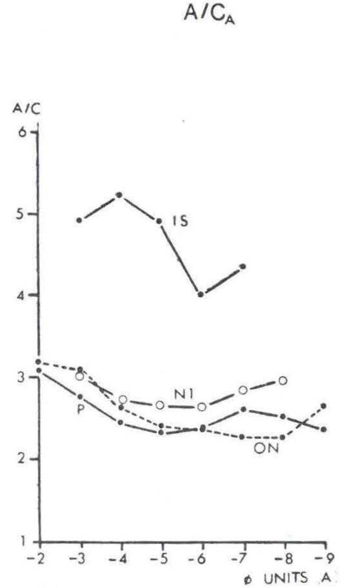


Figure 11.6a Relationship between phi size a axis and a/c ratio

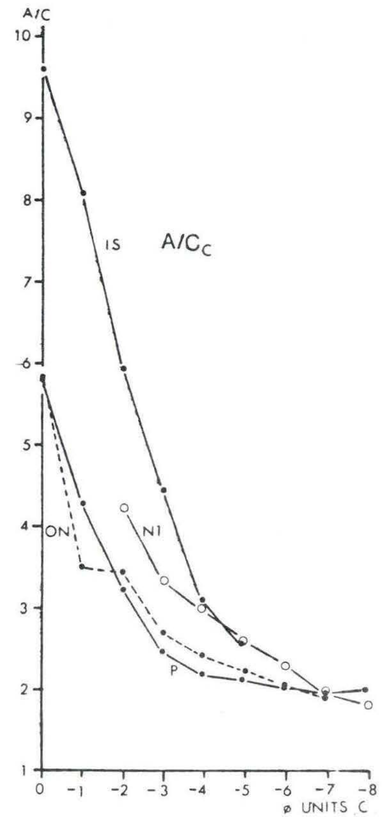


Figure 11.6b Relationship between phi size c axis and a/c ratio

two because the lower measurement cut-off in the field was related to a axis size. Also, partially as a result of this, there tends to be a much greater range of extreme values when the ratios are classified on the denominator rather than the numerator. The second set of variables are a true size-shape relationship. Because of their weight, large elongate or platy particles are more likely to break on impact than smaller particles of equivalent ratio shape, hence the larger fragments tend to be more compact in form. It would appear from the results in Figures 11.5 and 11.6, therefore, that it is the variations in the c axis which are the major determinants of changes in the a/c ratio.

The differences in bedding characteristics between the lithologies are clearly shown in Figure 11.5. The shales (not shown on Figure 11.5) at Surprise II have the thinnest partings followed by Isosceles and Scree No. 1. Old Nip and Palliser have similar fracture characteristics as both are massively bedded. The marked size gradient also shows that the larger fragments of all lithologies have a much more compact shape than the smaller ones. The two extreme values on the plot for Isosceles are not significantly different from their adjacent size classes. The decrease in axial ratio shows a marked break at between -3 and -5 ø, depending upon the lithology. This is probably due to the fact that many of the smaller fragments have relatively small c axes which cause more "extreme" ratios in the smaller size classes (see Appendix 3).

b/c Ratio

The variation in this ratio is obviously conditioned by the relative magnitude of variation in the other two. Since there is not much variation in the a/b ratios, the b/c ratios appear very similar to the a/c ratios except that the values are lower (Figure 11.7).

Folk Ratio

The Folk ratio (a-b/a-c) was derived to distinguish between disk-like and rodlike pebbles (Sneed and Folk, 1957, p. 124). Because most of the rock fragments measured are elongated, this parameter is not very useful for distinguishing between them. Only the shales are significantly different from all other lithologies, using this parameter, since they have a more tabular shape (Table 11.5). The size means plotted on Figure 11.8 show a general tendency to become more compact (rodlike) with increasing particle size, but there is considerable, possibly random, variation within and between lithologies. In all cases, using t tests, less than half the possible pair combinations of means for each lithology were significantly different at the 95% level (Isosceles, 33%; Scree No. 1, 15%; Old Nip, 42%; Palliser, 27%). In every case, except Old Nip and Palliser, ANOVA indicated no significant differences between lithologies or size groups.

When this value is plotted against the c/a ratio on the Folk Triangle (Figure 11.9, plotted here on normal rather than triangular graph paper), it gives an indication of overall particle shape. This figure clearly shows the increasing compactness with larger size; in all cases except Scree No. 1, the larger particles of individual lithologies are in a different shape class than the smaller ones. For comparison with the shales at Surprise II, the means of the other lithological groups are also shown in Figure 11.9.

Cailleux's Flatness Ratio

This ratio, although it involves all three axes, is very

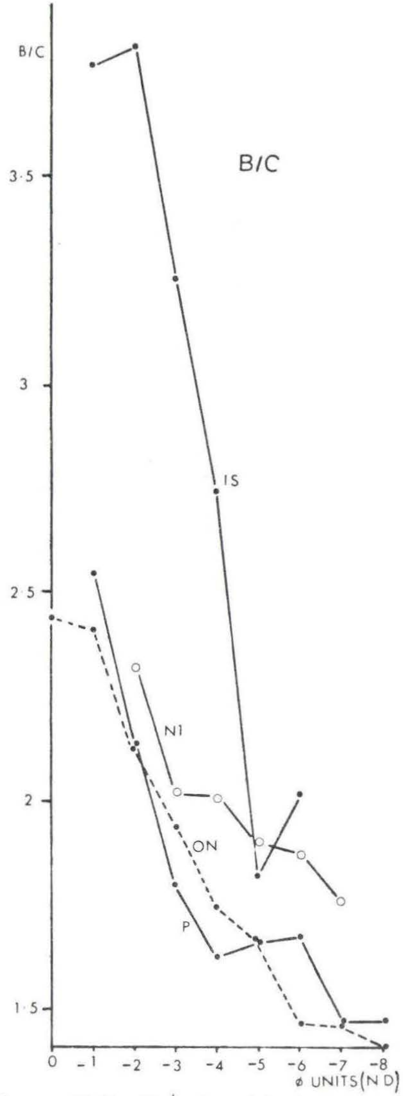


Figure 11.7 Relationship between phi size and b/c ratio

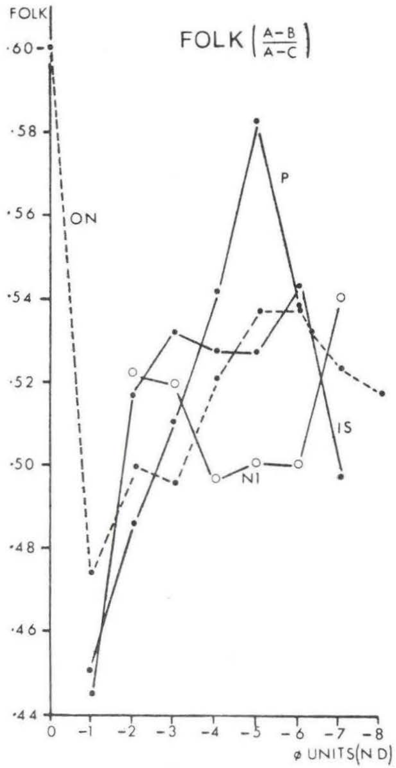


Figure 11.8 Relationship between phi size and the Folk parameter

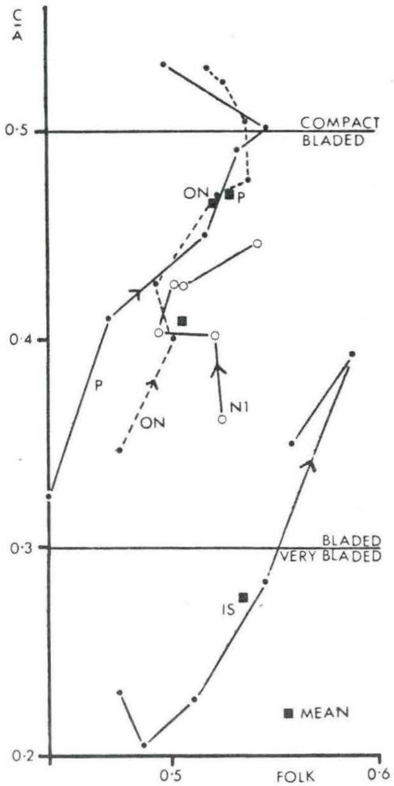


Figure 11.9 Changes of shape with increasing size (plotted on Folk triangle coordinates

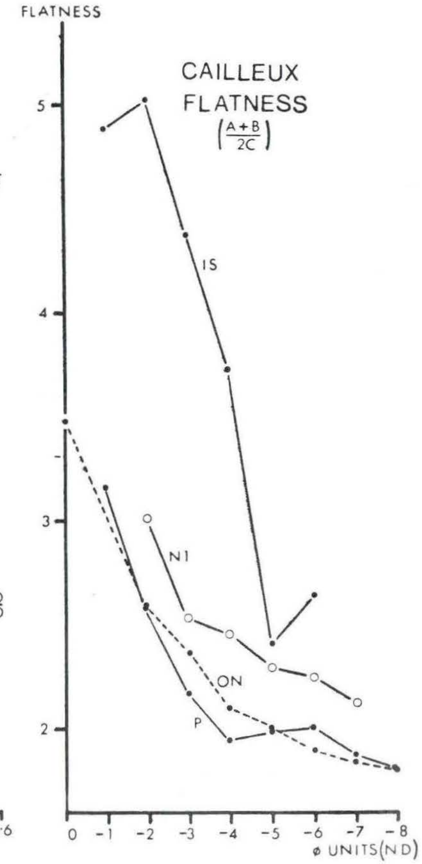


Figure 11.10 Changes of Cailleux flatness with increasing phi size

like the a/c or b/c ratios and the results on Figure 11.10 are similar to those on Figures 11.6 and 11.7. The index clearly differentiates between the lithologies (except Palliser and Old Nip) and shows the marked increase in blockiness with increasing size. The two kinks in the Isosceles plot are similar to those in Figure 11.6.

CONCLUSIONS

The preceding discussion has illustrated the variations in axial shape of the rock fragments measured on the screes in Surprise. While significant differences occur between the four main lithologies tested (shales, Isosceles, Palliser, Scree No. 1) the mixed massive limestones from Old Nip are not significantly different from those on the Palliser Cone. There are also significant differences in shape with variations in particle size; the larger the particle the more compact its form, whilst the smaller fragments tend to be more elongated or irregular in shape. Analysis of variance indicates that, for the four main sites, the lithological differences were more significant but when the Isosceles data were removed from the test, the two effects were of similar magnitude. These variations in shape are controlled largely by variations in the c axis which is mainly a function of bedding characteristics.

These differences in shape are shown diagrammatically in Figure 11.11 for those size-lithology classes with more than 25 observations. The individual blocks are all of equal volume with the axes scaled to maintain their true axial ratios. Both sources of variation are clearly visible as is the appropriateness of Folk's shape classes for these fragments (bladed, very bladed and compact bladed, see Figure 11.9).

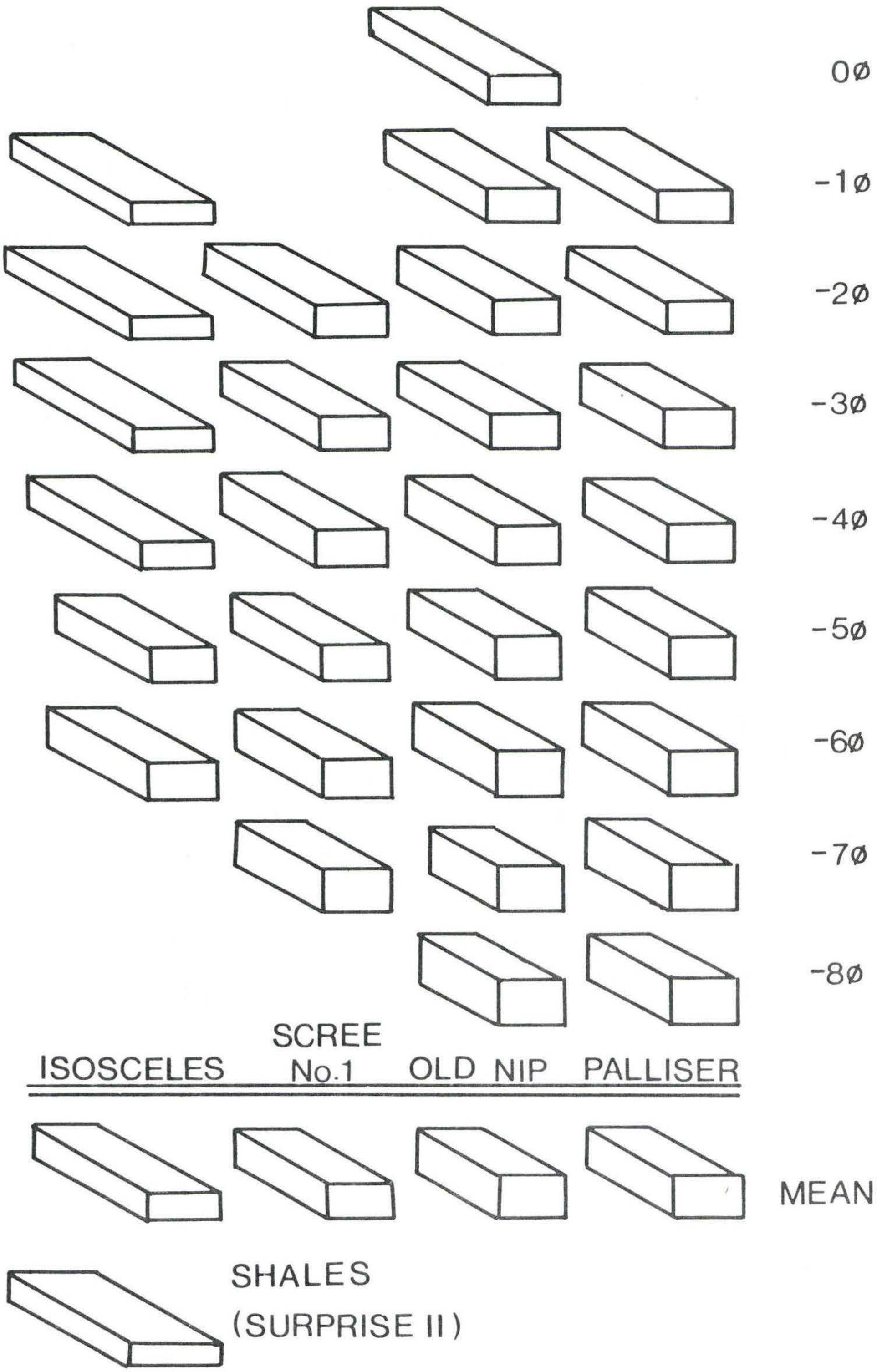


Figure 11.11 Variations in axial shape with changes in phi size and lithology

The most distinctive shape, apart from the shales which were not sampled in the major project, is the debris at Isosceles, whilst the debris at Scree No. 1 is less compact than the other two massive limestones.

It is difficult to estimate the effect of these axial ratio variations on the behaviour of a rolling or bouncing particle. The figures shown in Figure 11.11 are theoretical models of particles, and, as the discussion in Appendix 3 shows, axial ratios are a poor indicator of the true shape of a particle. The size sorting seen on screes may be aided by the size-shape linkage, since the larger particles, as well as having greater mass, also have a more efficient shape for rolling whilst the smaller, irregular fragments quickly come to rest. However, before discussing the problems of size sorting over the scree slope, it is necessary to look at the sample characteristics at individual points.

CHAPTER 12

THE CHARACTERISTICS OF THE SAMPLED DISTRIBUTIONS

Before any parametric statistical tests can be applied to a body of sample data, it is necessary to know the nature of the population distribution from which the samples are drawn and to see whether it approximates to a "normal" distribution. Since the overall characteristics of the size distribution of scree fragments are not known, the tests for goodness of fit must be made on the parameters of the individual samples. On the basis of the available literature, three different distributions were selected as possibilities for testing--the normal, log-normal (phi-normal) and Rosin distributions.

The vast majority of sedimentological studies deal with size measured as percentage weight between two size limits, usually determined by sieve or pipette analysis. These techniques are used because it is usually impracticable to measure the size of the individual fragments. The size of scree fragments in Surprise may be expressed either as a measure of length, volume or percentage weight (see Appendix 3). However, with the relatively small number of particles sampled and the occasional inclusion of extremely large boulders, the largest fragment may be over 90% of the total sample weight. Almost half of the samples from some sites in Surprise have one fragment which comprises more than 25% of the total sample weight (using nominal diameter cubed as a

TABLE 12.1: THE WEIGHT OF THE LARGEST FRAGMENT IN A SAMPLE EXPRESSED AS A PERCENTAGE OF TOTAL SAMPLE WEIGHT

Percent Weight of Largest Fragment	Percentage of Sites Greater Than Old Nip (A.B.T.)	Old Nip (RF)	Scree No. 1	Isosceles	Palliser
5	100	100	100	100	100
10	100	90.6	98.2	91.7	100
15	78.1	55.9	66.1	77.8	84.3
20	62.5	30.9	35.7	63.9	68.6
25	56.2	24.7	30.4	41.7	55.7
30	49.9	18.5	21.5	27.8	50.1
35	43.6	12.3	19.7	22.2	42.5
40	43.6	6.1	12.6	22.2	39.7
45	31.1	0	7.3	13.9	32.6
50	28.0		5.5	8.3	27.1
55	21.7		5.5	8.3	27.1
60	21.7		3.7	8.3	24.8
65	15.4		3.7	5.5	23.4
70	12.3		1.9	5.5	20.6
75	12.3		0	5.5	19.2
80	9.2			5.5	16.4
85	6.1			5.5	13.6
90	6.1			2.3	12.2
95	6.1			2.3	7.9
Number	32	32	56	36	70

NOTE: The figures show the percentage of sample sites where the weight of the largest fragment is greater than a given percentage of total weight.

surrogate of weight, Table 12.1). The use of a linear measure of size considerably reduces this emphasis and such measures are much more amenable to a large variety of statistical techniques. Thus, because of their inherent conceptual appeal and more desirable statistical properties, the first tests involved nominal diameter measurements rather than percentage weight data.

THE NORMAL AND LOG-NORMAL DISTRIBUTIONS

The normality of a distribution can be tested by examining the values for the third and fourth moments (skewness and kurtosis) and testing whether they are significantly different from zero. A table of critical values of skewness and kurtosis for measurements on individual particles has been published by Jones (1969). From this table (Jones, Table 1), it can be seen that, for N = 50 and at the 95% confidence levels, values of skewness between -0.640 and +0.640 and kurtosis between -0.93 and + 1.37 are not significantly different from zero. (The value for normal kurtosis is 3 (Griffiths, 1967, p. 88); the values used here are corrected by subtracting 3 to give a value of 0.) Using nominal diameter measurements, the moment measures were calculated for the samples at each site, including the additional samples which were not a part of the original sample design. The moments were calculated for the data expressed in millimetres and also on a phi transformation of the data to test for log-normality. The results are shown in Tables 12.2 and 12.3.

These results indicate that the log-normal distribution is the better approximation to the sampled distributions. Even so, between

TABLE 12.2: PERCENTAGE OF SAMPLES SHOWING LOG(PHI)-NORMALITY

Site	N	W	NORMAL	NOT NORMAL SK	K	SK&K	CHANGES N-S	N-K	NNK	Total
Entrance	7	0	42.9	14.2	14.2	28.6	-	-	-	42.9
"	7	1	57.1	0	14.2	28.6	0	0	-	57.1
"	7	2	42.9	0	14.2	28.6	14.2	0	0	57.1
Isosceles	43	0	60.5	18.6	0	20.9	-	-	-	60.5
"	43	1	67.4	23.3	0	2.3	0	7.0	-	74.4
"	43	2	76.7	16.3	0	0	0	0	7.0	83.7
Old Nip (A.B.T.)	39	0	64.1	15.4	5.1	15.4	-	-	-	64.1
"	39	1	74.4	15.4	2.6	2.6	0	5.1	-	79.5
"	39	2	61.5	17.9	2.6	0	5.1	7.7	5.1	79.5
Old Nip (Av.Apron)	10	0	80.0	0	20.0	0	-	-	-	80.0
"	10	1	70.0	0	20.0	0	0	10.0	-	80.0
"	10	2	30.0	0	20.0	0	0	40.0	10.0	80.0
Old Nip (Rockfall)	35	0	62.9	5.7	2.9	28.6	-	-	-	62.9
"	35	1	68.6	20.0	0	5.7	2.9	2.9	-	74.4
"	35	2	62.9	22.9	0	5.7	0	5.7	2.9	71.5
Palliser	77	0	53.2	10.4	10.4	26.0	-	-	-	53.2
"	77	1	61.0	17.0	5.2	10.4	1.3	5.2	-	67.5
"	77	2	61.0	13.0	3.9	3.9	1.3	11.7	5.2	79.2
Scree No. 1	62	0	61.3	16.1	4.8	17.7	-	-	-	61.3
"	62	1	72.6	21.0	1.6	3.2	0	1.6	-	74.2
"	62	2	62.9	16.1	1.6	1.6	1.6	14.5	1.6	80.6
Scree No. 1 (AV)	6	0	33.3	16.7	33.3	16.7	-	-	-	33.3
" (n=100)	6	1	33.3	16.7	33.3	16.7	0	0	-	33.3
"	6	2	50.0	0	33.3	16.7	0	0	0	50.0
Tumblin' Creek	9	0	100.0	0	0	0	-	-	-	100.0
"	9	1	100.0	0	0	0	0	0	-	100.0
"	9	2	77.7	0	0	0	11.1	11.1	0	100.0
Surprise II	12	0	83.3	8.3	8.3	0	-	-	-	83.3
"	12	1	75.0	8.3	8.3	0	8.3	0	-	83.3
"	12	2	66.7	0	8.3	0	8.3	16.6	8.3	91.7
TOTAL	300	0	61.3	12.3	6.7	19.7	-	-	-	61.3
"	300	1	68.3	17.0	4.0	5.7	1.0	4.0	-	73.3
"	300	2	62.7	14.0	3.7	3.0	2.3	10.0	4.0	79.3

NOTES: N = number of samples, SK = skewness
W = level of winsorization, K = kurtosis

Changes due to winsorization: N-S = normal to skewed
N-K = normal to leptokurtic
NNK = kurtosis remains leptokurtic at second level of winsorization after being normal.

The total is the sum of columns 3, 7, 8 and 9; i.e. all sites which are, or have been, normal and altered by further winsorization.

TABLE 12.3: PERCENTAGE OF SITES WITH AN ARITHMETICALLY NORMAL DISTRIBUTION

Site	N	W	NORMAL	NOT NORMAL SK	K	SK&K	CHANGES N-S	N-K	NNK	Total	Comparisons Both	Neither
Entrance	7	0	0	14.2	0	85.7	-	-	-	0	0	57.1
"	7	1	0	28.6	14.2	57.1	0	0	-	0	0	42.9
"	7	2	28.6	28.6	14.2	28.6	0	0	0	28.6	14.2	28.6
Isosceles	43	0	18.6	16.3	0	65.1	-	-	-	18.6	2.3	23.3
"	43	1	20.9	34.9	0	44.2	0	0	-	20.9	9.3	13.9
"	43	2	25.6	51.2	0	23.3	0	0	0	25.6	18.6	9.3
Old Nip (Av.Apron)	10	0	0	10.0	0	90.0	-	-	-	0	0	20.0
"	10	1	0	60.0	0	40.0	0	0	-	0	0	20.0
"	10	2	0	50.0	0	40.0	0	10.0	0	10.0	10.0	20.0
Old Nip (A.B.T.)	39	0	7.7	25.6	0	66.7	-	-	-	7.7	2.6	30.7
"	39	1	10.3	48.7	0	41.0	0	0	-	10.3	5.1	12.8
"	39	2	17.9	48.7	0	30.8	0	2.6	0	20.5	10.3	12.8
Old Nip (Rockfall)	35	0	25.7	25.7	0	48.6	-	-	-	25.7	11.4	21.4
"	35	1	34.3	45.7	0	17.1	0	2.6	-	37.0	22.9	11.4
"	35	2	40.0	48.6	0	2.9	0	5.7	2.6	48.6	22.9	2.9
Palliser	77	0	10.4	13.0	0	76.6	-	-	-	10.4	5.2	44.2
"	77	1	18.2	31.2	0	50.6	0	0	-	18.2	6.5	18.2
"	77	2	23.4	45.5	0	28.6	1.3	1.3	0	26.0	15.6	10.4
Scree No. 1	62	0	24.2	29.0	0	46.8	-	-	-	24.2	8.1	17.7
"	62	1	35.5	43.5	0	19.4	0	1.6	-	37.1	17.7	6.5
"	62	2	41.9	41.9	0	9.7	0	3.2	1.6	46.8	30.7	3.2
Scree No. 1 (AV)	6	0	0	0	0	100.0	-	-	-	0	0	67.7
"	6	1	0	0	0	100.0	0	0	-	0	0	67.7
"	6	2	0	50.0	0	50.0	0	0	0	0	0	50.0
Tumblin' Creek	9	0	11.1	11.1	0	77.8	-	-	-	11.1	0	0
"	9	1	0	22.2	0	66.7	0	11.1	-	11.1	11.1	0
"	9	2	11.1	44.4	0	33.3	0	0	11.1	22.2	22.2	0
Surprise II	12	0	0	16.7	8.3	75.0	-	-	-	0	0	16.7
"	12	1	0	41.6	8.3	50.0	0	0	-	0	0	16.7
"	12	2	8.3	58.3	8.3	25.0	0	0	0	8.3	8.3	8.3
TOTAL	300	0	14.7	19.7	0.3	65.3	-	-	-	14.7	5.0	29.3
"	300	1	20.3	38.7	0.7	39.3	0	1.0	-	21.3	9.0	14.3
"	300	2	26.7	46.7	1.0	22.0	0.3	2.3	1.0	30.3	20.7	11.0

NOTES: See Table 12.2 for explanation of abbreviations.

Also, Both = samples test as normal and phi-normal or with parameters modified from normal by winsorization.

Neither = sample is neither normal nor log-normal.

35 and 50% of the samples at major sites do not appear to be log-normal by this test (winsorization = 0, Table 12.2). The examination of histograms of the sampled distributions suggests that the excessive skewness of many of these samples is caused by one or two isolated values in the tails of the distributions.

Given a normal distribution, 99.73% of the observations should lie within three standard deviations of the mean, i.e. if 50 stones are sampled from each of 20 sites where the distributions are normal, only 2 or 3 of them will be more than three standard deviations away from the mean on the average. Thus, between 10 and 15% of the samples should contain such an observation. Table 12.4 shows the number of sampled sites in Surprise which have such extreme observations. Almost 30% of the phi-transformed samples contain an observation greater than three standard deviations away from the sample mean. These deviations occur in both tails of the distribution with a general tendency to be negative where the mean grain size is large and vice-versa. The arithmetic data show much greater amounts of skewness and all the deviations are positive. This is due to the fact that the standard deviation is frequently of the same order of size as the mean.

These extreme deviations from the mean can be accounted for by the action of certain processes on the scree slopes. The large boulders are avalanche debris (e.g. on the Palliser Cone) or rockfalls which, due to some combination of surface characteristics of the scree over which they were travelling or a low height of fall, came to rest on a higher part of the slope and are consequently much larger than the surrounding material. The distribution pattern of such boulders is discussed in

TABLE 12.4: SITES WITH OBSERVATIONS GREATER THAN THREE STANDARD DEVIATIONS AWAY FROM THE SAMPLE MEAN

Site	Samples	Number of Observations Greater Than (S.D.)					Percentage of Sites With Such Observations		
		-4	-3	+3	+4	+5	1	2	
(A) PHI DATA									
Entrance	6	0	1	1	0	0	33.3	0	
Isosceles	43	0	4	4	2	0	23.3	0	
Old Nip (Av.Apron)	8	0	0	0	0	0	0	0	
Old Nip (A.B.T.)	39	1	5	8	0	0	35.9	0	
Old Nip (Rockfall)	35	4	8	0	0	0	34.3	0	
Palliser	77	0	12	13	4	1	31.2	3.9	
Scree No. 1	61	4	10	4	0	0	26.3	1.6	
Tumblin' Creek	9	0	0	0	0	0	0	0	
TOTAL	278						28.1	1.5	
(B) UNTRANSFORMED DATA									
		-3	+3	+4	+5	+6	1	2	3
Entrance	6	0	3	4	0	0	83.3	16.7	0
Isosceles	43	0	23	5	2	3	56.1	9.3	0
Old Nip (Av.Apron)	8	0	6	2	1	0	62.5	25.0	0
Old Nip (A.B.T.)	39	0	10	12	4	3	65.1	5.1	0
Old Nip (Rockfall)	35	0	12	6	0	0	51.5	0	0
Palliser	77	0	39	19	8	10	62.3	18.2	0
Scree No. 1	61	0	27	9	4	0	55.8	4.9	0
Tumblin' Creek	9	0	11	1	0	0	55.6	22.2	11.1
TOTAL	278						68.8	9.0	0.4

NOTE: The data used are those sites with 50 observations, excluding the samples taken at Surprise II in 1968.

detail in Chapter 13. The smallest fragments would appear to be rock chips produced by in situ weathering, rockfall impact or avalanche deposition. Since only a few such fragments are present rockfall impact would seem to be the most probable mechanism, since both avalanche deposition and weathering would tend to produce a larger number of fragments (see Chapter 14).

Although these extreme values are an intrinsic part of the characteristics of the sampled distributions, they have an unduly large influence on the sample parameters. Both the standard deviation and skewness are particularly sensitive to these observations and, in such cases, the sorting characteristics (standard deviation) and skewness of the bulk of the population may be masked; when these parameters are compared over the sampled area of a scree, the differences may merely reflect the presence or absence of one of these extreme values. Thus, in order to study the characteristics of the main elements of the sample populations, it is important to eliminate the effects of these extreme observations.

The sampled distribution at any point can be subdivided into two major components; the main population and a randomly distributed addition which may or may not be present. The latter component cannot simply be removed, since this would result in unequal sample sizes and considerably limit the type of statisical test which could be used. Simple truncation of pairs of observations from both ends of the distribution maintains equal sample sizes but has undesirable effects on the moment measures of the samples. The most convenient technique available would seem to be winsorization (Dixon, 1960; Dixon and Massey, 1968).

Winsorization

Winsorization is a statistical technique used for the estimation of mean values where unrelated large values are thought to be present in the sample or some of the extreme values are known to be missing (Dixon and Massey, 1968, pp. 330-333). An estimate of the mean is obtained by equating the extreme values of the distribution (largest and smallest) with their nearest neighbours and using these values as estimates. This is known as "first level winsorization" and will be designated by the abbreviation W1. Higher levels of winsorization are possible using two (W2), three (W3) or more observations at each extreme.

The rationale behind this technique is as follows: if the distribution is normal, the "pulling in" of the two extreme values will not significantly affect the estimate of the sample mean whereas, if isolated extreme values are present from a different population, the estimate of the mean will be considerably improved. Dixon (1960) has calculated the efficiency of winsorized estimates of the mean and standard deviation for several levels of winsorization where $n = 20$. Using the equation given in Dixon and Massey (1968, p. 330), it can be calculated that, with $n = 50$, W1 and W2 estimates of the mean are 99.7 and 98.6% efficient compared with estimates from a similar, normal, distribution. A similar line of argument can be applied to winsorized estimates for the standard deviation and skewness, although the former would be slightly reduced even for a normal population. However, since winsorization alters the distribution in the tails, the distributions become more "peaked" (leptokurtic) as the level of winsorization is increased.

The results of winsorization of the third and fourth moments of the sampled distributions can be seen in the appropriate sections of Tables 12.2 and 12.3. When winsorized estimates are used up to the W2 level, between 74 and 83% of the samples at each scree are log-normal if allowance is made for the reduction of kurtosis values inherent in the technique. This factor causes many distributions which were originally platikurtic to become normal in terms of kurtosis, hence the relative increase in the number of sites which are merely skewed.

ROSIN DISTRIBUTION

The Rosin distribution is an empirically derived distribution for the analysis of crushed coal. It was originally described by Rosin and Rammler (1930) and theoretically justified by Bennett (1936). This size distribution, also known as Rosin's Law of Crushing, has been found to apply to materials other than coal and several geologists have suggested that this distribution may be a better approximation to the size distribution of certain clastic materials than the log-normal distribution. Krumbein and Tidsel (1940) found that the size distributions of seven samples of mechanically and chemically weathered granites appeared to fit the Rosin distribution and concluded that this was a result of random breakage of the materials during weathering. McEwen, Fessenden and Rogers (1959) report similar findings from weathered granites from Colorado and Kittleman (1964) found that the Rosin could be applied to several natural materials formed by "mechanical disintegration, crushing or volcanic origin" (p. 483), including two samples from a granite scree. In view of these results, it would seem reasonable to expect that the Rosin distribution might be a better approximation to the size distribution of scree materials than the log-normal distribution.

The Rosin distribution is applicable to measurements of size distribution by weight, usually measured by sieving. It is similar in form to the log-normal distribution but has a greater skewness towards the larger sizes and a longer tail of fines (Kittleman, 1964, Figure 1). Rosin's Law may be expressed in several forms, the most common of which is:

$R = 100e^{-bx^n}$ (Bennett, 1936, p. 37) where $b = \frac{1}{\bar{x}}$ and

R = percentage weight greater than the particle size x
x = particle size (any consistent units, Bennett, 1934, Footnote p. 23)
$\bar{x}$ = the absolute size constant
n = the distribution constant.

The constants $\bar{x}$ and n are known as the Rosin Numbers; $\bar{x}$ is a measure of size measured in the same units as x and corresponds to the 36.78th percentile of R; n is a parameter of sorting and is numerically equivalent to the tangent of the slope of the line on Rosin Plot coordinates (Kittleman, 1964, p. 487). The normal way of testing the fit of this distribution is by plotting the results of cumulative percentage oversize (i.e. greater than a certain size) on the specially prepared paper designed by Geer and Yancey (1938) or by a computer plot with $\log_e \log_e R$ on the ordinate and $\log_2 x$ (phi size) on the abcissa (Kittleman, 1964, p. 499). In both cases, Rosin distributions will plot as straight lines and the goodness of fit may be estimated by eye. However, upon detailed examination, the Rosin distribution may be recognized as a Weibull distribution (M. F. Goodchild, personal communication, November 1972) for which estimation procedures are available (Mennon, 1963;

Johnson and Kotz, 1970). The Weibull distribution was originally used to represent the breaking strength of materials and Weibull probability paper is identical to Geer and Yancey's graph, except that the ordinate is cumulative percentage rather than cumulative percentage greater than (see Johnson and Kotz, 1970, p. 265).

The sampled distributions were therefore tested for goodness of fit to the Weibull, normal and log-normal distributions, using nominal diameter as a measure of size and its cube as an estimate of weight (see Appendix 3). The goodness of fit was evaluated by a Kolmogorov-Smirnoff Test, using a programme written for that purpose by Professor Goodchild. The results are shown in Table 12.5.

These results indicate that over 90% of the sampled distributions tested fit a Weibull distribution. However, using the same test on nominal diameter data, all of those samples also fitted the log-normal distribution and only five of the samples were rejected at the 95% level. This result might have been expected since Kittleman (1964, p. 487) states that it may be impossible to distinguish the Rosin and log-normal when either is slightly skewed. It is also possible that, given such a relatively small sample size (50), the Kolmogorov-Smirnoff Test is not sensitive enough to differentiate between the distributions. In either case, the phi-normal data can be accepted as a better fit to the majority of the sampled distributions, both in terms of a lower Kolmogorov-Smirnoff statistic and a smaller number of rejections.

DISCUSSION

At first glance, there appears to be a major discrepancy between the results in Tables 12.2 and 12.3 and those in Table 12.5. The former show that, at the second level of winsorization, 30.3% and 79.3% of the samples are accepted as normal and log-normal at the 95% level, whilst the latter gives these figures as 63.1% and 98.3% respectively. These differences result from the nature of the two tests employed. Moment measures are particularly sensitive to observations in the tails of the distributions, whereas the Kolmogorov-Smirnoff Test treats the distribution as a whole and small numbers of extreme observations in the tails of the distribution have little effect on the whole cumulative frequency curve. Examination of histograms of those samples which have non-normal

TABLE 12.5: THE RESULTS OF GOODNESS OF FIT TESTS ON THOSE SAMPLES WITH FIFTY STONES USING THE KOLMOGOROV-SMIRNOFF TEST

Site	Number	Normal (%)	Log-Normal (%)	Weibull (%)	Other (%)
Entrance	6	66.7	100.0	100.0	0
Isosceles	43	58.1	97.7	81.4	0
Old Nip (Av.Apron)	8	25.0	100.0	100.0	0
Old Nip (A.B.T.)	39	54.9	100.0	89.7	0
Old Nip (Rockfall)	35	88.6	100.0	97.1	0
Palliser	77	48.1	94.8	84.2	5.2
Scree No. 1	61	88.5	100.0	96.7	0
Surprise II	12	33.3	100.0	100.0	0
Tumblin' Creek	9	66.7	100.0	100.0	0
TOTAL	290	63?	98.3	90.7	1.4

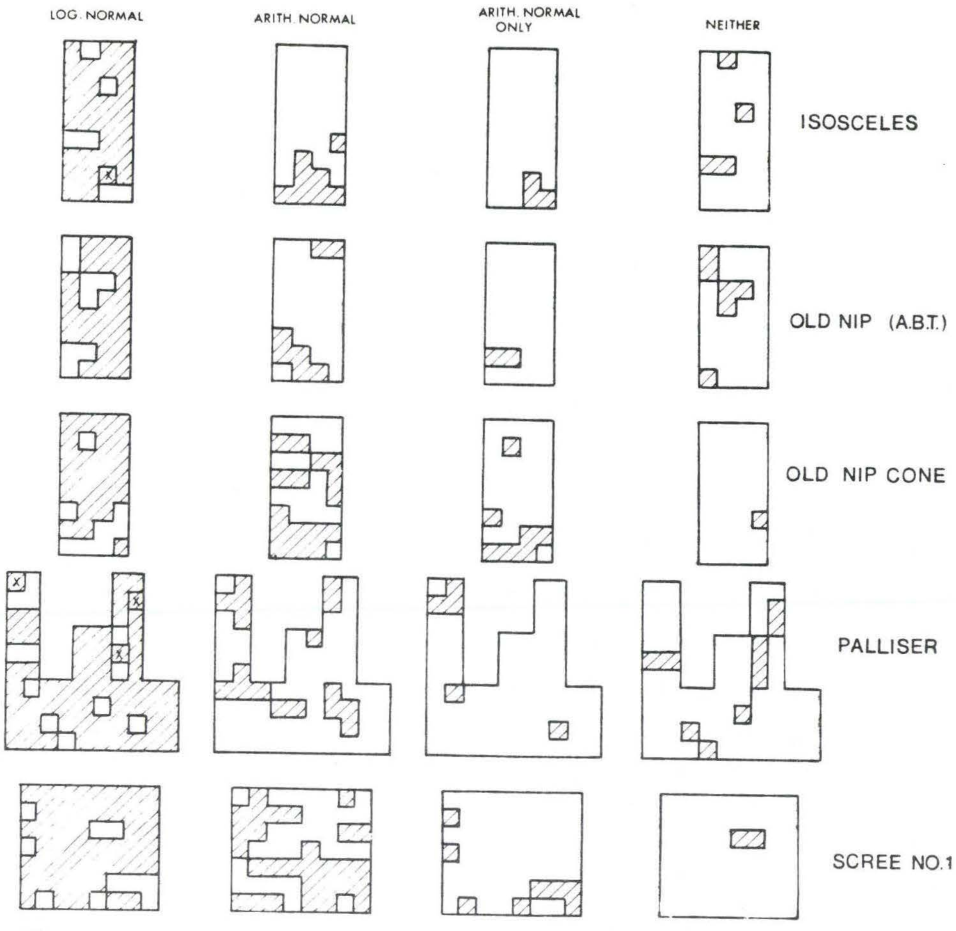
NOTE: The percentage given is the number of samples which fit the stated distribution at the 95% confidence level of the Kolmogorov-Smirnoff Test.

skewness and kurtosis at the second level of winsorization shows that they are slightly bimodal or have well marked tails. Thus, the Kolmogorov-Smirnoff results supplement the moment measure tests since they suggest that, if winsorization was extended further, nearly all the samples would test as being log-normal distributions. The deviation from log-normality at most of the samples sites is caused by the presence of small amounts of other populations in the tails of the sampled distributions. These additions may result from random variations in the controlling process (e.g. isolated boulders), differing sets of controls (e.g. the presence of a "floating layer") or the mixing of deposits from several sources. Examples of such variation are discussed in Chapter 13.

Distribution Over the Scree

The spatial variation of the characteristics of the sampled distributions was examined to see whether there were any major linkages between population characteristics, process and position on the slope. The distribution patterns are shown diagrammatically in Figure 12.1 where, despite considerable variation between sites, several general trends are visible. The normally distributed samples (including those which also test as log-normal) show a concentration towards the base of the scree where deviations from log-normality are also greatest. The sites which are neither normal nor log-normal are more common on the upper slopes, especially in areas which have been affected by avalanche erosion.

These variations may also be examined by regression and ANOVA techniques using the skewness and kurtosis values. The second level



NOTE SHADED AREAS ARE THOSE REFERRED TO IN HEADING (W2) X = NOT LOG. NORMAL (K.S.)

Figure 12.1 Spatial variation of grain size distributions over the sampled screes

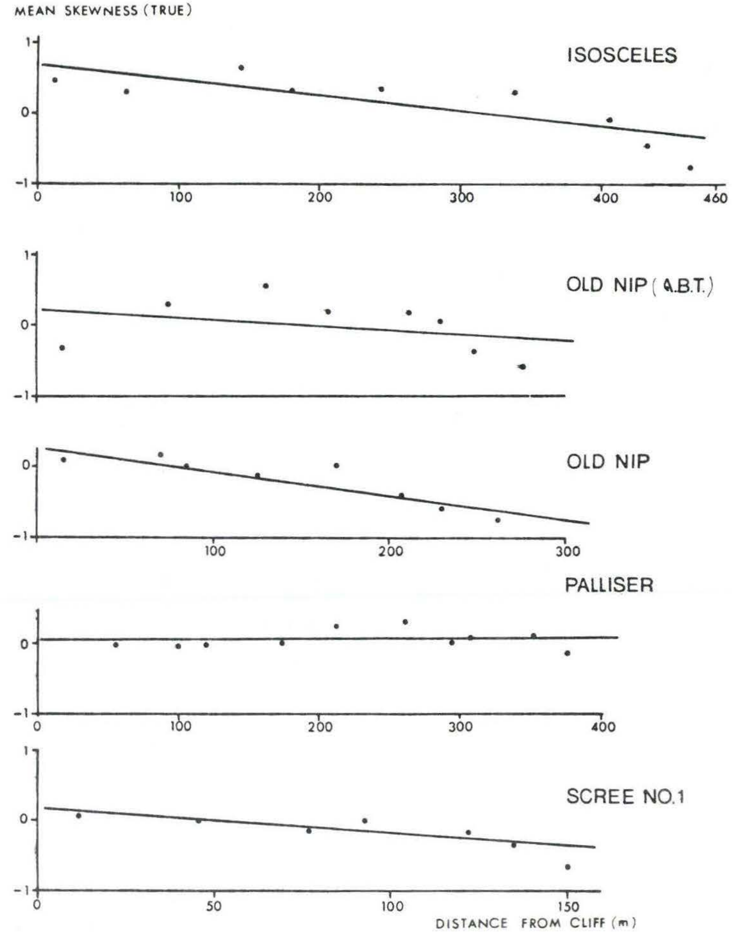


Figure 12.2 Relationship between mean skewness and distance from the cliff

winsorized estimates were again used to reduce the effect of the extreme values. The three rockfall sites (Isosceles, Old Nip Cone, Scree No. 1) all show a significant correlation between skewness and distance from the cliff (Table 12.6), but none of these correlations is very strong. The Old Nip A.B.T. is similar, except for the top two sites, but there is no apparent trend at the Palliser Site (Figure 12.2).

TABLE 12.6: CORRELATION COEFFICIENTS AND ANOVA SUMMARY FOR THE RELATIONSHIPS BETWEEN SKEWNESS, KURTOSIS AND POSITION ON THE SLOPE

Site	Distance vs.SK(W2)	Distance vs.SK(W2)	N	ANOVA Using SK(W2) Between Sites	Between Rows
Isosceles	0.638*	0.258	36	n.s.	99%
Old Nip (A.B.T.)	0.227	0.042	32	n.s.	99%
Old Nip (RF)	0.542*	0.432*	32	n.s.	n.s.
Palliser	0.015	-0.262*	70	n.s.	n.s.(all zones)
Scree No. 1	0.437*	0.407*	56	n.s.	95%

NOTE: Skewness values are given in a true sense, i.e. negative skewness is skewed to coarse. True phi skewness is the reverse.
*Significant at the 99% level.

The relationships between kurtosis and position are even weaker; the two significant results are in opposite directions (Table 12.6) and no general pattern is discernible. No apparent association was observed between skewness and kurtosis values and the major depositional process.

Most of these patterns are due to the fact that the basal sites tend to be more strongly negatively skewed, i.e. towards the smaller phi numbers (larger grain sizes), while there is little overall pattern on the higher parts of the slope. This may be explained simply in terms of the admixture of smaller debris by avalanches, weathering or impact fractures to the generally coarse basal debris, whilst the coarse tail is collapsed by the nature of the phi scale (see Chapter 11).

CONCLUSION

These results indicate that nearly all the sampled distributions (98.3%) can be accepted as log-normal, using a Kolmogorov-Smirnoff Test and that this distribution is a superior fit than either the normal or Rosin (Weibull) distribution. The major deviations from log-normality occur when the presence of extreme values in the tails of the distribution produces non-normal values for the third moment. However, the effects of these observations can be removed by the technique of winsorization to improve the skewness parameters. These deviations occur more or less randomly over the scree, although there is a tendency for the basal sites to be more strongly negatively skewed. However, despite these minor variations, the distribution of particle sizes at the sample sites is basically log-normal and therefore phi transformed data will be used throughout the rest of this thesis as a basic measure of particle size.

CHAPTER 13

THE VARIATION OF GRAIN SIZE OVER THE SCREE SLOPE

One of the central problems investigated in this thesis is the variation of particle size over the scree slopes studied and the relative importance of variations at the different levels of sampling. Several papers in the literature have dealt with variation in grain size from the base to the top of the slope, usually using qualitative data (see discussion in Chapter 10). This study will also consider the contribution of lateral and smaller scale variations to the overall pattern. Preliminary examination of the relative importance of these effects was carried out by the analysis of variance (ANOVA) on the sedimentary data. Following that analysis, the magnitude and causes of the different levels of sorting will be discussed separately and in detail.

ANALYSIS OF VARIANCE

The sampling design used may be considered either as a three-way factorial design with 50 observations in each cell or as a two-way design with two levels of replication. In both cases, the appropriate statistical model is the random effects model or Model II (Eisenhart, 1947; Krumbein and Graybill, 1965, pp. 197-199) since the sampled sites do not represent the whole of the available population of sites. The actual design used is, unintentionally, almost identical to that described by Griffiths (1967, pp. 418-422).

The assumption of normality was tested in the previous chapter and found to be approximately true. The other major assumption, that of homoscedacity, was tested using Bartlett's Test (Griffiths, 1967, pp. 363-364) and rejected at the 99% level for all sites. However, Dixon and Massey (1968, p. 161) state (with reference to the one-way test) that "investigation has shown that the results of the analysis are damaged very little by moderate violations of the assumptions of normal distribution and equal variance" (also, see details in Winer, 1971, p. 205). Therefore, since the test is a robust one, it would seem appropriate as an indicator of the relative importance of the effects, bearing in mind Cochran's warning that "since an experimenter could rarely, if ever, convince himself that all of the assumptions were exactly satisfied in his data, the technique must be regarded as approximate rather than exact" (Cochran, 1947, p. 37).

Seven different ANOVA experiments were needed to cover the four main sites, since the Palliser Cone had to be divided up into three zones and the two areas at Old Nip were treated separately. A summary of the major results is given in Table 13.1; the full ANOVA tables are given in Appendix 4. In view of the significant interactions, it is not possible to test for the main effects in the usual manner or by using the lower order interactions as an error term. To obtain a structurally correct F ratio to test for the main effects, a "quasi F" (F") ratio was used (Winer, 1971, pp. 375-378) which approximates the F distribution when special degrees of freedom are used calculated from the mean square and true degrees of freedom values. Details of this procedure are given in Winer (1971, p. 377).

TABLE 13.1: SUMMARY OF RESULTS OF ANOVA FOR THE ORIGINAL DESIGN TESTING WITH THE F AND F" (QUASI F) RATIOS*

Site	Significance Level for the Effect Tested						
	I	J	K	IJ	IK	JK	IJK
Palliser Lower	n.s.	97.5%	n.s.	97.5%	n.s.	n.s.	99.9%
Palliser Middle	n.s.	n.s.	n.s.	97.5%	n.s.	n.s.	97.5%
Palliser Upper	n.s.	n.s.	n.s.	99.9%	99%	99.9%	90%
Old Nip (A.B.T.)	n.s.	99%	n.s.	n.s.	n.s.	n.s.	99.9%
Old Nip (Rockfall)	n.s.	99.9%	n.s.	95%	n.s.	n.s.	95%
Scree No. 1	n.s.	99%	n.s.	99.9%	n.s.	n.s.	99%
Isosceles	n.s.	99.9%	n.s.	n.s.	n.s.	n.s.	99.9%

NOTE: I = columns; J = rows; K = replicate subsamples (right and left).

*The full results are given in Appendix 4.

With the exception of the upper two parts of the Palliser Cone, the results of the three-way analyses are very similar for all sites, although the detailed levels of significance differ. All sites have a significant second order interaction (IJK) and most of them also have a significant row-column (IJ) interaction. The only significant main effect is the row position on the scree (J). On the upper parts of the Palliser Cone, none of the main effects were significantly greater than the interactions indicating a complete absence of any trends.

Ideally, all interaction effects should be zero in ANOVA so that the main effects can be unequivocably tested. The interaction effects indicate that the differences over the factors are not consistent. The second order interaction (IJK) is predictable since, intuitively, unless there is a very marked lateral gradient, the differences between the two subsamples should be purely random and therefore not consistent. The only exception to this, the upper part of the Palliser Cone, has an interaction term which is significant at the 90% level. Since this third factor (K) in the design is in the same dimension (although at a different scale) to the column factor (I), this problem may be countered by collapsing the design and considering the subsamples as additional columns. Thus, for example, the 4 x 7 x 2 matrix at Scree No. 1 becomes an 8 x 7 matrix in this modification. Following this example, the analyses were re-run and the results are shown in Table 13.2.

The results in Table 13.2 are, in general, similar to those in Table 13.1; the clear division between the upper two Palliser sites and the others still holds and all sites show a significant row-column (IJ) interaction. None of the sites show significant lateral variation, whilst all except the upper Palliser pair show marked downslope sorting.

In summary, therefore, the results of the ANOVA tests indicate that there is a marked size gradient on all of the slopes except for the upper two-thirds of the Palliser Cone. In all cases, the dominant effect is related to the vertical position on the slope; even where four or five profiles were taken (Palliser and Scree No. 1), there is no consistent size gradation across the slope. This lack of major lateral trends may be partially related to the restricted nature of the sampled area, since only simple cliff forms were chosen and obvious differences in lithology or lateral variations in dominant processes were deliberately excluded. However, the presence of significant interactions between the row, column and subsample effects indicates that the downslope gradation, although dominant, is not a consistent one and that considerable small scale lateral variation exists. In the following sections, these main

TABLE 13.2: ANALYSIS OF VARIANCE FOR THE COLLAPSED DESIGN

Source	Sum Sq.	Mean Sq.	D.o.F.	F
Palliser Lower				
Mean	53084.66	53084.66	1	
I	93.34	10.37	9	1.61
J	801.73	267.24	3	45.71*
IJ	157.86	5.85	27	6.11*
K(IJ)	1874.71	0.96	1960	
Palliser Middle				
Mean	11888.56	11888.56	1	
I	71.11	14.22	5	0.85
J	101.58	50.79	2	3.04
IJ	166.83	16.68	10	14.72*
K(IJ)	999.36	1.13	882	
Palliser Upper				
Mean	10137.07	10137.07	1	
I	6.43	2.14	3	0.08
J	9.54	4.77	2	0.18
IJ	160.22	26.70	6	30.78*
K(IJ)	510.15	0.87	588	
Old Nip (Avalanche Boulder Tongue)				
Mean	28603.77	28603.77	1	
I	32.53	10.84	3	0.89
J	2159.27	308.47	7	24.76*
IJ	261.60	12.46	21	13.15*
K(IJ)	1484.98	0.95	1568	
Old Nip (Rockfall Cone)				
Mean	64271.25	64271.25	1	
I	5.97	1.99	3	0.77
J	1012.21	144.60	7	55.93*
IJ	54.48	2.59	21	4.67*
K(IJ)	870.48	0.56	1568	
Scree No. 1				
Mean	88976.44	88976.44	1	
I	97.45	13.92	7	1.43
J	1306.11	217.69	6	22.33*
IJ	409.44	9.75	42	17.21*
K(IJ)	1554.35	0.57	2744	
Isosceles				
Mean	31058.29	31058.29	1	
I	3.17	1.06	3	0.27
J	736.43	92.05	8	23.67*
IJ	93.33	3.89	24	5.31*
K(IJ)	1291.15	0.73	1764	

NOTE: I = number of columns; J = number of rows; K = number of observations in each cell (50)

*Significant at the 99% level.

effects will be discussed in turn beginning with the dominant pattern of downslope sorting.

DOWNSLOPE SIZE SORTING

All of the scree slopes sampled in this project showed an increase in mean particle size with distance from the cliff at greater than the 95% confidence level (only the avalanche boulder tongue at Old Nip was less than the 99% level). Since a logarithmic measure of size (i.e. ø units) was utilized, this supports Gardner's observation of a logarithmic downslope increase in particle size on the majority of the slopes he studied in the Lake Louise area (Gardner, 1968a, 1971). However, since the detailed form of the relationships observed in Surprise varies considerably from slope to slope and averaged results are misleading (see Tables 13.3A and 13.3B), each site will be described separately in more detail.

Scree No. 1

This is the simplest of the screes studied and is a relatively small straight apron scree. When the mean size at each sample site is plotted against its distance from the cliff, there is a consistent increase in particle size downslope. However, individual sample means (Figure 13.1A) show a wide scatter about these "row" means indicating considerable lateral variability and producing a relatively large standard error term (Table 13.3). While this lateral variability will be discussed in more detail later, several points may be advanced here to account for the seeming inefficiency of size sorting on this scree.

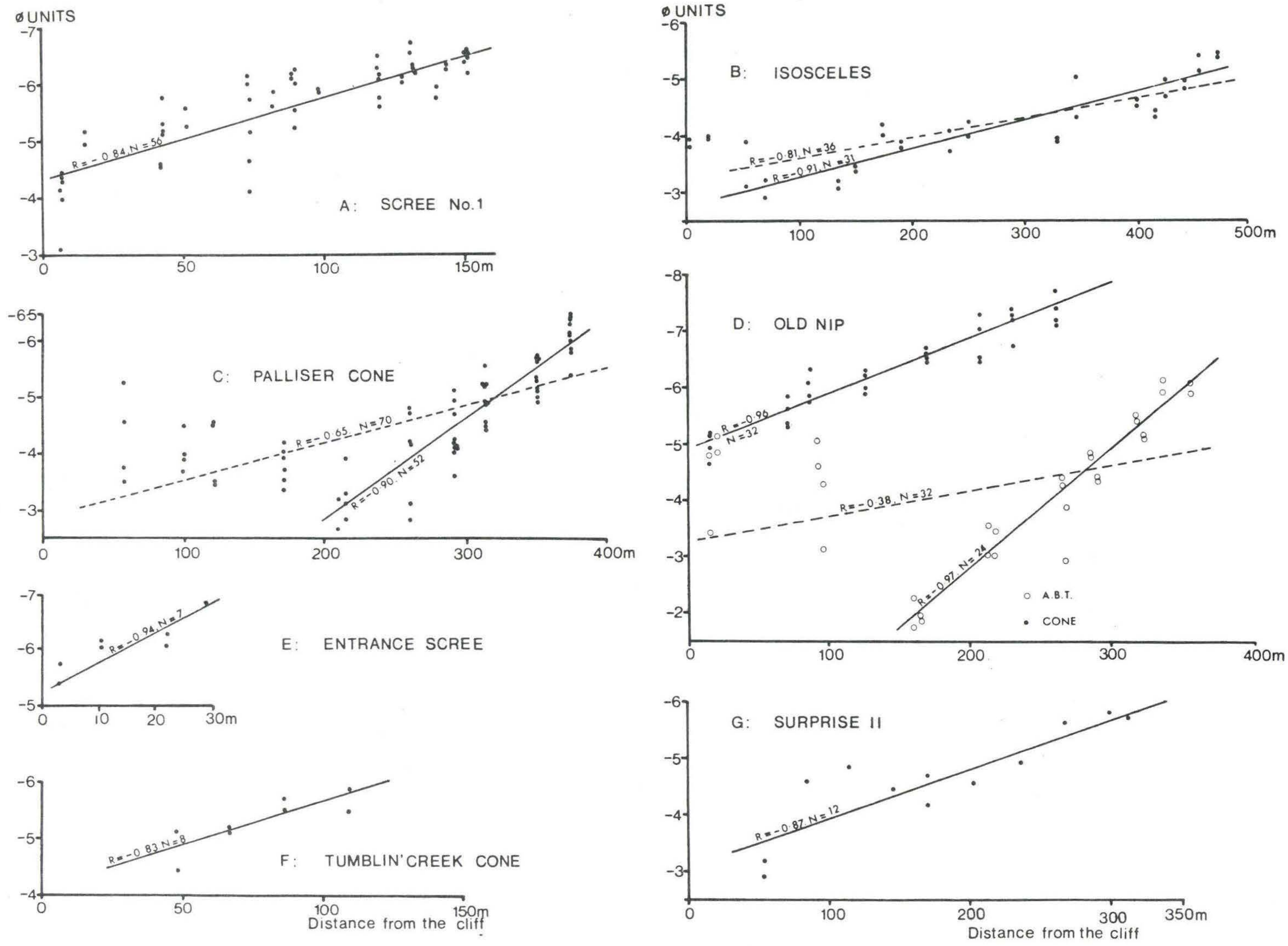


Figure 13.1 Relationship between mean grain size and measured distance from the cliff

TABLE 13.3: CORRELATION COEFFICIENTS BETWEEN MEASURED DISTANCE FROM THE CLIFF AND MEAN GRAIN SIZE OF SAMPLES

Site	Slope Length(m)	No. of Samples	Correlation Coefficient	R^2 x 100 (% Explanation)	S.E.
(A) ALL OBSERVATIONS					
Entrance	30	7	-0.945**	89.5	.16
Isosceles	465	36	-0.807**	65.1	.40
Old Nip (A.B.T.)	350	32	-0.382*	14.6	1.14
Old Nip (Rockfall)	260	32	-0.970**	94.1	.23
Palliser	330	70	-0.652**	42.5	.72
Scree No. 1	150	56	-0.840**	70.6	.44
Surprise II	260	12	-0.871**	75.4	.42
Tumblin' Creek	75	12	-0.827**	68.4	.24
(B) PARTIAL RESULTS					
Isosceles	416	32	-0.890**	79.2	.33
Isosceles	416	31	-0.912**	83.2	.30
Old Nip (A.B.T.)	270	24	-0.960**	92.2	.32
Palliser (1-6)	127	52	-0.896**	80.3	.44
Palliser (7-10)	203	18	0.398	15.8	.46
Palliser (1-5)	173	46	-0.847**	71.7	.44
Palliser (6-10)	157	24	0.626**	39.2	.46

NOTES: Since decreasing phi units indicate an increase in size, a negative correlation coefficient indicates a positive correlation between true grain size and distance.

The numbers for the subdivision of the Palliser Cone indicate the ranked position of the sites included (base = 1, etc.)

*Significant at greater than the 95% level.

**Significant at greater than the 99% level.

Firstly, the sampling on this scree covered a wider lateral extent than at any of the other sites, except the Palliser Cone which has a similarly high scatter (basal part, 1-5, Table 13.3B). Also, the sampling points are much closer together on the profiles (average 21 m) than on the other major screes (averages 33, 32.5, 44 and 51 m) and the mean size of most of the sites covers a limited size range (45 out of 56 are between 5.14 and 6.72 ø). These three factors may all contribute to the wide local variations.

Isosceles

Like Scree No. 1, this is basically a rockfall scree. However, unlike that site, Isosceles has a small area of coarser debris at the foot of the cliff on which four sample sites occurred. Site 34 (Figure 13.1B) is on similar material and if these five sites are excluded, the correlation coefficient is increased to -0.912 from -0.807 (Table 13.3B). This coarser capping near the foot of the cliff was found on several screes and probably represents rockfall material which either mires in soft snow upon impact or does not have enough momentum to travel further down the scree.

The size range at this site is less than at Scree No. 1 and there is also considerable lateral variability. There are also slight variations in the sorting pattern; the middle three sites are very similar, whilst the lowest three have the most marked gradation of size.

Palliser Cone

The sorting on this cone is more complex and the overall weak downslope sorting pattern is obviously composed of two distinct parts (Figure 13.1C). The lowermost part of the cone ("rows" 1-6) has a clearly marked increase in grain size downslope (correlation coefficient -.896, Table 13.3B), whereas the upper sites have a poorly defined increase in grain size in the reverse direction with the coarsest sites at the top. This latter effect is partially caused by an accumulation of rockfall debris at the apex of the cone (sites 51 and 52) and partially by avalanche erosion and stripping of the middle and upper parts of the slopes. Over most of this area the loose, coarser material has been stripped away and the surface is much finer material with patches or runnels of coarser debris and occasional very large boulders (see Figure 13.9B and later discussion) with no obvious lateral or downslope pattern. The surface material here is not as fine as that at Old Nip (A.B.T.), but the erosion covers a far more extensive section of the slope.

In the lower part of the cone, the surface material is well sorted with occasional accumulations of recently arrived boulders. Nearly all the larger fragments have been swept to the lowest part of the scree.

Old Nip

The two parts of this site provide a classic contrast between the effects of rockfall and avalanches on the same site (Figure 13.1D). The purely rockfall cone consists of almost perfectly size sorted, relatively coarse material with very little material below -5.0 ø (Figure 13.2). Avalanche erosion on the flanks of the cone has stripped off the loose, coarse material from the surface of the upper middle and middle of the cone, exposing much finer material. The loose material has been swept down the cone and deposited on top and beyond the limits of the

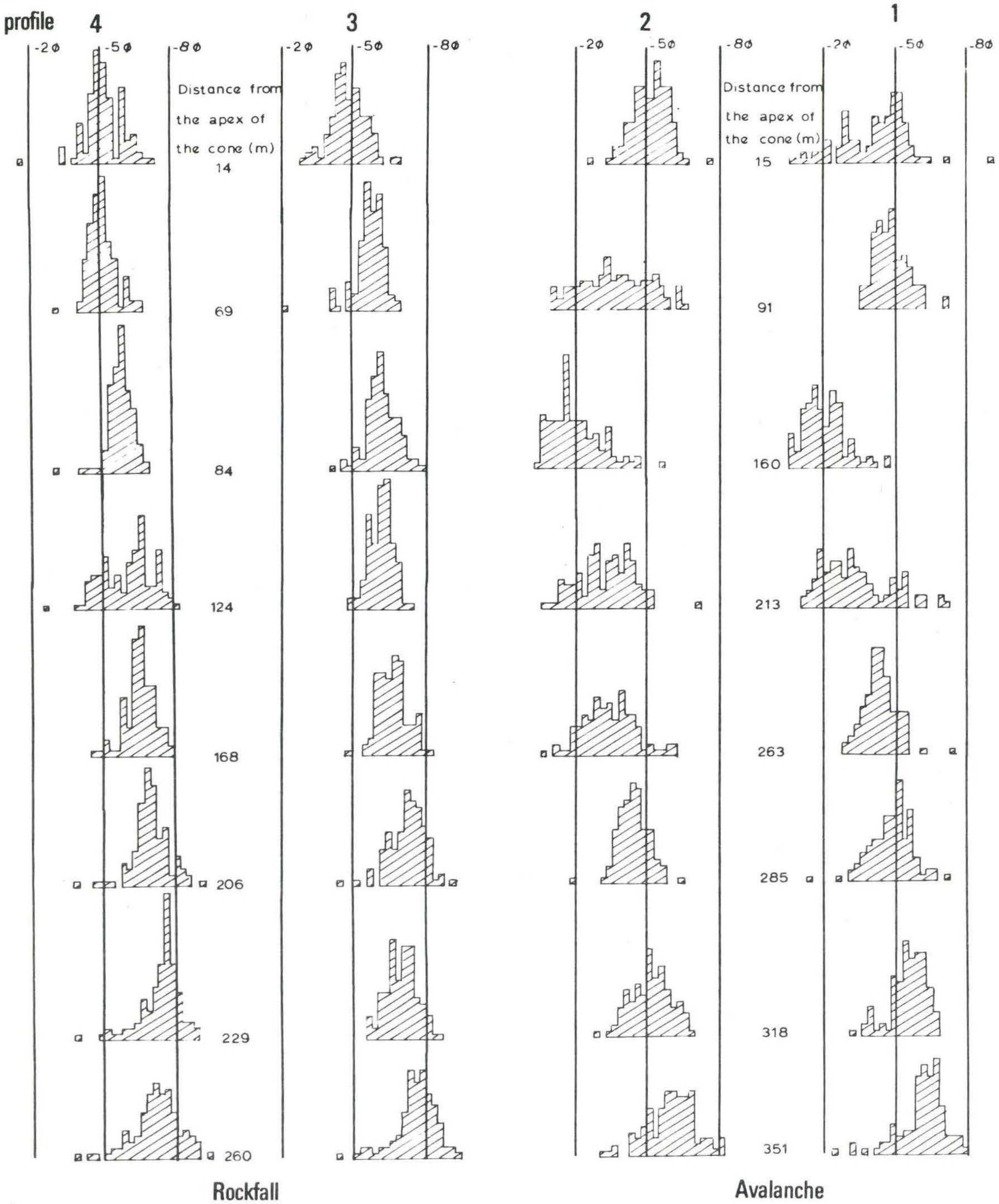


Figure 13.2 Grain size of the surface material at the Old Nip sites

rockfall scree, "diluting" the mean grain size with large inputs of smaller debris from further upslope. This means that, because of erosion, downslope transfer or burial, the mean size of the material on the avalanche modified section of the cone is much smaller than that on the corresponding rockfall section.

Observations made after sampling had been completed indicated that the impact point of the avalanches was not close to the apex of the cone as was originally thought but to the side, below the straight rockwall (see Figures 10.7 and 10.8). Thus, the top two sites on the profile are unmodified (samples 15, 16, 31, 32) or only partially modified (samples 13, 14, 29, 30) rockfall debris (see Figure 13.7). When these sites are excluded, the regression of mean size against distance from the cliff (Table 13.3) for the avalanche slope is considerably improved. It can also be seen from Figures 13.1D and 13.2 that avalanche modification increases the rate of downslope sorting.

<u>Entrance Screes, Surprise II and Tumblin' Creek</u>

These sites were sampled on a limited scale either as sampling experiments or, at Tumblin' Creek, as an incomplete project. Although there are minor differences in the techniques used at Surprise II and the sampling designs are different (see Chapter 10), these results may be used as additional data.

All three sites show significant increases of grain size downslope. Correlation coefficients range from -0.827 to -0.945 (Table 13.3). The Entrance Scree (Figure 13.1E) samples consisted of a basal sample of 100 fragments and six other samples of 50. The sample sites at Tumblin' Creek (Figure 13.1F) were all in the coarse basal part of the cone. At both these sites, there is a small range in the mean grain size sampled. While this is probably representative of the Entrance Screes, it is not an adequate sample of the Tumblin' Creek Cone, as the sampled area only covers the lower half of the cone.

The results at Surprise II are more difficult to evaluate because of the presence of several distinct lithologies in differing proportions at the sample sites. The pebbles measured were assigned shape classes on the basis of the shape descriptions recorded and nominal diameter values computed. The pattern of downslope size sorting shown in Figure 13.1G is repeated separately for each of the major lithologies sampled and, therefore, it would seem reasonable to infer that it is independent of the lithological composition. The anomaly in the relationship above 150 m coincided with a change in the surface characteristics of the scree which indicated a zone of avalanche deposition. Since avalanches have been observed to transport considerable debris from the cliffs at this site, it is possible that this effect may be attributable to avalanche deposition of coarser material from that source. However, since this anomaly was not shown on replicate profiles, it may simply be a result of random local variations in grain size which produce similar anomalies on some of the other profiles. Similar local reversals of sorting gradients have been reported for single profiles by Hamelin (1958) and Gardner (1968a).

Comparison of the Sites

The variety of results demonstrated in the previous section only represents a small selection of scree slopes in Surprise. Despite this limited sample, several general conclusions may be drawn from these data. All the slopes show a logarithmic increase in grain size downslope, although in some cases this is enhanced or disrupted by avalanche erosion or the accumulation of coarser debris immediately below the cliff. The effects of avalanching are well demonstrated in Figure 13.2 which also suggests that considerable avalanche activity, by erosion and resorting of debris, produces a much steeper sorting gradient than rockfall action alone.

Where the correlation coefficient between grain size and distance from the cliff is highly significant, the beta coefficient of the regression equation may be used as an estimate of the sorting gradient and, in an attempt to compare the downslope sorting patterns between the sites, this statistic was plotted against the length of the scree sampled (Figure 13.3). The three rockfall dominated main sites (Scree No. 1, Isosceles and Old Nip Cone) show an inverse relationship between length of slope and sorting gradient and two of the other sites also plot close to this line. The other rockfall site at the Entrance Screes has an exceptionally high sorting gradient which may be unduly affected by its extremely small size in relation to the other screes. The two major sites modified by avalanche erosion have much higher sorting gradients in relation to their length and fall well away from the line. The other two sites, Tumblin' Creek and Surprise II, are more like the rockfall screes. This may be due to the limited area sampled at Tumblin' Creek (only the coarse depositional zone was sampled) and the fact that the Surprise II Screes have not been modified by avalanche erosion to the same extent as Palliser and Old Nip (A.B.T.).

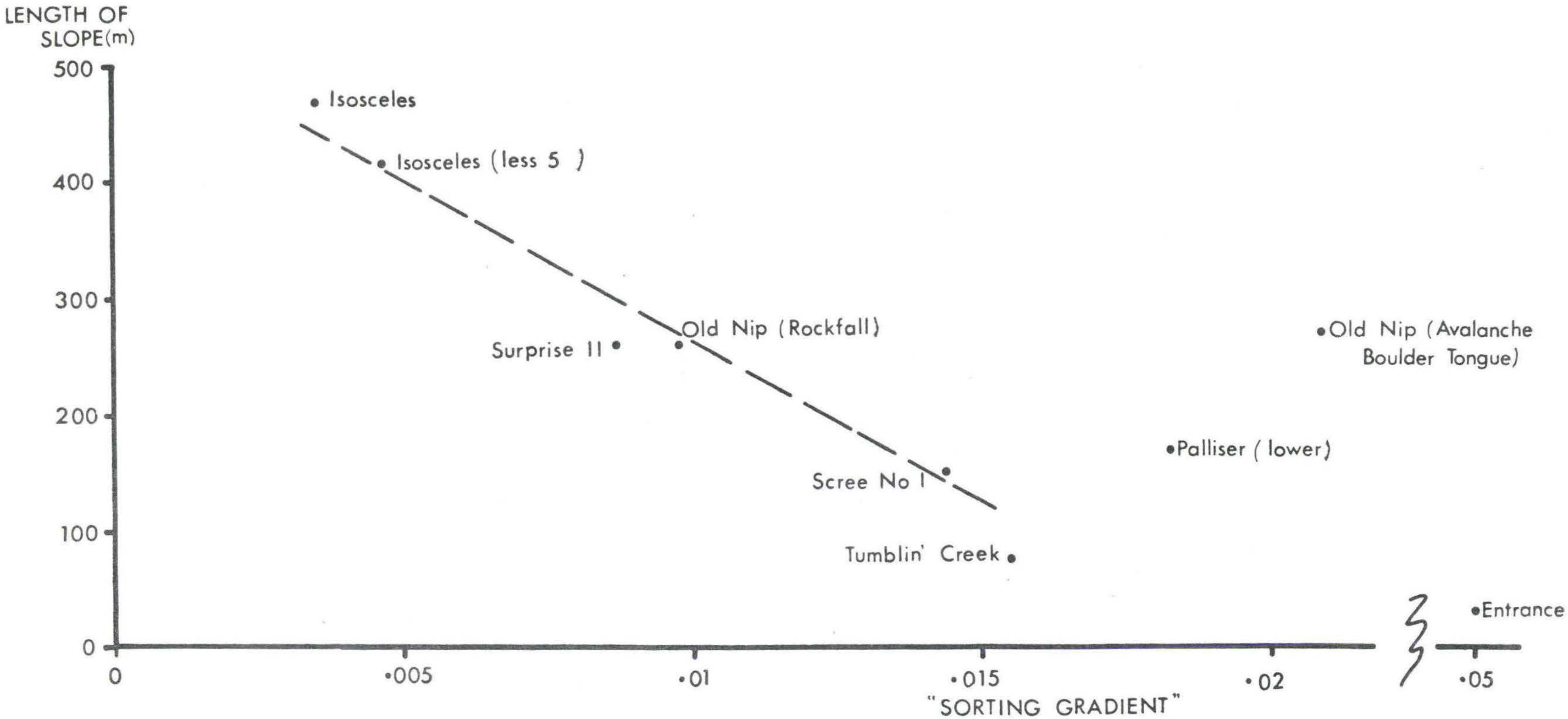


Figure 13.3 Relationship between the length of the scree slope and the "sorting gradient" (B coefficient of the regression equation)

These groupings and results are obviously tentative with so few points available. They indicate differences in sorting gradient between sites which are at opposite ends of a continuum from pure rockfall cones via multiprocess sites to avalanche boulder tongues. Many other factors, such as available size range, particle shape, etc., will affect the sorting pattern on a slope and a much greater amount of data and experimental work is needed before any concrete conclusions may be drawn about the detailed relationships between downslope sorting and dominant processes. The results given by Gardner (1968a, Figure 20) are not directly comparable with these data, due to differences in units and methods of calculation. Using the difference in mean size ($\log_{10}$) between the top and bottom sites divided by the distance between them as a measure of size gradient, Gardner found a similar relationship between the length of slope and the size gradient for the 20 slopes he studied in the Lake Louise area. However, there is a considerable scatter of points on his graph and the sites are not differentiated with respect to dominant processes.

Size Sorting of the Larger Debris

In addition to the main samples at each site, two other sets of measurements of particle size were taken; the five largest boulders within the sampled area (irrespective of whether they were in the sample) and the largest single boulder within five metres of the sampled point. The latter measure was taken to see whether the largest boulders at any point on the slope showed a gradation over the scree and the other set of measures was to try and establish whether a simple measure of this type was useful in investigating the general sorting pattern. A similar experiment was carried out by Stock (1968).

The relationships between these two parameters and distance downslope were examined by similar techniques to those used in the main investigation. Since a value for the "largest boulder" was measured for each sample taken, there are two for every sample point on the scree; the larger or both may be used as a measure of the largest boulder in five metres.

Size Sorting of the Largest Boulders

From the results in Table 13.4 and Figure 13.4, no clear relationship is evident between the size of the largest boulder in the environs of a sample point and the mean size of the sample or its position on the scree. All the relationships in Figure 13.4 are weak; those for Isosceles and Old Nip (A.B.T.) are not significant. Of the remainder, the two rockfall dominated screes show a positive relationship between size and the distance from the cliff, whilst the Palliser site, like the two non-significant sites, shows an increase in the mean size of the largest boulder towards the top of the scree. However, this overall trend has several components and the ANOVA results show a significant (99%) increase in size with downslope distance for the four lowest "rows" and an equally significant opposite effect for the middle three.

The degree and nature of this sorting may be tentatively related to the dominant process and grain size of the scree. The best fall sorting pattern is on the coarse rockfall screes but the finest scree has no distinct pattern. The difference might be attributable to the greater tendency for particles to "dig in" to the surface of the finer

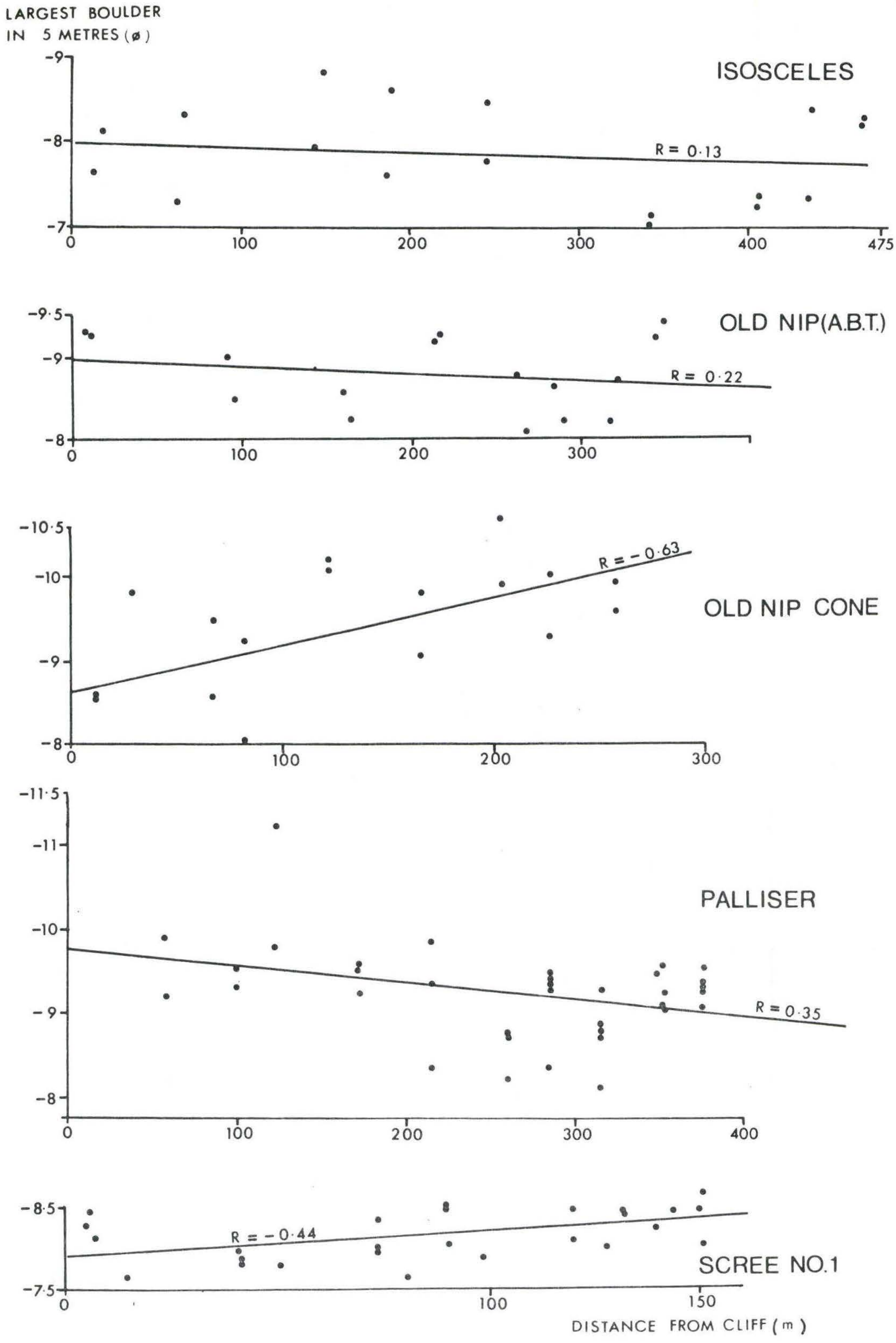


Figure 13.4 Relationship between the largest boulder within 5 metres of a sample site and distance from the cliff

TABLE 13.4: CORRELATION COEFFICIENTS BETWEEN THE MEASURED SIZE PARAMETERS AND DISTANCE FROM THE CLIFF

Variables Used	Isosceles	Old Nip (A.B.T.)	Old Nip (RF)	Palliser	Scree No. 1
Mean size v. mean (largest five)	0.47**	0.70**	0.88**	0.77**	0.83**
Mean size v. largest in 5 m	0.05	0.19	0.59**	0.07	0.42**
Mean (five largest) v. distance	-0.41**	-0.41**	-0.91**	-0.59**	-0.83**
Mean (largest in 5 m) v. distance	-0.03	-0.17	-0.63**	0.35**	-0.53**
Mean (largest in 5 m) v. distance (one value per sample point)	0.13	0.22	-0.63**	0.35*	-0.44**
Number of observations	36(18)	32(16)	32(16)	70(35)	56(28)

NOTE: A negative correlation indicates that fragment size increases downslope. The figures in brackets refer to the number of "largest in 5 m" boulders.

*Significant at the 95% level.

**Significant at the 99% level.

grained scree and lose some of their momentum. Also, the presence of fines is a major determinant of the amount and character of vegetation and collisions with willow scrub (Isosceles) or trees (of which there are several on the upper part of the Palliser Cone) would have a similar effect. These mechanisms may increase the probability, in marginal cases, of a boulder coming to rest higher on the slope than would be predicted by its size. Many other possibilities such as boulder shape or length of fall would also be important but could not be tested.

On the avalanche screes, it is possible that some of the larger boulders are too heavy to be removed by the majority of avalanches.

Several of the large boulders on avalanche slopes have been partially buried or exhumed by avalanche erosion.

These patterns and explanations obviously need the backing of much more data before they can be fully tested. They do, however, clearly illustrate, albeit in an extreme case, the results of the many random effects which may influence fall sorting. Although size sorting clearly occurs at these sites and the majority of the largest boulders do reach the lower part of the scree slope, single boulders of comparable size may be found in any position on the slope. At three of the five screes, the largest measured fragment was not at the lowest site (Figure 13.5). All of the observed patterns have a wide scatter of values and only the two coarse rockfall screes show trends which differ clearly from a random pattern.

Size Estimates by the Five Largest Boulders[1] in the Sampled Area

The results of the analysis of variance on these data are very similar to the main experiment and, using the IJK term as an error term, the following results were obtained (Table 13.5). There is little need for further comment on the pattern of size variation shown, since it has been discussed earlier. However, the efficiency of such data as an estimator of mean size varies from site to site (Table 13.6) and merits further comment.

Figure 13.5 illustrates the relationship between mean size of sample and the mean of the five largest boulders in the sampled area for

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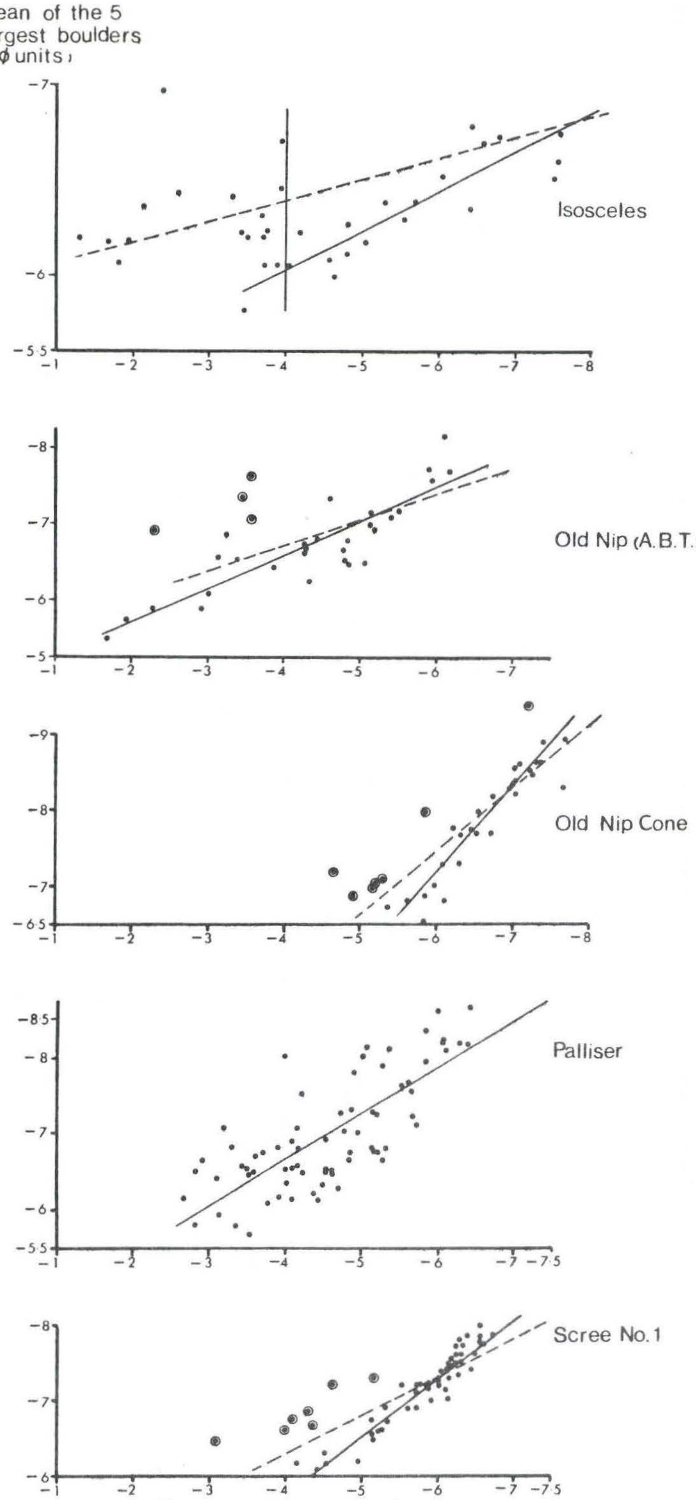
[1]In most cases, these observations do not include the largest boulder in 5 m.



NOTE: Dashed regression lines for all values. Solid lines exclude circled values and all sites greater than −4ϕ at Isosceles.

Figure 13.5 Relationship between the mean of the five largest boulders in the sampled area and the sample mean

TABLE 13.5: SUMMARY RESULTS OF ANOVA FOR THE FIVE LARGEST BOULDERS IN THE SAMPLED AREA

Site	Effects I	J	K	IJ	JK	IK
Isosceles	n.s.	95%	n.s.	99%	n.s.	n.s.
Old Nip (A.B.T.)	n.s.	99%	n.s.	99%	n.s.	95%
Old Nip (Rockfall)	n.s.	99%	n.s.	99%	n.s.	n.s.
Palliser (lower)	n.s.	99%	n.s.	99%	n.s.	n.s.
Palliser (middle)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Palliser (upper)	n.s.	95%*	n.s.	n.s.	n.s.	n.s.
Scree No. 1	n.s.	99%	n.s.	99%	n.s.	n.s.

*This is significantly greater than the IJK term; all other row effects are tested against the IJ term where it is significant.

TABLE 13.6: SUMMARY PARAMETERS OF THE REGRESSION EQUATIONS IN FIGURE 13.5 AND THEIR RELATIONSHIP TO THE RANGE OF MEAN SIZES OF THE SAMPLES

(A) All Samples

Site	N	R	S.E.	B Coefficient
Isosceles	36	0.47	0.23	0.18
Old Nip (A.B.T.)	32	0.70	0.43	0.34
Old Nip (RF)	32	0.88	0.36	0.82
Palliser	70	0.77	0.47	0.60
Scree No. 1	56	0.83	0.27	0.50

(B) Best Fit Lines

Site	N	R	S.E.	B Coefficient	Range of Mean Sizes of Sample Sites (ø)
Old Nip (A.B.T.)	28	0.90	0.27	0.44	4.42
Palliser	70	0.77	0.47	0.60	3.72
Scree No. 1	49	0.94	0.16	0.77	2.75
Old Nip (RF)	26	0.95	0.24	1.16	2.08
Isosceles (>4 ø)	18	0.90	0.11	0.52	1.43

each of the main sites. As might be expected, all sites show a statistically significant relationship (Table 13.6), although the pattern and scatter vary from scree to scree. The main trend in the data (fitted by the "best fit" regression lines) represents those sites which approximate a normal distribution and are unimodal. However, at all screes there are several sites which plot away from this grouping, usually indicating that the mean size of the largest boulders is greater than expected. Most of these sites are bimodal or have a coarse tail because of scattered larger boulders or groups of boulders which may be associated with the "floating layer" (see discussion below). These deviations are more pronounced on the two avalanche dominated slopes or where the surface material is small, as at Isosceles where the relationship breaks down below a mean size of -4.0 ø. The coarser rockfall sites (Scree No. 1, Old Nip Cone) show a much closer relationship.

The accurate usage of the largest boulders to estimate size grading or sorting patterns depends therefore upon the character of the scree. On coarse rockfall screes, it is a good estimator (crude correlation coefficients .83 and .85) but it is not suited to sites where there is fairly fine material, avalanche erosion, or where larger fragments are scattered over the surface and confuse the basic relationship. It is also interesting to note that the slope of the best fit regression equation is less than unity, except at the Old Nip Cone. This indicates that the difference in phi size between the mean of the five largest fragments and the sample mean increases as the mean size gets smaller. This may be a function of the measurement units, since each successive phi class encompasses an arithmetic size range equivalent to all previous ones (e.g. -8 ø ranges from 256-512 mm). Also, since the range of means of the five largest boulders is far less than the range of size of individual sample sites on a scree, the slope of the regression equation is much more strongly related to the latter (see Table 12.6).

LATERAL AND LOCAL VARIATION IN GRAIN SIZE

While the ANOVA results show that none of the screes studied has a consistent gradation of size across the slope, the presence of significant interaction effects indicates considerable lateral and local cariability in grain size. Figures 13.6-13.10 illustrate, far more adequately than mere verbal or statistical description, the character, variability and sorting characteristics of the surface materials on the screes studied. They also demonstrate some of the problems involved in sampling such sediments.

The lateral variations in grain size may be broken down into two major levels:

(a) "regional" variations--major differences between different sections of the scree; and

(b) "local" variations--governed by factors effecting a much smaller area.

Regional Variations

Two of the most obvious sources of such variation, differences in lithology and processes over the scree, were excluded specifically by the sample design employed and the limited nature of the sample framework at another three sites (Isosceles and both Old Nip sites) does not allow such differences to be detected. The mean sizes for

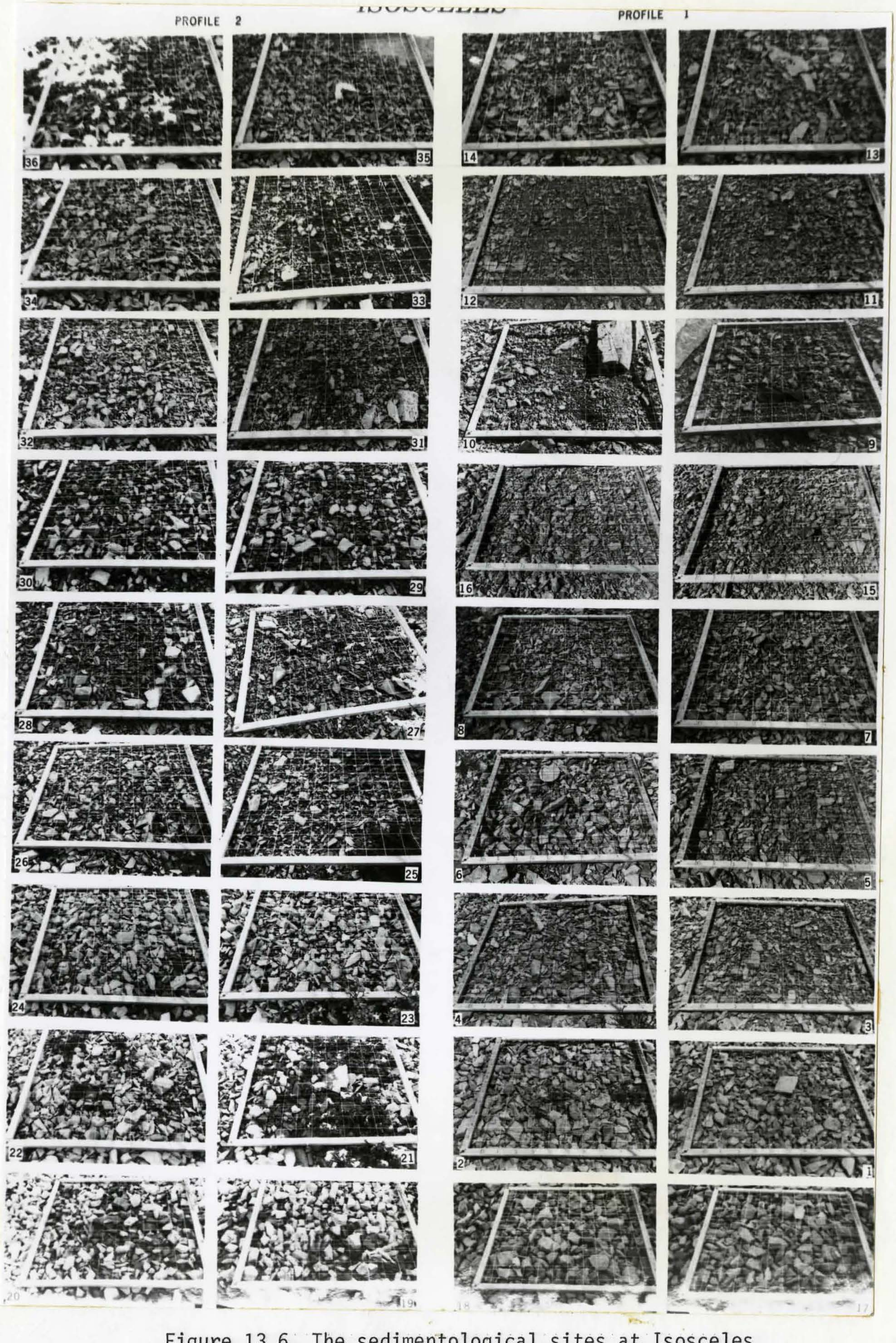


Figure 13.6 The sedimentological sites at Isosceles.

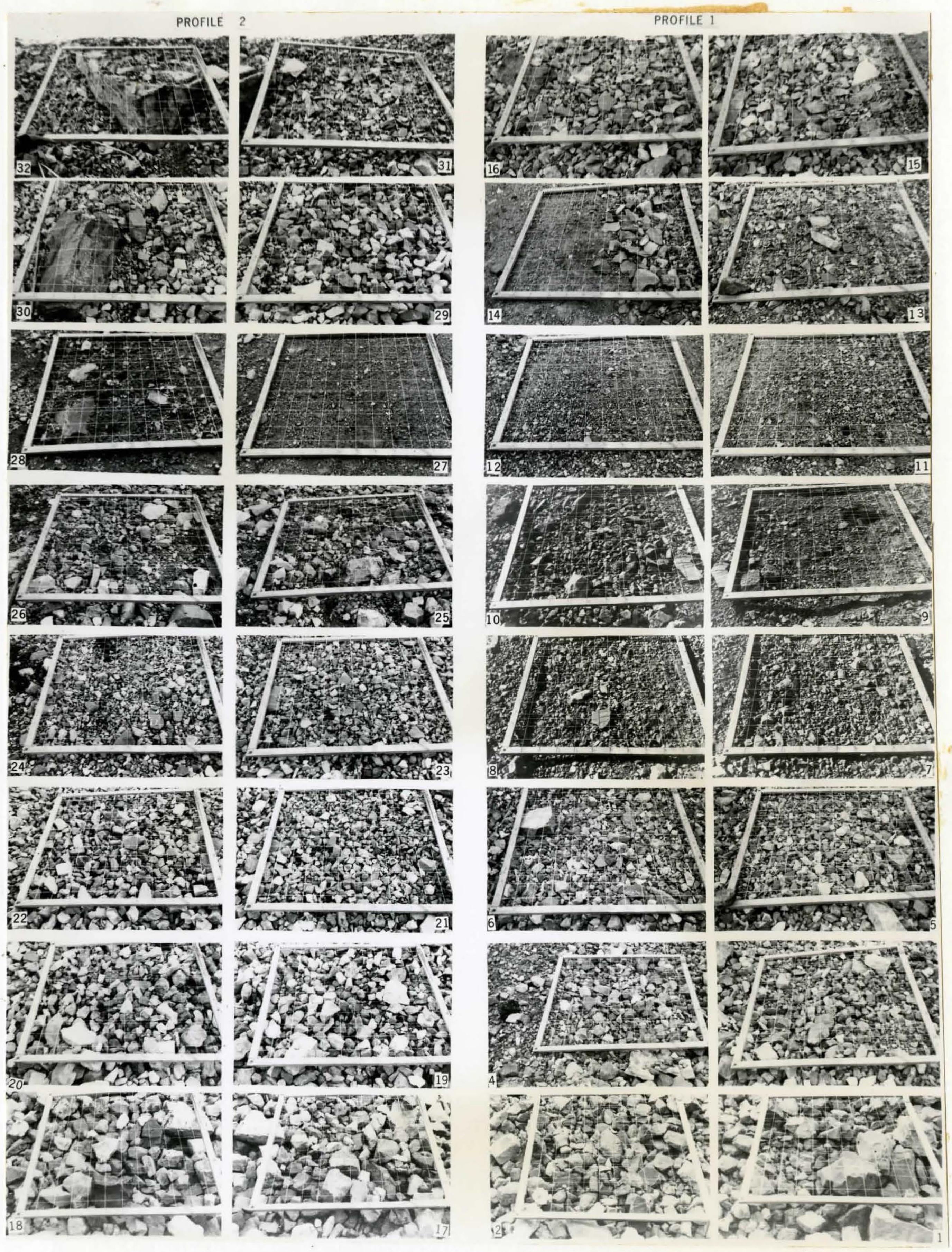


Figure 13.7 The sedimentological sites on the avalanche boulder tongue at Old Nip.

Figure 13.8 The sedimentological sites on the Old Nip Cone.

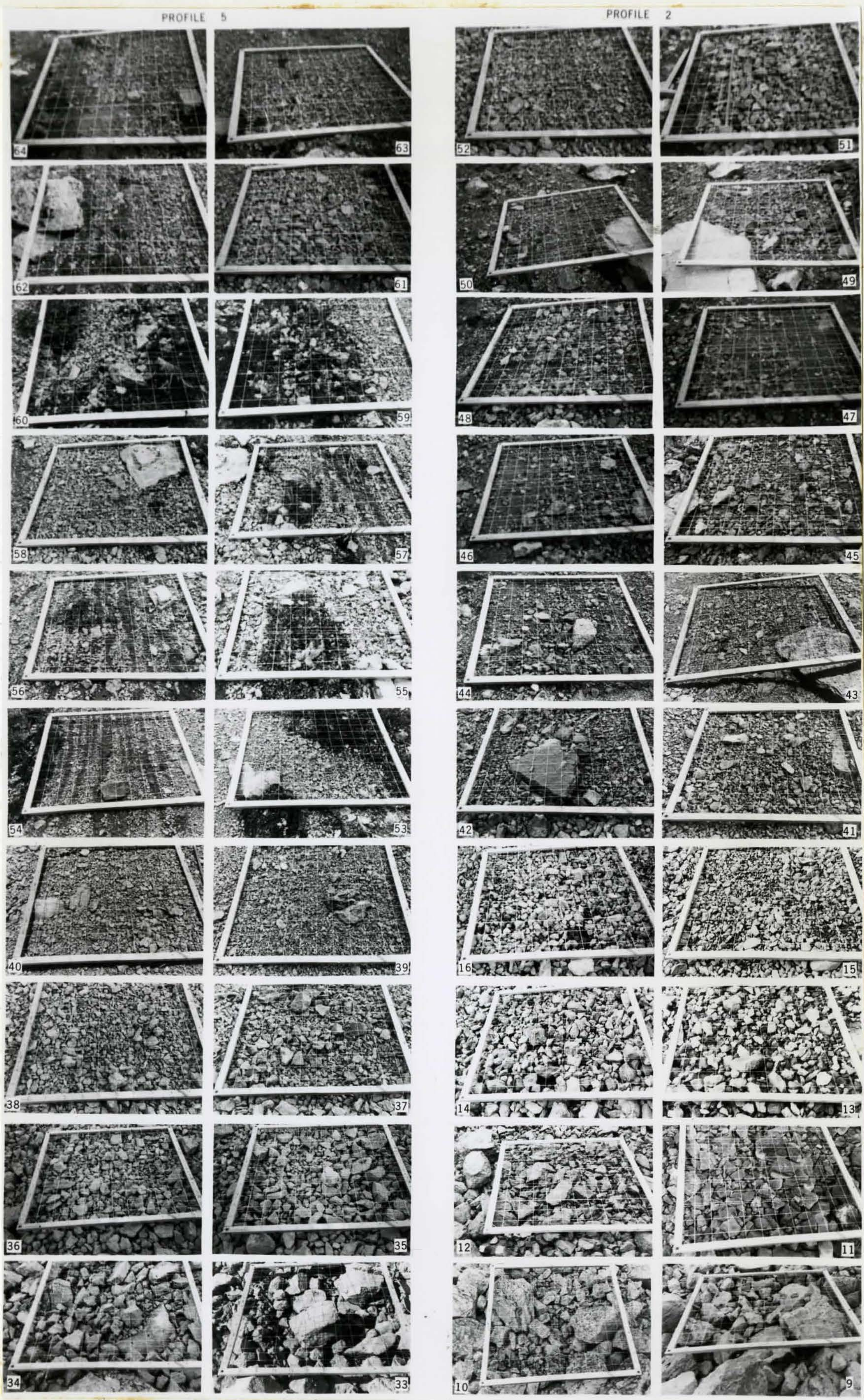


Figure 13.9A The sedimentological sites on profiles 2 and 5 on the Palliser Cone.

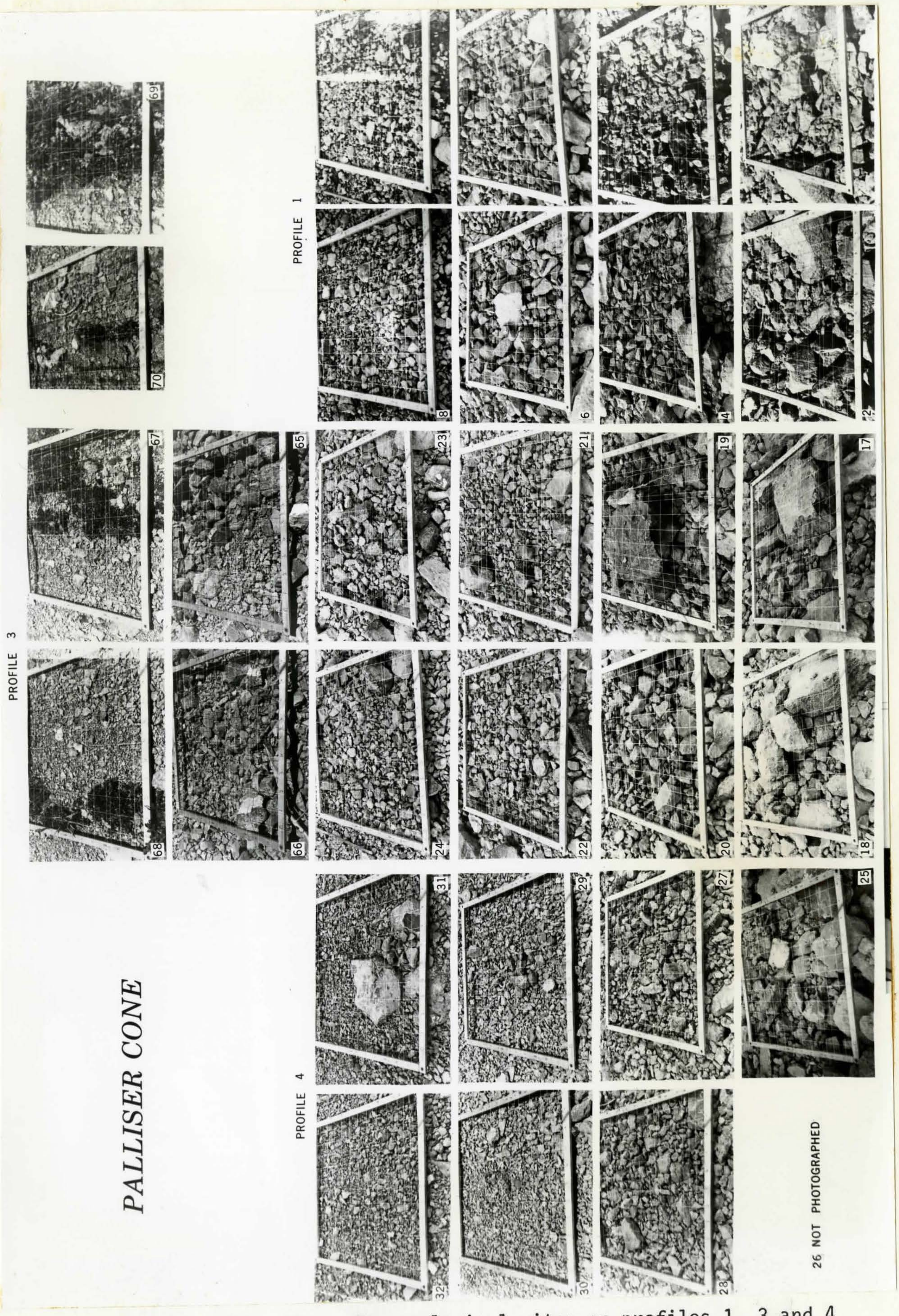


Figure 13.9B The sedimentological sites on profiles 1, 3 and 4 on the Palliser Cone.

Figure 13.10A <u>The sedimentological sites on profiles 1 and 2 at Scree No. 1</u>.

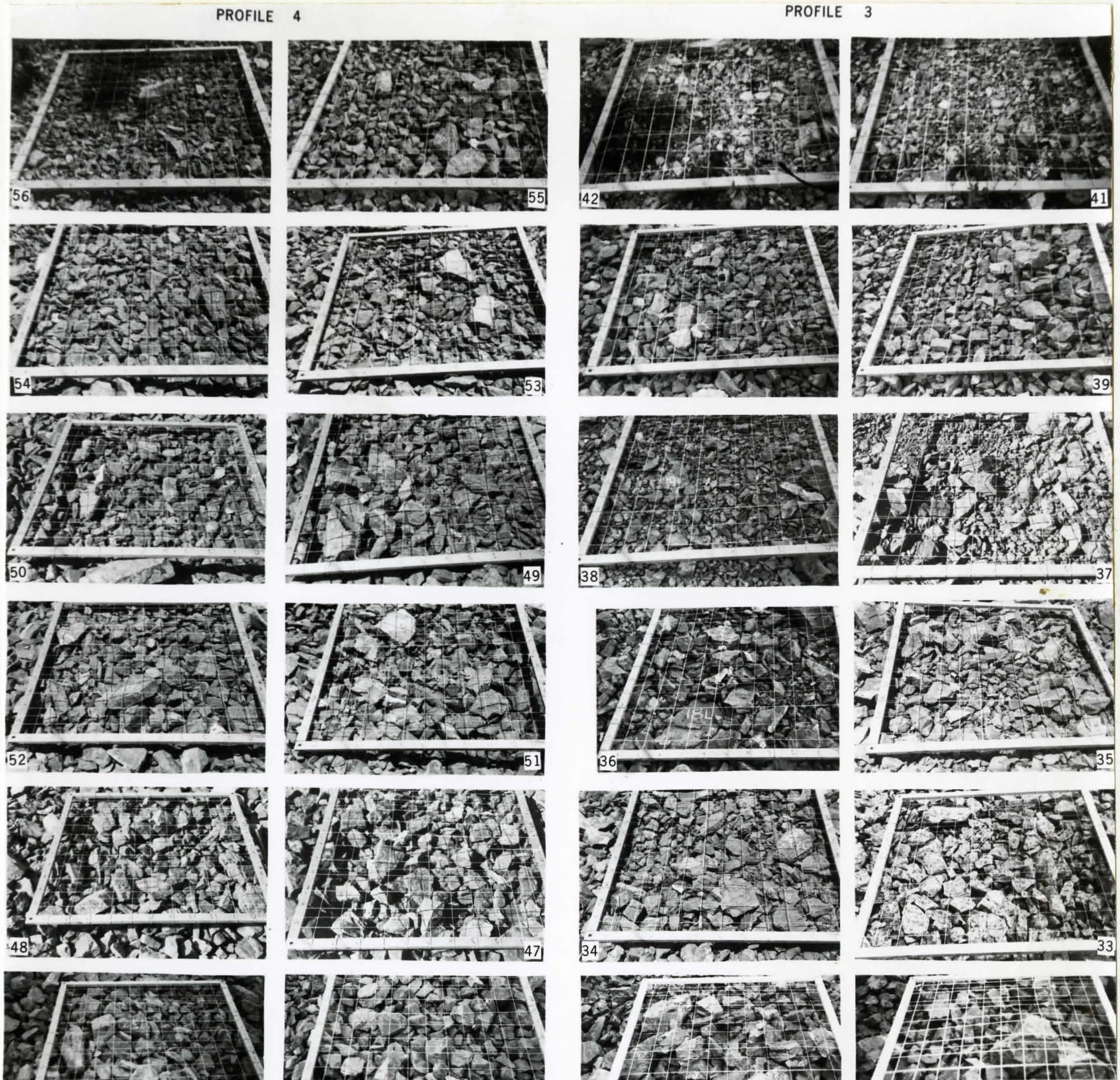


Figure 13.10B <u>The sedimentological sites on profiles 3 and 4 at Scree No. 1</u>.

each of the four profiles of Scree No. 1 are -5.74, -5.69, -5.35 and -5.76 ø. Although profiles 1 and 2 are coarser for the basal five "rows", this pattern is reversed for the upper two sites and there is no consistent pattern. On the lowest part of the Palliser Cone, the mean sizes for the four basal "rows" are -5.00, -5.39, -5.43, -4.98 and -4.96 ø respectively. These regional differences seem to be the result of lateral variation in avalanche activity; towards the sides of the cone, particularly on profiles 4 and 5, the irregular scatter of larger debris over the surface is not present and hence the surface material is finer and better sorted (see Figures 13.9A and B). This effect might be the result of more efficient erosion in this area or more deposition in the area of profiles 2 and 3. The evidence from measurements at this site is not very great (Chapter 8) but avalanche deposition at the base of profile 1 in 1971 suggests the former possibility.

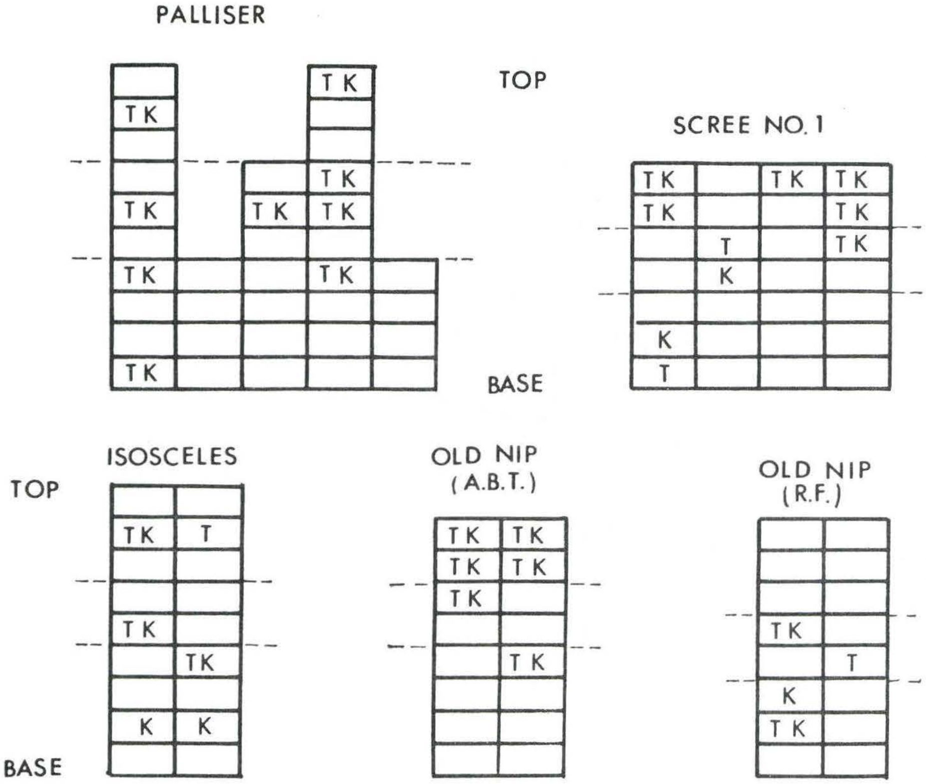
Local Variations

The results outlined above indicate, at least for the screes sampled, that the major sources of lateral variation are small scale local features caused by a variety of processes. These rapid local fluctuations in grain size may be observed on all the scree slopes sampled and range considerably in pattern and magnitude from isolated blocks through scattered clusters or patches to transitional or abrupt changes between two different size groupings. Because of the continuous scale of variation, it is very difficult to measure or describe on either a qualitative or quantitative basis.

Quantitative measures of this variability come from two main sources; the two levels of replication within the sampling design and a set of additional samples, the "EX" samples, taken on an ad hoc basis during the main sampling programme to illustrate extreme variations in grain size close to the sample sites.

The two subsamples at each site were taken 10 cm from the sample point and covered a zone 20 particles wide (see Chapter 10). Therefore, the area sampled is dependent upon grain size and ranged from extremes of 10-20 cm to 3 metres. Two tests were used to examine differences between these samples; the t test measures differences between means (Dixon and Massey, 1968, p. 116) and the Kolmogorov-Smirnoff two sample test examines whether the two samples have been drawn from the same population (Siegel, 1956, p. 127). The 95% confidence level was adopted and the results of these tests are shown diagrammatically in Figure 13.11. In the vast majority of cases (104/113), the results of both tests are similar and in eight more cases, the non-significant test was significant at greater than the 90% level. The only exception (Isosceles, sites 1 and 2) had four of the five largest fragments in site 1, whilst the bulk of that sample is slightly smaller than site 2.

Between 25 and 37.5% of the sample pairs at each site were significantly different by one or both tests (Table 13.7). The maximum difference was 1.37 ϕ (1.33 ϕ at the second level of winsorization) for Old Nip sites 31 and 32 at the top of the avalanche boulder tongue and all of the differences greater than 0.3 ϕ were significant. Details of the additional samples (the "EX" samples) are given in Table 13.8. The great majority of these samples were either taken from within the sample square (sampling from the other side of the square, i.e. from the right



T = SIGNIFICANT DIFFERENCE IN MEANS (T TEST)

K = SIGNIFICANT DIFFERENCE IN DISTRIBUTIONS(K.S.TEST)

Figure 13.11 Significant differences between subsamples at each sample point using t and Kolmogorov–Smirnov tests

TABLE 13.7: DIFFERENCES BETWEEN THE MEAN PHI SIZE OF ADJACENT SAMPLES*

Difference ø Units	Isosceles	Old Nip (A.B.T.)	Old Nip (RF)	Palliser	Scree No. 1	"EX"
Less than 0.1	44.4	25.0	37.5	37.1	28.6	6.9
0.1 - 0.2	5.6	18.8	6.3	11.4	21.4	0
0.2 - 0.3	22.2	16.3	37.5	14.3	21.4	3.4
0.3 - 0.4	16.7	16.3	12.5	8.6	10.7	3.4
0.4 - 0.5	0	12.5	6.3	8.6	3.6	0
0.5 - 0.6	0	12.5	0	5.7	7.1	3.4
0.6 - 0.7	0	0	0	5.7	3.6	13.8
0.7 - 0.8	11.1	0	0	2.9	0	3.4
0.8 - 0.9	0	0	0	5.7	0	13.8
0.9 - 1.0	0	6.3	0	0	0	13.8
1.0 - 1.1	0	0	0	0	3.6	6.9
1.1 - 1.2	0	6.3	0	0	0	3.4
1.2 - 1.3	0	0	0	0	0	13.8
1.3 - 1.4	0	6.3	0	0	0	6.9
1.9 - 2.0	0	0	0	0	0	6.9
Number of unequal pairs (both or either test)	33.3	37.5	25.0	25.7	35.7	-
Number of pairs	18	16	16	35	28	29

*The figures are percentages.

hand side of the right hand square instead of the left) or from areas adjacent to the sampled areas. The differences in means between these samples and adjacent sample sites is given in Tables 13.7 and 13.8. These values are, as would be expected, higher than those for the normal pairs, since they were selected to illustrate differences but the range is similar except for the extreme value of almost 2 ø units. In some cases, even these values are underestimates of the variation, since

TABLE 13.8: DETAILS OF ADDITIONAL SAMPLES TAKEN ON THE MAJOR SITES

Site	Height (m)	Cod-ing	No. of Sites	Range in Sizes	Nearest Site	Mean of Nearest Site	Size Ø	Difference	Comments
Isosceles	69	2EX	4	-4.32 to -4.61	3	-4.32	-5.06	.74	adjacent
	69	2EXR	4	-4.32 to -4.61	3	-4.32	-4.05	.27	same square
	140	3EX	4	-3.87 to -5.04	5	-4.32	-3.63	.69	same square
	334	5EX	4	-3.07 to -3.44	9	-3.35	-3.95	.60	same square
	334	16EX	4	-3.07 to -3.44	32	-3.07	-4.00	.93	same square
	416	6EX	4	-2.92 to -3.88	11	-3.23	-4.12	.89	same square
	416	17EX	4	-2.92 to -3.88	34	-3.88	-4.76	.88	same square
Old Nip (A.B.T.)	43	10EX	4	-5.15 to -5.50	20	-5.50	-3.56	1.94	on levee (2-3m)
	76	11EX	4	-4.33 to -4.84	21	-4.78	-3.70	1.08	5 metres away
	148	13EXR	4	-3.02 to -3.56	26	-3.56	-3.54	0.02	same square
	148	13EXL	4	-3.02 to -3.56	25	-3.03	-4.00	0.97	same square
	201	6EX	4	-1.74 to -2.28	11	-1.95	-3.18	1.23	same square
	201	14EX	4	-1.72 to -2.28	28	-2.28	-4.24	1.96	1-2m above in runnel
	346	16EX	4	-3.40 to -5.14	32	-3.40	-4.63	1.23	adjacent
Old Nip (Rockfall)	151	21R2	4	-5.87 to -6.30	41	-6.21	-5.03	1.18	repeat sample
	151	21EX	4	-5.87 to -6.30	42	-5.87	-5.29	0.58	3 metres away
	151	25EX	4	-5.87 to -6.30	56	-5.99	-5.36	0.63	2 metres away
Palliser	12	17EX	10	-5.37 to -6.42	34	-5.79	-6.56	1.23	adjacent
	73	15R	10	-4.39 to -5.54	38	-4.55	-3.67	0.88	1.5 metres away
	73	15EX	10	-4.39 to -5.54	38	-4.55	-3.32	1.23	2.5 metres away
	73	3EX	10	-4.39 to -5.54	5	-5.22	-4.26	0.96	2 metres away
	178	28EX	6	-2.83 to -3.93	55	-3.20	-4.09	0.89	adjacent
	216	29EX	6	-2.91 to -4.17	58	-4.01	-4.01	0	same square
	330	26EX	4	-3.53 to -5.27	51	-4.58	-3.52	1.06	2 metres away
Scree No. 1	35	17EX	8	-5.58 to -6.49	33	-5.74	-6.41	0.67	adjacent
	35	24EX	8	-5.58 to -6.49	47	-6.14	-5.16	0.98	1 metre upslope
	65	18EX	8	-5.21 to -6.25	35	-5.53	-5.91	0.38	3 metres away
	112	13EX	8	-4.51 to -5.77	25	-4.53	-5.90	1.37	4.5 metres away
	112	27G	8	-4.51 to -5.77	53	-5.25	-3.92	1.33	adjacent, grab sample of 100
	127	27EX	8	similar to above?		?	-6.36	1.00+	15m above site 53

areas of fines could not be adequately sampled and larger differences would have been found in examples such as site 14 at Old Nip (Figure 13.7).

These results indicate that within very short distances (1-2 metres), variations in grain size of half a phi unit are reasonably common and extreme variations of as much as two or, where fines are exposed, maybe four or five phi units may be encountered. However, as well as the magnitude of these differences, there is also a distribution pattern to these sites which is interesting and this is crudely depicted in Figure 13.11 and Table 13.9. From these data, it appears that the upper and middle zones of the scree are more prone to this type of variability than the basal part. This is particularly true at the two avalanche sites and Scree No. 1. Since most of the "EX" samples were also taken from these two zones, both sets of evidence suggest that the basal third of the scree has much less lateral variability than its higher parts where rapid local variations in size are much more common.

TABLE 13.9: PERCENTAGE OF THE SITES IN EACH OF THE THREE ZONES OF THE SCREE WHICH HAVE SIGNIFICANT DIFFERENCES BETWEEN THE SUBSAMPLES

Site	Lower	Middle	Upper
Isosceles	37.5	25.0	33.3
Old Nip (A.B.T.)	12.5	25.0	100.0
Old Nip (RF)	33.3	50.0	0.0
Palliser	15.0	44.0	33.3
Scree No. 1	25.0	37.5	62.5

Size Sorting at Individual Sites

Geologists have derived numerous indices to describe the size sorting of sedimentary populations (see, for example, King, 1966, pp. 280-282; Griffiths, 1967, p. 106). Since the size measure used here involves values for discrete particles, it would seem appropriate to use the standard deviation of these observations as a measure of sorting. These values are tabulated in Tables 13.10 and 13.11. The latter table is the winsorized (second level) estimates of the standard deviation. These values are slightly lower than the original standard deviations, but the pattern is much the same indicating that the scattered unusually large or small fragments (see Chapter 12) do not greatly affect the standard deviations.

The size groupings chosen for Tables 13.10 and 13.11 correspond to the sorting classification of Folk and Ward (1957) for values of their inclusive graphic standard deviation. Since this measure closely approximates the true standard deviation, these classes should also hold for that parameter. Two-thirds of the samples fall in the moderately sorted category, whilst another quarter are poorly sorted. In their study of the Brazos River bar, Folk and Ward (1957) found values ranging from 0.2 to 8.0. Griffiths (1967, p. 102) records a value of 0.88 for the phi deviation of scree deposits at Lamar, Pennsylvania, which is close to the average value of 0.81 for all the samples from Surprise. The sorting values given by Caine (1967, p. 799) are much lower averaging 0.63 with a maximum range of 0.42 - 0.82 ø units. However, his results are comparable with the rockfall cones (Scree No. 1, Old Nip Cone), although the mean size of debris is much larger.

TABLE 13.10: STANDARD DEVIATIONS OF SAMPLE POPULATIONS FOR ALL SITES USING PHI SIZE DATA

Site	Very well sorted < 0.35	Well sorted 0.35-0.5	Moderately sorted 0.5-1.0	Poorly Sorted 1.0-1.5	Very poorly sorted 1.5-2.0	Mean	S.D.	N
Entrance	0	0	42.9	57.1	0	0.93	0.16	7
Isosceles	0	0	91.7	8.3	0	0.83	0.18	36
Isosceles (all)	0	0	90.7	9.3	0	0.83	0.15	43
Old Nip (A.B.T.)	0	0	68.8	28.1	3.1	0.93	0.26	32
Old Nip (A.B.T., all)	0	0	66.7	30.8	2.5	0.93	0.26	39
Old Nip (RF)	3.1	9.4	84.4	3.1	0	0.71	0.19	32
Old Nip (RF, all)	2.9	14.3	80.0	2.9	0	0.69	0.21	35
Old Nip (Av. Apron)	0	0	0	70.0	30.0	1.32	0.19	10
Palliser	0	2.9	54.3	41.4	1.4	0.95	0.28	70
Palliser (all)	0	2.6	58.4	37.7	1.3	0.93	0.27	77
Scree No. 1	1.8	5.4	87.5	7.1	0	0.73	0.19	56
Scree No. 1 (all)	1.6	6.5	85.4	6.5	0	0.72	0.15	62
Scree No. 1 (Av.)	0	0	0	66.7	33.3	1.33	0.23	6
Surprise II	0	0	25.0	75.0	0	1.06	0.16	12
Tumblin' Creek	0	0	22.2	66.7	11.1	1.19	0.27	9
TOTAL	0.7	3.3	66.7	26.3	2.7	0.88	0.26	300
Rockfall dominated	1.4	6.1	83.7	8.8	0	0.76	0.17	147
Avalanche dominated	0	1.3	50.3	43.2	5.2	0.95	0.41	153

TABLE 13.11: SECOND LEVEL OF WINSORIZATION ESTIMATES OF THE STANDARD DEVIATIONS FOR ALL SAMPLE SITES USING PHI SIZE DATA

Site	Very well sorted <0.35	Well sorted 0.35-0.5	Moderately sorted 0.5-1.0	Poorly sorted 1.0-1.5	Very poorly sorted 1.5-2.0	Mean	S.D.	N
Entrance	0	0	85.7	14.3	0	0.85	0.13	7
Isosceles	0	2.8	88.9	8.3	0	0.77	0.13	36
Isosceles (all)	0	2.3	90.7	7.0	0	0.76	0.15	43
Old Nip (A.B.T.)	0	0	71.9	28.1	0	0.85	0.24	32
Old Nip (A.B.T., all)	0	0	71.8	28.2	0	0.85	0.24	39
Old Nip (RF)	3.1	15.6	78.1	3.1	0	0.64	0.17	32
Old Nip (RF, all)	2.9	22.8	71.4	2.9	0	0.62	0.19	35
Old Nip (Av. Apron)	0	0	0	90.0	10.0	1.28	0.15	10
Palliser	0	7.1	67.1	25.8	0	0.83	0.28	70
Palliser (all)	0	7.8	70.1	22.1	0	0.81	0.29	77
Scree No. 1	1.8	8.9	85.7	3.6	0	0.66	0.12	56
Scree No. 1 (all)	3.2	11.3	82.3	3.2	0	0.65	0.13	62
Scree No. 1 (Av.)	0	0	0	66.7	33.3	1.31	0.21	6
Surprise II	0	0	58.3	41.7	0	0.98	0.22	12
Tumblin' Creek	0	0	33.3	55.6	11.1	1.14	0.29	9
TOTAL	1.0	7.3	74.0	16.7	1.0	0.80	0.26	300
Rockfall dominated	2.0	10.9	82.3	4.8	0	0.69	0.17	147
Avalanche dominated	0	3.9	60.1	33.3	2.6	0.90	0.31	153

There is considerable fluctuation in the spread of values from site to site, but the major difference appears to be related to differences in dominant process. With the exception of the Entrance Screes, which are poorly sorted due to their small size, all the rockfall sites are much better sorted with an average standard deviation of 0.76 compared with 0.95 for the avalanche slopes. The mean standard deviations of the two groups are significantly different at greater than the 99.9% level, using a t test. Differences can also be seen at individual sites such as Old Nip where all three different areas (rockfall, A.B.T., avalanche apron) have significantly different sorting values. These contrasts may be ascribed to general differences in the origin of the deposits, although many of the local variations may affect sorting at individual sites so that they give atypical results.

As well as these differences between different types of scree deposits, there is also a considerable range in the sorting values on any one scree. Table 13.12 summarizes the relationship between the mean, standard deviation, coefficient of variation and distance from the cliff at the major sites. Although two of the sites show a weak positive correlation between phi size and the standard deviation (i.e. the standard deviation increases as mean particle size decreases), the maximum "explained variance" (r^2) is only 10.24% and it would seem reasonable from these results to conclude that the standard deviation (sorting) is virtually independent of the mean. The absence of a phi size sorting relationship for directly measured data was also noted by Griffiths; however, sediments measured by indirect procedures such as sieving do show a size-shape relationship (Griffiths, 1967, pp, 309-314).

TABLE 13.12: RELATIONSHIPS BETWEEN SORTING, MEAN SIZE, COEFFICIENT OF VARIATION AND DISTANCE FROM THE CLIFF FOR THE MAIN SCREES SAMPLED

Variables	Isosceles	Old Nip (A.B.T.)	Old Nip (RF)	Palliser	Scree No. 1
Mean size (ø) v. sorting (S.D.)	0.18	0.32*	-0.27	-0.12	0.25*
Distance from cliff v. sorting (S.D.)	-0.15	-0.14	0.30*	0.16	0.00
Mean size (ø) v. Coef. Variation	0.69**	0.88**	0.28	0.57**	0.72**
Distance from cliff v. Coef. Variation	-0.54**	-0.31*	-0.34*	-0.28**	-0.44**
Number of Observations	36	32	32	70	56

*Significant at the 95% level.

**Significant at the 99% level.

The results in Table 13.12 also show that for four of the five sites, there is no relationship between the standard deviation and the distance of the sample site from the cliff, although analysis of variance showed "row effects" to be significant at Isosceles, Scree No. 1 and the upper and lower parts of the Palliser Cone. Further examination of these data in detail (Figure 13.12) shows that there is considerable variation in sorting at all levels of the scree but for the lowermost three or four sites (except at Isosceles), the standard deviation increases towards the base of the scree and the greatest variation and lack of pattern is restricted to the upper and middle part of the slopes. The poorer sorting at the base of the scree may be a result of the much greater size range available, especially where secondary breakdown has taken place.

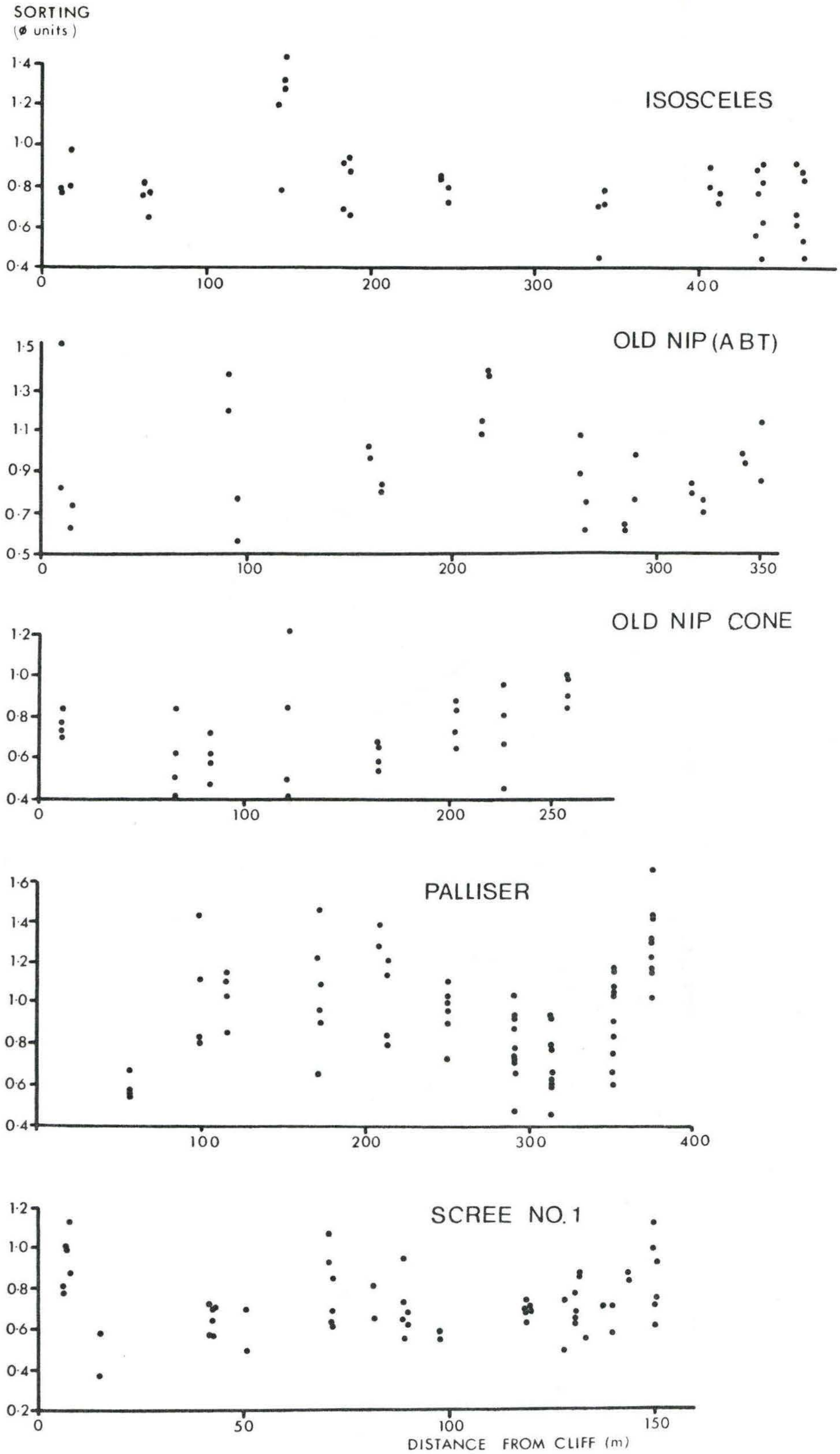


Figure 13.12 Relationship between sample sorting (standard deviation) and distance from the cliff

The relationship between the mean and standard deviation can also be examined by the coefficient of variation (standard deviation/ mean expressed as a percentage). At four of the five sites (Table 13.12), the coefficient of variation correlates strongly with phi size (i.e. the coefficient of variation increases as the mean size of particles gets smaller) and there is also a weaker relationship between the coefficient of variation and the distance from the cliff. The coefficient of variation reflects the increasing ratio of standard deviation to mean as the mean gets smaller while the standard deviation remains more or less constant or fluctuates randomly. This indicates that, in relative terms, the standard deviation increases as particle size decreases and therefore the coarser deposits are relatively better sorted than the finer ones. The relationship with position on the slope reflects the downslope increase of particle size. The exception to the pattern is the Old Nip Cone where the combination of the coarsest debris and the best (absolute) sorting produces no clear pattern.

The use of the coefficient of variation also enables a comparison of these data with Gardner's (1968a, p. 92), since he expressed sorting in that form. The results in Table 13.13 indicate that his values differ considerably from those in Surprise and also Caine's data (reworked from his Table 1, 1967). The much smaller coefficient of variation in Caine's data is consistent with the relationship between standard deviation and mean discussed above, since the particle size at his sample sites is considerably larger than that in Surprise. The maximum value in Surprise is -7.42 ϕ, whereas Caine's values range from -8.24 to -9.35 ϕ. The much larger values given by Gardner conflict with both other sets of results. This is because the measurements are transformed to $\log_{10}$ rather than phi units, otherwise the results would probably be comparable, indicating that his description of the surface material as "unsorted at any point on the scree" (1971, p. 15) is not proven.

TABLE 13.13: COMPARISON OF VALUES FOR THE COEFFICIENT OF VARIATION FOR SAMPLES FROM SURPRISE, TASMANIA, LAKE LOUISE AND PENNSYLVANIA

Site	Mean	Minimum	Maximum	Number of Sites
Isosceles	20.48	12.31	39.07	43
Old Nip (A.B.T.)	25.09	12.49	54.96	39
Old Nip (Rockfall)	11.49	6.84	20.84	35
Old Nip (Av. Apron)	28.26	22.91	34.79	10
Palliser	21.18	10.14	48.00	77
Scree No. 1	13.15	7.40	32.09	62
Scree No. 1 (Avalanche '69)	35.28	28.73	45.63	6
Entrance	15.21	12.65	18.14	7
Surprise II	24.13	12.82	43.61	12
Tumblin' Creek	22.00	16.98	29.03	9
Surprise Total	19.32	6.84	54.96	300
Tasmania (Caine, 1967)	7.07	5.04	9.33	23
Lake Louise Area (Gardner, 1968a)	74.00	37.00	265.00	117
Lamar, Pennsylvania (Griffiths, 1959)				
a axis	9.98	-	-	1
b axis	11.40	-	-	1
c axis	12.13	-	-	1

Discussion

The two preceding sections have illustrated the rapid local variations in grain size and sorting over the surface of the scree. These variations are most pronounced in the upper and middle parts of the scree slopes where the grain size is generally smaller. Differences in mean size of a similar order of magnitude occur in the basal areas at the Palliser Cone and at Scree No. 1 (Figures 13.1A and 13.1C) where there are more than two profiles and it is possible that similar undetected variations occur in the basal sections of other sites. The perception of lateral variations in grain size is in part scale dependent; it depends upon the position of the observer relative to the surface, his field of view, the size of the material involved and the scale of the variation. Other things being equal, there is more lateral variation observed in the sample squares at the top of the slope, partially because of the smaller scale of that variation and its component parts; at the base of a coarse rockfall slope (e.g. sites 33, 34, 47, 48 Old Nip), the area observed during sampling is about 50 particles wide, whereas at higher sites this may involve several hundred particle widths within the sample squares, hence the greater probability of observing differences. Thus, it may be that lateral variations in size and sorting in the coarser areas of the scree are comparable with those in the higher parts of the slope but that since the two scales are different, the scale at which sampling was carried out biases the results towards the observation of variations where the grain size is small or moderate relative to the square. This problem was not envisaged in the original design and an alternative design where distance measures for sampling were relative to the size of the boulders would be needed to fully explore it.

SIZE SORTING WITH DEPTH

The research design specifically concentrated on the surface material of the scree and no attempt was made to investigate any size sorting with depth. However, several observations made during sampling indicated that in some cases a relationship did occur and its understanding helps to explain some of the anomalous distributions seen at the sample sites.

To the author's knowledge, there is little or no published information on the variation in grain size with depth on scree slopes, probably due to the practical difficulties of excavation in this material. This idea has, however, been implied by the earlier characterization of the surface scree as a lag deposit where the finer material has fallen through to accumulate at some unknown depth beneath the surface. In the absence of natural sections, it has not been possible to substantiate this hypothesis with observations in the lower parts of the sampled screes. However, gully sections in a fossil scree, now vegetated, on the Eastern Valley Side opposite Surprise 1½ show tabular material, crudely bedded parallel to the slope with many of the voids filled with fines.

A much clearer example was noted in an old gravel pit (now used as a garbage dump for the Columbia Icefields Chalet) close to an abandoned section of the old Banff-Jasper Highway about two to three miles north of the Columbia Icefields (70 miles south of Jasper). The pit is in the basal section of a coarse, straight rockfall scree from Tangle Ridge. The surface material is typical basal rockfall scree with blocks about 200-400 mm in diameter, similar in size and character to the material at Scree No. 1. However, a small distance below the surface much finer material is visible and at depths of less than a metre all the voids are filled with fines and small rock fragments (Figure 13.13). It therefore appears, in this case, that the voids between the particles are filled at a depth of two to three times the average particle size, although there is no trace of this at the surface. The presence of such fines is the major reason why long rooted plants can survive on apparently very coarse screes.

Examples of this zone where fines fill the voids between rock fragments may be seen on the avalanche screes of the Palliser Cone, Tumblin' Creek and Old Nip (A.B.T.) where the coarser loose cover has been stripped away (see Figures 13.7 and 13.9). In such cases, patches or a thin layer of coarser material (up to -5 or -6 ø) may overlie this layer or it may be exposed at the surface (e.g. Old Nip 14, Figure 13.7). Excavation into the surface often reveals a thin crust of 10-40 mm thickness (probably formed as a result of the drying out of a damp surface layer) below which there is a dry unsorted mixture of fines and rock fragments. Several of the larger fragments at the sites on the upper and middle sections of the Palliser Cone were almost completely buried within this material and had to be excavated (Figure 13.14). The rapid local variations on the higher parts of the screes is, in part, a consequence of this layer of fines which may form a relatively smooth surface over which the coarser material rolls or slides more easily. The loose surface accumulations above such layers are the most mobile and unstable of the surface deposits encountered on screes in Surprise.

These scattered observations suggest that the coarse cohesionless

Figure 13.13 Vertical section in the scree at Tangle Ridge. This gravel pit section is about 2 m deep and the surface is a coarse well-sorted scree. June 1969.

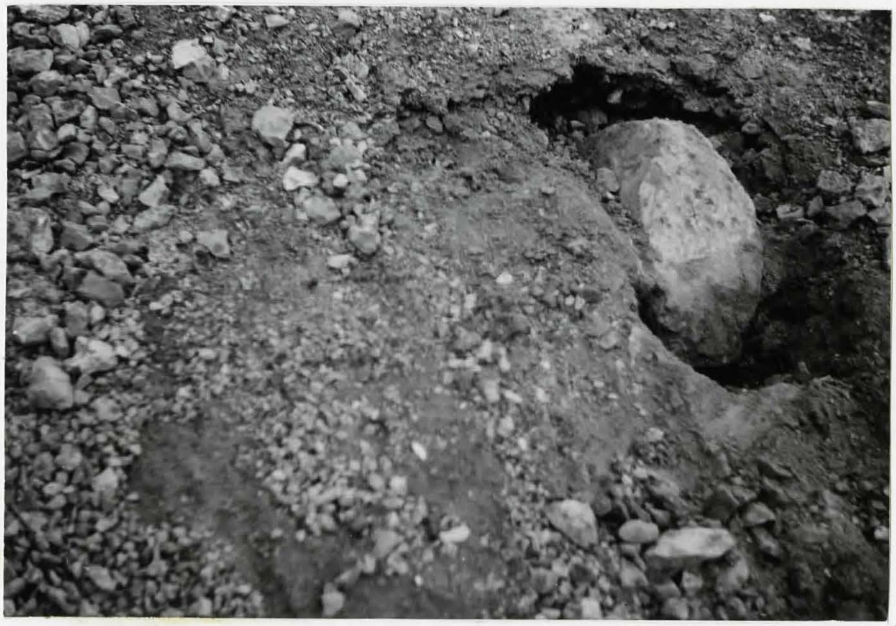


Figure 13.14 Excavation at site 14, Palliser Cone. This illustrates the mixture of fines and rock chips immediately below the surface of the upper and middle parts of this cone. Undisturbed surface material can be seen on the far left. The boulder is about 45 cm long. Compare with the site prior to excavation, sample 48, Figure 13.9A.

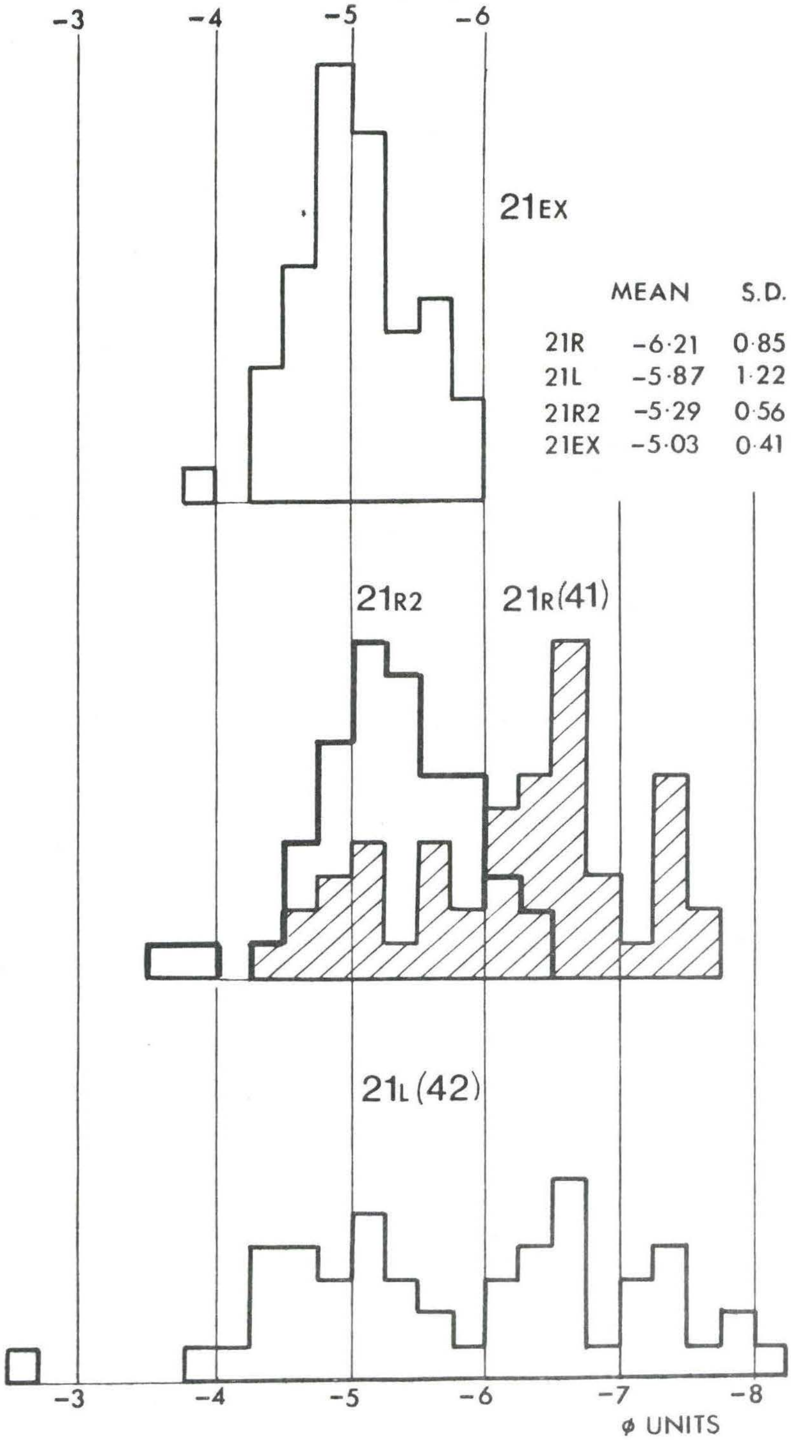
properties normally ascribed to scree deposits may only be limited to a surface veneer of varying, although limited, thickness. Beneath that surface is a heterogeneous deposit of coarse material in a much finer matrix which has quite different mechanical properties and is similar to several other more frequently encountered surficial deposits such as head or till. The origin of the fines is at present problematical; various combinations of direct accumulation, washing in or through the scree or mechanical and chemical weathering are all possible. There is no reason why water passing through the scree could not entrain the finer material and redeposit it. The role of fluvial activity within screes has been largely neglected and further studies, possibly involving some of the techniques used by Bones (1972) for tracing both water and sediment, would be pertinent in this regard.

The Floating Layer

As well as the infilling of voids by fines materials below the surface, another form of size sorting with depth was also apparent but restricted exclusively to the coarser rock fragments. This was the presence of a surface layer, often merely one fragment thick, which was considerably coarser than the underlying material. These areas ranged in size from a few boulders (e.g. Palliser 23, Figure 13.9A) to areas of several square metres and were seen on all the sampled screes. The general characteristics of this "rafted" or "floating" layer may best be described by an example from the Old Nip Cone, samples 41 and 42. Apart from the two normal samples at this point, two additional samples were taken; 21R2 on the site of sample 41 after that sample had been taken (i.e. it was a repeat sample) and 21EX about 3 metres from site 42 where no floating layer is present. Histograms of these samples are shown in Figure 13.15. The original sites can be seen in Figures 13.8 and Figure 13.16 shows site 41 after the initial sampling prior to the taking of sample 21R2. The two original sample sites are bimodal or multimodal, whilst the two samples from the underlying layer are clearly unimodal and have normal values of skewness and kurtosis. It is evident that there are at least two separate populations here; the main scree surface and a scattered veneer of coarser material. This example could be repeated from the other screes showing a continuum from single boulders (Isosceles, 10; Palliser, 49) through small groupings or scattered patches (Scree No. 1, 14, 26; Old Nip, 25, 26) to an almost total cover of the sampled area (Palliser, 18; Old Nip, 39). This kind of variation is one of the major causes of bimodality or excessive skewness in many of the samples and a major contributor to differences in sorting and mean grain size laterally over the scree.

While the origin and maintenance of this pattern of sorting is not fully understood, two possible causes may be put forward:

(i) Packing caused by repeated impacts.--Over a long time period, the scree may be envisaged as undergoing almost constant impacts from rockfalls over its surface. These impacts cause internal readjustments to take place within the surface layer of the scree. These adjustments may be analogous to the crude size sorting which develops in pebbles or peas which are shaken in a plastic bag where a crude size sorting develops as the coarser material moves to the surface and the finer material to the bottom. On a scree slope, the material rarely moves



	MEAN	S.D.	N.
21R	-6·21	0·85	50
21L	-5·87	1·22	50
21R2	-5·29	0·56	50
21EX	-5·03	0·41	50

Figure 13.15 Histograms of samples from the area of site 21, Old Nip, to illustrate the characteristics of the floating layer

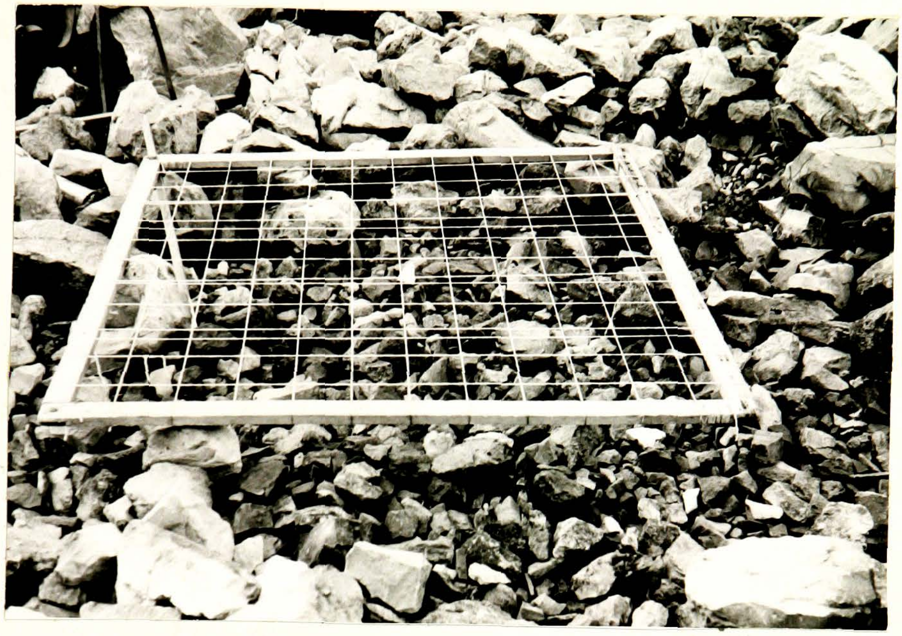


Figure 13.16 Site 21R(41), Old Nip, after sampling. This photograph was taken prior to taking sample 21R2 and should be compared with the original site (Figure 13.8, sample 41). Note that the coarse floating layer is only one or two particles thick. Also, see Figure 13.15.

Figure 13.17 Surface detail of the Palliser Cone. The square (extreme left) is on sample site 11 (Sample 21, Figure 13.9B). The larger boulders scattered over the surface appear to be an incipient form of the floating layer formed partially by avalanching at this site.

upwards but the larger material arriving at the surface cannot pass down through the voids in the surface and remains at the surface until buried or swept downslope. The smaller fragments may, however, pass down into any suitable voids which are created.

(ii) Accumulation upslope of randomly spaced obstacles.--In the discussion of the distribution of the largest boulders on a slope, it was noted that, due to a large number of randomly varying factors, large boulders may occur anywhere on the scree. Subsequent rockfalls may lose their downslope momentum after collision with such boulders and come to rest. If neither boulder moves any further downslope, the process may be repeated indefinitely, building up a trap for further debris, most of which is probably much coarser than the underlying material. This process accounts for the wide range of conditions of this type ranging from single boulders to more extensive areas. Figure 13.17 illustrates an example of this process from the Palliser Cone. Elsewhere at that site marker boulders from destroyed squares came to rest in similar positions indicating that this pattern may be initiated by avalanche deposition as well as rockfalls.

This latter hypothesis seems to match the observed distribution and character of these deposits better than the packing hypothesis, although that may also be important at some sites. The ultimate results of this process on the sorting of the surface deposits is difficult to envisage. It was not observed consistently over very large areas of scree and may be only of local importance. Alternatively, it may be destroyed by "catastrophic" impacts, burial or surface avalanching (small slides or slumps) after it has built up to some critical size.

SUMMARY AND CONCLUSIONS

Most sedimentary deposits are the result of a stress or series of stresses acting over a surface of particles. Certain particles are entrained and later deposited. Since most particles are exposed to similar stresses, particles of similar characteristics (usually size) tend to be taken up and deposited together or by similar regimes of 'flow'. This simplified rationale explains the occurrence of size sorting. Scree material is distinct from other sediments in that no overall force is usually involved (except gravity) and the deposition is the result of millions of independent events over a considerable time period. Sorting in this case represents a statistical average of the most likely events with considerable random effects involved. For example, the most probable resting place for a very large rockfall boulder is the base of the scree slope but, as has been shown, due to variations in some of the controlling variables (height of fall, surface condition of the scree, shape of the particle, etc.), it might come to rest at any position on the scree.

The best sorted samples are from the two screes dominated by rockfall and having generally coarse blocky debris. The other rockfall scree (Isosceles) has smaller debris of a more irregular shape and therefore sorting is a little poorer. The two avalanche screes are really avalanche modified rockfall screes and, since avalanches are less selective in the material they entrain (with respect to size), sorting deteriorates further and is most extreme where avalanche deposition is dominant (Old Nip Avalanche Apron, Tumblin' Creek). However, on any of the screes, there is a wide range in the sorting patterns encountered at sample sites as a result of the influences on fall sorting and the action of many other processes. These are discussed more fully below.

The pattern of size sorting over the scree as a whole may be divided into two distinct levels:

(a) an overall increase in grain size downslope, and

(b) local patterns of variability with a maximum observed range of up to 1.5-2.0 phi units between the means of samples up to 5 metres apart.

(a) Size Sorting Downslope

All of the scree sites studied showed an overall logarithmic increase in particle size away from the cliff. However, individual profiles do not show this relationship consistently because of the range in possible values at any position due to the lateral variability shown on the scree slopes. To properly separate these two trends, replication of profiles is desirable. On rockfall screes where the sampled distributions are unimodal, normal and the debris is fairly coarse (greater than about -4 ø), the five largest boulders in the sampled area are a reasonably accurate substitute for mean size and show similar patterns of lateral variation over the scree. However, the presence of the "floating" layer or avalanche activity obscures this relationship and weakens its utility. There was only a very weak relationship between position on the slope and the size of the largest boulder within five metres of the sample point. This illustrates the point that, while downslope size sorting is the average condition, many random factors can influence the individual cases resulting in considerable deviations from the "norm". In some cases, the relationship indicated an increase in the size of the largest boulder towards the cliff rather than away from it.

Avalanche modification of rockfall screes intensifies the sorting gradient on the two slopes studied by the transfer of unconsolidated debris from the upper to the lower parts of the slope. Long continuation of this stripping process may destroy any obvious pattern of sorting in the upper parts of the slope, leaving a more or less random pattern of grain size variation, for example, on the upper and middle parts of the Palliser Cone. Several examples of this stripping were described in Chapter 8.

(b) Local Variability

Differences of this type are produced by either the activity of localized queueing processes or by random or systematic deviations in the variables controlling the major processes. Examples of the latter effects might be considered to be the "floating" layer discussed above or the coarser rockfall capping found at the top of the scree slope at several sites. Avalanche activity can also produce wide local variations in grain size, since both avalanche erosion and deposition are confined to limited areas for individual avalanches and over a period of time some areas may be more affected than others on the same slope. Slopes subject to considerable avalanche stripping (e.g. upper and middle parts of the Palliser Cone and Old Nip, A.B.T.) show the greatest lateral variability in grain size; characteristically these slopes consist of a basal layer of mixed fines and rock fragments with scattered, almost remanié, patches of coarser debris of variable depth. These may be in protected lee locations, have a definite source or be distributed over the surface with no apparent pattern.

As well as the dominant processes, there are a great variety of queueing processes which may influence size sorting on the scree; small surface slides or runs of suitable material, frost sorting of the surface debris (e.g. Palliser 54, 56, 57); limited mudflow or fluvial activity producing levees (e.g. Old Nip 10EX, Table 13.8) or channels; bump holes and other impact effects, and the mechanical breakdown of debris reducing mean grain size at sites near the base of the scree (e.g. Palliser 34; Old Nip 33). At a smaller scale, there are linkages between the surface grain size and the microrelief of the surface, especially in the upper parts of the slope. Vegetation either selects or causes low rises in the general surface. Coarser debris tends to accumulate upslope of these features (aided by the effects of the vegetation) rather than in adjacent areas of scree. Similar effects are noted with large boulders (e.g. Palliser 42; Palliser 48 is on one such tail), together with a complementary lee effect where there is a dearth of the larger debris downslope of the boulder (Isosceles 10; Old Nip 32). On several screes, there is a microrelief of the order of 0.3-0.7 metres in amplitude with linear depressions (old stream courses?) running downslope. In such cases, the coarser debris concentrates in the bottom of these depressions forming runnels of larger material. This is particularly well illustrated in the gullies on the avalanche boulder tongue at Old Nip. Similar runnels may extend downslope from small fissures in a straight cliff which channel rockfall debris.

All of these minor sources of variation are most apparent in the upper parts of the slopes where there is a wider range of grain size available and it is more conducive to a greater variety of queueing processes (after all, there is very little process activity, except weathering, which can modify the surface of a very coarse scree). For this reason, size sorting in the upper parts of the scree is more variable, despite the perceptual problems involved, since there are far fewer influences on local sorting patterns at the base of the scree than at the top.

Fall Sorting

The controls and nature of the fall sorting mechanism have been discussed in Chapter 4. The sedimentological results, by demonstrating a downslope increase in grain size, confirm the dominance of rockfall in the building of these slopes since no other major process gives rise to this effect; avalanches only enhance or modify the pre-existing rockfall pattern. Once a size gradient is established, it becomes re-enforced by a frictional gradient, since the relative roughness of the surface is a function of its grain size, and, apart from variations introduced by the "floating" layer or partial avalanche modification, it seems to be maintained in a fairly stable form.

However, there are several examples described in the literature where a size sorting gradient does not exist or is the opposite of that described here (for example, Behre, 1933; Caine, 1967). These exceptions may be ascribed to one of two basic causes; either the size sorting pattern has been destroyed or it was never established. Destruction of the pattern would require major changes in the dominant process such as intensive avalanche erosion or deposition over most of the slope and therefore the most likely cause is the failure to develop a characteristic size sorting gradient.

The initiation of a size sorting gradient must depend upon particle momentum and the characteristics of the original surface, since the frictional gradient which is important to the maintenance of a fall sorting pattern is a result, not a cause of the initial pattern. Three major variables control particle momentum, particle size, height and nature of fall (i.e. form of the cliff). If the cliff is low or there are a large number of benches which impede movement, the largest particles may remain near the top of the slope because they lack sufficient momentum to continue downslope, thus producing the beginnings of an inverse sorting gradient. A very limited range in particle size or initiation purely by avalanche deposition from the cliffs without erosion of the scree might produce screes which showed no dominant size sorting. However, probably the most important control of the development of a scree is the form and characteristics of the surface on which the initial deposition takes place. This variable has been almost totally neglected in studies of screes and yet is probably the most significant control of scree form. Irregularities of this initial surface might lead to the disruption of sorting patterns due to momentum and prevent the establishment of a dominant pattern. Similarly, if there are differences in the character of the scree surface (snow cover, ice cover, bare, etc.) over time, short or long term, these could also result in the superimposition of several patterns with none of them dominant.

Thus, systematic variations in any of these variables might lead to the development of scree on which there was no dominant increase in particle size downslope. However, much more experimental or field observation is needed before the effects of these variables can be fully tested.

The Relationship Between Particle Size and Angle of Slope

Finally, before leaving the topic of downslope size sorting, it is important to clarify the relationship between particle size and angle of slope. This has been a topic of considerable controversy amongst geologists and geomorphologists (see Melton, 1965 and references therein). Experimental studies of the angle of rest or repose angles of coarse, cohesionless materials indicate that the angle of repose increases with decreasing particle size (van Burkalow, 1945), although the opposite relationship has also been noted (Carrigy, 1971), especially where the material is poorly sorted (van Burkalow, 1945, p. 681). Also, since the momentum of a particle moving over a slope is proportional to the sine of the angle of slope, this influences the momentum term in the equations of motion and could also have some effects on size sorting; for example, downslope momentum would be 42% and 57% respectively of that of a vertically falling particle on slopes of 25 and 35^{o}. However, in Surprise, the scree with the most clearly defined downslope sorting (Old Nip Cone) has a straight or slightly convex profile which indicates that size sorting must be more closely related to other properties of the surface, such as roughness or distance from the cliff, than it is to the angle of slope. The strong positive relationship between phi size and the various measures of slope angle (e.g. mean size is inversely related to slope angle) shown for most sites in Table 13.14 is due to the fact that both grain size and angle of slope are strongly related to distance from the cliff and hence are closely correlated where the slopes are concave in profile. These variations in slope angles will be further discussed in Section IV.

TABLE 13.14: RELATIONSHIPS BETWEEN MEAN PHI SIZE, DISTANCE FROM CLIFF AND ANGLE OF SLOPE

Variables Used	Isosceles	Old Nip (A.B.T.)	Old Nip (RF)	Palliser	Scree No. 1
Mean (ø) v. Angle	0.88**	0.35**	0.15	0.70**	0.57**
Mean (ø) v. Distance	-0.81**	-0.38**	-0.96**	-0.65**	-0.84**
Distance v. Angle	-0.90**	-0.72**	-0.17	-0.80**	-0.77**
Mean (ø) v. Au	0.86**	0.56**	0.22	0.70**	0.57**
Distance v. Au	-0.91**	-0.84**	-0.19	-0.91**	-0.77**
Mean (ø) v. Ad	0.85**	0.54**	0.41**	0.76**	0.68**
Distance v. Ad	-0.91**	-0.91**	-0.55**	-0.91**	-0.89**

NOTE: Angle = angle of slope at the sample site (mean of five or ten measurements).

Au = angle of section of profile immediately upslope of the site (measured over about 15 m).

Ad = angle of slope immediately below the site (measured over a length of 5-10 m).

**Significant at the 99% level.

CHAPTER 14

AVALANCHE DEPOSITS

As well as investigating the spatial variability of grain size over the scree, a major aim of the sedimentological programme was to examine whether any linkage could be found between dominant process and the sedimentological characteristics of the scree. In particular, interest was focussed on the characteristics of avalanche deposits, the possibility of distinguishing rockfall and avalanche debris and ascertaining the relative importance of each of these processes at a site. Before discussing the effects of avalanche deposition, it is necessary to examine the character of the avalanche deposits themselves.

Rock Debris in Avalanches

The rock debris deposited by avalanches is very variable in size, sorting, origin and its distribution through the avalanche snow. It may range from fines and rock chips to large boulders, from widely scattered individual fragments to areas where the surface of the scree was incorporated en masse (see Figures 9.1, 9.2 and 14.1). The rock material contained in avalanches is derived from two sources; debris swept from the cliff zone or eroded from the scree itself. Debris from these two sources may generally be differentiated by their characteristics (see Chapter 8); material eroded from the scree usually has a wider size

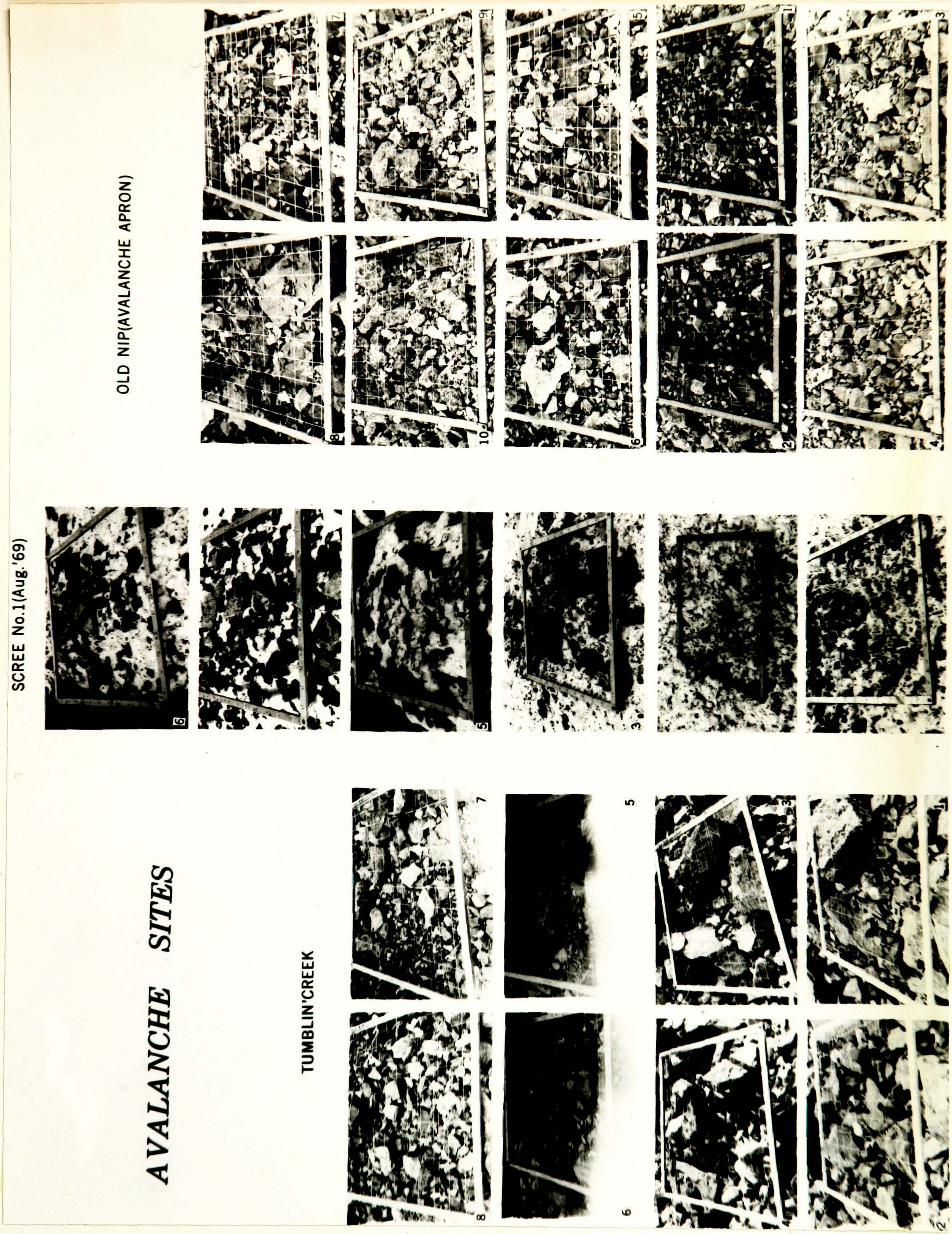


Figure 14.1 Examples of avalanche deposits from Old Nip, Scree No. 1 and the Tumblin' Creek Cone.

range than surface material due to the inclusion of finer material from below the scree surface.

Samples of avalanche transported materials were obtained in two ways; from measurement of debris on the sampling sites in the accumulation programme and by direct methods, either by sampling the total population of fragments on an area of snow or by the standard method employed in the sedimentological studies. This was used for six samples of 100 fragments from the avalanche snow on the basal sections of Scree No. 1 after the avalanches of August 4-5th, 1969 (Figure 14.1). Size was measured directly for compatibility with the other sedimentological data and is expressed as either nominal diameter or a axis length. However, the presence of considerable amounts of fine debris which could not be accurately measured by direct methods causes a marked measurement cut-off in most of the data. For the August 1969 samples at Scree No. 1, this cut-off is at about -3.0 ϕ (a axis); for the other data, it varies for individual sites according to the amount and size of debris present and the time available for measurement, ranging from about -3.0 to -5.5 ϕ (a axis size).

The effect of this cut-off on the form of the distribution may be seen in Figure 14.2. A large volume of debris was deposited on boulder 1 at Old Nip in 1969. The largest fragments were measured at the site and the remainder transported back to Hamilton where all fragments with an a axis of greater than -5.0 ϕ were measured. These results indicate that the measurement cut-off point employed in the field extends over a range of sizes, giving an impression of a skewed log-normal distribution. Further measurement of all particles held on a -3.0 ϕ sieve (extrapolated from the measurement of one-eighth of the total) shows a similar measurement cut-off (Figure 14.3, 1) because sieving tends to approximate b axis rather than a axis and also it is not very efficient for large numbers of irregularly shaped particles. Since the a/b ratio averages about 1.5 to 2.0 in this size range, the real cut-off is probably about -4.0 ϕ.

Figure 14.3 shows histograms of a axis size for a number of examples of avalanche debris. All are collected from accumulation sites, except the Tumblin' Creek avalanche sample which is all debris from a metre square on a dirty avalanche deposit on the west side of Lake Helen in 1969. The only site with a clearly defined measurement cut-off is that at Square 26, Scree No. 1, where all fragments with an a axis of greater than 10 mm were measured. However, despite differences in cut-off points, rock type, etc., the distributions are remarkably similar, all being highly skewed towards the smaller particles. With the exception of samples 6, 10 and possibly 8, all the samples shown are probably the result of avalanche erosion of the scree surface farther upslope. The other three samples are composite samples from a number of sites in the same area to illustrate the deposits from the large avalanches at Surprise II in 1970. Although these deposits appear to be derived from the cliffs, the form of the distribution is similar to the eroded samples, except that the grain size is smaller and the debris is more diffusely spread throughout the snow.

The samples illustrated in Figure 14.3 are obviously only partial distributions; because of the measurement problem, it is impossible to compute any valid statistical parameters for these samples. Such measures

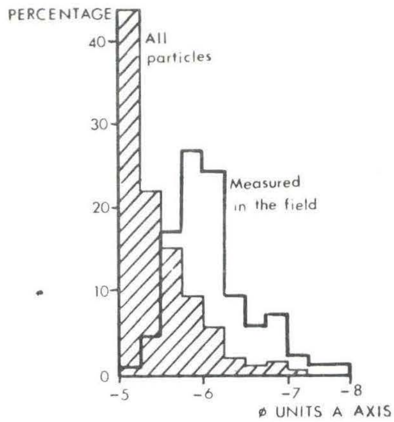


Figure 14.2 The measurement cutoff in field measurement of axial length:the example of B1,Old Nip, 1969

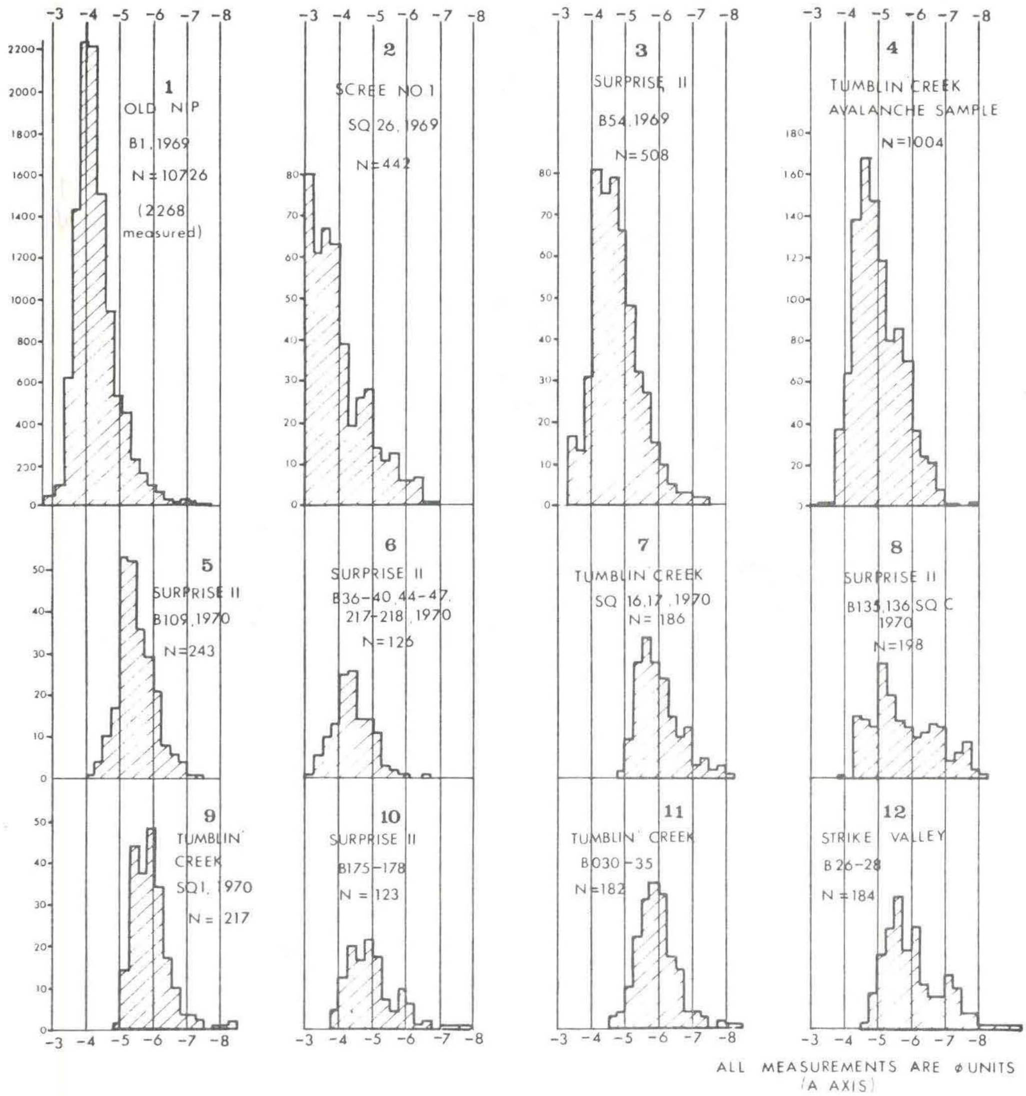


Figure 14.3 Selected examples of avalanche deposits from Surprise

would have to be based on percentage weight data rather than direct measurement of size. However, despite their incomplete nature, it is nevertheless possible to make some valid general statements about the characteristics of avalanche deposits.

(i) Although there is a great range in the character of these deposits, the mean fragment size is in all cases relatively small, i.e. the mean a axis is notably less than -2 to -3 ø (8 - 16 mm) and may be considerably smaller.

(ii) The main differences in the deposits are in terms of the size range which depends upon the source of material. Avalanches eroding the scree incorporate coarser material from the scree surface (-5 to -7 ø a axis) into the deposits.

(iii) The large, easily visible fragments are a very small proportion (numerically) of the total number of fragments, although they are very important in terms of total weight of debris moved.

(iv) The apparent log-normality of several of these examples is a result of a measurement cut-off resulting from the technique used. However, following ablation of the debris onto the scree surface, a similar effect is usually produced naturally because the finest debris (less than about 10 mm a axis (-3.3 ø)) falls or is washed down into the body of the scree over a relatively short period of time. Thus, avalanche deposition will superimpose a truncated and therefore highly skewed distribution on top of the existing distribution at the point of deposition.

(v) Although no direct evidence is available, it would seem reasonable to assume that the distributions sampled are truncated log (phi)-normal distributions with the lower size limit in the silt or clay range.

The Effects of Avalanching on the Sedimentary Characteristics of the Depositional Areas

The effects of avalanche deposition on scree characteristics depends upon the type, frequency and amount of avalanche deposition and the initial characteristics of the scree. Avalanche modification is most easily observed in the basal areas of screes where the contrasts are greatest but there is a wide gradational range from pure rockfall scree to avalanche boulder tongues. These effects may best be illustrated by a series of examples.

Infrequent avalanche deposition has little effect on the sedimentary characteristics of the scree surface except to produce a few "balanced boulders". The avalanches at Scree No. 1 in August 1969 were such a rare event. The avalanche debris was heterogeneous and poorly sorted. The truncated samples shown in Figure 14.4 have only a limited overlap in their coarser range with samples taken from the same area during the sampling project (sites 29-34, Figure 14.4). The latter samples were coarse and well-sorted by comparison and, although there were one or two avalanche boulders at each site, it is obvious from the histograms that the basal sites were not formed by avalanching. Comparison with samples from the upper part of the scree suggests that a large part of the material within the avalanches could have been derived from erosion of this area (sites 25-28, 41-42, Figure 14.4) supporting the field evidence of erosion.

More extensive avalanche deposition results in a considerable

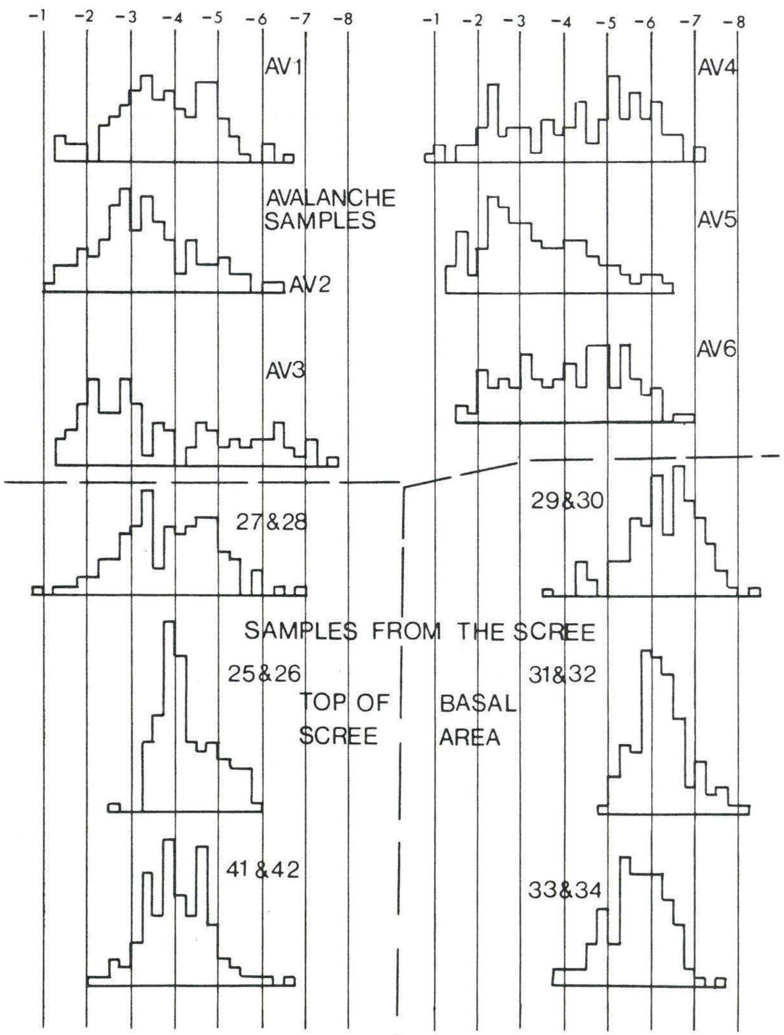


Figure 14.4 Comparison of avalanche and surface samples from Scree No.1

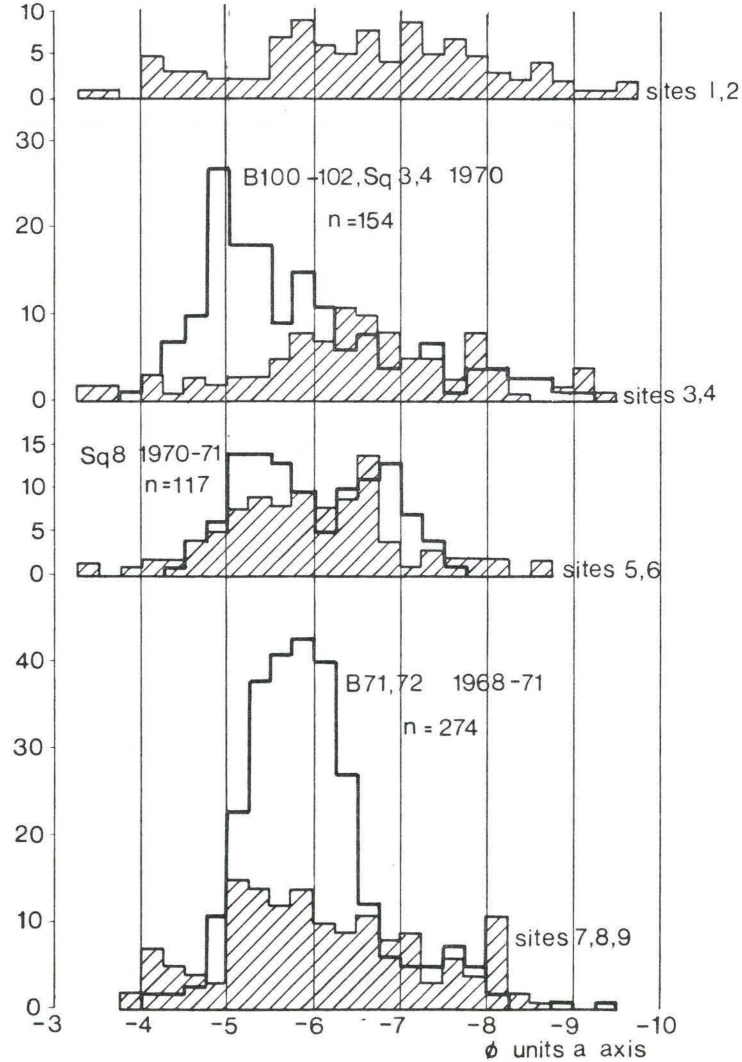


Figure 14.5 Comparison of avalanche and surface samples from the Tumblin' Creek Cone

modification of the scree characteristics. Figures 14.5-14.8 show comparative histograms of a axis size for samples of the surface material on the scree (measured during the sedimentological project) and debris deposited on sample boulders or squares in the immediate area over a one to three year period. The accumulation measurements show a measurement cut-off towards the smaller material, but, taking account of this, the size range of deposits is very similar (except at the Palliser site) indicating that the surface material could have been produced by similar deposition continued over a longer period of time. The generally coarser peak in the surface debris is a result of the finer debris deposited by avalanches falling or being washed into voids in the scree surface and the tendency for coarser material to remain at the surface and accumulate over a much longer time period. The large size range of many of the avalanche derived deposits is, in part, due to differences in the size range of materials deposited in successive years because of variation in the source of the materials.

The Palliser site is exceptional because of the coarse rockfall tail to the distribution. The material deposited at this site is obviously derived from an area very similar to the site further upslope (sites 3 and 4, Figure 14.8). A similar effect can be seen on the avalanche boulder tongue at Old Nip (Figure 14.6).

The most poorly sorted avalanche deposits occur where avalanche activity is purely depositional or a very wide range of material is involved. In such cases, there is a chaotic, unsorted plastering of debris over the coarser fragments typified by the sites on the Tumblin' Creek Cone and in the area peripheral to the avalanche boulder tongue at

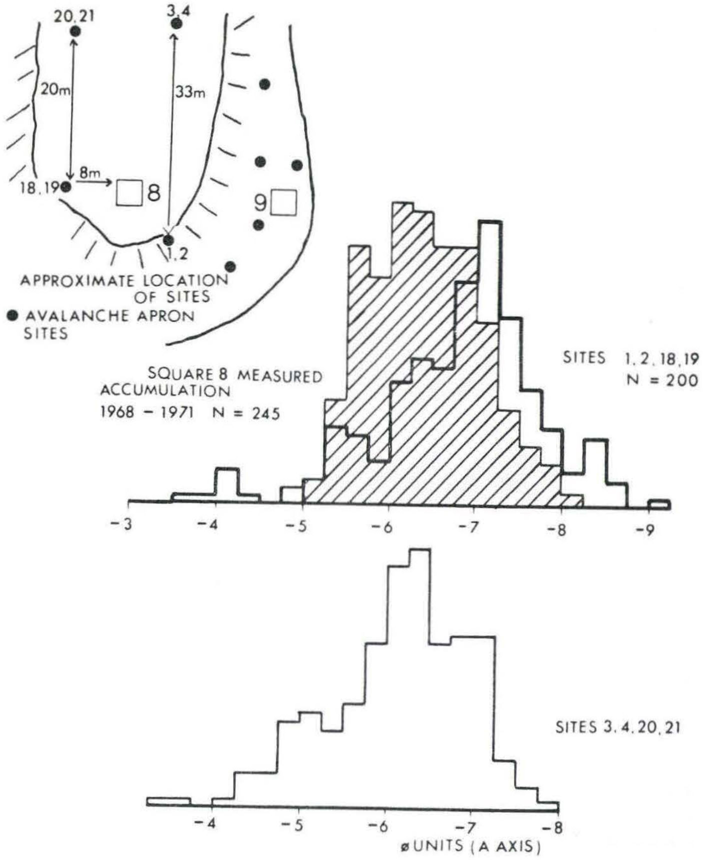


Figure 14.6 Comparison of avalanche and surface samples from Old Nip (A.B.T)

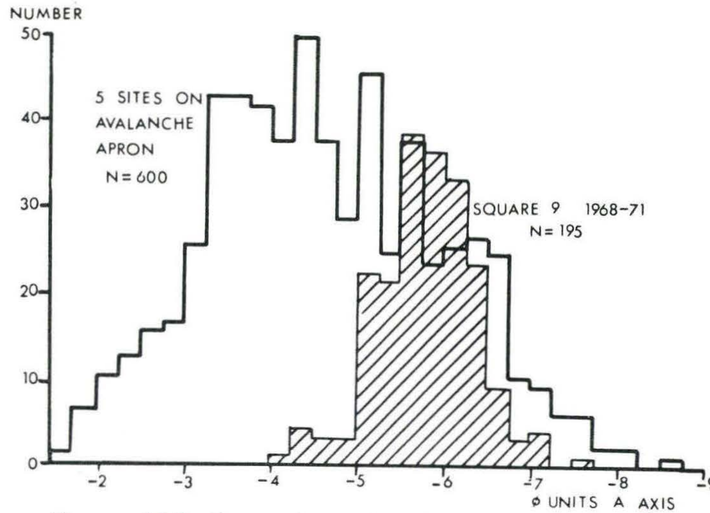


Figure 14.7 Comparison of avalanche and surface samples from the avalanche apron at Old Nip

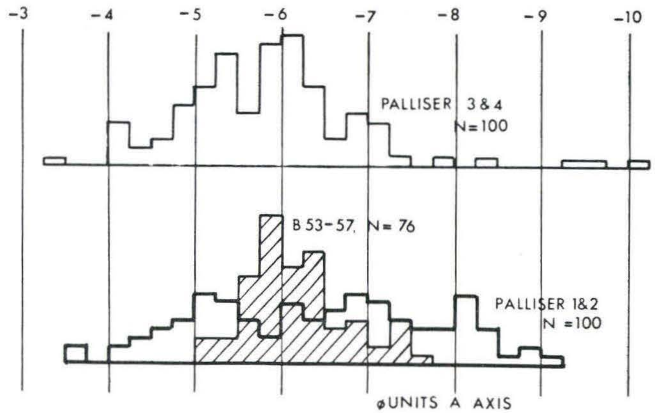


Figure 14.8 Comparison of avalanche and surface samples at the Palliser site

Old Nip (avalanche apron area, see Figures 14.1, 14.5 and 14.7). However, where there is also erosional trimming of the surface, the largest fragments are swept to the periphery of the avalanche track or may be completely buried beneath the rapidly accumulating debris. This, combined with the loss of the finer material into the body of the scree, improves the size sorting of the surface debris and some of the avalanche samples may be moderately to well sorted, e.g. on the A.B.T. at Old Nip (see Figure 13.2). Similar well sorted deposits were noted in sample rows 2-5 at the Palliser Cone (see Figure 13.9). The explanation for this may, however, be partially due to the breakdown characteristics of the rock. During experiments carried out in 1968, numerous blocks were rolled from the top of the Palliser cliffs flanking Strike Valley. All of these blocks shattered into many small fragments before reaching the scree. Similar fracture characteristics were noted in weathered debris on the Rockpile and it can be seen from Figure 11.1 that the Palliser debris has a very marked peak in the -3 to -5 ϕ range. Therefore, the sorting pattern observed is partially due to the restricted size range of available material.

Criteria for Distinguishing Rockfall and Avalanche Deposits

The differentiation between avalanche and rockfall deposits may be most clearly made in the lower parts of the scree or where the surface material is relatively coarse. Avalanche material may be recognized by the smaller size and heterogeneity of its deposits, the loose unstable nature of the surface (due to the presence of numerous balanced or perched boulders ablated from snow) and, in extreme cases, the presence of constructional landforms (avalanche boulder tongues). By contrast, rockfall material is relatively well sorted, coarse and contains few small fragments except where physical breakdown of the debris has occurred in situ. Higher up the scree the lack of coarse surface debris makes it difficult to distinguish balanced boulders from the rest of the scree. This, together with the greater local variability in size and possible modification of the surface by avalanche erosion make it much more difficult to distinguish avalanche deposits.

Two quantitative measures were investigated as possible indicators of the depositional activity of avalanches; the estimation of the number of "avalanche boulders" (perched boulders) within the sample square and the sample sorting. Although the avalanche boulder measurements provide a general guide to avalanche deposition, the technique suffers from measurement difficulties resulting from problems of definition. The recognition of an "avalanche boulder" depends upon a size differential between the avalanche debris and the surface material. Thus, in the absence of suitable relatively large boulders to act as collection surfaces it is impossible to differentiate the avalanche debris on the higher part of the screes (or other areas where coarse debris is lacking). This seriously limits the usefulness of the technique. There is also a problem in counting the debris when there are a large number of fragments including fines.

The results for the basal third of the screes are given in Table 14.1 and generally confirm other evidence of the relative importance of avalanches at these sites. The anomalous results for the upper sites on the Old Nip Cone are probably the result of human activity clearing the accumulation sites immediately upslope.

TABLE 14.1: AVALANCHE BOULDERS RECORDED AT THE SAMPLE SITES IN THE BASAL THIRD OF THE SAMPLED SCREES

PALLISER

0	0	0	0	1	2	0	0	0	0
1	1	0	0	1	5	1	2	5	1
2	3	3	3	5	13	4	6	5	5
2	3	10	8	12	15	11	13	5	5

SCREE NO. 1

0	0	0	0	1	0	2	1
0	0	0	0	2	0	3	3
0	0	1	2	5	4	2	3

ISOSCELES

0	0	3	0
0	0	0	0
0	0	1	3
3	3	3	4

OLD NIP (A.B.T.)

0	0	5	10
8	8	12	12
12	11	16	20
10	7	5	10

OLD NIP (ROCKFALL)

1	0	3	4
0	0	1	0
0	0	0	0

NOTE: The sites are arranged as in Figures 12.1 and 13.12 with the bottom line as the basal sites and the numbering from right to left.

Measures of sorting were generally discussed in Chapter 13 and it was shown that the average standard deviation of avalanche and rockfall dominated sample sites were significantly different. However, when the two distributions are compared (Figure 14.9), there is a wide area of overlap which makes it impossible to clearly separate the two groups. Thus, although the sorting (as measured by standard deviation) is better and has a smaller range for rockfall dominated screes, several sites may be poorly sorted due to the presence of the "floating layer" or other sources of local variability. Similarly, whilst many of the avalanche

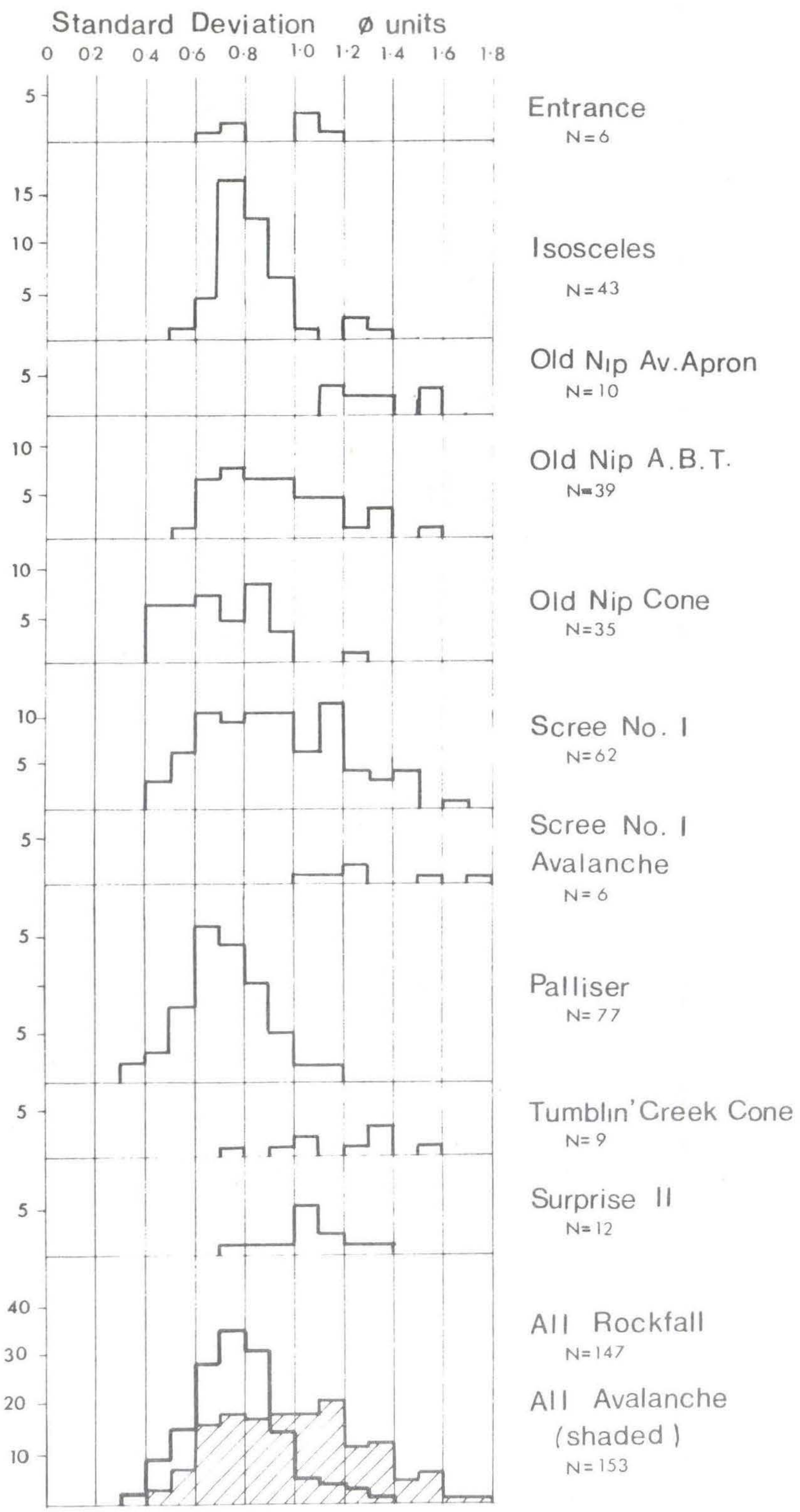


Figure 14.9 Differences in sorting(standard deviation) between the sampled screes

sites are poorly sorted, especially in purely depositional areas such as the avalanche apron at Old Nip, the sorting may be relatively good higher on the slope if avalanche stripping has not occurred. These factors, when combined with other controls of sorting such as available size range of materials (see earlier discussion of the Palliser), position on the slope (Figure 13.12), absolute size of debris, etc., obscure any simple process-sorting relationship. It is only in the basal areas of the screes where major differences can clearly be seen and, although poorer sorting values may indicate avalanche deposition, other possibilities must be checked by examination of the form of the distribution or the appearance of the scree.

In the light of these results, it is not possible to differentiate avalanche and rockfall scree precisely using simple quantitative sedimentological parameters, although a combination of sorting values and a measure of "avalanche boulders" might yield reasonable results. However, the broad generalizations which may be drawn from such parameters add little to the qualitative data which may be observed in the field and on photographs and, since they convey more information, these qualitative criteria are the most useful for distinguishing the two deposits. Even so, these criteria (size, sorting, fabric, accumulation forms) are only generally valid for areas of coarse debris where the contrasts between the two types of deposit are greatest and therefore most easily seen.

SECTION IV

SCREE FORM

Chapter 15: Scree Form and the Effects of Avalanche Activity

CHAPTER 15

SCREE FORM AND THE EFFECTS OF AVALANCHE ACTIVITY

The measurement, classification and description of scree forms has generally received more attention in the literature than either the sediments or processes involved in scree formation. In view of this, the detailed study of scree form was not a primary aim of this study. The observations presented here were collected mainly during the sedimentological projects in Surprise and therefore reflect the biases of that experimental design; no attempt (other than within that framework) was made to measure examples of all the scree forms present in Surprise. These results are presented for two main reasons:

(i) For descriptive purposes, to enable comparison with other studies of scree form;

(ii) Since scree form is the result of the interaction of processes and materials over time, it is possible to illustrate the long-term effects of some of the processes discussed in Section II. Following from this, the chapter ends with a discussion of the modification of scree form by avalanches.

The description of scree form may be considered in two parts; plan form and profile form.

PLAN FORM

The plan form and distribution of scree is governed by the balance of input, queueing and output processes and their controls. The most important of these are the form of the cliff (see discussion in Chapter 3), the configuration of the initial surface and the intensity of basal removal. Classifications of form are based on the division between uniform (straight screes) and spatially concentrated deposition (cones). In his study of the evolution of mountain walls, Rapp (1959) put forward a threefold division into simple talus cones (gully screes of Andrews, 1961), simple talus slopes (straight, apron or sheet screes) and complex talus (coalescing cones). Stock (1968, Figure 7) added a fourth class, debris slopes which he defined as coalescing straight screes. However, the use of this term should be avoided because of its more general use by Gardner (1968a) and Bones (1971) to indicate all types of scree (or talus) slopes. Rapp's basic tripartite division is probably the most suitable while recognizing that all the classes are gradational, both between each other and to the avalanche forms described elsewhere by Rapp (1959; also, see later discussion in this chapter). Most of the screes in Surprise are sheet screes with isolated cones and avalanche boulder tongues. Nowhere has the dissection of the cliffs proceeded sufficiently to give large gully fed screes such as those at Templefjorden (Rapp, 1959). Debris fall onto all slopes is from undissected cliffs except for the Eastern Valley Side Site and the Palliser Cone.

PROFILE FORM

Profile form is one of the easiest parameters of a scree slope to measure (King, 1967, p. 117) and, in recent years, increasing quantities of surveyed profile data have become available (Rapp, 1959, 1960a; Andrews, 1961; Caine, 1967, 1969a; Compton, 1968; Gardner, 1968a, 1971; Stock, 1968; Thornes, 1971; Bones, 1971). The great majority of these profiles are concave to rectilinear in form and noticeable differences have been recorded between screes influenced by different processes, having different forms (Stock, 1968, Table 10, although these sites are not differentiated as to dominant processes) and at different locations within the same general area (Stock, 1968, Table 9; also, see Table 15.2 below). These differences reflect the uncontrolled variation of the scree environments (Thornes, 1968, 1971) and therefore straightforward comparisons or conclusions are difficult to make.

Results from Surprise

Scree profiles were measured using a Brunton compass and tape during the sedimentological sampling. Maximum surveyed lengths were 15 - 17 m except at Isosceles and Surprise II where a maximum of 30 m was employed on the higher parts of the slope. Shorter lengths were recorded between individual sites and to show apparent breaks of slope. The results of these measurements are shown in Figure 15.1, together with a profile constructed from the tacheometric data at Tumblin' Creek since the tape survey of that site was not completed.

The profiles in Figure 15.1 all show a basal concavity with the exception of the Old Nip Cone which appears rectilinear. In fact, the

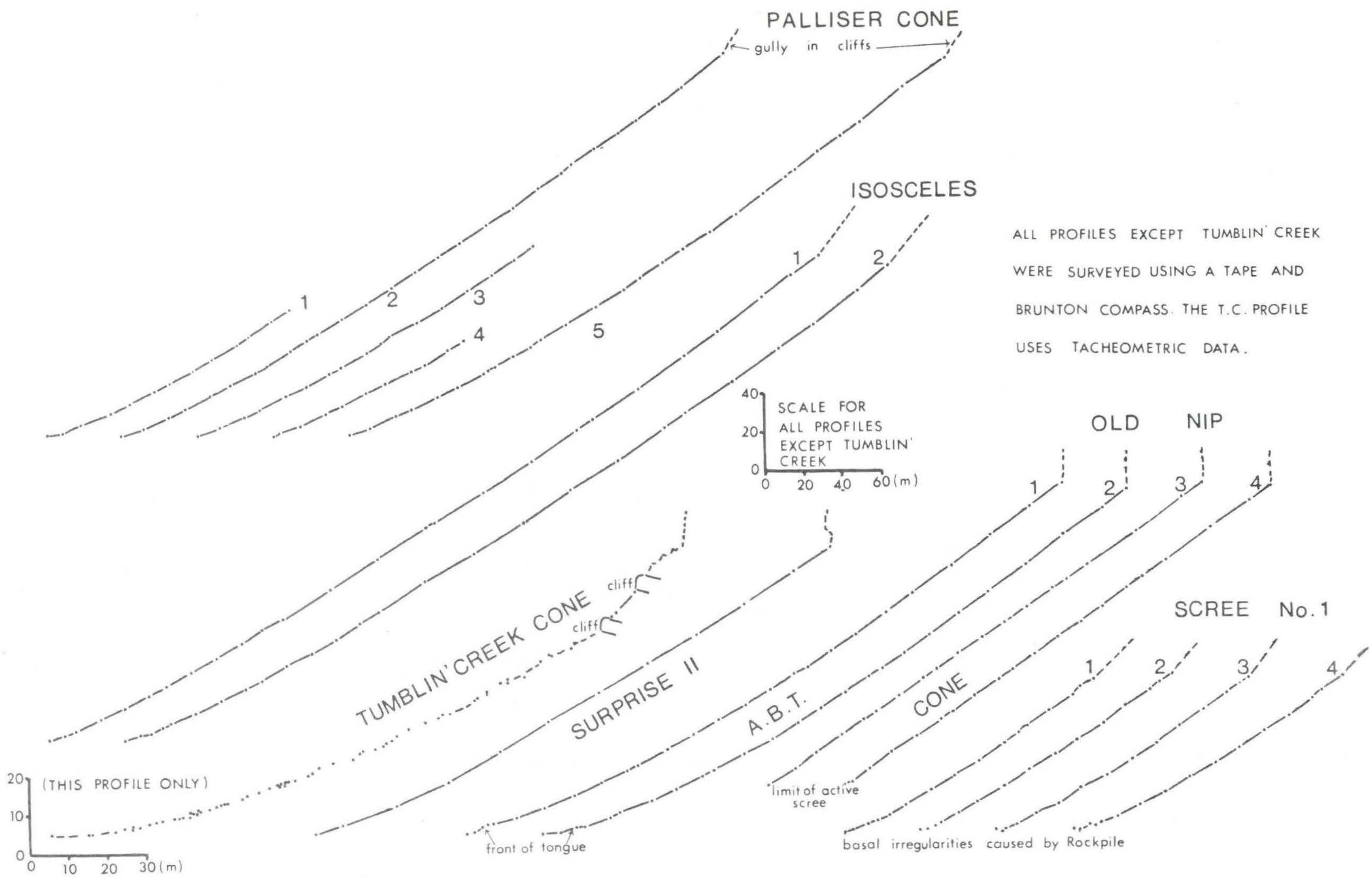


Figure 15.1 Profiles of the the sampled screes in Surprise

basal portion of this slope has a slight convexity since it is not possible to see the apex of the cone from some of the lower sample sites. The concavity is most marked at three of the four avalanche sites (Old Nip A.B.T., Surprise II, Tumblin' Creek) where the basal slopes are gentler and the concavity occupies the lower third to one half of the slope. The other avalanche slope (Palliser) is also concave with mean angles for each zone of 26.55^0, 32.07^0 and 35.23^0 (Table 15.1) but lacks the lower angle toe slope found at the other avalanche sites. This is due to a barrier formed by the Rockpile at the base of the scree. Since it is up to ten metres high, it effectively limits the downslope extent of avalanches, thus preventing the basal extension of the scree.

Similar well-developed concavities are typical of the avalanche slopes described by Daveau (1958), Rapp (1959), Potter (1968) and Caine (1969), but Gardner (1968a) found no relationship between distance from the cliff and slope angle for the three avalanche sites he examined and concluded they were not concave.

Angles of Slope

Two summary measures of slope angles from the slopes studied were used; measurements from the actual sample sites and measurements from the overall profile. Figure 15.2 shows the distribution of measured slope angles and their means at the major sites studied. The limited results from Tumblin' Creek and Surprise II are included for comparative purposes only, since sampling at those sites was much more limited. The variation in estimates of slope angles at a site is directly proportional to the size of the debris since it is easier to measure slope on a smoother surface. This can clearly be seen by comparing the scatter at

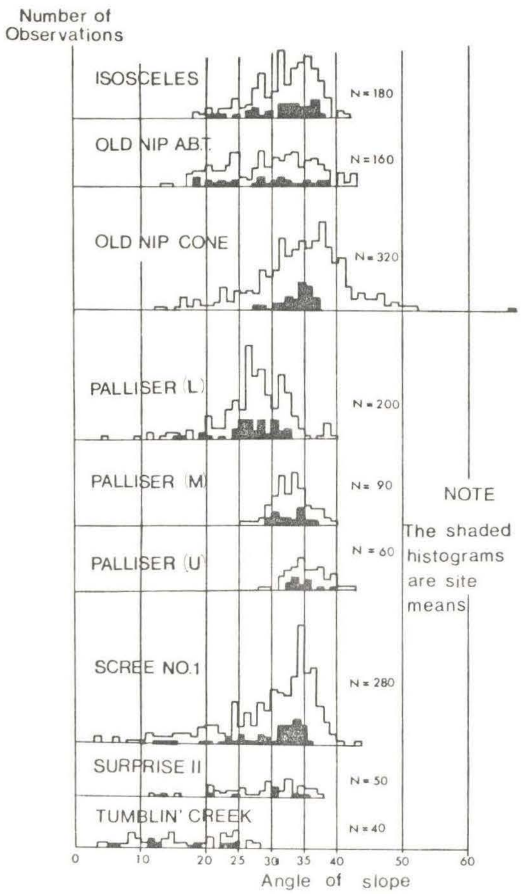


Figure 15.2 Angles of slope of the scree surface at the sample sites

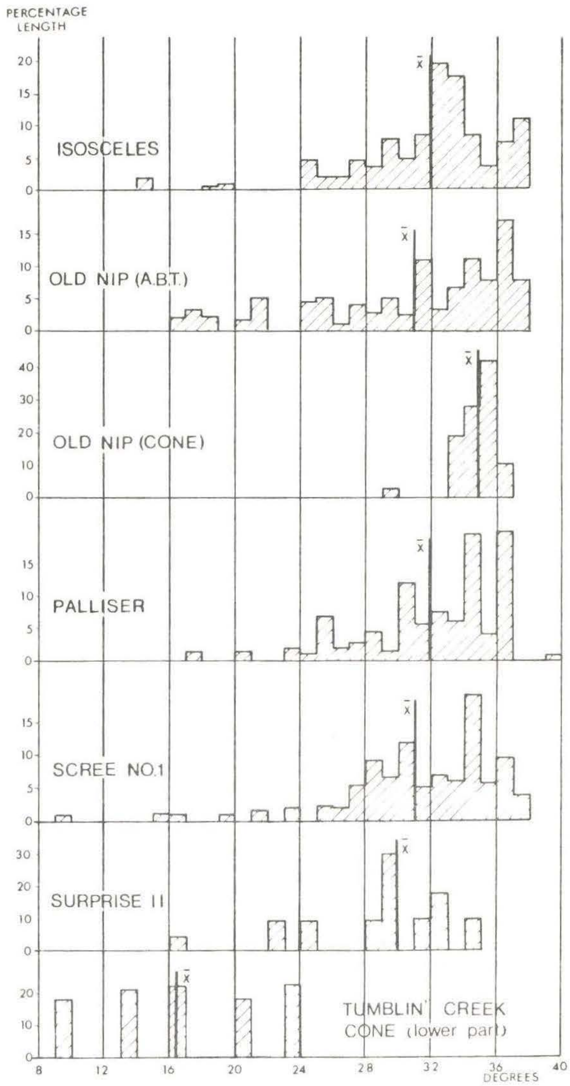


Figure 15.3 Slope angle data expressed as percentage length of slope of a given angle

the Old Nip Cone (the coarsest debris) to the Palliser Cone and Isosceles (the smallest debris). Most of the distributions are strongly negatively skewed towards the higher angles which dominate the straight sections of the upper parts of the slopes. However, the markedly concave avalanche slopes (Old Nip A.B.T., Surprise II, Tumblin' Creek) have a much more even distribution indicating their greater variation in slope angle.

These results are similar to those of Gardner (1968a), although the means are much higher. However, the results from Surprise are biased because there is no attempt to apportion the samples equally between the zones of the slope. To overcome this problem, the profile data were used to calculate the percentage of each profile in one degree classes. These data have the advantage that they give an adequate representation of the amount of the slope at each angle and also yields a true mean slope angle. A minor disadvantage is that the measured sections are not of equal length and where slopes are gently concave, the values recorded tend to average the true values producing "artificial" gaps in the histograms. This is particularly difficult where the measured length is long relative to the slope and is well shown in the results for Tumblin' Creek and Surprise II (Figure 15.3).

The results given in Table 15.1 show that four of the major sites have mean angles between 30.9^{o} and 32.1^{o}, two avalanche sites have angles below 30^{o} and the Old Nip Cone has the steepest and straightest profile with an angle of almost 35^{o}. However, the use of means alone for comparison is quite misleading, since there are marked differences in the distribution of angles of slope at these four sites. The two avalanche

TABLE 15.1: SUMMARY STATISTICS FOR SLOPE ANGLE DATA

Site	No. of Profiles	Total Length (m)	Mean	Median	Mode	Max-imum	Min-imum*
Isosceles	2	951	31.61	32	32	37	14
Old Nip Cone	2	563	34.66	35	35	36	16
Old Nip (A.B.T.)	2	712	30.91	32	36	36	16
Palliser	2	750	31.72	33	34/36	39	12
Palliser (lower)	5	587	26.55	24	28	33	12
Palliser (middle)	3	288	32.07	31	30/32	34	30
Palliser (upper)	2	338	35.23	35	36	39	33
Scree No. 1	4	641	31.03	32	34	37	19
Surprise II	1	312	29.39	29	29	34	16
Tumblin' Creek	1	75	16.40	16	13/16/23	23	9
Tumblin' Creek	1	c.150	24.00	-	-	-	-**

NOTES: The median is the class in which the 50th percentile occurs.
The mode is the highest single degree class.

*Values of less than 10^{0} are excluded from the minima at Scree No. 1 since they are only for very short lengths at the base of the slope.

**The data are calculated from the tacheometric survey. The other data refer to the basal half of the slope surveyed in 1969.

sites (Old Nip A.B.T., Palliser) are more strongly skewed with modes in the 35-37^{0} range representing the upper and middle slopes which have been affected by avalanche erosion. The values for the other two avalanche sites are lower because the basal concavity occupies a much greater proportion of the slope and is not offset by extensive straight, high angle slopes in the upper parts of the scree. The modes for the two rockfall slopes are lower (32-34^{0}), although they also have a secondary peak in the 36-37^{0} range reflecting slopes near the top of the scree which are underlain by fines or bedrock (Isosceles) at shallow depth. The reason for the lack of concavity at the Old Nip Cone is not apparent in the field; possibly it is related to the coarseness of the debris at this site.

It is difficult to draw any broad conclusions from the limited sample of slope profiles available from Surprise. At the major sites studied, all the slopes have at least 50% of their length between 32-37^{o} and generally avalanche slopes are less steep than rockfall dominated slopes. These results are comparable with measurements reported from other areas (see Table 15.2) but the variety of those results, even from a limited area (see Bones' data, Table 15.2), discourage detailed

TABLE 15.2: SUMMARY OF OBSERVATIONS OF MEAN SLOPE ANGLE OF SCREE SLOPES DOMINATED BY DIFFERENT PROCESSES

Source	Rockfall	Running Water or Mudflows	Basal Erosion	Slush or Snow Avalanches	Small Surface Slides
Surprise	32.43(3)	-	-	29.01(4)	-
Bones (1971, Table 9)					
Cape Liddon	35.72(4)	37.61(1)	39.37(1)	-	-
Caswall Tower	33.08(3)	33.29(3)	36.87(1)	-	-
Inland Plateau	32.53(2)	-	-	20.99(2)	-
Cape Ricketts	32.27(6)	34.00(1)	-	27.33(3)	-
Rapp (1959)	36-37	32-33	40	29-32	34-35
White (1968), Rapp and Fairbridge (1968)	37-40	30-38	-	30-35 or less	-
Gardner (1968a)	Undifferentiated 25.10(17)		-	14.33(3)	-

NOTE: The figures in brackets represent the number of slopes measured where given. The data from Bones are recalculated to separate out the slopes modified by avalanches.

comparisons, although all the other slopes seem to be considerably steeper than Gardner's measurements (1968a) for the Lake Louise area. Apart from his results, it appears that maximum angles for scree slopes are in the 35-37^{0} range, unless the scree is being actively undercut at the base, and that the "angle of rest" is only usually approached near the top of the slope where there is rapid accumulation and the mean grain size is small, often containing fines. Most of the slopes are below the 35^{0} commonly cited as the typical angle for scree slopes and are also concave in profile. Where extensive avalanche modification occurs, the basal concavity may be extended by deposition and surface slopes at the lower end of avalanche tongues may be as low as 0-5^{0} or even have a reverse gradient (Rapp, 1959; Potter, 1968).

SCREE FORMS RESULTING FROM AVALANCHE MODIFICATION

The geomorphic activity of snow avalanches and the resulting landforms were discussed in Chapter 5. Modified scree slopes or scree-like forms are a subset of those landforms and will be discussed in more detail here on the basis of the observations in Surprise.

Avalanche Boulder Tongues (Rapp, 1959)

Rapp divided these landforms into two types; roadbank tongues and fan tongues. The former are elongated, flat topped, asymmetric embankments of debris usually several metres thick which do not extend far onto the lower slopes beyond the scree. Fan tongues are larger, fan-like or more diffuse spreads of debris which may extend several hundred metres across slopes of as little as 5-10^{0} and may also be associated with fluvial activity. Similar forms have recently been described from the American Cordillera by Potter (1968), Gardner (1970a) and Luckman (1971).

The basis for Rapp's division was primarily morphological, although he considered fan tongues to be the product of a longer period of intensive avalanche modification because their deposits are scattered over a much wider area and are thinner than those of roadbank tongues. Rapp suggests that the fan tongues may be formed by much larger avalanches (Rapp, 1959, p. 47). It may also be argued that the difference in form is the result of varying spatial concentration of the avalanche activity, highly localized and repeated erosion and deposition producing roadbank tongues; whereas if there is considerable variation in the position of the deposition a fan tongue is more likely to result. Rapp does point out, however, that the forms are gradational, both between types and in degrees of modification of the original deposit (1959, p. 47).

Roadbank Tongues

About 15 of these tongues have been identified in Surprise and some of their salient characteristics are summarized in Table 15.3. These features are, on the whole, smaller and less well-developed than the examples described by Rapp, Potter and Gardner. Although several have an asymmetric cross-profile and plan curvature of the lowest part of the tongue similar to that described by Rapp and Potter, there is no pattern for the valley as a whole, although results are consistent at individual sites. Since most of the tongues are almost parallel to the major directions of weather movement (approximately west to east), the

TABLE 15.3: SUMMARY DESCRIPTION OF AVALANCHE BOULDER TONGUES (ROADBANK TYPE) IN SURPRISE

	Old Nip (A.B.T.)	Strike Valley	Hoodoo Valley	E.V.S.	Surprise II
Aspect of Cliff	E	ENE	WSW	WSW	ENE
Number of Tongues	1	3	c.10	1	several
Thickness(m)	2-3	2-4	2-4	1-2	c.1
Angle at Base	$17\text{-}18^{o}$	-	$19\text{-}24^{o}$	-	-
Asymmetry	N	S	S	S(?)	N
Curvature (Plan)	none	to N	to N	none	none
Width (m)	30	25-30	15-30	35	5-15

NOTE: The sites are illustrated in the following figures: Old Nip (Figures 8.12, 10.7 and Luckman, 1971, Figure 11); Strike Valley (Figure 15.5); Hoodoo Valley (Figure 15.4); E.V.S. (Figures 8.1 and 8.2). Some of the tongues at Surprise II can be faintly seen on Figure 8.23, between old squares 2 and 3 and the two lowest sites to the south of them. The figure for width is the maximum width of the tongue.

variation may reflect dominant local wind directions within the valley caused by topography. Field evidence suggests that the steep slope on the Old Nip tongue is on the leeward side of the tongue, as Rapp suggests (1959, p. 41), although observational evidence is lacking for the other sites.

Only the Old Nip tongue extends beyond the limits of the parent scree (except of course for the E.V.S. site) and maximum lengths for the depositional part of the tongues are 100-150 m. The small features at Surprise II are incipient forms; generally "smoothed" areas of scree delimited by a small, although marked, break of slope representing some of the more commonly used avalanche tracks.

The roadbank tongues found in Surprise are unusual because, unlike those described by Rapp, Potter and Gardner and with the exception of the E.V.S. site, all the sites occur below steep, straight cliffs without obvious areas for avalanche snow to accumulate. Thus, the tongues may be relatively small because the avalanches which create them are small. The evidence from Old Nip (Chapter 8) suggests that the tongue is formed by the action of slab or other avalanches starting on the slope itself but triggered by cornice falls from the cliff above and it is possible that the other tongues are formed in a similar manner. Three of the sites face eastwards and one westward, the latter having the largest number of tongues. However, this difference in aspect may not be critical because the location of cornice development depends upon wind direction in any particular storm, for example, the Medicine Lake road is severely effected by avalanches in some years but not in others. This, in part, depends upon whether the snow accumulates in the gullies on the east or west side of the ridge (W. Pfister, private communication, 1970). However, further fieldwork, either in winter or early spring, would be necessary to substantiate the cornice trigger hypothesis for the unusual location of these sites.

The evidence from the accumulation studies at Old Nip and Surprise II suggests that avalanche erosion may affect all the surface material on the upraised area of the tongue and that the steep frontal slope may be akin to the front of a prograding delta; material is swept over the edge and deposited on or beyond the face (see Figures 8.12 and 8.13). Thus, the form of the tongue is due largely to avalanche trimming of earlier deposited debris. The Old Nip tongue showed a well-developed

Figure 15.4 (left) Small avalanche boulder tongues at the Hoodoo Valley Screes. The fronts of the tongues are up to 2-4 m high. The coarse blocky material on the left is the moraine visible in Figure 8.3. The Hoodoos occur on tree covered till slope beyond the moraine.
29th July 1970.

Figure 15.5 (right) Avalanche boulder tongues at Strike Valley. The steep edges of three tongues are visible in the foreground facing the camera. (See Figure 8.17 for a plan view.) The small snowpatch is at the lower end of the sample site network covering the stream. The direction of view is northwards. Old Nip, the Palliser Bench and Surprise Lake are visible in the distance.
13th August 1971.

size grading over its surface (Chapter 13) and a similar, weaker, effect is illustrated by Potter (1968). Other observations in Surprise, e.g. at the E.V.S. site, suggest size sorting is present at other sites, although this characteristic was not emphasized by Rapp who found that only the largest debris, which was swept to the base or sides of the tongue, showed any evidence of size grading.

Balanced or perched boulders, characteristic of avalanche deposition elsewhere, are not as common on the "smoothed" upper surface of the tongues as they are in other areas where avalanche activity is purely depositional. Rapp also considered avalanche debris tails (Rapp, 1959, p. 40; Potter, 1968) to be a common feature of avalanche tongues. These are ridges of debris extending downslope from large boulders on the scree surface. Only one example of these forms was seen in Surprise (at the Hoodoo Valley site), although many boulders had small accumulations built up on their upslope sides. This absence may be due to the lack of suitable anchored large boulders on the screes studied.

Fan Tongues

Only one clear example of this type of tongue was observed in Surprise, the Tumblin' Creek Cone, which bears a marked morphological resemblence to the example cited by Rapp on Mount Tjåmohas (Rapp, 1959, Figure 8). This site has been described in detail elsewhere (Chapter 8). The main avalanche track at Strike Valley might also be considered a fan tongue where, due to the configuration of the valley, the thin veneer of debris is spread downvalley along the base of the scree rather than being built away from it. The heterogeneous avalanche debris is scattered over 200-300 metres of the flat stream channeled area at the base of the shale slope.

This relative paucity of fan tongues may be ascribed to two major causes:

(i) the lack of really large avalanche tracks which contain suitable amounts of debris in the area studied, and

(ii) many of the larger avalanches which were observed extended well below the treeline where little debris is available and deposition of scattered debris is masked by vegetation.

Intermediate Forms

As well as the well-defined avalanche boulder tongues, there are several other landforms within the valley which are affected by avalanches. Many of the cones below the gullies on the Eastern Valley Side or around Tumblin' Creek have probably obtained much of their debris by avalanche deposition rather than stream activity (see discussion in Veyret, 1959). However, there are two fairly distinct intermediate forms which may be recognized as the result of avalanche activity.

Avalanche Cones

This term is used for piles of avalanche debris below avalanche chutes and is the result of avalanche deposition alone, rather than the modification of scree or alluvial material. These may be distinguished from avalanche boulder tongues by their size and lack of any well-developed form. Several authors refer to similar small piles of avalanche debris, e.g. Matthes, 1938; Peev, 1966; Akif'eva and Kravtsova, 1967; and Tricart describes them as "a heap of material flung together in disorder like a rubbish tip" (Tricart, 1970, p. 192). Observations in Surprise suggest that these features are small, purely depositional cones, often with a very low angle of slope. They should be clearly differentiated from avalanche boulder tongues and the term avalanche cones is suggested. Several cones of this type occur at the base of the Pekisko cliff near Lake Helen where avalanches have tumbled over the cliff from chutes further upslope. However, as the debris pile increases in size, avalanches may begin to move down it, producing erosion and modifying the feature into an avalanche boulder tongue.

Bevelled Scree Cones

Where major scree cones develop below couloirs (gullies) in the cliffs, the couloir funnels several processes--rockfalls, avalanches, mudflows and streams--onto the cone below. Prolonged avalanche activity from the couloir modifies the cone by erosion in the neck and centre of the cone and building out a basal concavity. This gives the cone a spatulate form; the central part is bevelled by avalanche erosion and the erosion in the upper part of the cone produces a surface of exhumed boulders partially buried in a matrix of fines.

The Palliser Cone is the closest example to this form in Surprise, but due to the lack of well-developed cones most of the examples seen have been outside the valley, e.g. Terminal Mountain in Whistler's Creek near Mount Edith Cavell and at Lake Louise (see Gardner, 1970a, Figures 6 and 7; also, see Rapp, 1959, Plates XI, XV, XVII(a), Cones 4 and 5). Since these forms retain many of the characteristics of complex scree cones, they are best classed as an intermediate type although in form alone they may resemble poorly-developed fan tongues.

OTHER MODIFICATIONS OF SCREE FORM

Where large amounts of rock debris accumulate below cliffs and interstitial ice is present, rock glaciers may develop. There are a number of intermediate forms between scree and rock glaciers which have been discussed by Wallace (1968). Small valley side rock glaciers do exist in the upper part of the Tumblin' Creek valley (see Figure 2.2) and possible incipient, now fossil, proscree lobes (Wallace, 1968) occur between the lower part of Strike Valley and Old Nip where the lower part of the scree has in places a convex bulge or terrace like fringe 10-20 metres high. Parts of this can be seen protruding from beneath the snow cover in Figure 8.18 and also in Figure 8.10. Alternatively, this feature could be a wide, partially buried, protalus rampart.

Protalus ramparts are single or multiple arcuate ridges of debris formed at the base of scree slopes by the accumulation of debris sliding over permanent or semi-permanent snow patches (Andrews, 1961; Wallace, 1968 and references therein). A single well-marked rampart occurs at Surprise II (Figures 2.5 and 8.23) and a number of arcuate ridges 10-15 m high occur on the Palliser bench at the base of the screes between Cougar and Champagne Creeks. The absence of any embayment or corrie at this point suggest these are protalus ramparts of different ages built one against the other.

The protalus ramparts, proscree lobes and rock glaciers appear to be fossil features since they are often heavily lichen covered with frost shattering of the coarser debris and in places the development of a soil and vegetation cover. It seems probable that these features date from the final phases of deglaciation rather than Neoglacial (Gardner,

1972) time. The tree cover on the Cougar Creek-Champagne Creek ramparts is similar to that in adjacent areas and at Surprise II, a coral stem, 3.5 cm in diameter and 10 cm long, has been etched almost completely out of its host boulder and is only attached by an area of about 1 cm^2. A similar degree of weathering out of fossils is found on comparable boulders of the Hoodoo Valley moraine.

The presence of landforms of this type and areas of coarse, lichen covered blocky scree beyond the limits of the presently active screes at some locations (e.g. Old Nip Cone) emphasizes that screes may be polygenetic in both a spatial and a temporal sense. Scree development usually involves millions of individual events spread over a long period of time (see, however, Karlstrom, 1965, p. 133) during which the balance of dominant processes may change in kind or intensity. Madole (1972) has described screes of different ages overlapping one another in Colorado (although he finds difficulty in differentiating some of them) and relates them to stages in the neoglacial and late glacial chronology of the area. The careful selection of sites for the sediementological programme excluded such obvious irregularities but it should be recognized, particularly with complex screes, that differences of this type may be present and need to be taken into account in any comprehensive analysis of scree form.

CONCLUSIONS

The plan and profile form of the screes studied in Surprise are similar to other screes reported in the literature, although there are considerable differences in profile form between individual sites.

Maximum slope angles over the scree surface are between 35-37^{0} and mean angles range from 24^{0} to nearly 35^{0}. Four of the five main slopes studied have mean angles between 31^{0} and 32^{0}. With one exception, all the slopes were concave in profile and the basal concavity is particularly marked on avalanche dominated slopes where it results in a much lower mean angle of slope.

Both of the major types of avalanche boulder tongue recognized by Rapp (1959) are present in Surprise, although they are smaller in size than those he described, probably due to the smaller size of avalanches responsible for their formation. In addition, two new avalanche forms are recognized, the avalanche cone and the bevelled scree cone. The former are small cones produced by avalanche deposition below chutes whilst the latter are large, often multiprocess, cones which have been partially modified by avalanche erosion.

SECTION V

CONCLUDING REMARKS

Chapter 16: Conclusion

CHAPTER 16

CONCLUSION

The investigations carried out in Surprise have involved the detailed field examination of the characteristics of nine major scree slopes with additional observations from other locations. These observations have focussed unequally on three major topics; contemporary geomorphic processes, surface sediment characteristics and scree form. As well as being studies in their own right, these topics are strongly linked and reflect the interactions between processes, materials and form over successively longer periods of time. The character and arrangement of surface materials and gross scree form are the result of geomorphic activity during periods ranging from tens to thousands of years and may therefore be used to check the validity of extrapolations from short-term observations of contemporary processes (and vice versa). The major conclusions from these studies may be summarized under several different headings.

Controls of Scree Slope Characteristics

Screes are essentially gravitational deposits of mechanically weathered debris. The major controls of their distribution and character may be grouped into physical and climatic factors. Given a suitable climatic regime for the production of debris, the most important physical control is cliff form, since it determines the spatial distribution and character of deposition and input processes. Generally, as cliff dissection increases deposition becomes more localized, forming cones, and the number and complexity of the input processes increases. The available range of processes is also, however, governed by climatic parameters, e.g. snow avalanches.

The variety and relative importance of queueing processes (processes which move material over or within the scree) also depends upon site characteristics and the nature of the surface debris, particularly the presence of fines or other waterholding materials. The role and significance of output processes is largely a function of the relative position of the scree with regard to powerful erosional agents.

The cliffs in Surprise are largely undissected and the major processes affecting scree slopes are rockfalls and snow avalanches. The effects of other input or queueing processes are minor; such processes tend to be either strongly localized, isolated catastrophic events (e.g. rockslides or mudflows) or localized small scale processes which are usually dependent upon the presence of fines at or close to the surface. Initial results indicate that apart from such areas of fines and areas dominated by avalanche erosion, the movement of debris by talus creep is very slight. None of the screes studied are strongly affected by output processes.

Rockfall Activity

Rockfall occurs at all sites and is the most important input process in the valley as a whole. The inventory observations in 1969 showed that the pattern and intensity of rockfall activity varies seasonally (with spring and autumn maxima) and that marked differences occur between sites as a result of differences in their physical and microclimatic settings. The great spatial range and relatively insignificant volumes of rockfall activity observed make it impossible to reasonably estimate the magnitude-frequency spectrum of rockfalls from short periods of record. The overall dominance of rockfall is shown by the observations of its occurrence and the sedimentary characteristics of the screes.

The most significant conclusions arising from these observations relate to Gardner's concept of the "average day" and its use for describing temporal patterns of rockfall or other mass movement phenomena. Because of the wide variability of rockfall intensity between sites (and also between different periods at the same site), a more restricted experimental design is needed. Future studies should be confined to individual or almost identical sites where frequency is measured in terms of hourly probabilities rather than arithmetic averages. Since 71% of the hours of observation in Surprise had no rockfalls, the mean merely reflects the characteristics of the most intensive period of activity. Primary and secondary rockfalls should be studied as separate patterns since they usually have different causes.

The Role of Avalanches

The most important result of the process studies is the recognition of the importance of avalanche activity in the development of alpine scree slopes. Although spatially discontinuous and often strongly localized, avalanche activity is the dominant and most dynamic process on many of the screes studied in Surprise, causing considerable amounts of debris movement in a short period of time. Favourable conditions for avalanche activity arise where suitable accumulation areas for snow occur in the cliffs or external triggers (such as cornice falls) cause repeated avalanching of the snow cover of the scree at the same location in successive years.

Avalanches moving in contact with the ground surface rapidly entrain loose debris and therefore, in relation to scree slopes, may fulfill two basic roles. Firstly, they may act as an input process, sweeping fresh debris onto the scree from the cliff zone. Secondly, and possibly concurrently, they may act as a queueing process redistributing the surface material of the scree. Avalanches may also act as output processes inasmuch as they lead to the basal extension of the scree where continued deposition extends beyond its lower limits.

The relative importance of these roles varies with the characteristics of individual sites and it is often not possible (because of mixing) to differentiate between debris sources solely by the characteristics of the deposit. The results from Surprise indicate that the most heavily debris-laden avalanches are associated with marked erosion of the scree surface, although there have been a few notable exceptions (e.g. Surprise II, 1971). Avalanches are therefore the most important queueing process observed in Surprise and, at some sites (Surprise II, Tumblin' Creek Cone) may be the dominant input process as well. Individual avalanches have been observed with up to 20 m^3 of debris and it was estimated that up to 144 m^3 of debris was deposited by rockfalls and avalanches on the Tumblin' Creek Cone between 1968 and 1972. Other results from the accumulation studies indicate that sites with heavy avalanche deposition average 1-8 mm/year accumulation over their surface.

However, much of this was the downslope redistribution of surface scree, rather than fresh debris input from the cliff. Avalanche erosion and deposition were observed on all parts of such slopes at different times. No consistent distribution pattern of debris was observed within the deposits of individual avalanches, although a strong inverse relationship between deposition and distance from the cliff occurred where avalanche deposition did not reach the basal part of the slope.

The modification of screes by avalanches may take several forms. Purely depositional activity results in a chaotic plastering of heterogeneous debris over the scree surface, resulting in many balanced boulders. Similar small, purely depositional forms may occur below avalanche chutes and have been called avalanche cones. More usually, however, avalanches erode debris from the upper and middle parts of the scree and transport it downslope. If the avalanching extends to the base of the scree, the overlapping of erosional and depositional zones in different years results in the development of a marked basal concavity and extension of the scree. Strongly localized or intense avalanche erosion may produce avalanche boulder tongues of either type (Rapp, 1959), although on very large, multiprocess cones such activity only produces a partial modification of the scree form which has been termed a bevelled scree cone. Observations on roadbank tongues in Surprise indicate that their smoothed upper surfaces are produced by the erosional trimming of earlier deposits and that the form extends by deposition on its steep front and sides, rather like a delta. The differences between roadbank and fan tongues are thought to reflect differences in the temporal intensity and spatial concentration of avalanching combined with the amount of available debris. Such forms may be produced by repeated action of either wet snow avalanches from the cliffs or slab avalanches moving over the scree surface.

Debris Accumulation Measurements

The measurement of debris accumulation on cleaned boulder surfaces and polyethelene squares has proved to be a cheap, reliable and highly successful means of estimating the amount and distribution of avalanche deposition on scree slopes. The two methods yield comparable results and, despite initial problems of measurement and sample design, which may be remedied in future studies, they have provided the most comprehensive data yet available on debris shift by avalanches. The observation of the movement of marked boulders has also led to important conclusions about the erosional role of avalanches in the modification of scree slopes.

The major problem in the interpretation of these results is that it is usually not possible to differentiate the source of the debris (either with regard to its location or the depositional process) without additional information. Thus, while it can usually be assumed that most of the deposition is from avalanches, it is rarely possible to say whether the debris is a fresh input from the cliff or merely reworked scree without more extensive experimental work and observation. Such work would probably have to involve the marking of considerable areas of loose debris in the track and on the scree to establish the relative proportions of debris from each source in the avalanche deposits.

Although rockfall deposition is recorded by these methods, its quantity is considerably underestimated. This is due to the nature of the sampling methods and rockfall itself. Rockfalls are usually point located depositional events which are extremely variable in their spatial and temporal distributions and to obtain a reasonable estimate of their importance much larger areas of the scree must be covered with marker surfaces with special emphasis on the area close to the cliff. Such observations would have to involve sites of much greater area than those used in Surprise (e.g. Gray, 1972), but could only be used on screes where avalanche activity was very slight.

The results from Surprise have demonstrated the great temporal and spatial variability of depositional activity on scree slopes. Most of the measured deposition is from avalanches and all sites showed some evidence of avalanche activity in at least one of the five years of study. The occurrence of significant avalanche erosion ranged from once a year at the most intensive sites to one year in five (E.V.S.), whilst the avalanche erosion observed on Scree No. 1 in 1969 probably has a much greater recurrence interval. The amounts of activity and deposition also varied markedly from year to year and were not synchronous between sites in any one year. Therefore, local site conditions at the time of avalanching seem to be more important than the overall annual pattern in controlling the geomorphic activity of avalanches.

Sedimentary Characteristics

Major investigations were carried out on four screes with smaller experiments on three others. Over 16,000 scree fragments were measured. The results show that the total population of surface fragments at each scree approximates a log-normal (phi-normal) size distribution with marked differences in axial shape measures between lithologies. These differences are most strongly influenced by the c axis size which is strongly controlled by bedding characteristics. The two lithologies investigated which were not significantly different were both massive limestones. All lithologies also showed a significant relationship between phi size and axial ratio shapes, the larger fragments being much more compact in form.

Surface samples from points on the scree were also basically log-normal in character with 98% of the samples testing as normal, using a Kolmogorov-Smirnoff Test. However, many samples contained elements from other populations in the tails of the distributions causing abnormal values of skewness and kurtosis. These fragments were either rock chips, produced by weathering or avalanche deposition, or large boulders, often associated with the floating layer. Most of the sampled distributions also fit the Rosin distribution by weight, although the log-normal is a superior fit. At most of the scree sites studied, the basal samples tend to be negatively skewed due to the addition of a small amount of finer material from various sources.

Experimental observations have shown that the volume computed from triaxial measurements of rocks of all shapes is approximately 52.5% of true volume for the lithologies studied. Significant improvement of volume estimates for individual fragments can be made by using a crude shape parameter, estimated in the field, to convert the axial volume (see Appendix 3).

Size Sorting

Two major levels of size sorting were identified on the slopes examined. All slopes showed a significant overall downslope logarithmic increase in particle size on which is superimposed a local pattern of variability causing inconsistencies in the size gradient on individual profiles. Extreme differences of up to 1.3 ø were observed between adjacent subsample means of 50 stones with a maximum range of 1.5-2.0 ø between samples less than five metres apart. These local variations are most common on the upper and middle parts of the slope and may be attributed to the action of small scale queueing processes or local variations in the controls of the fall sorting pattern. The most common of these variations are the presence of a coarse capping of debris at the top of the slope (probably due to rockfalls miring in soft winter snow) and the floating layer. The latter is a layer of coarser debris one or two particles thick which is thought to build up as a result of accumulation behind randomly positioned obstacles. No systematic lateral variations in size were found on the screes studied but this may be attributed to the restricted sample design employed as such variations obviously exist due to differences in the geology of the cliff or lateral variations in dominant processes, e.g. at Old Nip.

The downslope increase of grain size is largely a fall sorting pattern produced by rockfall, although at some sites it has been modified by avalanching. This overall pattern is the result of millions of individual events and the size gradient reflects the most probable position that a boulder of a given size will come to rest. However, random variation of any of the variables controlling rockfall may lead to deposition of individual boulders at a higher position on the slope. Although most of the largest boulders are at the base of the slope, observations of those in the vicinity of the sample points usually indicate no consistent downslope increase in size, i.e. individual large boulders may be found at any position on the slope as a result of random effects on their downslope passage.

Also, since the best example of fall sorting occurs on the only straight slope, fall sorting is not directly related to the angle of slope. The apparent relationship between mean size and slope angle arises because most slopes are concave and therefore the angle, like grain size, is correlated with distance from the cliff. The present fall sorting pattern is maintained largely through frictional effects, although the original pattern must have developed purely as a result of differences in momentum related to size. Despite differences in the size of the constituent materials, the three main rockfall sites studied showed a general inverse relationship between the sorting gradient and the length of slope.

The sites affected by avalanching also showed a downslope increase in grain size, although its characteristics had been modified by the avalanche activity. The downslope transfer of loose debris by avalanche erosion exposes finer material on the upper slopes and buries the coarsest rockfall debris at the base of the slope. This usually results in a steeper sorting gradient over the slope but where avalanche erosion is severe the pattern may be completely destroyed on the upper slopes and replaced by isolated patches of loose, coarser debris resting on a compact mixture of rock debris and fines exposed by erosion. Where avalanche effects are purely depositional, anomalies are superimposed on the sorting pattern which may locally be reversed or destroyed.

Differentiation of Avalanche and Rockfall Deposits

Individual point samples from the scree surface samples in Surprise are moderately well sorted (using Folk's classification), unlike the examples described by Gardner (1968a, 1971). This difference is thought to be due to Gardner's use of a $\log_{10}$ transformation rather than phi units. Rockfall dominated screes are generally better sorted than avalanche dominated sites (mean standard deviations 0.76 and 0.95 ϕ respectively). The most poorly sorted samples are those from areas where the avalanche activity was purely depositional. Despite these differences, it was not possible to establish a simple quantitative criterion to differentiate these two types of deposit because of the overlap between the two groups. However, the deposits can be clearly distinguished in the field by their arrangement, size, sorting and general setting.

Avalanche samples taken during the accumulation measurements were generally similar in character to the adjacent screes, although they contained much more fine material which would be subsequently washed from the surface. The surface deposit is therefore a type of lag deposit and the finer material accumulates within the body of the scree.

Scree Form

The plan and profile form of the screes measured in Surprise is similar to other screes described in the literature. The mean slope angles of the six slopes ranged from 24° to 35°, although only two of the slopes were less than 30°. Maximum slope angles varied between 35° and 37° and most of the profiles are concave. This concavity is accentuated by avalanche activity and therefore the avalanche slopes have a lower mean angle of slope. Two transitional types of avalanche modified screes were identified, avalanche cones and bevelled scree cones. Several avalanche boulder tongues also occur. However, it must be emphasized that all these forms are parts of a continuum rather than individual, well defined forms and most of the large screes are clearly multiprocess forms.

Further Research

The major contribution of this thesis has been in the description and explanation of the surface sedimentary characteristics and contemporary geomorphic processes on a number of scree slopes in a small alpine valley. Although the screes in Surprise have been studied in more detail than any others, the present study has only, literally and metaphorically, scratched the surface of many of the problems of scree slope development and its responses to various controlling parameters. Varied though they are, the screes studied in Surprise are basically simple rockfall or avalanche screes unmodified by basal erosion; they only form a small subset of the possible combinations of state and environmental relationships suggested by Thornes (1968, pp. 14-15, 1971). However, since the relationships between state and environment have been clearly specified for the screes in Surprise, it is possible to compare them with similar slopes elsewhere. Initial observations suggest the conclusions may be extrapolated to many screes within Banff and Jasper National Parks, using the basic ideas on the controls of scree characteristics presented in this thesis. These emphasize local rather than regional controls of scree characteristics, although it is probable that broad regional changes in the relative importance of processes do occur, e.g. greater importance of snow avalanches with greater snowfall. However, since this study is only the second major investigation of scree slopes in such an alpine environment (nearly all the other detailed studies are from areas underlain with permafrost, e.g. Rapp, 1960a; Stock, 1968; Bones, 1971 and Gray, 1971), more investigations are needed to verify this generalization.

Many possible topics for further research have been mentioned throughout this thesis. The more important of these may be divided into two groups; those following directly from the results of this study and others arising from incidental observations connected with the work. Major topics within this latter group are the factors which control the initiation of fall sorting patterns and the characteristics of the scree below the surface. It has been argued within this thesis that the fall sorting patterns are maintained by surface friction effects and that the absence of fall sorting on a scree may be due to either its modification by the action of other processes or by variations in the controls of rockfall movement, particularly height of fall, range of grain size or the character of the initial slope. This hypothesis could be tested by isolating each variable in turn and examining the effects on the fall sorting pattern. This could be done either as a laboratory simulation or by the careful choice of appropriate experimental sites in the field, e.g. the Entrance Screes (Figure 8.3) for the study of the effect of cliff height.

The observation of fines small distances below the scree surface in several localities indicates the need to examine the variation of scree characteristics with depth. Is the coarse surface debris merely a veneer mantling a heterogeneous mixture of debris with the voids filled by fines? If this is so, how valid is the general assumption that scree profile form is controlled by the mechanical properties of a coarse cohesionless mass of solid particles? Are the mechanical controls of scree form different from slopes of similar dimensions in other loose materials? For practical reasons, these questions could not be investigated in Surprise but given suitable sites (or equipment) this could form the basis of an extremely interesting study.

In extending the work of the present study, it is hoped to continue the accumulation measurements in Surprise for as long as they are feasible. Despite the inadequacies of the sample site networks, these sites may yield extremely useful data on the relative magnitude-frequency spectra for individual sites. Using the experience of these initial observations, more sophisticated experiments can now be set up, both in Surprise and elsewhere, to investigate patterns and amounts of deposition by avalanches over a period of time. This should probably be done on an institutional rather than individual basis to ensure the continuity necessary for a long period of record. Detailed experiments might examine the development of specific forms (e.g. avalanche boulder tongues) or the relative importance of the different sources (cliff or scree) of the debris carried by avalanches. It is also hoped to measure the force exerted by avalanches using pressure gauges similar to those used by the Division of Building Research at Rogers Pass (D.B.R., 1971).

There is also a need for more detailed observations and measurement of the characteristics of scree slopes and scree slope processes in general. The total amount of quantitative data in the literature on the attributes of scree slopes or the relative importance of various processes is still very small. The results from Surprise have added to these data but further work is obviously needed to verify or replicate many of the observations noted from Surprise, e.g. the floating layer and the characteristics of downslope size sorting on avalanche boulder tongues. Although the interpretation of some of these features may change in the light of future observations or experience, these initial observations remain an important contribution in their own right. Measurements are also needed of the attributes of screes dominated by processes other than rockfall or avalanches and in other environments and states than those examined here.

Following the results from Surprise, the greatest need is for further observation, inventory and measurement of scree slope processes. Particular emphasis should be placed on controlled rockfall inventories, amounts and distribution of avalanche deposition and the observation of avalanche activity in the winter and early spring. Only by such direct observations might it be possible to discover more about the conditions which control the geomorphic significance of individual avalanches. Such observations may also yield additional data on the relative importance of the queueing and input roles of avalanche transport.

Finally, as with all process studies, there is the important element of time. One of the major conclusions from the process observations in Surprise is that, over such a short period of time, every year is different and adds some new, unpredictable element to the overall pattern. Much longer periods of observation are needed to eliminate such "surprises" and develop an adequate knowledge of the characteristics and magnitude-frequency spectra of the various processes which influence scree slope development.

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APPENDIX 1

SOME COMMONLY USED ABBREVIATIONS

Units

in = inches
mm = millimetres
cm = centimetres
dm = decimetres
m = metres
km = kilometres
cc = cubic centimetres

Place Names

E.V.S. = Eastern Valley Side Site
Ent. = Entrance Screes
Isos. or IS = Isosceles
O.N. = Old Nip
O.N. (Av.Apron) = Avalanche Apron at Old Nip
O.N. (A.B.T.) or ONAV = Avalanche boulder tongue at Old Nip
O.N. (Rf) or O.N. (R) = Rockfall cone at Old Nip (Old Nip Cone)
Pall. or P = Palliser Cone
N1 = Scree No. 1
S.V. = Strike Valley
S.II or S.2 = Surprise II
T.C. or T.C.C. = Tumblin' Creek Cone

Terminology

A.B.T. = Avalanche boulder tongue
ANOVA = Analysis of variance
a.s.l. = above sea level
B = sample boulder
D or D.o.F. = Degrees of Freedom
K or k = Kurtosis
K.R.G. = Karst Research Group (McMaster University)
Mean (3) or M(3) = the mean of those sites with at least three years of accumulation
min. = minimum
N or n = number (of observations, etc.)
N.S. or n.s. = not significant ($<$ 95% level); also, not set
R or r = Correlation coefficient
R^2 = Correlation coefficient squared or "percentage explanation" (of variance)
S.D. or s.d. = Standard deviation
S.E. or s.e. = Standard error
SK or sk = Skewness
Sq = sample square
T.W.R. = Talus Weathering Ratio (Schumm and Chorley, 1966)
W1 = First level of Winsorization
W2 = Second level of Winsorization
$\bar{x}$ = Mean

APPENDIX 2

COMPLETE DATA FOR THE ACCUMULATION MEASUREMENTS

This is a modified computer printout of the accumulation data. The headings are self-explanatory except for the coding and the mean. The mean is the mean value of accumulation per year for the number of years of record. Where the area of the sample sites changed over the period of record (mainly partially destroyed squares), the site is entered twice--once for each area. In such cases, the mean is the total sampled area divided by the total accumulation in the four year period.

The coding describes the results at each site in each year. The key to the numbers is as follows:

0 = site not set or not reset
1 = accumulation measured (one year)
2 = accumulation measured (two year total)
3 = accumulation measured (three year total)
4 = sample site rejected due to surface weathering, undue effects of creep, etc.
5 = sample site either underwater or under snow and not available for sampling in that year
6 = sample site has moved downslope. These sites were not used in subsequent years.
7 = Sample site lost. Most of these were moved and not found although some may have been buried or smashed. A few merely lost their painted numbers and were therefore indistinguishable.
8 = sample square destroyed by avalanches. This designation was used when no sample could be taken. This coding was also used for the one or two boulders which were smashed by rockfall impact
9 = polyethelene of square had perished

All the sample sites given are boulders unless the number if prefaced by the designation SQ or OSQ.

EASTERN VALLEY SIDE

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
E.V.S. 1	.3662	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 2	.2275	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 3	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 4	.2100	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 5	.1600	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 6	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 7	.2500	1111	.8	4812.8	0.0	.8	1203.6	4
E.V.S. 8	.5000	1111	.1	0.0	0.0	0.0	.0	4
E.V.S. 9	.1950	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 10	.1500	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 11	.3900	1111	0.0	0.0	2.1	0.0	.5	4
E.V.S. 12	.3600	1111	0.0	0.0	75.6	0.0	18.9	4
E.V.S. 13	.3650	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 14	.3000	1111	0.0	0.0	79.7	0.0	19.9	4
E.V.S. 15	.1900	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 16	.2100	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 17	.6600	1111	0.0	0.0	11.6	0.0	3.0	4
E.V.S. 18	.6750	1111	0.0	0.0	3.7	0.0	.9	4
E.V.S. 19	.1950	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 20	.5300	1111	0.0	0.0	348.9	0.0	87.2	4
E.V.S. 21	.8400	1111	0.0	0.0	11.0	0.0	2.7	4
E.V.S. 22	.2250	1111	0.0	0.0	48.0	0.0	12.0	4
E.V.S. 23	.2700	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 24	.4375	1111	0.0	0.0	5.5	0.0	1.4	4
E.V.S. 25	.2380	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 26	.2250	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 27		7000						0
E.V.S. 28	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 29	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 30	.3600	1111	0.0	0.0	16.4	0.0	4.1	4
E.V.S. 31	.4800	1111	1.0	1421.5	1998.5	0.0	855.3	4
E.V.S. 32	.2475	1111	0.0	0.0	25.9	0.0	6.5	4
E.V.S. 33	.8100	1111	2.3	0.0	347.9	0.0	87.6	4
E.V.S. 34	.2400	1111	0.0	0.0	47.5	0.0	11.9	4
E.V.S. 35	.1925	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 36	.2500	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 37	.3000	1111	5742.3	0.0	20.7	0.0	1440.7	4
E.V.S. 38	.9000	1111	0.0	0.0	36.8	0.0	9.2	4
E.V.S. 39	.3150	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 40	.6600	1111	0.0	0.0	23.3	0.0	5.8	4
E.V.S. 41	.4000	1111	0.0	0.0	924.0	0.0	231.0	4
E.V.S. 42	.5250	1111	0.0	0.0	14440.2	0.0	3610.0	4
E.V.S. 43	.2100	1111	0.0	0.0	1374.8	0.0	343.7	4
E.V.S. 44	.2000	1111	0.0	0.0	527.5	0.0	131.9	4
E.V.S. 45	.7500	1111	8.1	0.0	1072.7	0.0	270.2	4
E.V.S. 46	.2250	1111	0.0	0.0	9.3	0.0	2.3	4
E.V.S. 47	.3150	1111	0.0	0.0	23.8	0.0	6.0	4
E.V.S. 48	.2700	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 49	.2500	1111	2846.4	1435.6	16.0	0.0	1074.5	4
E.V.S. 50	.4500	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 51	.3400	1111	4.1	0.0	0.0	0.0	1.0	4
E.V.S. 52	.4800	1111	449.8	0.0	400.8	0.0	212.7	4
E.V.S. 53	.3000	1111	0.0	0.0	759.7	0.0	189.9	4
E.V.S. 54	.1500	1111	0.0	0.0	20981.3	0.0	5245.3	4
E.V.S. 55	.1350	1111	0.0	1074.1	2835.6	0.0	977.4	4
E.V.S. 56	.2040	1111	0.0	0.0	3695.6	0.0	923.9	4
E.V.S. 57	.3900	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 58	.4200	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 59	.3400	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 60	.2700	1111	0.0	0.0	285.9	0.0	71.5	4
E.V.S. 61	.1800	1111	0.0	0.0	0.0	0.0	0.0	4
E.V.S. 62	.4475	1111	0.0	0.0	210.5	0.0	52.6	4
E.V.S. 63	.1800	1111	0.0	0.0	102.2	0.0	25.6	4
E.V.S. 64	.4500	1111	0.0	0.0	171.3	0.0	42.8	4
E.V.S. 65	.1025	1111	0.0	0.0	2276.1	0.0	569.0	4
E.V.S. 66	1.4000	1111	0.0	0.0	3593.1	0.0	898.3	4
E.V.S. 67	.2400	1111	0.0	0.0	17338.3	10.4	4337.2	4
E.V.S. 68	.1000	1111	0.0	0.0	245627.0	0.0	61406.7	4
E.V.S. 69	.6000	1111	1.0	0.0	272.7	0.0	68.4	4
E.V.S. 70	.3000	1111	0.0	0.0	796.0	748.0	386.0	4
E.V.S. 71	.7150	1111	0.0	0.0	314.0	0.0	78.5	4
E.V.S. 72	.3263	1111	113.4	0.0	692.9	0.0	201.6	4
E.V.S. 73	.0875	1111	46.9	1013.7	0.0	0.0	265.1	4
E.V.S. 74	.3613	1111	0.0	6647.4	5.8	0.0	1663.3	4
E.V.S. 75	.2000	1111	0.0	0.0	16188.5	0.0	4047.1	4
E.V.S. 76	.4300	1111	0.0	0.0	11017.0	0.0	2754.2	4
E.V.S. 77	.3500	1111	0.0	0.0	11644.3	14.9	2914.8	4
E.V.S. 78	.3450	1111	0.0	0.0	273.3	0.0	68.3	4
E.V.S. 79	.9525	1111	.1	0.0	94.8	0.0	23.7	4
E.V.S. 80	.5760	1111	.5	0.0	13832.1	62.2	3473.7	4

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
E.V.S. 81	.1500	1111	0.0	0.0	644.0	0.0	161.0	4
F.V.S. 82	.1800	1111	652.8	0.0	332.8	0.0	246.4	4
E.V.S. 83	.4200	1111	1.7	0.0	0.0	1750.2	438.0	4
E.V.S. 84	.2925	1111	771.6	0.0	843.4	3322.4	1234.4	4
E.V.S. 85	.1050	1111	0.0	0.0	9354.3	54625.7	15995.0	4
E.V.S. 86	.7200	1111	4773.7	0.0	3961.9	14064.0	5699.9	4
E.V.S. 87	.1720	1111	2170.9	0.0	16417.4	0.0	4647.1	4
F.V.S. 88	.1035	1111	0.0	0.0	87.9	0.0	22.0	4
E.V.S. 89	.3970	1111	0.0	0.0	2600.8	0.0	650.2	4
E.V.S. 90	.2575	1111	0.0	15356.1	13925.4	0.0	7320.4	4
E.V.S. 91	2.0000	1111	2.2	0.0	2536.3	0.0	634.6	4
E.V.S. 92	.4400	1111	0.0	0.0	888.2	0.0	222.0	4
E.V.S. 93	.2400	1111	1403.3	0.0	32122.9	0.0	8381.6	4
E.V.S. 94	.3000	1111	0.0	0.0	15835.3	0.0	3958.8	4
E.V.S. 95	.3823	1170	741.6	0.0			370.8	2
E.V.S. 96	.1200	1111	0.0	0.0	158341.7	13575.0	42979.2	4
E.V.S. 97	.1800	1111	0.0	429.4	13068.3	3925.6	4355.8	4
E.V.S. 98	.3000	1111	0.0	0.0	12313.0	3124.0	3859.2	4
E.V.S. 99	.2638	1111	4609.6	0.0	20257.0	17210.8	10519.3	4
E.V.S.100	.1800	1111	0.0	0.0	156.1	696.7	213.2	4
E.V.S.101	.4820	1111	0.0	0.0	432.0	0.0	108.0	4
E.V.S.102	.1650	1111	0.0	0.0	7478.8	0.0	1869.7	4
F.V.S.103	.5950	1111	79.5	0.0	8314.8	2.5	2099.2	4
E.V.S.104	.6150	1111	1.6	0.0	0.0	0.0	.4	4
E.V.S.105	.5750	1111	0.0	0.0	154.4	0.0	38.6	4
E.V.S.106	.5520	1111	11.6	0.0	8259.1	0.0	2067.7	4
E.V.S.107	.2300	1111	0.0	97.0	1632.2	0.0	432.3	4
E.V.S.108	.1950	1111	0.0	0.0	2532.3	0.0	633.1	4
E.V.S.109	.2140	1111	0.0	0.0	4426.2	0.0	1106.5	4
E.V.S.110	.3650	1111	368.8	0.0	51.2	0.0	105.0	4
E.V.S.111	.1250	1111	1192.8	9.6	3729.6	5909.6	2710.4	4
E.V.S.112	.1381	1111	0.0	0.0	61157.9	0.0	15289.5	4
E.V.SH113	.1100	1111	0.0	0.0	18919.1	1049.1	4992.0	4
E.V.SH114	.2400	1111	0.0	0.0	626.7	0.0	156.7	4
E.V.SH115	.1225	1111	1793.5	0.0	0.0	0.0	448.4	4
E.V.SH116	.3500	1111	0.0	0.0	22.0	0.0	5.5	4
E.V.SH117	.2000	1111	0.0	171.5	0.0	0.0	42.9	4
E.V.SH118	.0700	1111	0.0	0.0	435.7	0.0	108.9	4
E.V.SH119	.1200	1111	0.0	0.0	80.8	0.0	20.2	4
E.V.SH120	.6000	1170	0.0	0.0			0.0	2
F.V.SH121	.1800	1160	0.0	75.0			37.5	2
E.V.SH122	.1225	1170	0.0	617.1			308.6	2
E.V.SH123	.1050	1160	19977.1	0.0			9988.6	2
E.V.SH124	.1600	1411	3974.4		22946.2	30.0	8983.5	3
E.V.SH125	.1025	1111	.5	0.0	15916.4	19.7	3984.2	4
E.V.SH126	.1400	1160	0.0	0.0			0.0	2
F.V.SH127	.1800	1111	139.4	6.7	7161.7	132.8	1860.1	4
E.V.SH128	.3200	1160	0.0	36.3			18.1	2
F.V.SH129	.3750	1160	0.0	147.2			73.6	2
E.V.SH130	.2200	1111	0.0	469.1	10363.6	201.4	2758.5	4
E.V.SH131	.2475	1170	126.9	156.4			141.6	2
E.V.SH132	.1470	1111	0.0	324.5	10172.1	2878.9	3343.9	4
E.V.SH133	.2100	1170	35.2	1.4			18.3	2
E.V.SH134	1.0200	1172	324.8	10.3		9484.9	2455.0	4
E.V.SH135	.2625	1111	4636.2	106.3	5194.7	1.9	2484.8	4
F.V.SH136	.1400	1111	434.3	604.3	5615.7	159.3	1703.4	4
F.V.SH137	.1200	1111	13.3	26.7	19780.8	0.0	4955.2	4
E.V.SH138	.1575	1111	0.0	0.0	0.0	0.0	0.0	4
FVS SQ S1	2.3226	1190	0.0	0.0			0.0	2
FVS SQ S2	2.3226	1190	0.0	0.0			0.0	2
EVS SQ S3	2.3226	1190	0.0	0.0			0.0	2
EVS SQA1	2.3226	1000	0.0				0.0	1
FVS SQ A2	2.3226	1000	0.0				0.0	1
EVS SQ A3	2.3226	1000	100.7				100.7	1

ENTRANCE

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
ENT. 1	.5525	1111	699.5	35.1	8.3	131.9	218.7	4
ENT. 2	.2700	1111	225.9	261.5	27.8	157.4	168.1	4
ENT. 3	.1800	1111	332.8	963.3	8.3	0.0	326.1	4
ENT. 4	.3600	1111	0.0	1008.3	123.3	193.1	331.2	4
ENT. 5	.1300	1111	0.0	143.1	28.5	11.5	45.8	4
ENT. 6	.1800	1111	17.8	22.8	36.7	28.3	26.4	4
ENT. 7	.4800	1111	.4	373.1	5.6	4.4	95.9	4
ENT. 8	.3300	1111	95.5	27.9	594.2	18.5	184.0	4
ENT. 9		7000						0
ENT. 10		4000						0
ENT. 11	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 12	1.2000	1111	1.5	0.0	0.0	0.0	.4	4
ENT. 13	.6000	1111	.5	0.0	0.0	0.0	.1	4
ENT. 14	1.5900	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 15	.7200	1111	1.8	0.0	0.0	31.0	8.2	4
ENT. 16	.9800	1111	0.0	0.0	10.7	0.0	2.7	4
ENT. 17	.2500	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 18	.4800	1111	0.0	0.0	6.2	107.7	28.5	4
ENT. 19	1.1350	1111	0.0	0.0	0.0	2.1	.5	4
ENT. 20	.3600	1111	3.6	0.0	0.0	0.0	.9	4
ENT. 21	.3000	1111	0.0	0.0	59.7	0.0	14.9	4
ENT. 22	.4000	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 23	.1500	1111	4562.7	0.0	11.3	0.0	1143.5	4
ENT. 24	.0500	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 25	.1750	1111	0.0	0.0	1001.7	0.0	250.4	4
ENT. 26	.2400	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 27	.5025	1111	4.2	0.0	24.5	0.0	7.2	4
ENT. 28	.1000	1111	0.0	0.0	38.0	0.0	9.5	4
ENT. 29	.0600	1111	0.0	0.0	3.3	0.0	.8	4
ENT. 30	.0700	1111	31.4	1115.7	45.7	0.0	298.2	4
ENT. 31	.1575	1111	0.0	0.0	737.8	0.0	184.4	4
ENT. 32	.1500	1111	0.0	0.0	10.0	0.0	2.5	4
ENT. 33	.1950	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 34	.3000	1111	32.3	0.0	246.3	0.0	69.7	4
ENT. 35	1.0200	1111	.4	0.0	0.0	0.0	.1	4
ENT. 36	.6400	1111	0.0	0.0	2548.3	0.0	637.1	4
ENT. 37	.8000	1111	0.0	0.0	0.0	0.0	0.0	4
ENT. 38	.1225	1111	38.4	0.0	88.2	0.0	31.6	4
ENT SQ 1	2.3226	1000	1667.1				1667.1	1
ENT SQ 2	2.3226	1000	296.2				296.2	1
ENT SQ 3	2.3226	1000	0.0				0.0	1

OLD NIP

SITE			AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
O N		1	1.8350	1111	16233.9	404.9	805.4	249.9	4423.5	4
O N		2		6000						0
O N		3	.8700	1111	5.9	0.0	0.0	0.0	1.5	4
O N		4	.4020	1111	0.0	0.0	0.0	0.0	0.0	4
O N		5	.3600	1111	.6	0.0	0.0	0.0	.1	4
O N		6	1.0400	1111	0.0	16.5	128.0	1.2	36.4	4
O N		7	.2700	1111	.7	0.0	0.0	0.0	.2	4
O N		8	.4125	1111	0.0	0.0	0.0	0.0	0.0	4
O N		9	4.6000	1111	4.0	15.8	31.6	.8	13.0	4
O N		10	.4800	1111	2.1	.4	6.2	0.0	2.2	4
O N		11	.6500	1111	0.0	0.0	0.0	.5	.1	4
O N		12	.4200	1111	6.4	82.6	0.0	0.0	22.3	4
O N		13	.3000	1111	0.0	31.3	0.0	0.0	7.8	4
O N		14	.4500	1111	1.3	0.0	4617.3	0.0	1154.7	4
O N		15	.1800	1111	0.0	0.0	7797.8	0.0	1949.4	4
O N		16	.2025	1111	0.0	0.0	4.9	0.0	1.2	4
O N		17	1.1950	1111	.3	0.0	19311.9	0.0	4828.0	4
O N		18	1.2600	1111	0.0	0.0	17943.1	4.4	4486.9	4
O N		19	.4700	1111	0.0	0.0	13304.3	0.0	3326.1	4
O N		20	.4900	1111	0.0	0.0	27904.3	0.0	6976.1	4
O N		21	.1200	1111	0.0	0.0	8.3	0.0	2.1	4
O N		22	.1375	1111	0.0	2.9	111927.3	2.2	27983.1	4
O N		23	.2500	1111	0.0	31.6	0.0	19362.0	4848.4	4
O N		24	.1400	1111	0.0	0.0	0.0	0.0	0.0	4
O N		25	.2100	1111	0.0	0.0	11.0	0.0	2.7	4
O N		26	2.1600	1111	1.0	6.4	.9	0.0	2.1	4
O N		27	.5400	1111	0.0	8.9	385.0	0.0	98.5	4
O N		28	.5500	1111	0.0	23.8	3.5	11912.7	2985.0	4
O N		29	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
O N		30	.6600	1111	0.0	0.0	0.0	0.0	0.0	4
O N		31	.1800	1111	0.0	0.0	0.0	0.0	0.0	4
O N		32	.0525	1111	0.0	0.0	0.0	0.0	0.0	4
O N		A	.0600	1111	0.0	8.3	156058.3	690.0	39189.2	4
O N		B	.8000	1111	0.0	37.7	2400.0	18.2	614.0	4
O N		C	.1800	1111	0.0	0.0	1207.8	16.1	306.0	4
O N		D	.0850	1111	0.0	0.0	387.1	0.0	96.8	4
O N		E	.0460	1111	0.0	1300.0	12591.3	0.0	3472.8	4
O N		F	.0700	1111	0.0	982.9	11790.0	995.7	3442.1	4
O N		G	.1350	1111	1445.9	0.0	1237.0	0.0	670.7	4
O N		H	.1600	1111	35.6	5.0	4673.1	224.4	1234.5	4
O N		I	.0640	1111	0.0	0.0	0.0	0.0	0.0	4
O N		J	.1575	1111	0.0	0.0	531.4	0.0	132.9	4
O N		K	.1500	1111	0.0	0.0	1470.0	0.0	367.5	4
O N		L	.1000	1111	0.0	0.0	5.0	0.0	1.2	4
O N		M	.5400	1111	0.0	0.0	0.0	0.0	0.0	4
O N		N	.1400	1111	0.0	0.0	0.0	0.0	0.0	4
O N		O	.5400	1111	.3	0.0	13.0	0.0	3.3	4
O N		P	.1600	1111	0.0	0.0	6.2	0.0	1.6	4
O N		Q	.1575	1111	0.0	.9	106.0	12.7	29.9	4
O N		R	.1145	1111	9.6	210.5	8.7	0.0	57.2	4
O N		S	.0825	1111	0.0	0.0	470.3	0.0	117.6	4
O N		T	.0825	1111	0.0	4.8	3.6	0.0	2.1	4
O N		U	.1230	1111	0.0	0.0	0.0	0.0	0.0	4
O N		V	.2250	1111	0.0	80.0	3084.0	13.3	794.3	4
O N		W	.2500	1111	0.0	1.6	415.2	80.0	124.2	4
O N		X	.4750	1111	.6	93.1	175.4	1095.4	341.1	4
O N	SQ	1	2.3226	8000						0
O N	SQ	2	2.3226	1190	110.7	121.9			116.3	2
O N	SQ	3	2.3226	1119	0.0	.3	0.0		.1	3
O N	SQ	4	2.3226	1190	0.0	0.0			0.0	2
O N	SQ	5	2.3226	1111	391.0	0.0	0.0	0.0	97.7	4
O N	SQ	6	2.3226	1190	0.0	0.0			0.0	2
O N	SQ	7	2.3226	1152	593.2	.3		3854.4	1112.0	4
O N	SQ	8	2.3226	1111	15799.9	12171.0	1944.1	0.0	7478.7	4
O N	SQ	9	2.3226	1111	2529.9	1618.4	2167.5	0.0	1579.0	4
O N	SQ	10	2.3226	1190	.0	0.0			.0	2
O N	SQ	11	2.3226	1190	.1	0.0			.0	2
O N	SQ	15	2.3226	0180		1.6			1.6	1
O N	SQ	16	2.3226	0811			3008.6	41.4	1525.0	2
O N	SQ	17	2.3226	0111		5.3	715.4	.9	240.5	3
O N	SQ	18	2.3226	0119		0.0	1507.4		753.7	2
O N	SQ	19	1.7420	0819			2773.8		2773.8	1
O N	SQ	20	2.3226	0111		182.9	1222.7	8.0	471.2	3
O N	SQ	21	2.3226	0180		1298.3			1298.3	1

PALLISER

SITE		AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
PALL	1	1.2000	1111	14.3	2.2	3.3	2.7	5.6	4
PALL	2	.1320	1111	0.0	3.8	41.7	0.0	11.4	4
PALL	3	.3500	1111	1.7	51.4	0.0	1.1	13.6	4
PALL	4	.2700	1111	17.8	0.0	0.0	44.1	15.5	4
PALL	5	.3600	1111	0.0	0.0	1.4	51.7	13.3	4
PALL	6	.4200	1111	7.6	0.0	1.9	98.1	26.9	4
PALL	7	.5400	1111	0.0	0.0	5.0	2.2	1.8	4
PALL	8	1.0000	1111	0.0	0.0	29.5	48.9	19.6	4
PALL	9	1.8000	1111	0.0	0.0	14.9	0.0	3.7	4
PALL	10	.4800	1111	0.0	0.0	111.5	0.0	27.9	4
PALL	11	.3000	1111	0.0	0.0	2.3	250.7	63.2	4
PALL	12	.5400	1111	0.0	0.0	0.0	40.2	10.0	4
PALL	13	.5700	1111	0.0	6744.9	0.0	0.0	1686.2	4
PALL	14	.7200	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	15	.4800	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	16	.9600	1111	10.5	0.0	0.0	0.0	2.6	4
PALL	17	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	18	3.2000	1111	3.4	0.0	0.0	3.9	1.8	4
PALL	19	.4800	1111	0.0	10.6	0.0	0.0	2.7	4
PALL	20	.5000	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	21	.3900	0111		0.0	0.0	0.0	0.0	3
PALL	22	.6000	1111	.2	223.5	0.0	0.0	55.9	4
PALL	23	.5600	1111	.7	0.0	0.0	0.0	.2	4
PALL	24	.6600	1111	.6	0.0	0.0	76.7	19.3	4
PALL	25	.3900	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	26	.4200	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	27	.2700	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	28	.2700	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	29	.2400	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	30	.2000	1111	0.0	.5	0.0	0.0	.1	4
PALL	31	.2000	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	32	.1400	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	33	.2800	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	34	.3200	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	35	.1750	1111	.2	0.0	0.0	0.0	.1	4
PALL	36	.3900	1111	6.4	0.0	0.0	0.0	1.6	4
PALL	37	.4900	1111	0.0	5.9	0.0	0.0	1.5	4
PALL	38	.0600	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	39	.3600	1111	6.9	0.0	0.0	0.0	1.7	4
PALL	40	.2700	1111	15435.9	.7	0.0	0.0	3859.2	4
PALL	41	.5600	1111	0.0	0.0	0.0	347.7	86.9	4
PALL	42	.7200	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	43	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	44	.6300	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	45	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	46	.2700	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	47	.3000	1111	1.0	0.0	0.0	0.0	.3	4
PALL	48	.1800	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	49	.1350	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	50	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	51	.2400	1111	0.0	0.0	0.0	0.0	0.0	4
PALL	52	.1400	1111	0.0	0.0	2274.3	0.0	568.6	4
PALL	53	1.0800	1111	0.0	0.0	1226.1	.8	306.7	4
PALL	54	.7700	1111	1.2	0.0	2651.3	.6	663.3	4
PALL	55	.2000	1111	8.5	0.0	7239.5	8.0	1814.0	4
PALL	56.	.4200	1111	0.0	.7	13547.9	217.9	3441.6	4
PALL	57	.3600	1111	0.0	0.0	6131.9	1.1	1533.3	4
PALL	58	.3000	1111	0.0	0.0	1704.7	0.0	426.2	4
PALL	59	.8100	1111	0.0	0.0	414.6	0.0	103.6	4
PALL	60	.1500	1111	0.0	0.0	26.7	0.0	6.7	4
PALL	61	.5400	1111	0.0	0.0	98.5	.9	24.9	4
PALL	62	.1915	1111	.2	0.0	15.7	0.0	4.0	4
PALL	63	5.9400	4004						0
PALL	64	.2400	1160	0.0	0.0			0.0	2
PALL	65	.1915	1111	0.0	0.0	10.4	0.0	2.6	4
PALL	66	.2100	1111	0.0	0.0	118.1	6578.6	1674.2	4
PALL	67	.1800	1111	0.0	0.0	97.2	2293.9	597.8	4
PALL	68	.1050	1111	0.0	0.0	42.9	10436.2	2619.8	4
PALL	69	.2400	1111	47250.0	0.0	9.2	2368.3	12406.9	4
PALL	70	.3500	1111	73.1	0.0	2.9	51652.0	12932.0	4
PALL	71	.1050	1111	0.0	0.0	10.5	828.6	209.8	4
PALL	72	.1750	1111	2.9	0.0	0.0	225400.6	56350.9	4
PALL	73	.2000	1111	0.0	0.0	1236.0	126.0	340.5	4
PALL	74	.2100	1111	0.0	0.0	4.8	967.1	243.0	4
PALL	75	.2500	1111	0.0	0.0	57.2	147.6	51.2	4
PALL	76	.1625	1111	0.0	0.0	364.9	0.0	91.2	4
PALL	77	.2700	1111	0.0	0.0	41.9	1115.2	289.3	4
PALL	78	.6000	1111	0.0	0.0	95.2	637.3	183.1	4
PALL	79	.1200	1111	0.0	0.0	2220.8	0.0	555.2	4
PALL	80	.0909	1111	0.0	0.0	3725.7	0.0	931.4	4

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
PALL 81	.1350	1111	0.0	0.0	375.6	2217.3	648.3	4
PALL 82	.2200	1111	0.0	0.0	523.6	0.0	130.9	4
PALL 83	.1800	1111	5.6	0.0	1002.2	22.4	257.6	4
PALL 84	.3000	1111	3.0	0.0	185.7	33.7	55.6	4
PALL 85	.1050	1111	0.0	0.0	6385.7	471.4	1714.3	4
PALL 86	.2450	1111	264.9	0.0	76.7	0.0	85.4	4
PALL 87	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 88	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 89	.4200	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 90	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 91	.1650	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 92	.4800	4000						0
PALL 93	8.4000	4000						0
PALL 94	5.5000	4000						0
PALL 95	.9600	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 96	1.2000	1111	0.0	0.0	0.0	3.7	.9	4
PALL 97	.5400	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 98	.5400	1111	2.4	0.0	0.0	99.6	25.5	4
PALL 99	.2700	1111	0.0	0.0	0.0	0.0	0.0	4
PALL 100	.2500	1111	2935.6	0.0	0.0	0.0	733.9	4
PALL 101	.2200	1111	959.5	0.0	0.0	185.9	286.4	4
PALL 102	.2200	1111	442.3	0.0	0.0	0.0	110.6	4
PALL 103	.3075	1111	551.2	0.0	0.0	0.0	137.8	4
PALL 104	.4000	1111	38.2	0.0	0.0	44.5	20.7	4
PALL 105	.2500	1111	436.0	0.0	0.0	0.0	109.0	4
PALL 106	.1200	1111	64831.7	0.0	0.0	0.0	16207.9	4
PALL 107	.2475	1111	35.2	0.0	0.0	0.0	8.8	4
PALL 108	.2380	1111	280.7	0.0	0.0	0.0	70.2	4
PALL 110	.5000	0111		0.0	20.0	0.0	6.7	3
PALL 111	.2100	0111		0.0	0.0	0.0	0.0	3
PALL 112	.0750	0111		0.0	0.0	31564.0	10521.3	3
PALL 113	.0900	0111		0.0	0.0	0.0	0.0	3
PALL 114	.2100	0111		0.0	0.0	0.0	0.0	3
PALL 114A	.1650	0111		0.0	0.0	0.0	0.0	3
PALL 115	.2100	0111		0.0	0.0	0.0	0.0	3
PALL 116	.5300	0111		5920.9	22.1	0.0	1981.0	3
PALL 117	.1000	0111		0.0	0.0	0.0	0.0	3
PALL 118		0700						0
PALL 119	.3000	0111		0.0	206.7	0.0	68.9	3
PALL 120	.2025	0111		0.0	0.0	0.0	0.0	3
PALL 121	.3000	0111		0.0	35.0	0.0	11.7	3
PALL 122	.3000	0111		6.0	7.7	1.3	5.0	3
PALL 123	.3000	0111		0.0	4.3	0.0	1.4	3
PALL 124	.3600	0111		0.0	0.0	0.0	0.0	3
PALL 125	.2700	0111		0.0	0.0	0.0	0.0	3
PALL 126	.1500	0111		0.0	0.0	0.0	0.0	3
PALL 127	.3475	0111		0.0	0.0	0.0	0.0	3
PALL 128	.1500	0111		0.0	0.0	0.0	0.0	3
PALL 129	.1350	0111		0.0	0.0	299.3	99.8	3
PALL 130	.1800	0111		0.0	0.0	0.0	0.0	3
+AL SQ 4	2.3226	1190	42.6	57.6			50.1	2
+AL SQ 5	2.3226	1190	7603.0	0.0			3801.5	2
+AL SQ 6	2.3226	1190	2.2	0.0			1.1	2
+AL SQ 7	2.3226	1190	74.5	3.4			39.0	2
+AL SQ 8	2.3226	8000						0
+AL SQ 9	2.3226	8000						0
+AL SQ 10	2.3226	1900	1613.9				1613.9	1
+AL SQ 11	2.3226	1190	.0	0.0			.0	2
+AL SQ 12	2.3226	1190	.4	3.0			1.7	2
+AL SQ 13	2.3226	1190	0.0	0.0			0.0	2
+AL SQ 14	2.3226	1190	1.9	0.0			.9	2
+AL SQ 15	2.3226	1190	2.8	39.2			21.0	2
+AL SQ 16	2.3226	1190	0.0	0.0			0.0	2
+AL SQ 17	2.3226	1190	0.0	0.0			0.0	2
+AL SQ 18	2.3226	1900	0.0				0.0	1
+AL SQ 19	2.3226	1900	1280.3				1280.3	1
+AL SQ 20	2.3226	1111	4473.8	4.0	0.0	23.6	1125.3	4
+AL SQ 21	2.3226	1190	236.4	0.0			118.2	2
+AL SQ 22	2.3226	1190	0.0	0.0			0.0	2
+AL SQ 23	2.3226	1190	1.1	0.0			.6	2
+AL SQ 24	2.3226	1190	0.0	0.0			0.0	2
+AL SQ 25	2.3226	1119	1661.0	285.5	0.0		648.8	3
+AL SQ 26	2.3226	1190	1668.6	0.0			834.3	2
PAL SQ 30	2.3226	0111		0.0	35.1	2882.3	972.5	3
PAL SQ 31	2.3226	0119		0.0	180.0		90.0	2
PAL SQ 32	2.3226	0119		74.9	13148.1		6611.5	2
PAL SQ 33	2.3226	0180		1114.1			1114.1	1
PAL SQ 34	2.3226	0119		90.6	969.6		530.1	2
PAL SQ 35	2.3226	0180		270.0			270.0	1
PAL SQ 36	2.3226	0119		703.7	3488.7		2096.2	2
PAL SQ 37	2.3226	0189		0.0			0.0	1
PAL SQ 38	2.3226	0119		0.0	881.1		440.5	2

STRIKE VALLEY

SITE		AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
S V	1	1.3600	1111	0.0	0.0	0.0	0.0	0.0	4
S V	2	.9750	1111	0.0	0.0	0.0	0.0	0.0	4
S V	3	.2100	1111	0.0	0.0	0.0	0.0	0.0	4
S V	4	.5600	1111	0.0	0.0	0.0	0.0	0.0	4
S V	5	.3600	1111	0.0	0.0	0.0	0.0	0.0	4
S V	6	.2450	1111	0.0	0.0	0.0	0.0	0.0	4
S V	7	.1790	1111	0.0	5.0	0.0	0.0	1.3	4
S V	8	.4125	1111	0.0	0.0	0.0	0.0	0.0	4
S V	9	.3200	1111	0.0	0.0	0.0	0.0	0.0	4
S V	10	.6300	1111	0.0	0.0	0.0	0.0	0.0	4
S V	11	.4350	1111	0.0	0.0	0.0	0.0	0.0	4
S V	12	.6300	1111	0.0	0.0	0.0	0.0	0.0	4
S V	13	.4050	1111	0.0	0.0	0.0	0.0	0.0	4
S V	14	.5950	5211		24.7	609.1	0.0	158.4	4
S V	15	.5400	1111	974.8	232.0	3929.4	0.0	1284.1	4
S V	16	.9000	1111	11.6	0.0	337.3	0.0	87.2	4
S V	17	.4500	1111	1.6	0.0	16092.4	2.0	4024.0	4
S V	18	.8000	1111	820.7	0.0	6.4	0.0	206.8	4
S V	19	.4425	1111	36965.2	15.1	371.8	1135.6	9621.4	4
S V	20	1.3300	1111	9836.3	14.0	4188.9	2.3	3510.4	4
S V	21	2.7900	1111	4534.7	295.8	2790.2	1.7	1905.6	4
S V	22		7000						0
S V	23	.3700	1111	14538.4	11796.5	31.6	11.4	6594.5	4
S V	24	.8400	1600	62.5				62.5	1
S V	25	.3500	1111	31695.1	26850.3	2010.9	6.6	15140.7	4
S V	26	.5170	1111	6.2	10535.4	2067.3	13702.9	6577.9	4
S V	27	.5800	1111	1204.1	22637.1	1028.1	2.6	6218.0	4
S V	28	.8375	1111	260.7	13510.8	695.3	65.2	3633.0	4
S V	29	.4200	1111	0.0	24040.5	91.4	0.0	6033.0	4
S V	30	1.0500	1111	8620.7	185.5	276.1	.6	2270.7	4
S V	31		7000						0
S V	32	.4050	1111	6125.7	1695.8	580.2	4.4	2101.5	4
S V	33	.4200	1111	196.0	2429.8	4.8	42.1	668.2	4
S V	34	.7700	1111	19310.5	3.9	34.7	2014.2	5340.6	4
S V	35	1.2000	1111	479.7	7166.5	6.6	30.2	1920.8	4
S V	36	.3500	1111	0.0	153.4	0.0	234.0	96.9	4
S V	37	1.3500	1111	4459.5	11.0	35.3	3899.6	2101.4	4
S V	38	.9000	1111	8022.7	1862.1	7.3	11724.1	5404.1	4
S V	39	1.6500	1111	5.9	2.6	.6	78.2	21.8	4
S V	40	.3600	1111	0.0	10.6	0.0	1.1	2.9	4
S V	41	.1400	1111	0.0	5.7	0.0	0.0	1.4	4
S V	42	.6600	1111	19.7	2592.3	0.0	0.0	653.0	4
S V	43	.4400	1111	.5	770.5	0.0	0.0	192.7	4
S V	44	1.3085	1170	13.3	2751.5			1382.4	2
S V	45	.8750	1111	8445.0	51.5	2696.8	7.8	2800.3	4
S V	46	.7350	5211		2079.5	907.1	1.4	747.0	4
S V	47	.8250	1111	212.7	38969.9	135.9	4.8	9830.8	4
S V	48	1.8000	1111	20213.8	1414.6	71.0	3.8	5425.8	4
S V	49	1.5100	1111	32.4	102.1	190.2	.7	81.3	4
S V	50	1.4450	1111	15.5	21163.4	701.7	139.2	5505.0	4
S V	51	1.1700	1111	3.0	761.8	2582.9	12.1	839.9	4
S V	52	.4200	1110	0.0	912.4	2441582.9		814165.1	3
S V	52	2.7000	0001				14.3	259062.3	4
S V	53	.5850	1111	98.3	1154.7	5.1	3.4	315.4	4
S V	54	1.1500	1111	.1	2054.7	5070.9	11.3	1784.2	4
S V	55	.5637	1111	0.0	954.6	.9	0.0	238.9	4
S V	56	.6000	1111	0.0	1272.8	18.3	24.2	328.8	4
S V	57	.9800	1111	0.0	188.7	1.0	0.0	47.4	4
S V	58	.3300	1111	0.0	1.5	0.0	0.0	.4	4
S V	59	.4500	1111	.7	49275.6	0.0	0.0	12319.1	4
S V	60	.3300	1111	.2	2046.1	2.7	0.0	512.3	4
S V	61	1.4400	1111	.3	155.1	9.6	0.0	41.2	4
S V	62	.1750	1111	0.0	2.9	0.0	0.0	.7	4
S V	63	.2250	5211		38907.1	0.0	0.0	9726.8	4

SURPRISE 2

SITE		AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
S2	1	.8880	1111	0.0	2.8	365.7	2.5	92.7	4
S2	2	.4300	1521	0.0		81.6	0.0	20.4	4
S2	3	.8880	1521	0.0		212.2	0.0	53.0	4
S2	4	.8040	1521	.4		31.0	0.0	7.8	4
S2	5	.5600	1111	2.7	74.1	27.7	0.0	26.1	4
S2	6	.2800	1521	69.3		56.6	64.6	47.7	4
S2	7	.4800	1521	23.7		13.7	14.2	12.9	4
S2	8	.4200	1111	24.3	101.0	66.7	24.0	54.0	4
S2	9	.4200	1111	12.6	2524.3	147.6	2.4	671.7	4
S2	10	.4500	1111	0.0	201.3	0.0	13.3	53.7	4
S2	11	.7200	1111	.1	210.6	8.1	0.0	54.7	4
S2	12	.4050	1111	.5	350.1	44.2	47.7	110.6	4
S2	13	.8400	1155	1.1	124.4			62.7	2
S2	14	.4050	1155	.5	26.4			13.5	2
S2	15	.7200	1111	0.0	7.5	2.8	0.0	2.6	4
S2	16	.6300	1152	.5	17.6		12.1	7.5	4
S2	17	.3900	1111	2.3	7.2	5.1	0.0	3.7	4
S2	18	.5350	1111	0.0	63.7	1.9	0.0	16.4	4
S2	19	1.1300	1521	1.1		11.2	0.0	3.1	4
S2	20	.6000	1521	0.0		17.0	0.0	4.2	4
S2	21	1.4600	1521	3.4		80.8	0.0	21.0	4
S2	22	.3300	1521	0.0		42.7	0.0	10.7	4
S2	23	.3500	1521	0.0		104.6	0.0	26.1	4
S2	24	.7600	1521	0.0		25.7	.4	6.5	4
S2	25	.6400	1521	0.0		65.5	.3	16.4	4
S2	26	.2000	1521	9.0		121.5	0.0	32.6	4
S2	27	.4800	1521	11.7		52.5	0.0	16.0	4
S2	28	.3700	1111	1.1	52.2	4.1	0.0	14.3	4
S2	29	.2700	1111	0.0	201.1	1.9	0.0	50.7	4
S2	30	.9600	1521	1.3		36.1	.6	9.5	4
S2	31	.9000	1521	.1		147.6	0.0	36.9	4
S2	32	.4000	1521	0.0		88.0	1.2	22.3	4
S2	33	.4200	1521	0.0		125.0	0.0	31.3	4
S2	34	.6300	1111	0.0	106.8	17.6	0.0	31.2	4
S2	35	2.2500	1111	.2	23.0	.9	0.0	6.0	4
S2	36	1.2000	1111	7.6	45.3	0.0	0.0	13.2	4
S2	37	.7000	1111	.1	47.9	7.7	465.3	130.2	4
S2	38	.4500	1111	29.1	112.7	200.2	0.0	85.5	4
S2	39	1.1800	1111	11.5	23655.3	23.2	93.2	5945.8	4
S2	40	.8100	1111	57.2	95.1	4.7	0.0	39.2	4
S2	41	.1500	1111	4.0	284.7	14.7	0.0	75.8	4
S2	42	.1352	1111	0.0	6.7	0.0	0.0	1.7	4
S2	43	.0816	1111	23.3	23.3	0.0	0.0	11.6	4
S2	44	.3125	1111	1.0	42.2	3.8	.3	11.8	4
S2	45	.4500	1111	31.1	29.6	24.9	2.0	21.9	4
S2	46	.4200	1111	2.4	219.8	1.4	.2	56.0	4
S2	47	1.1800	1111	35.1	18.0	.4	0.0	13.4	4
S2	48	.3600	1111	68.6	56.4	0.0	0.0	31.3	4
S2	49	1.4000	1111	3.1	146.6	0.0	0.0	37.4	4
S2	50	.9600	1111	2.6	42.1	1.6	0.0	11.6	4
S2	51	.4200	1521	52.4		76.4	1.0	32.4	4
S2	52	1.5375	1111	103.7	30.0	0.0	0.0	33.4	4
S2	53	.7200	1521	1380.8		555.4	1.5	484.4	4
S2	54	2.4300	1111	2338.0	108.2	.4	.4	611.8	4
S2	55	1.0200	1111	4924.8	329.2	6.0	1.0	1315.2	4
S2	56	.6450	1111	371.3	467.8	4.7	.3	211.1	4
S2	57	.4400	1111	10.9	161.6	0.0	0.0	43.1	4
S2	58	.3880	1111	3637.9	152.1	0.0	0.0	947.5	4
S2	59	.2550	1111	6797.3	47.5	0.0	0.0	1711.2	4
S2	60	.2670	1111	1613.1	0.0	3.7	0.0	404.2	4
S2	61	.2100	1111	964.8	0.0	0.0	0.0	241.2	4
S2	62	1.5300	1111	619.3	17.5	1.1	0.0	159.5	4
S2	63	.3500	1111	516.0	.1	1.4	0.0	129.4	4
S2	64	.5800	1111	2558.8	1.4	.9	0.0	640.3	4
S2	65	.3250	1111	820.6	6.2	11.4	0.0	209.5	4
S2	66	.3600	1111	271.7	43.9	5.6	.6	80.4	4
S2	67	.2250	1111	1256.9	3.6	2.2	72.0	333.7	4
S2	68	.1100	1111	298.2	7.3	0.0	2111.8	604.3	4
S2	69	.6000	1111	758.8	7.3	42.5	34.2	210.7	4
S2	70	.1350	1111	231.1	3.0	0.0	51.9	71.5	4
S2	71	.1575	1111	200.6	23.5	6.3	63.5	73.5	4
S2	72	.3270	1111	1102.1	83.8	3.1	60.2	312.3	4
S2	73	.1857	1111	383.4	8.1	10.8	236.9	159.8	4
S2	74	.2700	1111	464.8	80521.1	47.0	515.9	20387.2	4
S2	75	.1756	1152	287.6	0.0		1521.1	452.2	4
S2	76	.1200	1111	45.8	6.7	113.3	1696.7	465.6	4
S2	77	.0875	1111	1834.3	33.1	57.1	54.5	489.7	4
S2	78	1.4625	1111	4189.1	264.2	118.9	49.1	1155.3	4
S2	79	.3120	1111	826.9	6.1	44.3	833.0	437.5	4
S2	80	.6400	1111	32094.5	103.3	5777.7	119.5	9723.7	4

SITE		AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
S2	81	.2375	1111	10022.7	41.7	107.8	4.2	2544.1	4
S2	82	.0900	1111	18.9	708.9	22.2	64.4	203.6	4
S2	83	.1400	1111	47.1	34.3	35.7	0.0	29.3	4
S2	84	.2110	1111	263.5	314.7	5983.9	.5	1640.6	4
S2	85	.1950	1111	1346.7	95.9	5.1	80.0	381.9	4
S2	86	.2075	1111	542.2	984.1	8536.9	1088.2	2787.8	4
S2	87	.1375	1111	400.0	4186.2	1136.7	8182.5	3476.4	4
S2	88	.0750	5290		150.7			75.3	2
S2	89	.1200	1111	1610.0	3200.8	5629.2	1243.3	2920.8	4
S2	90	.1050	1111	117.1	1571.4	27384.8	29700.0	14693.3	4
S2	91	1.1625	1111	525.5	1108.4	10229.2	22254.4	8529.4	4
S2	92	.2100	1111	733.8	1180.5	8943.3	4028.1	3721.4	4
S2	93	1.7200	1111	264.0	59.2	1648.2	796.6	692.0	4
S2	94	.9100	1111	201.4	144.7	2200.7	499.6	761.6	4
S2	95	.0952	1170	219840.3	542.0			110191.2	2
S2	96	.4050	1111	1917.5	1715.6	63465.7	2979.3	17519.5	4
S2	97	.2100	1111	138487.6	6677.1	8877.6	3283.3	39331.4	4
S2	98	.1550	1170	22067.7	250.3			11159.0	2
S2	99	1.3300	1111	966.0	530.7	973.8	3015.5	1372.0	4
S2	100	.6400	1111	2668.3	1870.2	36850.9	9495.3	12721.2	4
S2	101	.0675	1111	6669.6	20.7	5694.8	183.7	3142.2	4
S2	102		7000						0
S2	103	.2400	1111	1456.2	2320.4	208.3	2115.6	1525.2	4
S2	104	.3600	1111	2760.8	2124.7	539.2	229.2	1413.5	4
S2	105	.0480	1111	927.1	2120.8	760.4	17414.6	5305.7	4
S2	106	.0550	1111	5372.7	805.5	37083.6	1136.4	11099.5	4
S2	107	.4800	5211		148.3	736.2	1210.4	523.7	4
S2	108	.0750	1111	600.0	4929.3	533.3	2686.7	2187.3	4
S2	109	3.1500	1111	1177.0	2386.1	709.4	321.9	1148.6	4
S2	110	.8400	1111	289.9	74.0	59.0	294.8	179.4	4
S2	111	.4800	1111	0.0	85.8	3.1	.4	22.3	4
S2	112	.1800	1111	0.0	656.1	7.2	0.0	165.8	4
S2	113	.5400	1111	15.4	143.7	0.0	3.1	40.6	4
S2	114	.4250	1172	0.0	293.2		204.0	124.3	4
S2	115	.1050	1111	0.0	36.2	0.0	398.1	108.6	4
S2	116	.1000	1111	.4	67.0	23.0	0.0	22.6	4
S2	119		7000						0
S2	117	.1562	1111	0.0	258.6	8.3	1392.4	414.9	4
S2	118	.1200	1111	5930.8	41.7	26.7	5.8	1501.2	4
S2	120	.3200	1111	2373.7	391.9	384.7	52.2	800.6	4
S2	121	.8800	1111	581.9	48.0	14.0	24.5	167.1	4
S2	122	1.3200	1111	323.9	232.3	4.2	132.3	173.2	4
S2	123	.1797	1111	13.4	310.0	0.0	2936.0	814.8	4
S2	124	.3300	1700	.8				.8	1
S2	125	.4200	1111	.1	5.5	0.0	130.5	34.0	4
S2	126	.3600	1111	0.0	665.6	0.0	8.3	168.5	4
S2	127	.8400	1111	587.1	656.7	0.0	2265.8	877.4	4
S2	128	.3000	1152	2.7	814.7		23.0	210.1	4
S2	129	.9900	1152	48825.3	212.7		49.7	12271.9	4
S2	130	.3600	1152	9.2	2701.7		13.9	681.2	4
S2	131	.1800	1152	10.0	31.1		16.7	14.4	4
S2	132	.5500	1152	.7	40.5		614.0	163.8	4.
S2	133	.7500	1152	0.0	0.0		66.9	16.7	4
S2	134	.4400	1152	.9	0.0		16.6	4.4	4
S2	135	.7400	1152	2.4	14595.0		750.7	3837.0	4
S2	136	2.0840	1152	43.6	7754.3		521.0	2079.8	4
S2	137	.2880	1152	7736.8	6.9		0.0	1935.9	4
S2	138	.1220	1152	280841.0	0.0		0.0	70210.2	4
S2	139		6000						0
S2	140	.1050	1152	0.0	0.0		0.0	0.0	4
S2	141	.1350	1152	11.1	8.1		0.0	4.8	4
S2	142	.1575	1111	0.0	14.6	0.0	0.0	3.7	4
S2	143	.1480	1111	13.5	3994.6	0.0	4637.2	2161.3	4
S2	144	.8400	1111	4.8	68.0	0.0	0.0	18.2	4
S2	145	.2560	1152	0.0	0.0		0.0	0.0	4
S2	146	.4320	1152	0.0	.0		0.0	.0	4
S2	147	.0845	1111	0.0	0.0	0.0	0.0	0.0	4
S2	148	.1800	1111	3.3	651.1	0.0	0.0	163.6	4
S2	149	.0385	1111	.8	0.0	0.0	0.0	.2	4
S2	150	.5250	1111	0.0	.4	0.0	0.0	.1	4
S2	151	.1485	1111	0.0	0.0	0.0	0.0	0.0	4
S2	152	.0450	1111	11.1	28.9	695.6	0.0	183.9	4
S2	153	.0375	1111	2605.3	138.7	0.0	0.0	686.0	4
S2	154	.1800	1111	0.0	0.0	0.0	0.0	0.0	4
S2	155	.1800	1111	27.2	0.0	0.0	0.0	6.8	4
S2	156	.0625	1111	0.0	0.0	116.8	0.0	29.2	4
S2	157	.0975	1111	0.0	0.0	0.0	0.0	0.0	4
S2	158	.2400	1111	0.0	12.9	0.0	0.0	3.2	4
S2	159	.1650	1111	34.5	0.0	0.0	0.0	8.6	4
S2	160	.1800	1111	0.0	6.1	0.0	0.0	1.5	4
S2 SQ	A	2.3226	1152	0.0	36.9		122.2	39.8	4
S2 SQ	B	2.3226	1152	25.9	659.0		2302.9	746.9	4
S2 SQ	C	2.3226	1159	30.4	7220.7			3625.5	2

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
S2SO D	1.1613	1152	3.0	.7		12.2	4.0	4
S2SO E	2.3226	1150	29.5	122.0			75.7	2
S2SO E	1.0000	0002				1228.0	237.7	2
S2 SO 0 1	2.3226	1111	55.3	25.6	2.2	29.2	28.1	4
S2 SO 0 2	2.3226	1199	3480.4	3.1			1741.8	2
S2 SO 0 3	2.3226	1110	673.5	1.4	5.8		226.9	3
S2 SO 0 3	1.0000	0001				1001.1	324.1	1
S2 OSO 4	.2200	1010	3889.1				3889.1	1
S2 OSO 5		8000						0
S2 OSO 6	.6000	1000	1089.8				1089.8	1
S2 OSO 7		8000						0
S2 OSO 8	1.1500	1010	5823.6				5823.6	1
S2 SO 0 9	2.3226	1159	0.0	100.0			50.0	2
S2 SO 010	1.1613	1159	0.0	4.1			2.1	2
S2 SO 011	2.3226	1521	5.1		15.9	0.0	5.2	4
S2 SO 012	2.3226	1559	0.0				0.0	1
S2 SG 1	2.3226	0111		29.7	20.5	0.0	16.7	3
S2 SG 2	2.3226	0111		5.1	28.6	0.0	11.2	3
S2 SG 3	2.3226	0111		80.8	613.6	.4	231.6	3
S2 SG 4	2.3226	0119		19.4	43.6		31.5	2
S2 SG 5	2.3226	0111		242.4	469.3	1707.1	806.3	3
S2 SG 6	2.3226	0111		159.6	3661.7	915.6	1578.9	3
S2 SG 7	2.3226	0111		140.5	134.3	164.4	146.4	3
S2 SG 8	2.3226	0111		64.2	46.2	826.9	312.4	3
S2 SG 9	2.3226	0111		88.0	233.0	203.5	174.8	3
S2 SG 10	2.3226	0111		40.9	146.4	696.5	294.6	3
S2 SG 11	2.3226	0811			966.5	38.4	502.4	2
S2 SG 12	2.3226	0111		474.6	741.2	37.9	417.9	3
S2 SG 13	2.3226	0811			244.7	46.4	145.6	2
S2 SG 14	2.3226	0111		26.0	408.7	29.7	154.8	3
S2 SG 15	2.3226	0111		185.4	74.7	82.7	114.3	3
S2 SG 16	2.3226	0111		94.8	94.5	66.0	85.1	3
S2 SG 17	2.3226	0111		4571.5	285.5	175.7	1677.6	3
S2 SG 18	2.3226	0111		512.8	1476.6	317.1	768.9	3
S2 N 150	.3060	0111		5.9	0.0	602.3	202.7	3
S2 N 151	.2000	0111		0.0	167.5	34.0	67.2	3
S2 N 152	.1200	0111		0.0	38.3	0.0	12.8	3
S2 N 153	.2000	0111		51.0	4.5	18.0	24.5	3
S2 N 154	.2300	0111		9.1	560.0	0.0	189.7	3
S2 N 155	.1050	0111		41.0	0.0	0.0	13.7	3
S2 N 156	.1575	0111		125.7	0.0	0.0	41.9	3
S2 N 157	.0875	0111		1.6	0.0	0.0	.5	3
S2 N 158	.3600	0111		276.9	0.0	36.7	104.5	3
S2 N 159	.0875	0111		625.1	0.0	0.0	208.4	3
S2 N 160	.0700	0111		44.3	578.6	0.0	207.6	3
S2 N 161	.1650	0111		18.2	23.6	0.0	13.9	3
S2 N 162	.2950	0111		43.4	0.0	46.1	29.8	3
S2 N 163	.1200	0111		30.8	0.0	26.7	19.2	3
S2 N 164	.2100	0111		489.5	11.0	0.0	166.8	3
S2 N 165	.1800	0111		20.0	0.0	0.0	6.7	3
S2 N 166	.2025	0111		984.2	0.0	41.5	341.9	3
S2 N 167	.1225	0111		6.5	0.0	0.0	2.2	3
S2 N 168	.2000	0111		19.0	0.0	0.0	6.3	3
S2 N 169	.1680	0169		236.9			236.9	1
S2 N 170	.0600	0111		78.3	0.0	0.0	26.1	3
S2 N 171	.2000	0111		1249.0	49555.0	220.5	17008.2	3
S2 N 172	.1350	0111		56.3	6.7	388.1	150.4	3
S2 N 173	.1050	0111		173.3	5.7	1195.2	458.1	3
S2 N 174	.1350	0111		45.2	11.9	29.6	28.9	3
S2 N 175	1.6200	0111		937.0	1.9	52.8	330.5	3
S2 N 175A	.4500	0111		142.9	9.8	78.3	77.0	3
S2 N 176	.6325	0111		55.5	13.9	238.3	102.6	3
S2 N 177	.4200	0111		155.2	10.2	155.5	107.0	3
S2 N 178	1.6500	0111		410.4	3.0	84.1	165.8	3
S2 N 179	1.3500	0111		376.4	5.2	522.5	301.4	3
S2 N 180	.7200	0111		149.0	244.0	105.3	166.1	3
S2 N 181	.5100	0111		463.3	1.0	125.5	196.6	3
S2 N 182	.3600	0111		434.7	65.9	116.7	205.1	3
S2 N 183	.2300	0111		83.5	1146.0	478.1	569.2	3
S2 N 184	.3675	0111		196.7	463.9	446.5	369.1	3
S2 N 185	.2200	0111		143.2	1.4	7067.3	2403.9	3
S2 N 186	.4200	0111		168.6	14.0	6094.3	2092.3	3
S2 N 187	.1575	0111		18.4	10.8	6052.7	2027.3	3
S2 N 188	.1050	0111		46.7	9.5	6606.7	2221.0	3
S2 N 188A	.2400	0111		140.0	17.5	10569.2	3575.6	3
S2 N 189	.3325	0111		11.1	71.9	1580.5	554.5	3
S2 N 190	.3613	0111		62.0	77.8	14711.7	4950.5	3
S2 N 191	.5500	0111		63.8	50.0	652.9	255.6	3
S2 N 192	.3675	0111		493.3	646.3	263.7	467.8	3
S2 N 193	.1125	0111		32.0	99.6	680.9	270.8	3
S2 N 194	1.2775	0111		178.1	71.5	603.8	284.4	3
S2 N 195	.2400	0111		74.2	17.5	525.0	205.6	3
S2 N 196	.1650	0111		655.8	100.6	655.8	470.7	3

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
S2 N 196A	.4000	0111		243.2	43.2	1879.0	721.8	3
S2 N 197	.2200	0111		232.7	31.8	428.6	231.1	3
S2 N 198	.2700	0170		71.1			71.1	1
S2 N 199	.2400	0111		165.4	2518.3	117.1	933.6	3
S2 N 200	.4150	0111		102.2	13435.2	1110.1	4882.5	3
S2 N 201	1.9750	0111		310.6	1043.4	384.8	579.6	3
S2 N 202	.2250	0111		5388.4	38.2	88.9	1838.5	3
S2 N 203	.1050	0111		35.2	6489.5	131.4	2218.7	3
S2 N 204	.0875	0115		115.4	45.7		80.6	2
S2 N 210	.2100	0111		67.6	7.1	24.8	33.2	3
S2 N 211	.2250	0111		233.8	4.4	23.1	87.1	3
S2 N 212	.3100	0111		180.3	1.6	106.5	96.1	3
S2 N 213	.7650	0111		17.6	17.0	74.1	36.3	3
S2 N 214	.4700	0111		76.2	2.1	242.1	106.8	3
S2 N 215	.4950	0111		168.1	5.5	61.8	78.5	3
S2 N 216	.2600	0111		830.0	0.0	45.0	291.7	3
S2 N 217	.3300	0111		46.4	3.0	31.5	27.0	3
S2 N 218	.1925	0111		60.8	5.7	0.0	22.2	3
S2 N 219	.1750	0111		161.1	39.4	0.0	66.9	3
S2 N 220	.6750	0111		35.0	.7	.7	12.1	3
S2 N 221	.6650	0111		32.5	3.6	0.0	12.0	3
S2 N 222	.1200	0111		141.7	0.0	0.0	47.2	3
S2 N 223	.0875	0111		40.0	0.0	0.0	13.3	3
S2 N 224	.3400	0111		41.8	.6	0.0	14.1	3
S2 N 225	.1750	0111		13.7	38.9	0.0	17.5	3
S2 N 226	.2700	0111		39.3	1.9	5.6	15.6	3
S2 N 227	.2000	0111		57.0	9.0	0.0	22.0	3
S2 N 228	.6000	0111		40.7	2.2	0.0	14.3	3
S2 N 229	.1800	0111		4.4	0.0	0.0	1.5	3
S2 N 230	.1225	0111		1.6	0.0	0.0	.5	3
S2 N 231	.1500	0111		54.7	0.0	0.0	18.2	3
S2 N 232	.1500	0111		1918.7	0.0	0.0	639.6	3
S2 N 233		0600						0
S2 N 234	.3100	0111		5206.8	0.0	0.0	1735.6	3
S2 N 235	.3900	0111		57.9	0.0	0.0	19.3	3
S2 N 236	.1400	0111		72.9	0.0	0.0	24.3	3
S2 N 237	.1225	0111		71.8	35.1	0.0	35.6	3
S2 N 238	.1200	0111		59.2	33.3	0.0	30.8	3
S2 N 239	.2700	0111		20172.6	3.7	0.0	6725.4	3
S2 N 240	.5400	0111		18.3	10.4	0.0	9.6	3
S2 N 241	.3175	0111		12.6	0.0	5.7	6.1	3
S2 N 242	.2700	0111		14.8	0.0	0.0	4.9	3
S2 N 243	.2100	0111		6008.1	0.0	0.0	2002.7	3
S2 N 244	1.0050	0111		27.0	9.5	0.0	12.1	3
S2 N 245	.4200	0111		410.7	0.0	0.0	136.9	3
S2 N 246	.2500	0111		81.2	0.0	0.0	27.1	3
S2 N 247	.4050	0111		6.9	0.0	0.0	2.3	3
S2 N 248	.1800	0111		32.8	0.0	0.0	10.9	3
S2 N 249	.2310	0111		1461.5	0.0	0.0	487.2	3
S2 N 250	.3600	0111		771.7	0.0	0.0	257.2	3
S2 N 251	.9300	0111		2166.5	.5	0.0	722.3	3
S2 N 252	.4950	0111		21.8	0.0	0.0	7.3	3
S2 N 253	.9000	0111		33.1	1.1	0.0	11.4	3
S2 N 254	.1551	0111		172.8	0.0	0.0	57.6	3
S2 N 255	.5650	0521			134.3	.5	45.0	3
S2 N 256	.2250	0521			26.7	0.0	8.9	3

TUMBLINICREEK

SITE			AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
T	C	1	1.1250	1111	0.0	0.0	0.0	0.0	0.0	4
T	C	2	1.7543	1111	0.0	32.3	0.0	.5	8.2	4
T	C	3	1.9500	1111	12.5	1.8	0.0	18.3	8.1	4
T	C	4	.4900	1111	0.0	1.6	0.0	3.1	1.2	4
T	C	5	.4700	1111	0.0	.2	0.0	4.7	1.2	4
T	C	6	.4300	1111	1.2	0.0	0.0	18.4	4.9	4
T	C	7	1.5300	1111	6.6	0.0	0.0	1.0	1.9	4
T	C	8	.8050	1111	24.6	0.0	0.0	21.5	11.5	4
T	C	9	.1200	1111	16.7	0.0	0.0	0.0	4.2	4
T	C	10	.5600	1111	564.8	37.0	0.0	268.6	217.6	4
T	C	11	.1008	1111	85.3	0.0	0.0	0.0	21.3	4
T	C	12	.2100	1111	4.8	0.0	0.0	3.5	2.0	4
T	C	13	.5000	1111	0.0	0.0	0.0	0.0	0.0	4
T	C	14	.0420	1111	16.7	0.0	0.0	0.0	4.2	4
T	C	15	.2600	1111	0.0	0.0	0.0	0.0	0.0	4
T	C	16	.9400	1111	0.0	0.0	153.2	0.0	38.3	4
T	C	17	.2800	1116	0.0	0.0	0.0		0.0	3
T	C	18	.1875	1111	1.1	0.0	0.0	5268.3	1317.3	4
T	C	19	.3000	1111	0.0	0.0	0.0	0.0	0.0	4
T	C	20	.3500	1111	124.3	900.3	879.4	339.1	560.8	4
T	C	21	.2700	1152	0.0	8565.2		0.0	2141.3	4
T	C	22	.2100	1111	3.8	0.0	14556.7	2.4	3640.7	4
T	C	23	.7600	1141	850.9	0.0		1008.4	619.8	3
T	C	24	.5100	1111	.2	9.8	240.2	0.0	62.5	4
T	C	25	.2800	1111	.7	8052.1	97.1	0.0	2037.5	4
T	C	26	.2250	1111	1.3	0.0	18.2	0.0	4.9	4
T	C	27	.3600	1111	.3	3.3	1.4	4.4	2.4	4
T	C	28	.0960	1111	5.2	1329.2	41.7	0.0	344.0	4
T	C	29	.1200	1111	0.0	3623.5	62.5	43968.3	11913.5	4
T	C	30	.0725	1111	0.0	13300.7	0.0	27.6	3332.1	4
T	C	31	.0600	1111	0.0	2801.7	100361.7	0.0	25790.8	4
T	C	32	.1209	1111	0.0	28046.3	7683.2	2421.8	9537.8	4
T	C	33	.4680	1111	20.3	26399.6	24796.6	31.6	12812.0	4
T	C	34	.2700	1111	0.0	24280.7	585.6	0.0	6216.6	4
T	C	35	.1800	1111	0.0	11821.7	5.6	0.0	2956.8	4
T	C	36	.2445	1111	52.8	312.9	54.0	0.0	104.9	4
T	C	37	.2200	1111	5.5	841.4	4.5	0.0	212.8	4
T	C	38	.3290	1111	82.1	4091.5	15.2	1.2	1047.5	4
T	C	39	.3150	1111	364.8	1156.5	120.6	1.6	410.9	4
T	C	40	.3150	1111	4.8	66.3	34.3	0.0	26.3	4
T	C	41	.2000	1111	88.5	750.0	5.5	7.5	212.9	4
T	C	42	.4200	1111	0.0	286.0	463.6	0.0	187.4	4
T	C	43	.1375	1111	0.0	11209.5	66.2	101.1	2844.2	4
T	C	44	.2610	1111	57070.9	1019.2	9.6	588.5	14672.0	4
T	C	45	.6300	1111	8.6	8033.7	620.2	367.5	2257.5	4
T	C	46	.1140	1111	0.0	2414.9	165.8	169.3	687.5	4
T	C	47	.2640	1111	34174.2	674.6	545.1	6.4	8850.1	4
T	C	48	.1935	1111	67.2	391.7	77.5	5.2	135.4	4
T	C	49	.2800	1111	65.7	1201.8	1076.8	243.6	647.0	4
T	C	50	.3402	1111	4.4	1635.2	2303.9	150.2	1023.4	4
T	C	51	.5400	1111	106.7	774.4	1953.9	2.8	709.4	4
T	C	52	.7800	1111	2.6	1499.0	331.5	1.0	458.5	4
T	C	53	.4050	1111	165.7	772.8	32.3	302.2	318.3	4
T	C	54	.1400	1111	135.7	2316.4	2119.3	90001.4	23643.2	4
T	C	55	.2220	1111	6.3	136.0	3.2	175.7	80.3	4
T	C	56	.8400	1111	81.7	206.0	2088.8	14.6	597.8	4
T	C	57	.1540	1111	62.3	47.4	26135.7	9.1	6563.6	4
T	C	58	.2950	1111	23.4	25.8	7894.2	1444.7	2347.0	4
T	C	59	.5400	1111	9327.2	1062.4	8230.9	1571.9	5048.1	4
T	C	60	.5400	1111	5599.1	291.1	12.2	5605.0	2876.9	4
T	C	61	.2350	1111	1739.6	497.4	3259.1	419.1	1478.8	4
T	C	62	.4200	1111	890.0	194.8	890.2	448.3	605.8	4
T	C	63	1.0200	1111	776.4	9.0	999.2	2699.4	1121.0	4
T	C	64	4.0000	1111	3078.0	18.2	627.3	13888.3	4403.0	4
T	C	65	.9550	1111	697.1	145.3	49.6	5431.6	1580.9	4
T	C	66		6000						0
T	C	67	.1800	1111	673.9	35.9	43380.6	33775.6	19466.0	4
T	C	68	.8650	1111	1292.6	391.8	1162.0	5485.7	2083.0	4
T	C	69	.2156	1170	16044.5	41405.8			28725.2	2
T	C	70	.2000	1160	25371.5	2392.5			12882.0	2
T	C	71	1.0400	1111	11531.2	2022.8	7925.9	96251.7	29432.9	4
T	C	72	1.9000	1111	5868.0	63.8	46075.9	22753.7	18690.4	4
T	C	73	.2570	1116	3833.5	2154.1	0.0		1995.8	3
T	C	74	.4800	1111	2522.1	1633.1	60977.7	13213.5	19586.6	4
T	C	75	.3450	1600	12487.8				12487.8	1
T	C	76	.9500	1111	52.4	933.6	3509.5	684.2	1294.9	4
T	C	77	.1220	1111	1668.9	557.4	146.7	2122.1	1123.8	4
T	C	78	.3150	1111	118.7	0.0	191.4	26967.9	6819.5	4
T	C	79	.7750	1111	6411.4	13.2	1751.0	11519.6	4923.8	4
T	C	80	1.1200	1111	4511.0	65.7	470.5	4918.5	2491.4	4

SITE		AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
T C	81	.1350	1111	3.0	105.2	0.0	3.7	28.0	4
T C	82	.1750	1111	3689.7	22.3	8.6	25.1	936.4	4
T C	83	.3000	1111	16.7	1.3	31.3	4.3	13.4	4
T C	84	.5000	1111	2.8	17.2	14.6	347.0	95.4	4
T C	85	.1200	1111	.3	6.7	1119.2	0.0	281.5	4
T C	86	.5800	1111	2.6	235.9	44.5	442.1	181.2	4
T C	87	.3825	1111	0.0	8.9	9.9	0.0	4.7	4
T C	88	.9000	1111	28.1	687.0	1.1	5.9	180.5	4
T C	89	.2400	1111	943.3	7.5	29.2	8.3	247.1	4
T C	90	.2700	1111	14.4	176.3	363.3	10.4	141.1	4
T C	91	.2722	1111	71.6	0.0	3.7	74.6	37.5	4
T C	92	.1290	1172	5.4	0.0		0.0	1.4	4
T C	93	.1075	1111	0.0	10.2	4331.2	0.0	1085.3	4
T C	94	.2400	1111	536.7	3900.0	27168.7	0.0	7901.4	4
T C	95	.1050	1111	0.0	0.0	0.0	1468.6	367.1	4
T C	96	.1600	1111	0.0	4455.0	18.7	0.0	1118.4	4
T C	97	.6700	1111	0.0	1204.6	612.1	10.7	456.9	4
T C	98	.6400	1111	0.0	15985.0	30885.9	0.0	11717.7	4
T C	99	.1500	1111	0.0	68929.3	0.0	0.0	17232.3	4
T C	100	.6300	1111	43.5	309.2	27873.7	1.6	7057.0	4
T C	101	1.7870	1111	3.3	4345.6	180.1	1.0	1132.5	4
T C	102	.3600	1111	0.0	4808.1	2.8	0.0	1202.7	4
T C	103	.3400	1111	0.0	55863.5	31345.3	0.0	21802.2	4
T C	104	.3160	1111	.3	1575.0	22608.5	6.6	6047.6	4
T C	105	.1500	1111	2.7	43672.7	579.3	3.3	11064.5	4
T C	106	.2362	1111	0.0	36.0	751.1	12.3	199.8	4
T C	107	.3600	1111	99687.5	1093.9	294.4	1.7	25269.4	4
T C	108	1.5000	1111	0.0	124.5	55003.1	0.0	13781.9	4
T C	109	.2900	1111	57.9	326.6	238965.5	0.0	59837.5	4
T C	110	.1600	1600	0.0				0.0	1
T C	111	.7000	1111	1.3	96.1	20.4	0.0	29.5	4
T C	112	.1750	1111	0.0	1854.3	616.0	0.0	617.6	4
T C	113	.1787	1170	0.0	26.9			13.4	2
T C	114	.1350	1111	0.0	3796.3	22.2	0.0	954.6	4
T C	115	.1575	1111	0.0	70576.5	27468.6	0.0	24511.3	4
T C	116	.6800	1111	90.9	471.8	22.9	0.0	146.4	4
T C	117	.2200	1111	2.3	50065.0	2.3	0.0	12517.4	4
T C	118	.5800	1111	0.0	3.3	58.4	0.0	15.4	4
T C	119	.2112	1111	13.7	447.0	57.8	948.4	366.7	4
T C	120	.7200	1152	483.5	3845.0		7345.4	2918.5	4
T C	121	.3000	1111	0.0	1515.3	98.7	0.0	403.5	4
T C	122	.3755	1111	18.9	0.0	0.0	0.0	4.7	4
T C	123		7000						0
T C	124	1.1120	1111	6.0	7.0	9323.7	242.8	2394.9	4
T C	125	.1000	1117	0.0	55275.0	505.0		18593.3	3
T C	126	.3150	1550	0.0				0.0	1
T C	127	.1250	1111	0.0	127926.4	236.8	16756.0	36229.8	4
T C	128	.0750	1111	8.0	0.0	0.0	280600.0	70152.0	4
T C	129	.1800	1111	.6	51.1	0.0	260553.3	65151.2	4
T C	130	.2100	1111	0.0	57.1	0.0	0.0	14.3	4
T C	131	.1575	1550	0.0				0.0	1
T C	132	.1875	1111	0.0	12.8	0.0	0.0	3.2	4
T C	133	.1225	1011	0.0		0.0	0.0	0.0	3
T C	134	.1750	1111	0.0	0.0	0.0	0.0	0.0	4
T C	135	.0800	1111	0.0	0.0	0.0	0.0	0.0	4
T C	136	.2000	1553	0.0			0.0	0.0	4
T C	137	.6400	1553	18.1			277.7	73.9	4
T C	138	.3600	1553	0.0			0.0	0.0	4
T C	139	.3600	1111	38.9	46.7	0.0	0.0	21.4	4
T C	140	.2800	1550	2.1				2.1	1
T C	141.	.8800	1111	0.0	401.1	.5	0.0	100.4	4
T C	142	.1000	1111	67.0	3617.0	3.0	0.0	921.7	4
T C	143	.3600	1111	561.4	446.7	4.2	20.6	258.2	4
T C	144	.6400	1111	1258.3	287.0	207.7	1150.5	725.9	4
T C	145	.5700	1152	3.3	0.0		0.0	.8	4
T C	146	.1650	1553	4.2			14443.6	3612.0	4
T.C.	147		7400						0
T C	148	.7200	1553	.1			1748.7	437.2	4
T C	149	.7000	1553	390.7			8937.7	2332.1	4
T C	150	.1400	1111	9.3	1432.9	0.0	0.0	360.5	4
T C	151	1.4400	1111	311.2	0.0	0.0	0.0	77.8	4
T C	151A	.7250	1111	231.2	309.2	41.2	0.0	145.4	4
T C	152	1.5470	1111	36.5	0.0	0.0	46.8	20.8	4
T C	153	.4400	1111	0.0	0.0	0.0	0.0	0.0	4
T C	154	.5600	1111	0.0	60.5	0.0	226.1	71.7	4
T C	155	.2250	1111	10.7	50.7	0.0	7.1	17.1	4
T C	156	.2200	1111	0.0	0.0	0.0	0.0	0.0	4
T C	157	.0900	1111	0.0	0.0	0.0	0.0	0.0	4
T C	158	.0875	1111	2.3	41.1	0.0	0.0	10.9	4
T C	159	.2900	1111	0.0	0.0	0.0	0.0	0.0	4
T C	160	.7750	1111	2.1	73.2	0.0	0.0	18.8	4
T C	161	.2100	1111	0.0	3.8	0.0	0.0	1.0	4
T C	162	.4300	1111	0.0	5.3	0.0	0.0	1.3	4

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
T C 163	.2950	1111	53.2	0.0	26.1	58.0	34.3	4
T C 164	.4600	1111	19.3	73.7	0.0	335.7	107.2	4
T C 165	.2025	1150	655.8	9277.5			4966.7	2
T C 166	.2450	1111	10022.4	0.0	381.6	503.7	2726.9	4
T C SQ 1	2.3226	1111	7.0	10924.0	25.8	8.6	2741.3	4
T C SQ 2	2.3226	1111	6.2	417.9	45.8	2.2	118.0	4
T C SQ 3	2.3226	1111	1.8	20345.5	117.0	85.5	5137.4	4
T C SQ 4	2.3226	1111	7.3	64479.4	7478.1	4.3	17992.3	4
T C S 5	2.3226	8811			668.3	4.0	336.2	2
T C SQ 6	2.3226	1111	5.7	21.9	95.5	40.8	41.0	4
T C SQ 7	1.5561	0010			5718.7		5718.7	1
T C SQ 7	2.3226	0100		1514.5			3201.1	2
T C SQ 8	1.8581	0010			19813.6		19813.6	1
T C SQ 8	2.3226	0100		2102.0			9973.9	2
T C SQ 9	2.3226	0180		806.2			806.2	1
T C SQ10	2.3226	1880	46.1				46.1	1
T C SQ11	2.3226	0180		412.3			412.3	1
T C SQ12	2.3226	0180		45.4			45.4	1
T C SQ13	2.3226	0180		974.2			974.2	1
T C SQ14	2.3226	0180		204.6			204.6	1
T C SQ15	2.3226	1180	1832.5	3431.5			2632.0	2
T C SQ16	2.3226	0180		7536.7			7536.7	1
T C SQ17	2.3226	0180		3423.3			3423.3	1
T C SQ18	1.1613	0115		259.0	0.0		129.5	2
T C SQ19	1.1613	0155		25.4			25.4	1
T C SQ 20	2.3226	0109		96.9			96.9	1
TC OSQ 9	2.3226	4009						0
TC OSQ 10	1.1613	1009	295.6				295.6	1
TC OSQ 10	.5806	0029			2306.6		373.7	3
TC OSQ 11	2.3226	1199	0.0	0.0			0.0	2
TC OSQ 12	1.4000	1119	868.6	1297.9	371.4		846.0	3
T C N 1	.5225	0111		32147.6	170.5	1.9	10773.3	3
T C N 2	.5400	0115		795.2	2592.6		1693.9	2
T C N 3	.7000	0155		5348.0			5348.0	1
T C N 4	.9450	0155		1698.9			1698.9	1
T C N 5	.4800	0155		38.8			38.8	1
T C N 6	.3500	0115		82.3	0.0		41.1	2
T C N 7	.2250	0155		131.1			131.1	1
T C N 8	.1200	0155		20.8			20.8	1
T C N 9	.9000	0155		168.1			168.1	1
T C N 10	.1400	0111		77.9	0.0	0.0	26.0	3
T C N 11		0700						0
T C N 12		0700						0
T C N 13	.1500	0111		169779.3	52.7	3.3	56611.8	3
T C N 14	.2700	0111		80065.2	22.6	1.9	26696.5	3
T C N 15	.1500	0111		78882.0	42.0	0.0	26308.0	3
T C N 16	.2250	0111		2074.7	232.0	0.0	768.9	3
T C N 17	.4600	0111		6885.2	55.2	0.0	2313.5	3
T C N 18	.1200	0111		57.5	0.0	0.0	19.2	3
T C N 19		0700						0
T C N 20	.2500	0111		8.8	4.0	0.0	4.3	3
T C N 21	.1000	0111		554.0	0.0	0.0	184.7	3
T C N 22	.0875	0111		40.0	34.3	5.7	26.7	3
T C N 23	.2000	0155		14.0			14.0	1
T C N 24	.5900	0111		1365.9	264.7	0.0	543.6	3
T C N 25	.3150	0111		325.1	3.2	0.0	109.4	3
T C N 26	.2000	0111		1450.5	20.0	2.5	491.0	3
T C N 27	.3600	0111		1357.5	160.6	1.1	506.4	3
T C N 28	.4200	0111		1337.9	0.0	0.0	446.0	3
T C N 29	.4900	0115		607.6	0.0		303.8	2
T C N 30	.2400	0115		308.3	20.8		164.6	2
T C N 31	.4400	0155		438.4			438.4	1
T C N 32	.3000	0155		7750.7			7750.7	1
T C N 33	.2370	0155		4204.2			4204.2	1
T C N 34	.2800	0155		12641.1			12641.1	1
T C N 35	.2800	0155		6443.2			6443.2	1
T C N 36	.2000	0155		33.5			33.5	1
T C N 37	.6000	0155		553.3			553.3	1
T C N 38	.6650	0115		53761.4	0.0		26880.7	2
T C N 39	.3500	0155		4.3			4.3	1
T C N 40	.4850	0155		8946.0			8946.0	1
T C N 41	.0875	0155		2658.3			2658.3	1
T C N 42	.1849	0155		30.8			30.8	1
T C N 43	.5700	0155		55.6			55.6	1
T C N 44	.2400	0155		10.4			10.4	1
T C N 45	.6750	0155		66.1			66.1	1
T C N 46	.1540	0155		5901.9			5901.9	1
T C N 47	.6600	0155		1582.3			1582.3	1
T C N 48	.4750	0155		122.1			122.1	1
T C N 49	.1200	0155		20.8			20.8	1
T C N 50	.2400	0155		4.6			4.6	1
T C N 51	.1800	0111		203.9	24.4	0.0	76.1	3
T C N 52	.2700	0111		373.3	18.5	5.6	132.5	3

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
T C N 53	.6895	0111		21649.9	148.7	0.0	7266.2	3
T C N 54	.3975	0111		21757.5	169170.6	0.0	63642.7	3
T C N 55	1.2750	0111		4135.5	.8	.5	1378.9	3
T C N 56	.2475	0111		1153.9	1131.3	109.9	798.4	3
T C N 57	.4500	0111		10190.2	0.0	1.1	3397.1	3
T C N 58	.3000	0111		7404.7	3526.3	0.0	3643.7	3
T C N 59	.1875	0152		158.9		0.0	53.0	3
T C N 60	.6600	0111		13328.8	0.0	0.0	4442.9	3
T C N 61	.5000	0115		164.8	1100.0		632.4	2
T C N 62	.1968	0115		148.4	15.2		81.8	2
T C N 63	.1350	0115		867.4	0.0		433.7	2
T C N 64	.1400	0115		68807.9	0.0		34403.9	2
T C N 65	.2700	0111		37416.3	260.7	0.0	12559.0	3
T C N 66	.2100	0115		5174.3	0.0		2587.1	2
T C N 67	.2700	0155		538.9			538.9	1
T C N 68		0700						0
T C N 69	.1200	0155		26643.3			26643.3	1
T C N 70	.1500	0155		285.3			285.3	1
T C N 71	.2125	0155		21707.3			21707.3	1
T C N 72	.2250	0115		17514.2	0.0		8757.1	2
T C N 73	.7950	0115		13917.5	0.0		6958.7	2
T C N 74	.3300	0155		1753.9			1753.9	1
T C N 74A	.2000	0111		2388.5	4423.5	0.0	2270.7	3
T C N 75	.3600	0111		23358.1	2877.5	0.0	8745.2	3
T C N 76	.1750	0115		51.4	2453.7		1252.6	2
T C N 77	.2750	0115		82.5	0.0		41.3	2
T C N 78	.0900	0115		12.2	444.4		228.3	2
T C N 79	.1500	0115		1.3	0.0		.7	2
T C N 80	.4225	0115		210.4	47.3		128.9	2
T C N 81	.2925	0115		167.2	1025.6		596.4	2
T C N 82	.4350	0115		3.0	574.7		288.9	2
T C N 83	.3200	0111		2.5	323.4	0.0	108.6	3
T C N 84	.2400	0115		0.0	625.0		312.5	2
T C N 85	.7200	0115		12.6	1388.9		700.8	2
T C N 86	.3600	0111		219.4	37.8	0.0	85.7	3
T C N 87	.6300	0111		707.9	743.7	7.5	486.3	3
T C N 88	.1800	0111		0.0	0.0	0.0	0.0	3
T C N 89	.1200	0111		0.0	0.0	0.0	0.0	3
T C N 90	.3000	0111		0.0	8.0	0.0	2.7	3
T C N 91	.2000	0111		0.0	5240.5	0.0	1746.8	3
T C N 92	.1200	0111		0.0	917.5	9.2	308.9	3
T C N 93	.1200	0111		0.0	325.0	0.0	108.3	3
T C N 94	2.2500	0111		.6	112.9	39.5	51.0	3
T C N 95	.3000	0111		280.0	0.0	27.3	102.4	3
T C N 96	.2000	0111		0.0	9117.0	3382.0	4166.3	3
T C N 97	.3300	0111		6.4	106.4	0.0	37.6	3
T C N 98	.4050	0111		4744.2	3.7	0.0	1582.6	3
T C N 99	.0900	0111		417.8	26365.6	0.0	8927.8	3
T C N 100	.1250	0117		54.4	35054.4		17554.4	2
T C N 101	.1200	0160		0.0			0.0	1
T C N 102	.4500	0111		1571.1	17582.2	134.9	6429.4	3
T C N 103	.3000	0111		124.3	350.7	0.0	158.3	3
T C N 104	.2500	0111		233.6	2090.4	0.0	774.7	3
T C N 105	.6000	0111		293.2	70290.8	22.5	23535.5	3
T C N 106	.5500	0111		3570.5	7950.5	135.5	3885.5	3
T C N 107	.2080	0111		234.6	1841.8	62.5	713.0	3
T C N 108	.2231	0111		88.7	42676.8	0.0	14255.2	3
T C N 109	.3500	0111		2148.6	4666.0	0.0	2271.5	3
T C N 110	.4950	0111		4586.3	7.1	26.3	1539.9	3
T C N 111	.3000	0111		47.7	19335.3	22500.0	13961.0	3
T C N 112	.2700	0111		185.9	83448.1	0.0	27878.0	3
T C N 113	.2100	0111		120.5	28.6	0.0	49.7	3
T C N 114	.3900	0117		36663.6	12.1		18337.8	2
T C N 115	.2065	0170		62997.1			62997.1	1
T C N 116	.2000	0170		93.5			93.5	1
T C N 117		0700						0
T C N 118		0700						0
T C N 119	.4350	0111		4721.1	112.2	3770.6	2868.0	3
T C N 120		7000						0
T C N 121	.2250	0111		888.4	2504.0	13.3	1135.3	3
T C N 122	.0400	0180		4455.0			4455.0	1
T C N 123	.1000	0111		37364.0	6321.0	176.0	14620.3	3
T C N 124		0600						0
T C N 125	.2900	0111		430.7	531.4	774.8	579.0	3
T C N 126	.8000	0111		3097.5	8481.2	47080.7	19553.2	3
T C N 127	.1250	0111		0.0	5080.0	16.0	1698.7	3
T C N 128	.3600	0111		105.5	446.6	63158.2	21236.8	3
T C N 129	.1350	0160		6718.5			6718.5	1
T C N 130	.0564	0111		0.0	145.4	12826.2	4323.9	3
T C N 131	.2750	0170		216.0			216.0	1
T C N 132	.1350	0170		290.4			290.4	1
T C N 133	.1200	0160		5630.8			5630.8	1
T C N 134	.1125	0160		2246.2			2246.2	1

SITE	AREA SQ.M	CODING	VOLUME OF ACCUMULATION (C.C./SQ.M) 1969	1970	1971	1972	MEAN	YEARS OF RECORD
T C N 135		0600						0
T C N 136	.8250	0111		2196.1	4903.4	571.4	2557.0	3
T C N 137		0600						0
T C N 138	.1500	0111		515.3	14433.3	1242.7	5397.1	3
T C N 139		0600						0
T C N 140	.2400	0160		6644.6			6644.6	1
T C N 141	.1200	0170		0.0			0.0	1
T C N 142	.1350	0111		2554.8	1089.6	7568.1	3737.5	3
T C N 143	.2925	0111		3476.6	20.5	42746.0	15414.4	3
T C N 144	.1125	0111		231.1	3310.2	0.0	1180.4	3
T C N 145	1.1400	0111		207.5	291.9	16282.0	5593.8	3
T C N 146	.2750	0111		158.5	44489.8	5285.5	16644.6	3
T C N 147	.1200	0170		0.0			0.0	1
T C N 148	.3900	0181		178.5		57844.9	29011.7	2
T C N 149	.3375	0111		752.3	1072.6	6703.4	2842.8	3
T C N 150	.1238	0111		542.0	0.0	67613.1	22718.4	3
T C N 151	.2300	0170		26.1			26.1	1
T C N 152	.1138	0160		0.0			0.0	1
T C N 153	.1250	0111		0.0	16.0	5600.0	1872.0	3
T C N 154	.0863	0170		67.2			67.2	1
T C N 155		0800						0
T C N 156		0600						0
T C N 157	.4400	0111		0.0	6.8	267.3	91.4	3
T C N 158	.2100	0170		17.1			17.1	1
T C N 159	.1500	0160		5.3			5.3	1
T C N 160	.1200	0160		856.7			856.7	1
T C N 161	.3905	0170		1684.8			1684.8	1
T C N 162	.0646	0170		5856.0			5856.0	1
T C N 163	.1200	0160		0.0			0.0	1
T C N 164	.1575	0160		1448.9			1448.9	1
T C N 165	.0550	0170		516.4			516.4	1
T C N 166	.0800	0170		2192.5			2192.5	1
T C N 167	.1350	0160		17.0			17.0	1
T C N 168	.1750	0111		93.1	828.0	681.1	600.8	3
T C N 169	.2200	0111		43.2	1097.3	24.1	388.2	3
C N 170		0700						0
C N 171		0700						0

APPENDIX 3

THE MEASUREMENT OF SIZE

The Choice of Technique

There are two basic approaches to the determination of size in coarse sediments; either the direct measurement of a particular linear dimension or set of dimensions which are deemed to be significant (e.g. triaxial measures or sieving) or the measurement of some other parameter which is closely linked to size, such as weight or settling velocity in water. The vast majority of sedimentological studies have dealt with material of sand size or less where grouped measures, such as the weight between certain sizes of sieve, are commonly used. The larger particle size and weight of gravels enables the measurement of individual particles to be made more easily and sieving becomes more difficult in view of the weight of the loaded sieves. As size increases further, it becomes impracticable to weigh the particles because they may become too heavy to lift (see, for example, Caine's study of blockfields (1968)).

Scree particles cover a wide range of size from very fine material to huge blocks, although the finer material (sand size and below) is only locally important. With the exception of the recent work by Bones (1971), all previous studies known to the author have measured the size of scree particles directly using all or one of the three mutually perpendicular axes (a, b, c) of the fragment. The obvious advantage of such measurements is that the same instrument and technique of measurement can be used over a wide range of size which covers almost all the particles commonly found on scree slopes. The instrument is easily portable, whereas to weigh particles over the same size range several types of scale would be needed ranging from grams to kilograms. The portable scales used by Bones weighed only up to two kilograms and there are obvious limits to their use even if particles can be broken. An alternative method, used occasionally in studies of fluvial deposits, is to record the volume displacement of the particles in water. However, the much wider size range and poorer sorting of scree debris, plus the lack of water on many scree slopes, make this method impracticable unless the sample is carried to the base of the slope. The size of the larger particles usually prohibits measurement away from the sample site.

If the practical difficulties can be overcome, it would appear that the measurement of size by weight offers the most promising possibilities for reasonably accurate, consistent results regardless of variations in shape and lithology of the debris involved. However, in the majority of screes seen by the author, the size range present would make weighing of the coarser debris impossible.

In carrying out the present study, it was considered that the adoption of one technique of measurement over the whole size range to give a consistent set of data compensated for the inaccuracies inherent in this method (see discussion below). Thus, even if the errors involved in the computation of volume from triaxial measures proved to be too great to be acceptable, it would still be possible to use one of the measured axes as a surrogate of volume to give consistent results. These considerations, together with the portability and robust nature of the equipment, the ease with which it could be replaced in the event of accidental breakage, and its possible use in all weathers, lead to the decision to measure size rather than weight.

Measurement Procedure

For each fragment, three mutually perpendicular axes were measured using a wooden caliper-like device 60 cm long. This appears as a scale on several of the figures, e.g. Figures 9.1 and 9.2. The longest (a) axis was operationally defined as the longest axis paralleling the axis of symmetry of a particle, i.e. fitting the measurements to a model of a rectangular solid. This was done to avoid undue errors in conversions to volume, e.g. the longest axis of a rectangular block is in fact the diagonal of the major face rather than its length which is the measure used to compute volume. The intermediate (b) and short (c) axes were similarly defined. All three are maximum figures except in cases where unusually long irregularities occurred which, if included, would considerably inflate computed volume. In these cases, a more representative measure was taken.

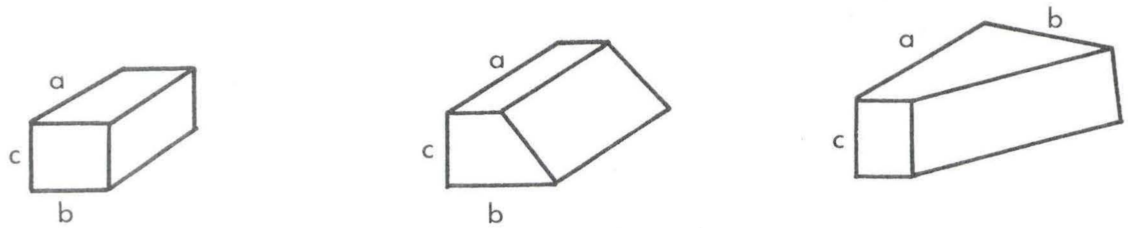
When the volume of a particle is computed using such triaxial measurements, one makes the assumption that the particle is a rectangular block. Examination of scree particles indicates that this is not a very good model and, although a series of basic shapes may be defined, in reality there is an almost infinite number of possible shapes which the particles can assume. In view of this, an attempt was made to correct for this shape variation by obtaining a descriptive shape measure for each fragment which could then be used to adjust the figures computed from triaxial measurements. The bulk of the rest of this appendix is a discussion of the methods used to correct for shape and experiments carried out to test the validity of these measures.

The Measurement of Shape

Caine (1967), working on a scree slope composed of fairly regular dolerite blocks, used conversion values based on the number of major faces of the block. The values used were as follows:

Number of Sides	Correction to Volume (%)
Less than 4	50
4	25
5	50
6	100
Greater than 6	75

These values were obtained from purely theoretical considerations (Caine, private communication, 1969). However, although the number of major faces is a good guide, considerable variation is still possible in each class. For example, the following figures all have six major faces:



Therefore, in the present study, as well as noting the number of major faces, a second index of shape was added by comparing the volume of the rock fragment to that of a rectangular solid of equal dimensions, i.e. 1/3, 1/4, 1/2, 2/3, 3/4. The combination of these two measures produced a large range of possible shape classes, e.g. 6, 6-1/2, 6-2/3, 6-3/4, etc. The three most common classes were 4, 5-1/2 and 6-3/4.

Experimental Studies

(a) Experimental Design and Data Manipulation

In an attempt to obtain a quantitative estimate of the meaning of these shape classes, an experiment was carried out at McMaster using debris collected as part of the process studies in Surprise. In view of the physical limitations of backpacking, the maximum size of these particles was about 150 mm a axis and a maximum weight of about 400 gms. The samples used were: 515 stones from an avalanche sample on the west side of Tumblin' Creek in 1969, 443 fragments from Boulder 21 in Strike Valley, also in 1969, and 100 shale fragments from various boulders at Surprise II in 1970. The latter group was included since neither of the other samples contained any shale debris. Lithologies from Scree No. 1, the Eastern Valley Side, Isosceles and the Palliser Cone were not included because adequate debris was not available. It is assumed that the relationship between the shape classes in the sample used will be similar to those between the shape classes of these lithologies.

Measurements were taken of the three axes and the weight in grams of each fragment, together with a note of the lithology and both shape measures. For each fragment, the "apparent density" was calculated using the formula $Ad = (\frac{w}{abc})$ where Ad is the apparent density, abc is the product of the three measured axes in cubic centimetres and w is the weight in grams. This figure, when divided by the true density, gives an estimate of the ratio between the true volume and the product of the three axes, assuming that volume is proportional to weight. Density figures for the individual lithologies were not available and the true density was assumed to be 2.5. This figure was derived by dividing the weight of all the samples of avalanche debris collected in 1970 from Tumblin' Creek, Surprise II and Strike Valley by their displaced volume in water (34,754.66 gm/13,916 cc = 2.4975).

The original data were divided in 12 lithological groups and 25 possible shape classes. However, since many of these shape classes had only a small number of observations, the data were regrouped, using the preliminary results from the 25 x 12 matrix, into an 8 x 5 matrix. The main components of the five shape classes were as follows:

Shape 1	4 and less than 4 sides	"4 sides"
Shape 2	5-1/2, 6-1/2, 7-1/2, 8-1/2, etc.	"5-1/2 sides"
Shape 3	5-2/3, 6-2/3, 7-2/3, 8-2/3, etc.	"5-2/3 sides"
Shape 4	5-3/4, 6-3/4, 7-3/4, 8-3/4, etc.	"6-3/4 sides"
Shape 5	6-7/8, 6	"6 sides"

The lithology classes were:

Lithology 1	black crystalline limestone
Lithology 2	fine dark grey limestone and grey crinoidal limestone
Lithology 3	grey limestone
Lithology 4	fine light grey limestone and buff limestone
Lithology 5	white limestone
Lithology 6	fine white crystalline limestones
Lithology 7	shales
Lithology 8	lithology not recorded

The results of this analysis are shown in Table A3.1. From this table, it can be seen that the shales (Lithology 7) show very high values particularly in shape classes 4 and 5. This appears to be a result of the characteristic shape of the shale debris combined with the measurement technique. The accuracy of measurement of the axes is probably of the order of ±0.5 mm and, as the smallest axis decreases in size, the possible error term becomes larger. For example, the difference between

TABLE A3.1: MEAN APPARENT DENSITY FOR LITHOLOGICAL AND SHAPE CLASSES, ALL OBSERVATIONS

	Lithological Groups								
Shape	1	2	3	4	5	6	7	8	Mean
1	1.139	1.034	1.095	1.058	1.112	1.257		1.101	1.092
N	48	53	53	18	17	6		5	
2	1.225	1.195	1.318	1.385	1.449	1.695	1.520	1.318	1.325
N	58	84	134	44	43	14	24	3	
3	1.502	1.322	1.563	1.486	1.538	1.611	1.440	1.261	1.460
N	16	32	25	8	10	5	8	2	
4	1.499	1.475	1.621	1.643	1.766	1.760	2.058	1.505	1.662
N	54	70	46	27	29	12	53	5	
5	1.831	1.757	1.946	1.896	2.106	2.335	2.486	2.063	2.096
N	6	8	9	6	2	1	17	1	
	1.328	1.275	1.370	1.433	1.505	1.652	1.954	1.348	

a measurement of 10 and 11 mm is about 10%, whereas the same difference between 3 and 4 mm is 25-30%. Figure A3.1 is a frequency plot of apparent density differentiating between those fragments with a c axis less than 10 mm and the rest of the sample. It can be seen that those estimates for fragments with c <10 mm form a larger proportion of the total observations in the higher values of apparent density. This can be interpreted as a consistent bias by the operator to underestimate the c axis when it is small and thus giving larger weight:volume ratios. Since much of the shale debris is platy or tabular in shape, errors of this type are more common, accounting, in part, for the high values in Table A3.1.

However, even when those particles with c <10 mm are removed from the sample (Table A3.2), the shale values are still high, especially when it is realized that shale, on the whole, is usually less dense than limestones. Shale is the only lithology within the sample which

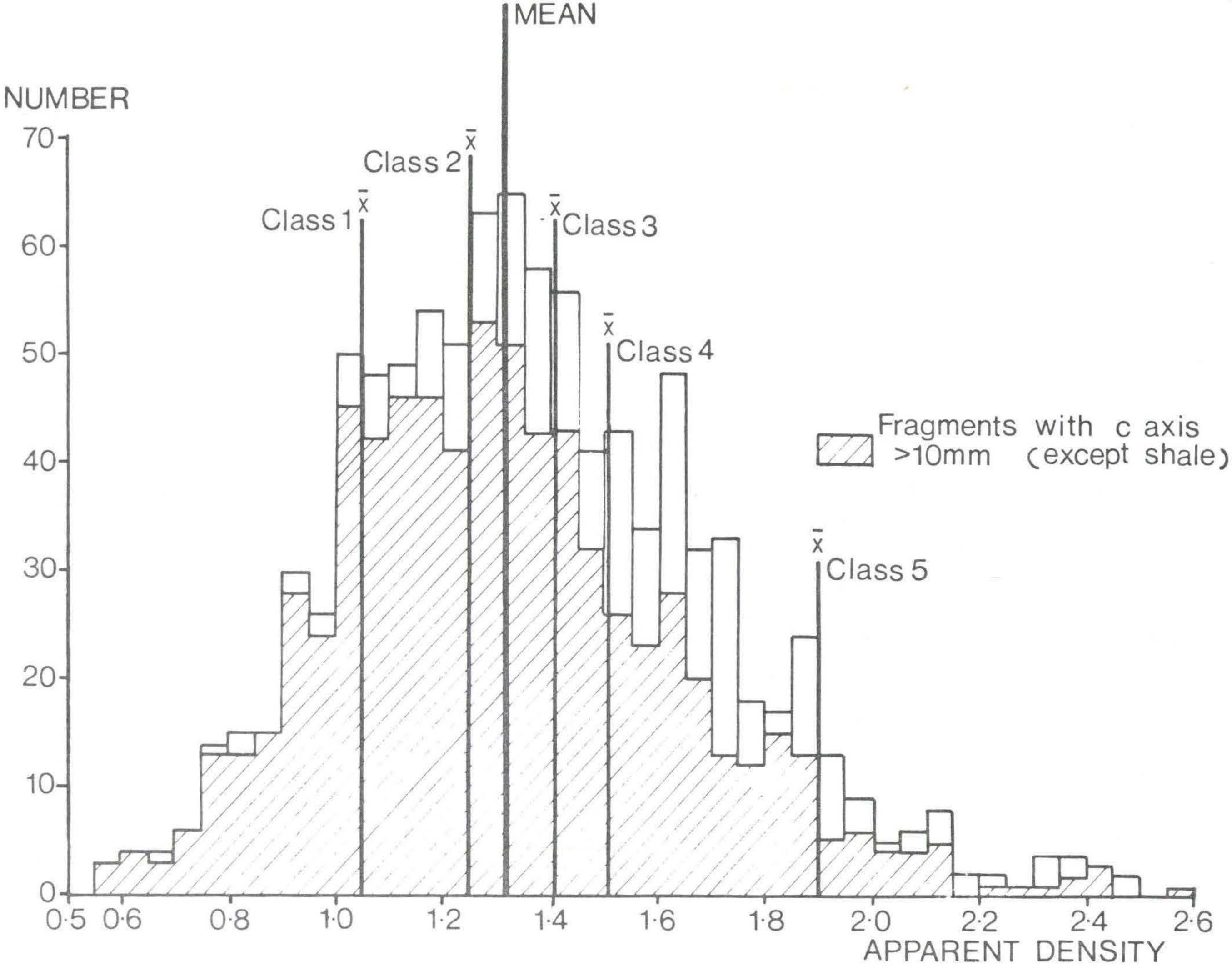


Figure A3.1 Frequency plot of apparent density measurements consistently breaks down to tabular debris and therefore approximately fits the assumed model of a rectangular solid. Out of the original sample, almost 70% of the shale is in shape classes 4 and 5 and it is this difference in shape, in comparison to the other lithologies (which mainly break down to variants of 4 and 5-sided fragments), that accounts for the high values in Table A3.2. By comparison with the other lithologies, shale fits the model too well! Since the values for the shape classes were to be used for all lithologies, it was felt that the shales should be excluded from the sample, as well as those stones with a c axis < 10 mm. Therefore, the accepted values for the shape classes are those given in the end column of Table A3.2.

TABLE A3.2: MEAN APPARENT DENSITY FOR LITHOLOGICAL AND SHAPE CLASSES FOR ALL OBSERVATIONS WITH THE C AXIS > 10 MM

	Lithological Groups									Mean Less Shale
Shape	1	2	3	4	5	6	7	8	Mean	
1	1.098	1.013	1.056	0.964	1.078	1.162	-	1.101	1.050	1.050
N	33	45	40	13	15	3		5		
2	1.189	1.178	1.251	1.330	1.384	1.515	1.386	1.318	1.257	1.254
N	48	73	105	35	32	8	6	3		
3	1.496	1.291	1.549	1.414	1.518	0.901	1.290	1.261	1.409	1.415
N	12	27	18	7	8	1	4	2		
4	1.455	1.425	1.533	1.603	1.681	1.777	1.841	1.505	1.531	1.513
N	44	57	28	19	17	8	10	5		
5	1.911	1.757	1.946	1.985	2.106	-	2.238	2.063	1.949	1.908
N	4	8	9	4	2		4	1		
	1.297	1.243	1.309	1.376	1.424	1.536	1.701	1.348		1.314

(b) The Interpretation of the Results

The figures given for apparent density in Tables A3.1 and A3.2 are open to variation from three main sources:

(i) the shape of the rock fragment,

(ii) variations in true density due to differences in lithology, and

(iii) measurement errors.

This section discusses the influence of each of these sources of variation on the results of the experiment.

The possible measurement error of ±0.5 mm discussed above probably increases to ±1.0 mm over about 40 mm and could be as much as 5-10 mm where large fragments are concerned (i.e., greater than 300 mm). However, in limiting the sample to fragments where the c axis is >10 mm, this error should never exceed 20% of the computed volume and usually it is much less. Since measurement errors can be assumed to be randomly distributed throughout the data, they are unlikely to affect the values shown in Tables A3.1 and A3.2.

Variations in density between lithological groups are apparent from Tables A3.1 and A3.2. Ideally, it should be possible to assess shape variation independently of density differences by examining a single lithological group. In practice, however, nearly all the rocks found in the area of study are part of a gradational sequence of pure to muddy, crinoidal and occasionally partially crystalline limestones and dolomites. Thus, even the groups shown in Tables A3.1 and A3.2 are only general descriptive classes. The only two really distinctive lithologies are the shales, which are atypical, and a dense white crystalline limestone (lithology 6) which is not very common. Since the groups in Tables A3.1 and A3.2 are themselves combinations of lithologies, it seems reasonable to assume from Figure A3.2 that there is little difference between these groups and that the variations in density due to lithological influence have a negligible effect on the variations in apparent density. This assumption was tested using the Kolmogorov-Smirnov two sample test (Siegel, 1956, pp. 133-134) from which the statistical significance can be assessed using the chi-squared distribution with two degrees of freedom (Table A3.3).

TABLE A3.3: VALUES OF CHI-SQUARED USING THE KOLMOGOROV-SMIRNOV TEST BETWEEN APPARENT DENSITIES OF THE LITHOLOGICAL GROUPS SHOWN IN TABLE A3.2 (EXCLUDING SHALE)

Lithology	1	2	3	4	5	6	8	Total
1	-	4.11	1.21	3.61	5.80	10.85**	1.02	1.16
2		-	4.23	10.67**	14.29**	13.80**	2.53	6.57*
3			-	5.36	7.28*	9.69*	1.71	0.85
4				-	1.35	6.49*	1.42	4.14
5					-	4.60	2.10	6.90*
6						-	4.67	10.51**
8							-	1.30

*Significant at the 95% level.
**Significant at the 99% level.

From Table A3.3, it can be seen that the only statistically significant differences involve groups 2, 5 and 6. The numbers involved in group 6 are so small (20 out of 735) that the effect of this group can be considered negligible. Also, since lithologies 2 and 5 occur in similar proportions in the individual shape groups, they should not

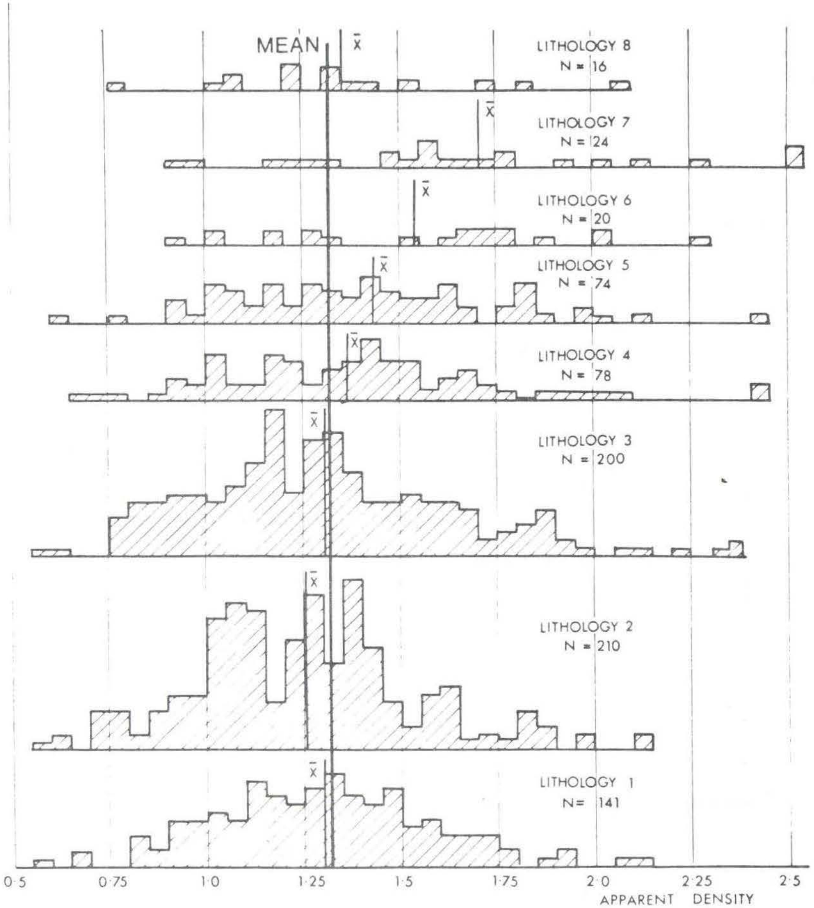


Figure A3.2 Variation in apparent density with lithology (c axis>10mm)

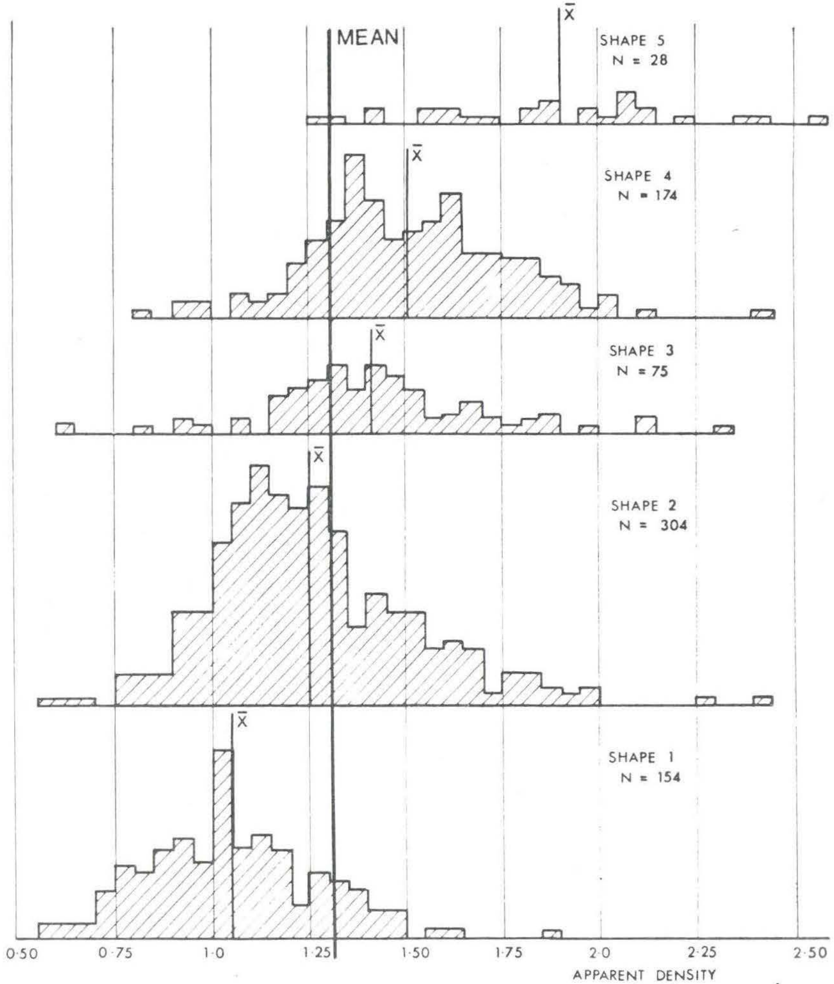


Figure A3.3 Variation of apparent density with the five shape classes (c axis>10mm, no shale) affect the relative values for the shape classes given in Table A3.2. Thus, although the variations due to density and shape are confused in this experimental design, it can safely be assumed that the differences in apparent density of shape classes shown in Figure A3.2 reflect the control of shape and that density differences are a very minor influence. When the shape classes are tested using the Kolmogorov-Smirnov test (Table A3.4), all are significantly different at the 99.9% level and each group is significantly different from the total at greater than the 99% level.

TABLE A3.4: VALUES OF CHI-SQUARED USING THE KOLMOGOROV-SMIRNOV TEST BETWEEN APPARENT DENSITIES OF THE SHAPE GROUPS SHOWN IN TABLE A3.2 (EXCLUDING SHALE)

Shape	1	2	3	4	5	Total
1	-	56.31**	76.19**	162.19**	74.33**	76.64**
2		-	23.51**	110.67**	57.14**	13.61*
3			-	15.48**	34.49**	15.10**
4				-	27.28**	67.39**
5					-	46.70**

*Significant at the 99% level.
**Significant at the 99.9% level.

Figure A3.3 shows that, despite these results, there is considerable overlap between the shape groups, particularly groups 2, 3 and 4. This is not surprising when it is remembered that the shape measures are only relatively crude, highly subjective estimates and by its operational definition group 3 is intermediate between groups 2 and 4 (i.e. too big to be 5-1/2, too small to be 5-3/4). The bimodality of the histograms for shapes 2 and 4 is doubtless due to the inclusion of fragments which should have been in group 3. However, similar errors probably occurred in the field and therefore no attempt was made to adjust these sample values to reduce this effect.

The significance of the variation within and between classes can be tested by the analysis of variance. Although the statistical assumptions of this test are not fully met, the deviations from normality in the data do not appear to be very great and the test is known to be a very robust one. The results are shown in Table A3.5.

TABLE A3.5: ANALYSIS OF VARIANCE TABLE FOR (1) VARIATIONS IN SHAPE, (2) VARIATIONS IN LITHOLOGY, USING THE APPARENT DENSITY DATA OF TABLE A3.2 (EXCLUDING SHALE)

Group	Sum Squares	Degrees of Freedom	Mean Square	F
All observations	77.3480	735		
Between shape classes	0.4759	4	0.1190 (A)	
Within shape classes	76.8721	731	0.1052 (B)	1.1312 (A/B) F = 3.32 (95%)
Between lithologies	0.0717	6	0.0120 (C)	
Within lithologies	77.2763	729	0.1060 (D)	8.8333 (D/C) F = 6.88 (99%)

These results indicate:

(i) that the variation between lithological groups is much less than the within group variation. Since, in using an F test, F cannot be less than 1, the null hypothesis must be changed to postulate that there is a significant difference. This hypothesis can then be rejected at the 99% level, i.e. there is no significant difference.

(ii) that the variation between the shape groups, although slightly greater than the within group variation, is not large enough to be statistically significant. In other words, despite the results shown in Table A3.4, the shape groups are only very crude estimators of the effect of the variation of shape on the measurement of apparent density. This result is supported by the data given in Table A3.6.

TABLE A3.6: REGRESSION OF SIZE VARIABLES AGAINST WEIGHT AND LOG_{10} WEIGHT FOR 958 ROCK FRAGMENTS (DATA FROM TABLE A3.1, NO SHALE)

	Variable	Units	Weight R	Weight R^2	Weight S.E.	Log Weight R	Log Weight R^2	Log Weight S.E.
1	A AXIS	mm	0.7967	0.6347	11.4121	0.8754	0.7663	9.1261
2	B AXIS	mm	0.7917	0.6268	7.5238	0.8653	0.7436	6.2365
3	C AXIS	mm	0.7598	0.5773	5.6067	0.8182	0.6696	4.9580
4	A AXIS	ø	0.6926	0.4797	0.4667	0.9214*	0.8490	0.2541
5	B AXIS	ø	0.6892	0.4750	0.4580	0.9072*	0.8230	0.2660
6	C AXIS	ø	0.6384	0.4076	0.6195	0.8529*	0.7274	0.4203
7	ABC	mm^3	0.9661*	0.9333	5671.0	0.7341	0.5389	14914.4
8	ABC(L)	mm^3	0.9792*	0.9588	4621.1	0.7258	0.5268	15672.3
9	ABC(C)	mm^3	0.9137*	0.8348	12198.4	0.6528	0.4261	22733.4
10	$\sqrt[3]{ABC}$	mm	0.8679	0.7532	4.5030	0.9441	0.8913	2.9886
11	$\sqrt[3]{ABC(L)}$	mm	0.8815	0.7770	4.3127	0.9491	0.9008	2.8770
12	$\sqrt[3]{ABC(C)}$	mm	0.8574	0.7351	5.1353	0.9105	0.8290	4.1260
13	$\sqrt[3]{ABC}$	ø	0.7388	0.5488	0.4250	0.9811*	0.9626	0.1220
14	$\sqrt[3]{ABC(L)}$	ø	0.7473	0.5585	0.4213	0.9878*	0.9757	0.0986
15	$\sqrt[3]{ABC(C)}$	ø	0.7261	0.5272	0.4598	0.9554*	0.9128	0.1975

*Linear relationship on a graphical plot.

(c) The Choice of Relevant Size Parameters

In order to assess which parameters were the most pertinent ones to use as estimators of volume, weight and size in this study, the data used to establish the shape measures were fed into a regression programme and tested against several variables. The results are shown in Table A3.6. The expression $\sqrt[3]{ABC}$ is the length of side of a cube of equal volume to the fragment measured. It was thought that this measure was a better approximation to reality than using "nominal diameter" and comparing the volume to that of a sphere of equal volume as Caine (1967, 1968) and Gardner (1968a) have done. The coefficients C and L are derived from Caine (1968) and this study, respectively, and are corrections for shape. From this table, it can be seen that variables 7 and 8 correlate most highly with weight and variables 13 and 14 correlate most highly with the logarithm of weight. In all cases, the use of Caine's shape corrections results in a much poorer fit than using the uncorrected data, probably reflecting the fact that his figures are derived for rectangular solids from theoretical considerations. It can also be seen that quite high correlations may be obtained using one axis alone (variables 1-6). These results are very similar to those of a more refined experiment carried out by Griffiths and Smith (1964) in which they found that up to 93% of the variation in the logarithm of volume could be predicted from three mutually perpendicular axes. However, in contrast to their results, it would appear that the a axis is the best single estimator of weight or log weight, followed by the b axis. They considered that the c axis "explained" the greatest amount of the variation in volume.

The close agreement between the correlation coefficients of variables 7 and 8 and 13 and 14 suggests that the improvement of r is only very small when the values are corrected for shape and obviously raises the question of whether this slight improvement is worth the additional effort involved in its calculation. To assess this question, it is necessary to consider the uses for which the calculated measurements are desired.

The size measurements of debris in this study are required for two specific purposes:

(a) the measurement of the volume of debris accumulation on cleaned boulder surfaces; and

(b) to provide a summary measure of size for use in the sedimentological studies. Ideally, this should be a linear rather than a volume measure and expressed in phi units.

The original idea to correct for shape came from the field observation that individual rock fragments with similar dimensions may have considerably different weights or volumes depending upon their shape. When large numbers of observations are involved, these variations tend to be random and the mean of the distribution becomes a measure of "mean shape". The close approximation of, for example, variables 7 and 8, can therefore be attributed to grouping effects due to the large number of observations involved. Five subsample means are used to adjust the values instead of the grand mean and one might expect the overall results to be similar. However, in the two uses outlined ealier, one is often dealing with small samples and the interest is focussed on the relationships of individual particles as well as the measurement of means or totals. In many cases, particularly in the accumulation studies, the largest fragment may be anything up to a thousand times larger than the rest of the sample put together. In these cases, grouping cannot be relied on to balance out these errors and it becomes essential to try and reduce the error term associated with each fragment as much as possible. Although Figure A3.3 and Table A3.5 indicate that the shape measures are crude and there is a wide range in each class, Figure A3.3 also demonstrates that a better estimate of the true volume may be made by using the means of the shape classes rather than the grand mean. From Table A3.6, it can be seen that when this shape correction is applied, there is a significant drop in the standard error term, as well as the increase in the correlation coefficient, indicating a better estimate of the volume of individual pebbles.

Thus, taking into account these results and the types of measures needed for the analyses in Sections II and III, all calculations given in this thesis are corrected individually for shape unless otherwise stated. Measurements of volume or weight use variable 8 and measurements of size refer to variable 14.

Summary and Conclusions

The size of particles was determined by triaxial measurements in the field using a wooden caliper-like device. Two shape measures were also estimated in the field, one based on the number of major faces of the block as used by Caine (1967) and the other by comparing the volume of the fragment to a rectangular solid with the same dimensions. Experimental work suggests that, if the rock fragments in the sample are assumed to be of similar density, the combination of these two shape measures can be reduced to five shape measures which are shown in Table A3.7.

TABLE A3.7: SUMMARY OF THE SHAPE MEASURES USED

Class	N	Percent of True Weight	Mean (%)	Name of Class
1	154	42	8.84	4 sides
2	314	51	10.42	5-1/2 sides
3	75	57	11.51	5-2/3 sides
4	188	61	9.87	6-3/4 sides
5	28	76	13.20	6 sides
All	759	52.50	12.98	--

These classes are statistically significantly different using the Kolmogorov-Smirnov test, but there is considerable overlap between the groups and analysis of variance indicates that the variation within the groups is almost as great as the variations between them. Despite this result, which largely reflects the crudity of the shape measures employed, regression analysis indicates that the accuracy of the estimates of the weight can be considerably improved for individual particles by the use of these conversion values although, for estimates involving the total of a large number of observations, the difference between corrected and uncorrected values is not very great.

Various parameters were tested as estimates of weight and the most efficient was found to be the product of the three axes and the conversion factors given above. This accounted for 95.88% of the variation in weight. The most efficient linear measure was the cube root of this product expressed in phi units which accounted for 97.57% of the variation in the $\log_{10}$ of weight.

APPENDIX 4

ANALYSIS OF VARIANCE TABLES FOR THE VARIATION OF GRAIN SIZE OVER THE SAMPLED SCREES

Throughout these tables, the following subscripts are used:

I = Number of columns

J = Number of rows

K = Subsamples (right and left) at each site

L = Number of items samples in each subsample (50).

Source	Error Term	Sum Squares	Mean Square	D.o.F.	F	F"	D.o.F. Num.	D.o.F. Denom.
1. Palliser Lower								
Mean		53084.66	53084.66	1				
I		88.60	22.15	4		2.23	5	14
J		801.73	267.24	3		25.28*	3	13
K		0.46	0.46	1		2.08	3	7
IJ	IJK	121.91	10.16	12	3.55*			
IK	IJK	4.28	1.07	4	0.37			
JK	IJK	1.58	0.53	3	0.18			
IJK	L(IJK)	34.36	2.86	12	2.99**			
L(IJK)		1874.71	0.96	1960				
2. Palliser Middle								
Mean		11888.56	11888.56	1				
I		50.11	25.06	2		0.59	3	6
J		101.58	50.79	2		1.41	2	4
K		1.46	1.46	1		0.49	5	2
IJ	IJK	153.64	38.41	4	11.66*			
IK	IJK	19.54	9.77	2	2.97			
JK	IJK	0.02	0.008	2	0.00			
IJK	L(IJK)	13.18	3.29	4	2.91*			
L(IJK)		999.36	1.33	882				

*Significant at the 95% level.

**Significant at greater than the 99% level.

APPENDIX 4 (Cont'd)

Source	Error Term	Sum Squares	Mean Square	D.o.F.	F	F"	D.o.F. Num.	D.o.F. Denom.
3. Palliser Upper								
Mean		10137.07	10137.07	1				
I		0.25	0.25	1		0.03	2	2
J		9.54	4.77	2		0.09	3	3
K		0.00	0.00008	1		0.14	2	3
IJ	L(IJK)	136.86	68.43	2	78.66**			
IK	L(IJK)	6.18	6.18	1	7.10**			
JK	L(IJK)	19.10	9.55	2	10.98**			
IJK	L(IJK)	4.26	2.13	2	2.46***			
L(IJK)		510.15	0.87	588				
4. Old Nip (Avalanche Boulder Tongue)								
Mean		28603.77	28603.77	1				
I		27.56	27.56	1		1.60	2	8
J		2159.27	308.47	7		12.03**	7	12
K		0.08	0.08	1		0.89	7	5
IJ	IJK	134.26	19.18	7	1.77			
IK	IJK	4.89	4.89	1	0.45			
JK	IJK	51.53	7.36	7	0.68			
IJK	L(IJK)	75.82	10.83	7	11.44**			
L(IJK)		1484.98	0.95	1568				

** Significant at greater than the 99% level.

*** This value is between the 90 and 95% levels. Where the second level interaction is not significant, the error term for the first level interactions remains the L(IJK) term (Griffiths, 1967, p. 418). Only the IJ interaction is significantly greater than the IJK interaction (99.9% level).

APPENDIX 4 (Cont'd)

Source	Error Term	Sum Squares	Mean Square	D.o.F.	F	F"	D.o.F. Num.	D.o.F. Denom.
5. Old Nip (Rockfall Cone)								
Mean		64271.25	64271.25	1				
I		3.37	3.37	1		0.90	2	7
J		1012.21	144.60	7		21.92**	7	11
K		2.58	2.58	1		2 18	2	7
IJ	IJK	34.79	4.97	7	4.38*			
IK	IJK	0.02	0.02	1	0.02			
JK	IJK	11.76	1.68	7	1.48			
IJK	L(IJK)	7.94	1.13	7	2.04*			
L(IJK)		870.48	0.56	1568				
6. Scree No. 1								
Mean		88976.44	88976.44	1				
I		77.38	25.79	3		1.21	4	21
J		1306.11	217.69	6		10.27**	6	21
K		8.83	8.83	1		2.03	7	6
IJ	IJK	352.74	19.60	18	7.74**			
IK	IJK	11.24	3.75	3	1.48			
JK	IJK	11.11	1.85	6	0.73			
IJK	L(IJK)	45.60	2.53	18	4.47**			
L(IJK)		1554.35	0.57	2744				
7. Isosceles								
Mean		31058.29	31058.29	1				
I		2.72	2.72	1		1.02	5	8
J		736.43	92.05	8		12.27**	9	11
K		0.43	0.43	1		3.10	9	8
IJ	IJK	51.56	6.44	8	1.67			
IK	IJK	0.02	0.02	1	0.00			
JK	IJK	10.96	1.37	8	0.36			
IJK	L(IJK)	30.81	3.85	8	5.26**			
L(IJK)		1291.15	0.73	1764				

*Significant at the 95% level.
**Significant at greater than the 99% level.

APPENDIX 5

THE ROLE OF SNOW AVALANCHES IN THE EVOLUTION OF ALPINE TALUS SLOPES

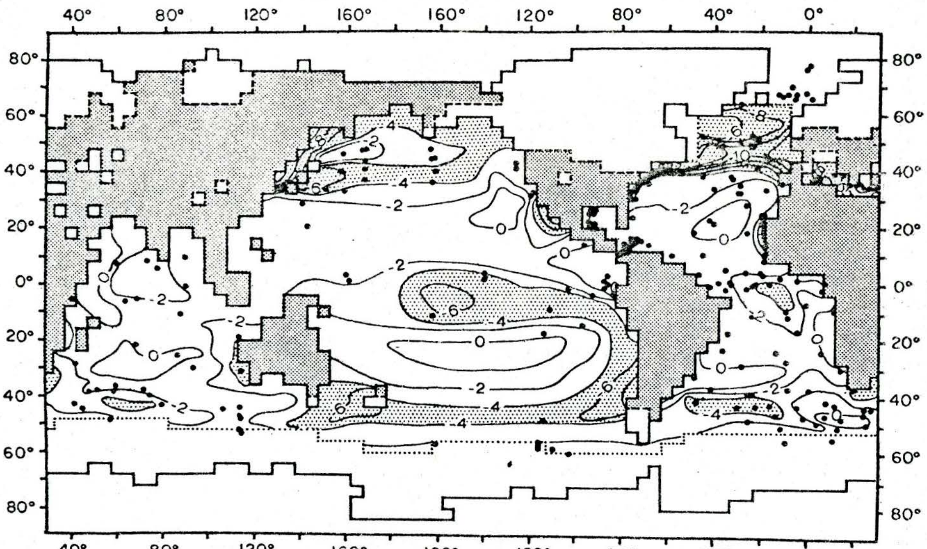


Fig. 2. Difference between August sea-surface temperatures 18,000 years ago and modern values. Contour interval is 2°C. Areas where the temperature change was greater than 4°C are shown in light stippling. Ice-free land areas are shown in darker stippling. Continental and ice outlines conform to a grid spacing of 4° latitude by 5° longitude. Heavy solid lines indicate continental outlines; dashed lines are ice margins on land; dotted lines indicate sea-ice margins. Large dots mark the locations of cores used in reconstructing sea-surface temperatures 18,000 years ago (*38*).

cores that show this distinctive lithologic sequence of glacial clay overlain by Holocene diatoms. The northern limit of winter (Southern Hemisphere) sea ice 18,000 B.P. must fall between the Antarctic Polar Front (identified faunally) and the summer ice boundary. We drew it halfway between.

The technique of isotopic stratigraphy is based on the demonstration that downcore variations in the oxygen isotope composition of calcareous shells reflect primarily variations in continental ice volume (*37*). Because these variations are synchronous within the mixing time of the world ocean, and have been dated in suitable cores by carbon-14, a detailed chronostratigraphic framework of global extent can be constructed. This framework, extended locally by standard micropaleontological and lithologic techniques, and checked againt carbon-14 dates, has made it possible to identify a set of 247 samples representing sediment that accumulated on the sea floor approximately 18,000 B.P. (*38*). The error in the selection of the 18,000 B.P. level is estimated to be less than ± 2000 years in most cores. If the marine climate was changing rapidly during the interval around 18,000 B.P., there might be serious inaccuracies in Fig. 1. However, there is ample evidence from deep-sea cores that the interval in question was relatively stable over the period from 24,000 to 14,000 B.P. (*33*).

Map construction. The process of constructing a paleoisotherm map (Fig. 1) is comprised of seven steps. First, a suite of deep-sea cores is obtained to provide both surface and downcore samples over a broad geographic area. Second, the relative abundance of the species in the surface samples is determined, and species assemblages are defined by factor analysis (*34*). This provides a quantitative statement of the relative importance of each species in each assemblage and of each assemblage in each surface sample. The assemblages are then checked to see that they form coherent distributional patterns that can be related to surface water masses in the modern ocean (*39–41*). The third step is to establish, by means of a regression equation, the relationship between the average August sea-surface temperature (*42*) and the numerical value of the assemblages at each sample site (Table 2). This equation expresses sea-surface temperature as a function of the various assemblages (*32*). If the seabed data set includes a wide range of ecologic and diagenetic conditions, the equation is insensitive to nonthermal effects. The accuracy and reproducibility of the equations are then tested on an independent set of data (*39*). Fourth, the stratigraphy of the time interval under study is determined by using paleontological, geochemical, and paleomagnetic techniques, and a suite of isochronous samples are chosen that represent the sediment deposited at the time we wish to reconstruct. Each sample represents 1 cm of sediment and integrates the climatic record over a certain time interval. This interval is based on the average accumulation rate in our open-ocean cores (about 1 to 10 cm per 1000 years) and, allowing for mixing by burrowing organisms, it is estimated to range between 4000 and 400 years. Fifth, the microfossils in these sediments are examined and counted. Each sample is then described in terms of the assemblages defined in the surface sediments. Sixth, from this numerical description of the ice-age samples in terms of modern assemblages and the regression equations relating modern assemblages to temperature, an estimate of the 18,000 B.P. temperature is made for each sample. Finally, the results are plotted and contoured to yield paleoisotherm maps.

The reconstruction of sea-surface conditions (Fig. 1) was controlled by 247 data points. The quality of this control (Fig. 2) ranged from good in the North Atlantic to poor in the South Pacific. To guide the contouring in poorly controlled regions, therefore, it was helpful to formulate a general view of the nature of oceanic circulation at 18,000 B.P. and to employ biotic assemblages as water-mass indicators. Without exception, these radiolarian, foraminiferal, and coccolith assemblages are related to water-mass boundaries (*39–41*). It was therefore reasonable to assume that their distribution in the past can be used to indicate the positions of surface water-masses and currents. In the regions of poor control we assumed that changes in oceanic gyre geometry between 18,000 B.P. and today were similar to those that occurred in regions where our control is good—that is, that the major gyres of the ocean circulation were not disrupted at 18,000 B.P., but were shifted in position or changed in size or shape.

Discussion

Land albedo. The reconstruction of the distributions of vegetation types during the last ice age (Fig. 1) indicates that desert regions, steppes, grasslands, and outwash plains expanded at the expense of forests, yielding a slight increase in the albedo of land areas not covered by ice. Although the effect of this vegetational change on the dynamics of the global climate system may have been slight, the effect of the increase in albedo associated with the great expanse of land ice may have been quite large.

Cryosphere. The most striking feature of the 18,000 B.P. world was the Northern Hemisphere ice complex, consisting of land-based glaciers, marine-based ice sheets, and either permanent pack ice or shelf ice (Fig. 1). This complex stretched across North America, the polar seas, and parts of northern Eurasia. By contrast, large arctic areas in Alaska and Siberia remained unglaciated. In the Southern Hemisphere the most striking difference was the winter extent of sea ice, which was significantly greater than it is today. Changes in land ice were small. This extensive ice cover in the North Atlantic and southern oceans may have reduced the loss