Géographie physique et Quaternaire

Debris Accumulation Patterns on Talus Slopes in Surprise Valley, Alberta

Les modes de mise en place des débris sur les talus d'éboulis, Surprise Valley, Alberta

Anordnung der Gesteinstrümmeranhäufung an Geröllhalden in Surprise Valley, Alberta

Brian H. Luckman

Volume 42, Number 3, 1988

URI: https://id.erudit.org/iderudit/032735ar
DOI: https://doi.org/10.7202/032735ar

See table of contents

Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

Explore this journal

Cite this article

Luckman, B. H. (1988). Debris Accumulation Patterns on Talus Slopes in Surprise Valley, Alberta. *Géographie physique et Quaternaire*, *42*(3), 247–278. https://doi.org/10.7202/032735ar

Article abstract

This paper presents the results of the measurement of debris accumulation processes, patterns and volumes at seven sites over a 13-year period in Surprise Valley, Alberta, Canada. Mean accumulation rates range up to ca 5 mm/yr and are strongly influenced by the amount and frequency of snow avalanche activity. All talus slopes studied experienced avalanches during the 13-year period and avalanche erosion is important in modifying and reworking the surface of these slopes. Mapped depositional patterns on selected slopes indicate deposition is more probable and usually greater on upper an middle slopes but avalanche erosion may result in greater volumes of deposition on lower slopes in some years (almost one year in two at the most active sites). There is high year-to-year and site-tosite variation in avalanche activity indicating that local, site specific controls are the most important determinant of depositional patterns. Rockfall amounts are underestimated by the point sampling techniques used in this study. Limited available data suggest rockfall inputs to the talus exceed those by snow avalanches (much of the avalanche deposition is reworked from upslope) and a least two major debris-flow generating events were recorded over a 13-year period.

Géographie physique et Quaternaire, 1988, vol. 42, n° 3, p. 247-278, 25 fig., 6 tabl., 1 app.

DEBRIS ACCUMULATION PATTERNS ON TALUS SLOPES IN SURPRISE VALLEY, ALBERTA

Brian H. LUCKMAN, Department of Geography, University of Western Ontario, London, Ontario N6A 5C2.

ABSTRACT *This paper presents the results* of the measurement of debris accumulation processes, patterns and volumes at seven sites over a 13-year period in Surprise Valley, Alberta, Canada. Mean accumulation rates range up to *ca* 5 mm/yr and are strongly influenced by the amount and frequency of snow avalanche activity. All talus slopes studied experienced avalanches during the 13-year period and avalanche erosion is important in modifying and reworking the surface of these slopes. Mapped depositional patterns on selected slopes indicate deposition is more *probable and usually greater on upper an* middle slopes but avalanche erosion may result in greater volumes of deposition on lower slopes in some years (almost one year in two at the most active sites). There is high year-to-year and site-to-site variation in avalanche activity indicating that local, site specific controls are the most important determinant of depositional patterns. Rockfall amounts are underestimated by the point sampling techniques used in this study. Limited available data suggest rockfall inputs to the talus exceed those by snow avalanches (much of the av*alanche deposition is reworked from upslope)* and a least two major debris-flow generating events were recorded over a 13-year period.

RÉSUMÉ *Les modes de mise en place des débris sur les talus d'éboulis, Surprise Valley, Alberta.* On présente ici les résultats de mesures prises au cours d'une période de 13 ans sur les processus, les modes de mise en place et le volume des débris dans Surprise Valley, en Alberta. Les taux d'accumulation moyens s'élèvent jusqu'à environ 5 mm/an et sont grandement dépendants de la quantité et de la fréquence des avalanches. Tous les talus d'éboulis ont été affectés par les avalanches au cours de ces 13 années, et l'érosion provoquée par les avalanches est *importante en ce qu'elle modifie et remanie* la surface des versants. Les modes de mise en place sur quelques versants choisies démontrent que l'accumulation est davantage probable et plus importante dans les parties supérieures et moyennes des versants, mais que l'érosion par les avalanches peut donner de plus grandes accumulations dans les parties inférieures des versants selon les années (presque un an sur deux aux sites les plus actifs). On note une forte variation de l'activité des avalanches d'une année à l'autre et d'un site à l'autre, démontrant ainsi que les forces *locales spécifiques à chacun des sites sont* les éléments les plus importants déterminant le mode d'accumulation. Selon les techniques utilisés dans ce travail, les éboulis rocheux sont sous-estimés. Les quelques données disponibles laissent croire que les débris produits par les éboulis rocheux sur les talus sont plus volumineux que ceux résultant des avalanches (la plus grande partie de l'accumulation entraînée par les avalanches est remaniée à partir de la partie supérieure de la pente). Au moins deux événements importants responsables de coulées de débris *ont été enregistrées au cours des 13 années.*

ZUSAMMENFASSUNG *Anordnung der Gesteinstrümmeranhäufung an Geröllhalden in Surprise Valley, Alberta.* Dieser Artikel stellt die Messungsergebnisse von Verlauf, Anordnung und Volumen der Gesteinstrümmeranhäufung dar, die über einen Zeitraum von 13 Jahren in Surprise Valley, Alberta, durchgeführt wurden. Die durchschnittlichen Akkumulationsraten reichen bis zu etwa 5 mm/Jahr und sind sehr stark durch die Menge und Frequenz der Schneelawinen beeinflusst. Alle untersuchten Geröllhalden sind während dieser Zeitspanne von 13 Jahren durch La*winen beeinflusst worden, und die durch La*winen herbeigeführte Erosion spielt eine wichtige Rolle bei der Veränderung und Umarbeitung der Oberfläche dieser Halden. Die für ausgewählte Halden kartographierten Anordnungsmuster der Ablagerung zeigen, dass die Ablagerung in den höheren und mittleren Halden wahrscheinlicher und normalerweise grösser ist, aber die Erosion durch Lawinen kann in manchen Jahren zu grösseren Ablagerungsvolumen in den niedrigeren Halden führen (fast jedes zweite Jahr an den aktivsten Plätzen). Die Lawinen-Aktivität var*iiert von Jahr zu Jahr und Platz zu Platz sehr* stark, was zeigt, dass für die Anordnung der Ablagerungen die örtlichen und platzspezifischen Einflüsse am wichtigsten sind. Mit den in dieser Studie verwendeten punktuellen Untersuchungen wird die Menge des Gesteinsfalls unterschätzt. Die wenigen vorhandenen Daten lassen vermuten, dass der Gesteinsfall mehr zu den Halden beiträgt als die Schneelawinen (ein grosser Teil der Ablagerung durch Lawinen wird vom oberen Teil der Halde aus umgearbeitet). In der Zeitspanne von 13 Jahren werden mindestens *zwei wichtige Ereignisse registriert, die zum* Fliessen der Gesteinstrümmer führten.

Manuscrit reçu le 8 mars 1988; manuscrit révisé accepté le 11 avril 1988

INTRODUCTION

Debris slope is a general term for the continuum of features resulting from the accumulation of rock clasts on slopes by mass-wasting processes (see Church *et al.*, 1979; Gardner, 1973; Rapp, 1960). The detailed morphological and sedimentologic characteristics of such slopes depend on the volume and lithology of rock debris, the geomorphic processes involved, local topographic controls and the geomorphic history of the site. Talus or scree slopes are the best known and most frequently studied phenomena within this continuum. Although rockfall is often assumed to be the dominant process involved in talus formation, most basic definitions (*e.g.* Rapp and Fairbridge, 1968) are couched in terms of the topographic position, thickness or composition of the landform rather than the geomorphic processes involved in its formation. Many geomorphic processes may modify or contribute debris to talus slopes (*e.g.* rockfalls, snow avalanches, debris flows, etc.) and the resulting morphological differences have been acknowledged by the recognition of different types of talus by several authors (*e.g.* White, 1981; Caine, 1974; Church *et al.*, 1979). However, observational difficulties and accessibility have limited detailed process studies that evaluate the role or relative importance of these processes in different geomorphic environments. This paper presents the results of a study of the geomorphic processes and depositional patterns on a series of talus slopes in the Canadian Rockies between 1968 and 1981. It demonstrates the diversity and variable intensity of these processes in a relatively small area of mid-latitude temperate mountains where snow avalanches may be a significant factor in talus slope development. Preliminary results from this study have been reported previously (Luckman, 1971, 1972a and b, 1977, 1978a) and the measurement techniques evaluated (Luckman, 1978b). Other long-term talus studies have been carried out in Sweden (Rapp, 1960), Poland (Kotarba *et al.*, 1979) and elsewhere in the North American Cordillera (Caine, 1976; Gray, 1973; Gardner, 1979; Gardner *et al.*, 1983) using different techniques. Some of Gardner's sites are very similar to those reported here.

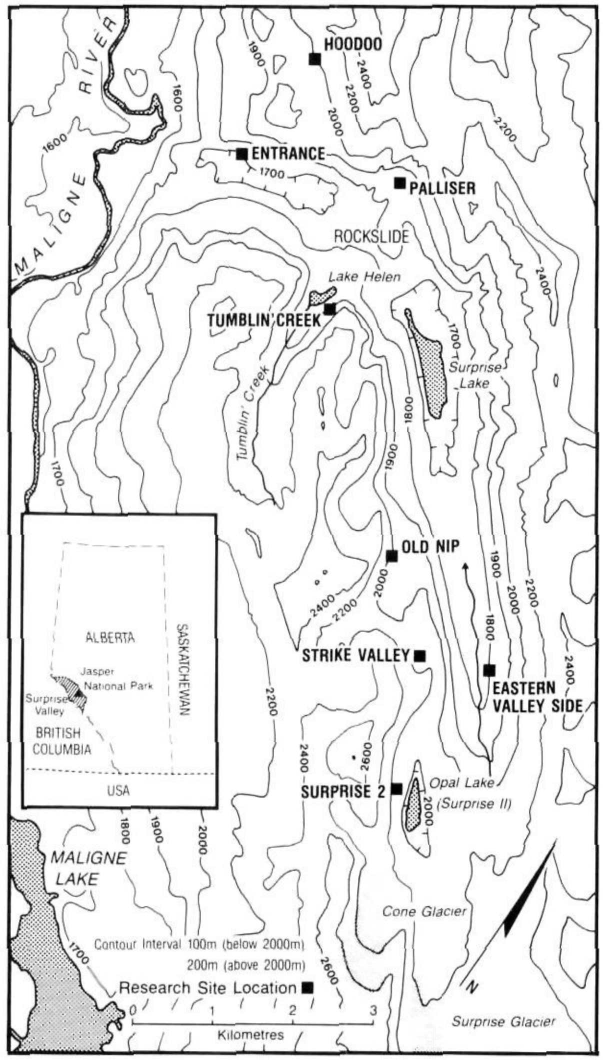


FIGURE 1. Location of Surprise Valley, Alberta. Note that all place names used within the valley are unofficial and do not appear on topographic maps. The names Opal Lake and Opal Mountain (west of Opal Lake) are used occasionally by people from Maligne Lake.

Localisation de Surprise Valley, en Alberta. À noter que les noms de lieux s'appliquant à la vallée ne sont pas officiels et n'apparaissent pas sur les cartes topographiques. Les noms Opal Lake et Opal Mountain (à l'ouest de Opal Lake) sont parfois utilisés par les habitants de Maligne Lake.

CHARACTERISTICS OF THE STUDY AREA

Surprise Valley is a small alpine valley in the Queen Elizabeth Ranges of the Canadian Rocky Mountains (Fig. 1). The main valley axis parallels the regional strike and the valley lies almost completely within a single thrust-faulted wedge of sedimentary rocks ranging from Lower Ordovician to Triassic in age. The western flank of the valley contains high cliffs formed in horizontal or, southwards, increasingly westward dipping, massive, Mississippian and Upper Devonian limestones: the eastern valley side conforms with a steep dipslope (30-50°) developed on the underlying Lower Devonian shales and limestones. Cliff aspect, plan and profile morphology are the principal controls of the spatial variation in debris-transfer processes from the cliffs and consequently the most significant controls of talus morphology. The sharp geological contrast between these valley sides has resulted in a great diversity of easily accessible cliff and talus environments in a relatively small and compact area. The major debris transfer processes on these slopes are rockfalls and snow avalanches. Seven principal study sites were chosen, varying in elevation from about 1680-2100 m (Table I). They include a range of talus types and aspects with varying combinations in the relative significance of rockfalls and snow avalanches based on morphological characteristics of the talus and observations of avalanche deposits at these sites in June 1968. The primary goals were to evaluate the relative importance of snow avalanche activity in the development of these slopes and the utility of cleaned boulder and polyethelene square networks for the measurement of debris accumulation patterns (Luckman, 1978b).

Climatic data for this area are sparse (Janz and Storr, 1977). Jasper townsite, about 40 km NW and 600 m lower

TABLE I

Summary of study site characteristics in Surprise Valley, Alberta

Site	Elevation Base talus (m)	Elevation Top cliff (m)	Aspect	Nature of cliff	Geology[a]	Nature of talus	Major process
Eastern Valley Side	1900	2300	SW	straight, dipslope *ca* 40-50°	MH	avalanche tongue on vegetated talus	avalanche
Entrance	1680	1820	S	straight, vertical	P,B	sheet with minor cones	rockfall
Old Nip	1940	2500	E	straight, vertical	R	sheet with major rockfall cone	rockfall with local avalanche
Palliser*	1840	2200	S	rockslide scar	Pa	rockfall cones, avalanche modified	rockfall and avalanche
Scree No. 1*	1840	2200	SW	straight, 40-50°	S	sheet talus	rockfall
Strike Valley	2060	2520	E	embayment in *ca* 60-70° straight cliff	R	avalanche track across sheet talus	avalanche and rockfall
Surprise II	2000	2800	E	straight with gullies *ca* 50-70°	R, RMF	multiprocess sheet and cones	avalanche, rockfall
Tumblin' Creek	1800	2300	E&W	avalanche chutes and benched cliff	R,B	avalanche tongue, cones and sheets	avalanche

* adjacent sites

[a] Key to Geology (after Mountjoy, 1964)
RMF = Rocky Mountain Fm. (Permian and/or Pennsylvanian) cherty brown sandstone
R = Rundle Group (Mississippian) dolomites, limestones and shales
P = Pekisko Fm. (Rundle Group) dolomite
B = Banff Fm. (Rundle Group) limestone and calcareous shale
Pa = Palliser Fm. (Devonian) massive fine crystalline limestone
S = Sassenach Fm. (Devonian) sandstone and siltstone
MH = Mount Hawk Fm. (Devonian) argillaceous limestone

than Surprise Lake, has a mean annual temperature of 2.8°C, with mean January and July temperatures of −12.8 and 15.1°C, respectively (AES, 1982). Lapse rate calculations suggest mean annual temperatures at the talus sites studied range from *ca* 0 to −4°C. Precipitation at the warden station at Maligne Lake (1676 m) between October 1963 and May 1971 averaged 563 mm/yr (272 mm rainfall, 291 cm snowfall, S.M. Elder, pers. comm., July 1972). Janz and Storr (1977) estimate precipitation amounts on the ridge between the Surprise and Maligne Valleys to be between 750-1000 mm/yr of which 60-70% is snowfall (1977, Fig. 5.7a). The talus sites usually become snow-free between May and late July depending on elevation, aspect, snowfall amounts and the volume of avalanche snow deposited on the slope.

METHODS

A. MEASUREMENT

Sampling networks were established at seven sites (see Appendix I for a definition of terms) in Surprise during August 1968 and supplemented in 1969 (Luckman, 1978b, Table 1). These networks consisted of polyethelene squares (2.32 m^2, anchored with marker boulders) and relatively large, flat-topped boulders (Figs. 2, 3) that were swept clean of debris and numbered (sample boulders). Each sample site was visited annually from 1969-1978, in 1980 and 1981 (Table II), the accumulated debris measured and the sample site swept clean. In almost all cases the sampled boulder surface is some distance above the adjacent talus slope surface (Fig. 3) and therefore talus creep is eliminated as a possible depositional mechanism. Of the 1051 boulder sites set between 1968 and 1973, 84% were re-measured in 1981. Most squares were abandoned after a few years because of problems of site maintenance due primarily to avalanche erosion (see Appendix I and Luckman, 1978b). Solid volumes for the larger accumulated fragments (usually >100 mm "a" axis) were calculated from the product of triaxial measurements and an empirically determined "shape coefficient" (range 0.42-0.76, Luckman, 1973). The volume of smaller fragments was measured by immersion in water in 1969 and estimated visually in subsequent years. Sampling sites missed in one year, usually due to late-lying snow cover, could be sampled in subsequent years (see notes, Appendix I). Sample boulders buried, removed by avalanches or destroyed by impact were not replaced except for 24 boulders at the Tumblin' Creek site in 1973.

For convenience annual measurement periods are referred to by the year of measurement, *e.g.* "1973" data refer to activity (deposition, avalanche erosion, etc.) between August 1972 and August 1973.

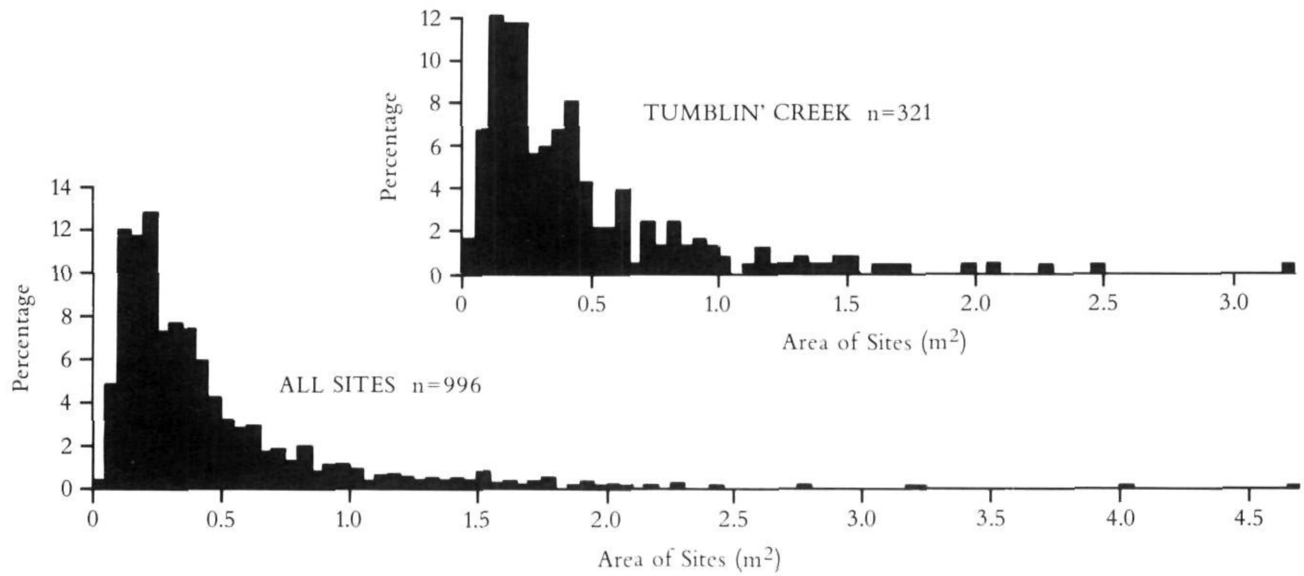


FIGURE 2. Histogram showing surface area for sample boulder sites set for the 1969-70 winter at all sites and at Tumblin' Creek, Surprise Valley, Alberta.

Histogramme montrant la superficie des sites de blocs témoins à tous les sites pour l'hiver 1969-70 et à Tumblin'Creek, Surprise Valley, Alberta.

TABLE II

Data collection periods in Surprise Valley, 1968-1981

Site	Date set up	Major collection dates*											
		1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981
Eastern Valley Side	10.8.68	24.7	18.7	21.8	21.8	11.8	31.7	1.9	21.8	20.8	16.7	11.8	11.7
Entrance	16.8.68	16.7 17.7	2.7	20.8	18.8	27.8	2.8	1.9 7.9	22.8	15.7	27.8	12.8	10.7
Old Nip	14.8.68 30.9.69	17.7	30.6	21.8	21.8	10.8	1.8	31.8	21.8	20.8	16.7	11.8	11.7
Palliser	18.8.68 27.9.69	23.5 6.7	24.6	20.8	20.8	9.8	12.7	1.9	12.8	15.7	17.7	12.8	10.7
Strike Valley	11.8.68	16.7 17.7	11.7 13.8	13.8	21.8	10.8	1- 23.8	31.8	21.8	20.8	16.7	11.8	11.7
Surprise 2	9-19.8.68 23.9.69	9- 19.7	1.7- 22.8	15.8 16.8	22.8	10- 27.8	1.8- 11.9	1.9	21.8	20.8	16.7 27.8	11.8	11.7
Tumblin' Creek	17.8.68 23.9.69 27.8.73	25.5- 6.7	25.5 19.8	12.6- 22.8	19.8 20.8	8.6 27.8	12.7- 11.9	31.8	14.8 4.9	15.7 23.8	15.7 27.8	12.8	30.6

* Dates are day, month, year. Where more than two dates occurred only the first and last days are given separated by (-)

B. DATA MANIPULATION

As sample sites vary in area (most boulders were between 0.1-0.7 m², Fig. 2: squares were originally 2.32 m²) accumulated volumes were corrected for surface area to provide point estimates of deposition expressed as average depth in millimetres. Summary measures derived from these data include sample site means for the period of record, annual site means (combining results from several sample sites) and site means for 1968-1981 (Appendix I). However, the frequency distribution of annual volumes of deposition on sample sites is highly skewed: 53% of the 10,885 single site-years of data were zero and 11.3% of the total accumulation (1968-81) was a single boulder deposited at Strike Valley in 1971. At many sites over 50% of the total annual accumulation in any given year is from a single sample site (Appendix I) and therefore year to year and site to site variation in annual means may be strongly influenced by these maximum values which may not reflect other measures of deposition at the sites. In skewed distributions the median or 50th percentile is often a better measure of central tendency but, at many sites in Surprise, the median sample site accumulation value is zero and therefore not a good discriminator between sites.

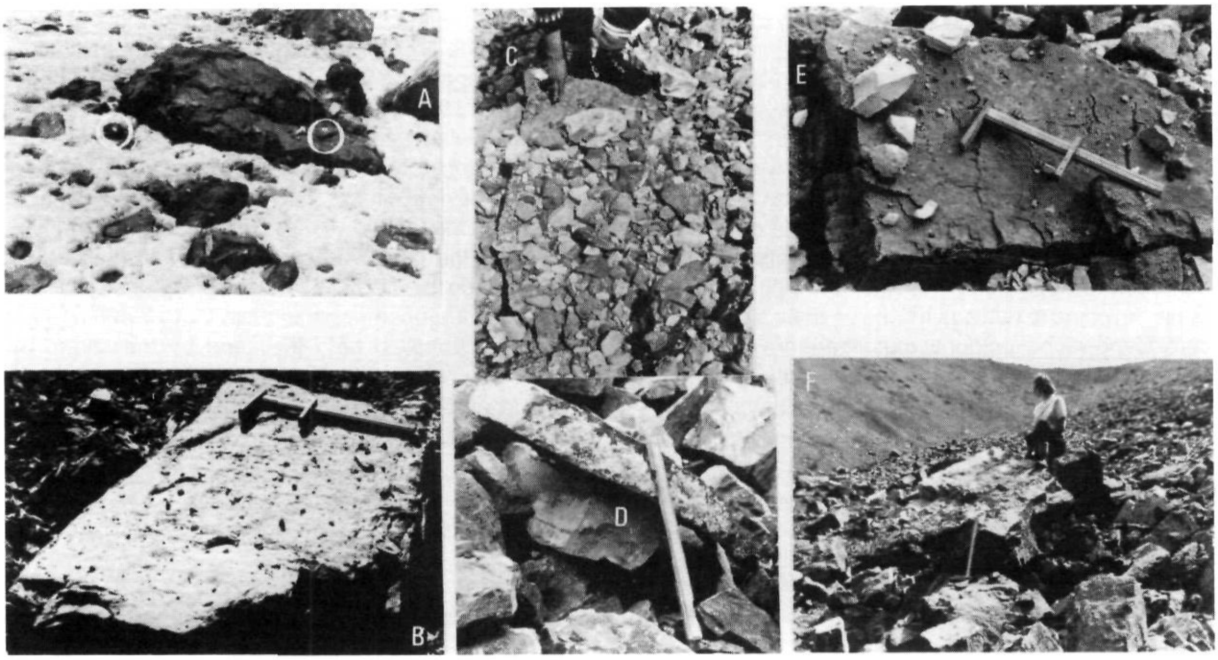


FIGURE 3. Accumulation on sample boulder surfaces, Surprise Valley, Alberta. These examples illustrate the range of material encountered and some of the information that may be derived from these deposits. A: Tumblin' Creek Cone, 27.5.1970. Except for the three largest boulders (the largest is a sample boulder *ca* 2 m "a" axis) all the debris visible is resting on the snow. The circled marker boulders were eroded from a square further upslope. B: Surprise II, 13.7.1970. This debris is typical of the fine rock chips carried to the base of the slope by large snow avalanches from the cliffs in 1970. C: Tumblin' Creek Cone, 27.5.1970. Sample boulder with almost total debris cover eroded from the talus surface upslope (photograph courtesy of S. B. McCann). D: Tumblin' Creek 2, 15.7.1977. The sample boulder is identified by the letter D. The overlying slab was probably a rockfall, sliding downslope on the snow cover. E: Surprise II, 14.8.1970. This coarse debris is from a sample boulder outside the area covered by the avalanche at site B, above. F: Strike Valley, 13.8.1971. The sample boulder site is at the lower end of the "ruler" (0.6 m long). The boulder resting on its surface was the largest measured in Surprise (1.03 m^3).

L'accumulation à la surface des sites de blocs, Surprise Valley, Alberta. Ces exemples illustrent la gamme de matériaux observés et une partie des renseignements qu'on peut en retirer. A: le cône de Tumblin' Creek, 27.5.1970. Sauf pour les trois plus gros blocs (le plus gros est un échantillon dont l'axe "a" est de 2 m), tous les débris reposent sur la neige. Les blocs encerclés proviennent d'un carré de polyéthylène situé plus haut sur le versant. B: Surprise II, 13.7.1970. Ce type de débris est caractéristique des fins éclats de roche qui sont transportés vers la base du versant par les grosses avalanches à partir des escarpements, en 1970. C: Le cône de Tumblin' Creek, 27.5.1970. Bloc témoin dont la plus grande partie du couvert de débris a été érodé de la partie supérieure de la surface du talus (photo de S.B. McCann). D: Tumblin' Creek 2, 15.7.1977. Le bloc témoin est identifié par la lettre D. La dalle sus-jacente est probablement un éboulis de roche qui a glissé vers le bas sur le couvert de neige. E: Surprise II, 14.8.1970. Ces débris grossiers proviennent d'un bloc témoin situé à l'extérieur de la zone du site B (ci-dessus) affectée par l'avalanche. E: Strike Valley, 13.8.1971. Le site du bloc témoin est situé à la partie inférieure de la règle (0,6 m de long). Le bloc qui repose sur la surface est le plus gros qui ait été mesuré dans la vallée (1,03 m^3).

The most simple element of the depositional record of sample sites at Surprise is whether or not deposition occurred during a given sample period. Therefore the most basic measure of the amount (and extent) of deposition at a site in each year is the number (or percentage) of sample sites with deposition (the "zero" value is defined as <1 cc of debris to avoid minor sweeping errors). Differences in the magnitude of deposition may be evaluated by comparison of the percentage of sample sites with depositional values greater than some arbitrary threshold (*e.g.* 1 mm thickness or 1000 cm^3/m^2) or by comparing the cumulative frequency distributions themselves. Complete summary data of this type, with site means, are given in Appendix I.

Evaluation of average depositional patterns at a site may be accomplished in a similar manner. Depositional values used were from the 1968-1978 period for those sample sites with >5 years of data. The number of years with accumulation in this period could be used to define and, in some cases, map the probability of deposition at individual sample sites (*e.g.* 2 years deposition in 10 = probability of 0.2, Fig. 7a, below). Data may also be derived for the probability of receiving greater than «x» mm of deposition. Isolines of 0.5 probability (one year in two) were extracted from a series of these maps and used to produce summary diagrams depicting the average depositional pattern over the 10 year period. These maps may be compared with isoline maps showing the arithmetic mean accumulation over the same period (*e.g.* Fig. 7b and 7c) to evaluate long-term depositional patterns.

OBSERVATIONS AND RESULTS FROM INDIVIDUAL SITES

INTRODUCTION

The sampling networks used in this study were usually transects or profiles and are biassed towards basal sites for reasons of access, safety, boulder availability and erosion of sample sites from some upper slopes. A primary goal was to determine rates of activity in the basal portion of the talus and for selected areas/environments upslope. At three sites (Eastern Valley Side, Surprise II and Tumblin' Creek Cone) the sample site network is sufficiently extensive to provide a more complete view of depositional patterns. The measurement techniques used primarily record deposition from an ablating snow cover and are unlikely to record deposition for the 2-5 months (depending on elevation) when the slope is snowfree unless blocks come to rest against the upslope side of sample boulders. Depositional amounts must therefore be thought of as minimum values, biassed towards avalanche deposition and considerably underestimating rockfall amounts (Luckman, 1978b). Both the depositional process and debris may originate in the cliffs or on the slope itself (*e.g.* avalanche erosion of surface materials) and are not observed directly. In some cases reasonable inferences can be made about debris source and processes from the nature of the deposit and its spatial distribution (Fig. 3) but mixed deposits (*e.g.* rockfall onto avalanche snow) cannot be differentiated. Furthermore, as depositional amounts may not be a net input to the talus slope, these data cannot be used to infer rates of cliff recession or net talus accumulation. They are simply indicative of the rates of debris transfer in selected cliff-talus slope systems.

Results from this study will be presented initially on a site by site basis beginning with the more completely sampled sites which are also those most affected by snow avalanches. During the first four seasons (1968-1971) considerable information about debris transport was also obtained from inspection of the spring snow cover at these sites.

TUMBLIN' CREEK SITE

The lower end of Surprise Valley is blocked by a large rockslide that also dams the tributary Tumblin' Creek Valley to form Lake Helen. This small lake is flanked by 4-500 m high cliffs and the talus slopes that comprise the Tumblin' Creek site. The west-facing cliffs are a series of alternating vertical limestone walls and intervening shaley slopes developed on Mississippian rocks of the Rundle group (Figs. 4 and 5). The geology of the east facing slope is complicated by thrusting and the benches are less well defined. Talus sheets form two sides of the lake which covers the basal 25-35% of these slopes in summer. The lake drains underground and usually empties completely in the winter. The original 176 sites were set up around the lake in 1968 and the sampling network on the cone enlarged from 91 (Luckman, 1971, Fig. 9) to 296 sites in September 1969 (Luckman, 1978b, Fig. 1). About 35 of these sites were subsequently discovered to be below mean late-summer lake levels and could not be sampled. Although contiguous, the sample sites are reported as four areas (Tumblin' Creek Cone, TC1, TC2 and TC3) because of differences in dominant geomorphic processes and talus morphology.

Tumblin' Creek Cone

The Tumblin' Creek Cone is the most consistently dynamic avalanche slope in Surprise and has the densest sample site network. It is situated below a major avalanche chute and is an avalanche boulder tongue (Rapp, 1959), built across the lake and separating it into two parts at low water (Figs. 4-6). Below the "80 m" contour this feature has a mean slope of only 16°. Avalanches descending the cliffs entrain debris from higher sections of the chute as it crosses the gentler slopes between the vertical cliffs. The avalanches become airbourne as they descend the lowest cliff, land in the lowermost chute, run out on the cone and occasionally into the trees on the opposite side of the lake. These avalanches are probably initiated on the open upper slopes, up to 3-400 m above the talus, and funnelled onto the cone by the chute. Smaller cones occur below chutes on the other side of the lake.

Erosion by snow avalanches has been a critical component in the development of the Tumblin' Creek Cone. In June 1968 the cone surface between the 45-55 m contours was blanketed by the remains of a large dirty avalanche (Luckman, 1971, Fig. 4), containing at least 10-20 m^3 of rock debris in large

FIGURE 4. Tumblin' Creek Cone from the west, August 1971. The avalanches begin well above the upper cliff shown, crossing a series of similar vertical cliffs and benches before dropping over the lowest, Pekisko cliff onto the funnel-shaped head of the cone.

Cône de Tumblin' Creek vue de l'ouest, août 1971. Les avalanches commencent bien au-dessus des escarpements que l'on voit et traversent une série d'escarpements et de gradins verticaux semblables avant de tomber sur le plus bas escarpement Pekisko, à la tête du cône en forme d'entonnoir.

blocks which was probably eroded from the upper slopes of the cone. Deposition was far less extensive in 1969 but one sample boulder was moved about 40 m downslope and marker boulders from two of the upper squares were also displaced (Fig. 6). In an attempt to monitor erosion six lines of painted boulders were set up across the upper part of the cone (Fig. 6; Luckman, 1972a, Table I). Extensive erosion occurred in the central part of the cone in 1970 with sample boulders, marker boulders and smashed fragments of a wooden sampling square (left on the slope in the preceding October) being moved considerable distances downslope (see also Fig. 8). Debris deposited on the lake-floor ice by this event was redistributed by ablation from ice floes as the lake filled (Luckman, 1975). The squares were reset but in 1971 the upper 11 squares, 18 of the highest 20 sample boulders and most painted boulders from the lower lines were eroded and deposited downslope. Although some debris must have been carried into the lake, the pattern of the 300+ painted boulders recovered clearly

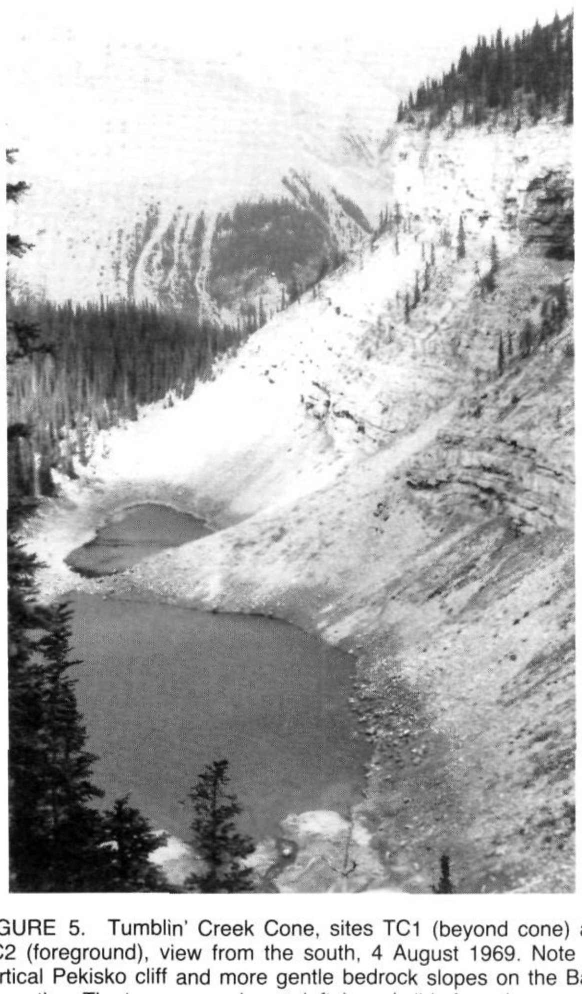


FIGURE 5. Tumblin' Creek Cone, sites TC1 (beyond cone) and TC2 (foreground), view from the south, 4 August 1969. Note the vertical Pekisko cliff and more gentle bedrock slopes on the Banff Formation. The tree-covered area, left, is rockslide from the opposite side of Surprise Valley.

Cône de Tumblin Creek, sites TC1 (au-delà du cône) et TC2 (au premier plan), vus du sud, le 4 août 1969. À noter l'escarpement Pekisko vertical et les pentes plus douces de la Formation de Banff. La partie boisée, à gauche, est un glissement d'éboulis rocheux provenant du côté opposé de Surprise Valley.

outlines the area covered by this avalanche (Fig. 6). The painted boulders that survived 1971 had disappeared by 1972 (eroded or buried) and one of the sample boulders at the apex of the cone was moved 6 m downslope. The upper sample boulder network was partially replaced in 1973 but one of these boulders was lost in 1974 and another seven were eroded in 1976 (Fig. 6). Significant erosion of boulder sites has not occurred since 1976 (it could be argued that only the best anchored ones remain!) but the volumes of deposition in 1973, 1980 and 1981 are comparable with those years when avalanche erosion is known to have occurred. In both 1970 and 1971 balls of soil/fines were found in avalanche snow and on the talus indicating some erosion of cohesive soil surfaces in the track.

It is clear from these observations that avalanches may erode loose material from almost the entire length of the cone surface and move it downslope (Fig. 6). The position of the erosional zone varies from year to year probably reflecting avalanche volumes, impact point and the variation and timing of accumulation and ablation patterns of snow on the slope. In 1969 and 1970 a carapace of ice, nourished from the spring at the head of the chute, was observed on the upper slope and may have protected the underlying talus from avalanche erosion. The grassy, smooth area in the central part of this cone is periodically swept clear of loose debris by avalanche erosion and many of the large boulders on that surface (including sample boulders!) are simply in temporary storage until they are moved to the end of the runout zone. This periodic erosion and the overlapping of erosional and depositional zones in different years produce the characteristic linear sorting gradient typical of many avalanche modified slopes (Rapp, 1959; Luckman, 1978a).

Depositional patterns on the cone are complex with both avalanche and rockfall components. Although these components cannot normally be separated a few rockfall events can be distinguished at this site. In 1972 several large, angular fragments of cream-coloured limestone (at least 1.5-2 m^3) were deposited amongst the sample sites between the 60-75 m contours. Similar evidence indicates a rockfall of at least 1 m^3 of Banff formation in 1980. Bumpholes, 0.5 m deep, and impact fractures on sample sites indicate a freshly broken 0.9 m^3 boulder, with tufa on three faces, was a rockfall in 1973. Many boulders in the 0.1-0.5 m^3 range were deposited on top of marker or painted boulder debris or adjacent to sample boulder sites during the study period at this site. These results suggest that the large boulders scattered over the sample sites on this slope are quite typical of depositional events over this 13 year period.

Between 1978 and 1980 a debris flow occurred on the northern flank of the cone, cutting a channel about 1 m deep and 2-3 m wide on the upper slopes and depositing at least 5-10 m^3 debris as levees. One sample boulder was completely buried and two others partially covered. A similar flow also occurred in the TC3 area in 1980. Morphological evidence at both localities indicates previous debris flows at these sites: however, as only one event was recorded during the 1968-81 period this suggests a minimum recurrence interval of 1 year in 14 for these two sites (see discussion below).

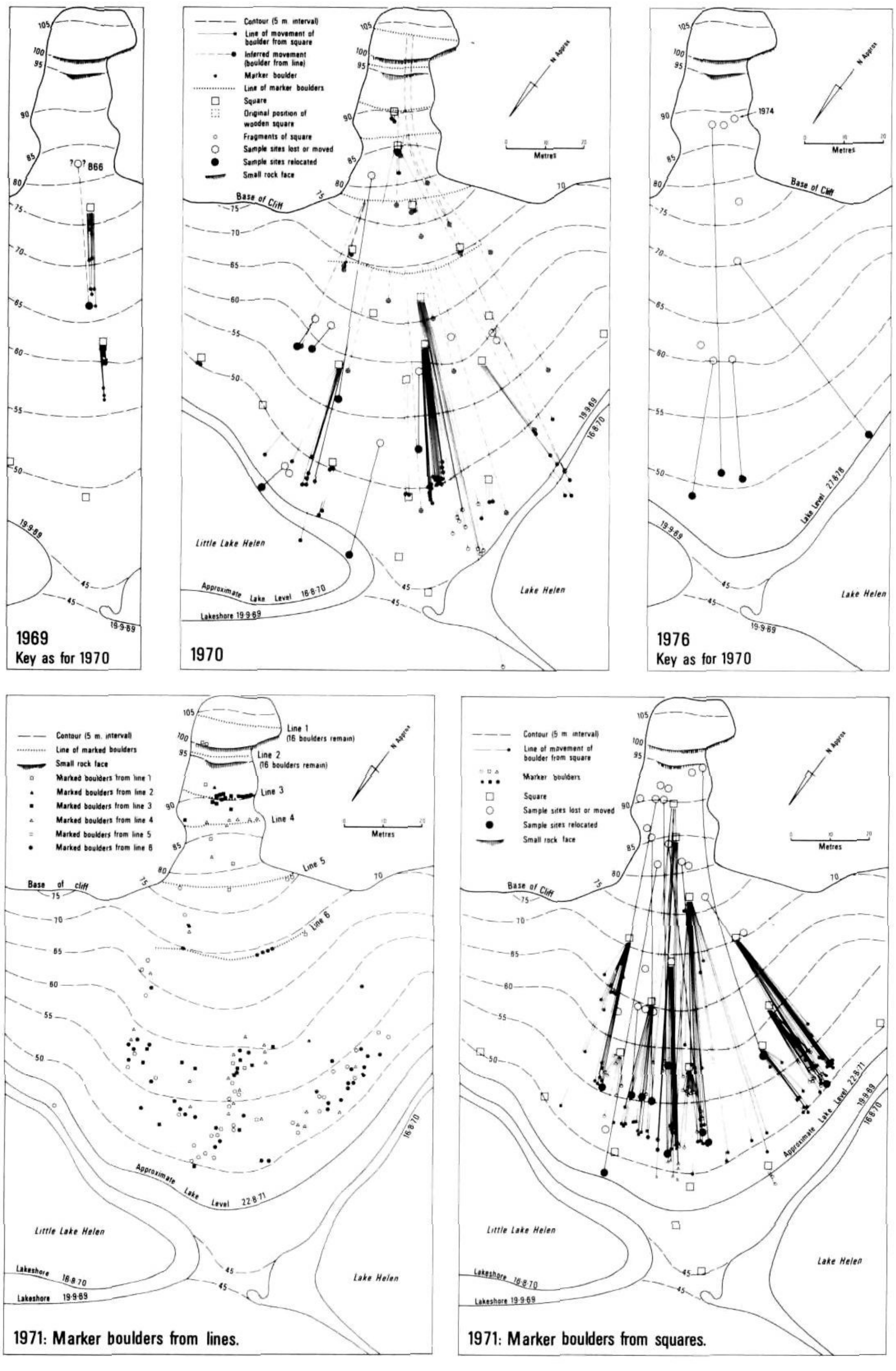


FIGURE 6. Erosional patterns on the Tumblin' Creek Cone, 1969-1976. Note the differences in the amount, extent and location of erosional zones, particularly between 1970 and 1971, and the clustering of deposition of debris from several sources. In 1970 some of the debris from a wooden square was deposited on the opposite side of the lake.

Les patrons d'érosion sur le cône de Tumblin' Creek, de 1969 à 1976. À noter les différences entre l'étendue des zones d'érosion et leur localisation, particulièrement entre 1970 et 1971, et le regroupement des débris déposés à partir de plusieurs sources. En 1970, une partie des débris provenant d'un carré boisé a été déposée du côté opposé du lac.

At the Tumblin' Creek Cone only a single small sample boulder (0.18 m^2, near the eastern base of the cone) had no deposition between 1968 and 1981. Almost all sites above the 60 m contour have a 100% probability of deposition (see Fig. 7a). Deposition was mainly confined to this zone in 1969 (Luckman 1971, Fig. 8), 1972, 1973, 1975, 1977 and 1978, *i.e.* 50% of the years for which data are available. The two probability diagrams in Figure 7 indicate that deposition is most frequent and most likely to be heaviest on the upper part of the cone and declines fairly regularly downslope. Values for mean accumulation are much higher and the zone of heaviest deposition is more uniformly spread over the cone. This apparent discrepancy reflects the redistribution of coarse debris to the base of the cone by avalanche erosion which offsets the higher probability of deposition on the upper slopes. These two diagrams (mean accumulation and 50% probability) indicate the probable long term development of this slope. Although deposition is generally greatest and most frequent on the upper part of the cone (50% probability) the cone is not building up (steepening) because of periodic avalanche reworking of this material, redistributing it more evenly and leading to progradation of the cone and maintenance of the relatively low angle of slope.

The Tumblin' Creek Cone has the greatest density and most complete areal coverage of sample sites (1.0-1.7% of the cone surface) on the slopes investigated in Surprise. Estimates of the total volume of deposition for each year between 1969 and 1978 were obtained by summing the product of the average depositional thickness and area for each contour interval above 45 m. The estimated annual volumes were 16.2, 40.6, 52.1, 32.8, 36.4, 13.7, 4.2, 35.8, 12.6 and 6.7 m^3, respectively. Estimates for the volumes of individual avalanches at these and other sites suggest these are the right order of magnitude but should probably be considered to be maximum figures because of the small area sampled.

Tumblin' Creek Sites 1 and 2 (TC1 and TC2)

Both of these sites are straight sheet talus slopes flanking the Tumblin' Creek Cone and dominated by rockfall activity (Fig. 5). The TC1 site is less active with 20 of 27 sample boulders having depositional probabilities of <0.35. Four of the remaining sample boulders are flush with the talus surface on their upslope side and their higher depositional probabilities (0.75-0.92) largely reflect small amounts of creep onto their sampled surfaces. Depositional amounts are quite small with larger values generally reflecting a single boulder rather than more extensive deposition.

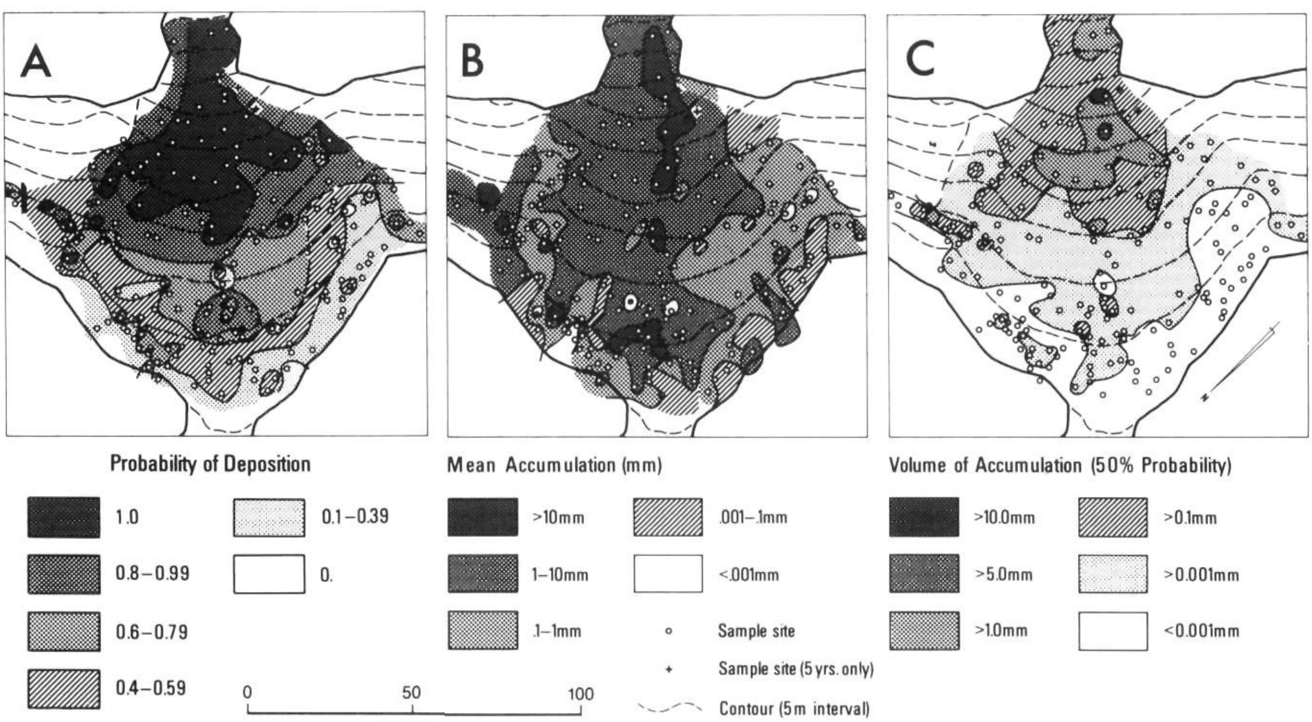


FIGURE 7. Depositional patterns on the Tumblin' Creek Cone (1968-78). A: The probability of receiving deposition in any year; B: Mean annual accumulation on sample sites; C: Volume of accumulation equalled or exceeded one year in two (50% probability map). The isolines are drawn at 0.5 probability, *e.g.* the sites within the lightest stippled area received deposition of between 0.0001 and 0.1 mm for at least five of the ten years between 1969 and 1978 (see text). Note: in these diagrams volumes of accumulations are reported as depth (thickness) in millimetres.

Patrons de mise en place des débris sur le cône de Tumblin' Creek (1968-1978). A: La probabilité de recevoir des dépôts quelle que soit l'année; B: Accumulation annuelle moyenne sur les sites témoins; C: le volume d'accumulation égalé ou dépassé une année sur deux (carte de probabilité à 50%). Les isolignes sont dessinées selon une probabilité de 0,5, les sites à l'intérieur du grisé le plus pâle ayant reçu des dépôts entre 0,001 et 0,1 mm pendant au moins cinq des dix années entre 1969 et 1978 (voir le texte). Note: dans le cas de ces diagrammes, les volumes d'accumulation sont donnés sous forme de profondeur (épaisseur) en millimètres.

FIGURE 8. Detail of avalanche deposits on snow, east flank of the Tumblin' Creek Cone, 29 May 1970. The figure stands about 15 m west of the polyethylene square on the "50 m contour" (1970 diagram, Fig. 6). The debris downslope of the figure has been eroded from the talus surface upslope (see Fig. 3C). Debris from the larger avalanche(s) which covered the entire cone is also visible.

Détail de dépôts d'avalanche sur la neige, flanc est du cône de Tumblin' Creek, 29 mai 1970. Le personnage est à environ 15 m à l'ouest du carré de polyéthylène sur la courbe de niveau de 50 m (diagramme de 1970 de la fig. 6). Les débris situés sous le personnage ont été transportés à partir de la surface du talus (voir la fig. 3C). On voit également les débris transportés par de plus grosses avalanches qui recouvrent tout le cône.

The cliff above the TC2 site is higher and longer with some avalanche chute development but no well defined tracks are identifiable across the talus. Small dirty avalanche deposits were noted on these slopes in the spring of 1969 and 1970 and some avalanche activity is inferred in later years from deposits on sample sites. Summary statistics indicate that TC2 has more avalanche deposition (51% site-years >0: 30% for non-creep sites on TC1) and heavier amounts of accumulation (29% >1 mm: 7% for TC1, see Appendix I). TC2 may also have a higher rockfall frequency as large boulders were recorded more frequently from this site (Fig. 2D). One sample boulder was smashed by rockfall impact in 1969 and in 1970 a primary rockfall of 10-15 m^3 fell onto the talus from the Banff cliffs.

Tumblin' Creek Site 3 (TC3)

This site is more complex than TC1 or 2 as it includes basal transects of two cones. Both are fed by well developed chutes but, based on cone morphology and vegetation, the avalanche runout zone is restricted to a narrow track on the margin of the cones. Nevertheless, a small dirty avalanche ran down one of these cones in 1969, incorporating 3-5 m^3 of talus from the lower cone and obliterating a small section of shoreline terraces cut into the talus. Significant avalanche activity was also noted in 1968, 1970 (based on snowcover observations), 1974-78 and 1980. Differences in depositional volumes generally reflect differences in the amount of avalanche erosion except for 1976 (see below) and 1969 when the observed depositional zone lay between sample sites. However it is interesting to note that avalanche erosion on opposite sides of the lake is not synchronous: both sides had large avalanches in 1970 but avalanche erosion only occurred on the Tumblin' Creek Cone in 1971 and extended further downslope and was more important on TC3 in 1969.

In 1976 a large primary rockfall fell *ca* 200 m down one of the chutes, clearing a fresh track through mature vegetation and depositing many blocks of 0.5-1.0+ m^3 on the talus (estimated total volume 100-150 m^3). One sample boulder was split and several others bruised or damaged by this event.

SURPRISE II SITE

The Surprise II site lies in a blind strike valley, 120-160 m deep, between the dipslope of a ridge of Palliser limestone and the cliffs of the east face of Opal Mountain (see Luckman, 1971, Fig. 5; Ford, 1979, Fig. 15). The cliff is basically straight in plan, 300-600 m high, with a mean slope of 50-70°. Broad avalanche chutes occur on the upper slopes but are poorly defined on the lower, steeper cliffs below a dark shale bench about half way down. Many avalanches are airbourne before they hit the talus and, in most years, debris covered snowcones persist at the apex of the larger talus cones. Snow caves are created in these features by small intermittent streams that drain the cliffs. Avalanche activity at this site continues until June or July with many small wet avalanches fed by residual snow patches in the cliffs. Based on spring snow cover characteristics this site has the greatest number and diversity of avalanches, including the largest ones seen in Surprise. Most of the other sites studied in Surprise are within a single avalanche track but the Surprise II cliffs contain numerous avalanche source areas, all of which may contribute debris to the slopes below.

The talus slopes are basically straight sheet talus with several overlapping multi-process cones, four of which are associated with the Surprise II site (Fig. 9). Cone D is 312 m long, has an average gradient of 29° with maximum angles of 32-34° in the upper 100 m (Luckman, 1973, Fig. 15.3). The sampling network originally consisted of sample boulders in a basal transect and profile (Luckman, 1971, Figs. 7, 8), supplemented by 105 boulders set in 1969 (Luckman, 1978b, Fig. 1). This configuration largely reflects the distribution of suitable boulder sites on the slope. A basal transect and a downslope profile of seven squares, *ca* 45 m apart, was set

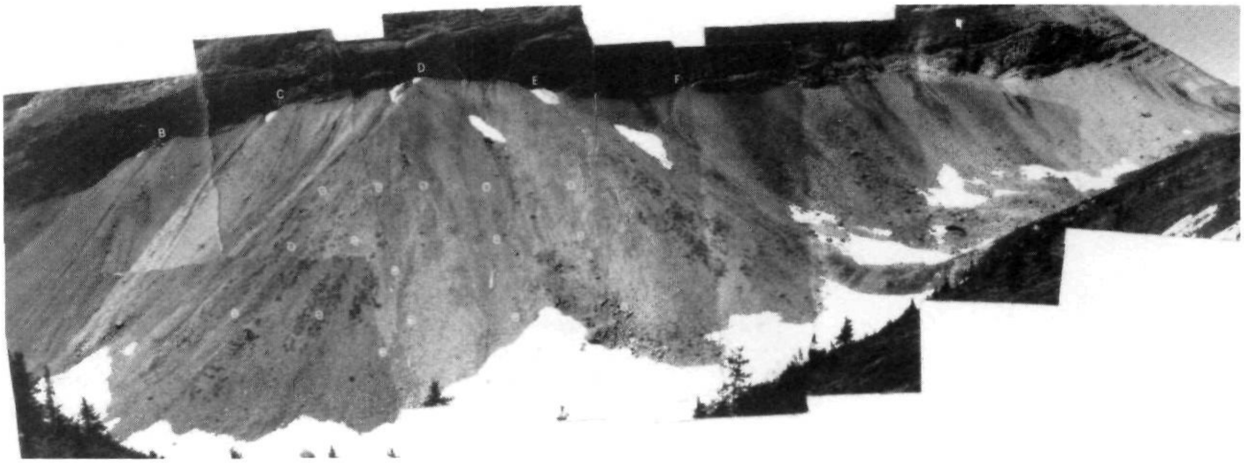


FIGURE 9. The Surprise II site from the east 19.7.1970. The lowest part of the talus is still covered with up to 8 m of avalanche snow. The five southermost "columns" of squares are clearly visible, although square 11 (in the centre, see Fig. 12) is missing. The two "misaligned" squares are remnants of the 1968 profile. Note the clear morphological evidence of debris flow activity and the protalus rampart. Point "Z" is approximately at the 60 m contour. The Strike Valley site lies immediately beyond the shale slope on the skyline, upper right. The letters B,C,D,E,F identify major talus cones.

Le site de Surprise II vu de l'est, le 19.7.1970. La partie inférieure du talus est encore recouverte jusqu'à 8 m de neige d'avalanche. Les cinq «colonnes» de carrés les plus au sud sont nettement visibles, bien que le carré n° 11 (au centre, voir la fig. 12) soit absent. Les deux carrés mal alignés sont les vestiges du profil de 1968. À noter les manifestations morphologiques nettes d'activité de coulées de débris et la levée. Le Z est à peu près sur la courbe de niveau de 60 m. Le site de Strike Valley est situé immédiatement derrière le versant de schiste à l'horizon, à la droite supérieure. Les lettres B,C,D,E,F, identifient les cônes d'éboulis les plus importants.

up on Cone D in 1968 but the top 4 sites were destroyed by avalanches in 1969 and not reset. In 1969 a network of 18 squares was set up (three horizontal rows, 45 m apart and six columns 45 or 30 m apart) and maintained until 1974 (see Fig. 9).

In the following section (and Appendix I) these sites are divided into three zones; upper sites, above the 105 (N) or 110 m (S) "contours"; lower sites below the 65 m (N) or 60 m (S) "contours" and the middle sites which include the 18 1969 squares. The lower transect covers a wider range of environments including the basal slopes of cone B. Few sites were set close to the cliff because of a minor basal overhang and high rockfall hazard.

Results

The Surprise II site is the largest and most complex studied. It has the longest lasting snow cover (see Fig. 9) and late-lying avalanche snow restricted sampling particularly in 1970, 1973, 1974 and 1981. In mid-July 1970 some basal sample sites were still covered by 6-8 m of avalanche snow and 2-3 m of snow remained in late August 1970 and 1973. Small spring and summer avalanches have been observed at this site (Luckman, 1976, Fig. 1) but observations between 1968 and 1971 indicate most avalanche activity takes place earlier when the talus is still snow-covered. The spring snow cover contains evidence of multiple avalanches ranging from narrow (5-20 m) "flow-like" (slush?) dirty avalanches that may run 50-300 m over the snow (Luckman, 1971, Fig. 6) to events which blanket large areas of talus with a relatively uniform cover of avalanche snow and rock fragments (Figs. 10, 11). In May 1969 and in 1970 the snow cover on cone D was redistributed by slab avalanching.

Many large avalanches at Surprise II (*e.g.* Fig. 10) have a relatively uniform debris concentration which consists mainly of rock chips (Fig. 3B) and suggests that a considerable proportion of the avalanche debris at this site is derived from the cliff zone. However, avalanche erosion also occurs, mainly on the upper and middle slopes. In 1969 all 5 squares set above the 80 m contour were destroyed and marker boulders carried up to 50 m downslope (Luckman, 1971, Fig. 7). Two of the new squares were eroded in 1970 but replaced (Fig. 12). However, selected limited erosion continued with a single square plus an entire "column" eroded in 1973 (squares 7, 8 and 9 see Fig. 12: the adjacent "columns", squares 4-6 and 10-12, were undamaged), one square in 1974 and three more in 1975 (two of these were one above the other). By 1975 the polyethelene from most squares had been lost and measurement was discontinued. However, the survival of eight of the top twelve squares at this site from 1970-1974 and the selective erosion patterns of those squares lost indicated that erosion is relatively local and minor compared with that at the Tumblin' Creek Cone.

Rockfalls were difficult to identify in deposits at this site although rockfalls in the range of 0.1-0.5 m^3 were seen on the snow in several years and single boulders >1 m^3 noted on two occasions. Systematic recording of debris volumes on avalanche snow was not carried out but two estimates of 15-30 m^3 (1971, Fig. 11) and 8-16 m^3 from the basal area in 1974 indicate considerable local deposition. Complete debris cover on snow cones and patches at the base of the cliffs indicates that maximum deposition probably occurs at such sites.

The talus slopes at Surprise II have greater morphological evidence of debris flow activity than other sites in Surprise. A large fresh debris flow 5-10 m wide ran to the base of Cone C in 1975 and was probably triggered by the storm of August 1 that generated debris flows at the lower end of the valley

FIGURE 10. Dirty avalanche debris, Cone F., Surprise II site, 16 June 1968. A great variety and number of discrete avalanche deposits can be identified on this photograph of the upper two-thirds of the snow-covered talus. On the basis of their morphology the narrow linear deposits are possibly more accurately classified as dirty slush avalanche features. Such deposits were common on the spring snow cover of the upper and middle talus slopes at this site and are probably generated during the spring snowmelt period.

Débris d'avalanche, cône F, site de Surprise II, 16 juin 1968. Une grande variété et un grand nombre de débris ponctuels d'avalanches peuvent être identifiés dans les deux tiers supérieurs du talus couvert de neige. Selon la morphologie des dépôts linéaires étroits, on peut les classer comme étant des marques d'avalanche humide. De tels dépôts étaient courants sur le couvert de neige printanier des talus d'éboulis moyens et supérieurs de ce site et étaient probablement provoqués au cours de la fonte printanière.

(Luckman, 1981). Smaller flows were noted near the apex of Cone D in 1976 (*ca* 1-3 m^3) and on Cone E in 1977.

The complexity of depositional patterns and processes and the small sampled area prohibit reconstruction of detailed annual depositional patterns at this site (see however, Luckman, 1971). Nevertheless, despite this complexity, the year to year variation in observed depositional pattern at Surprise II is less than at most other sites. Summary data are given in Figure 13. Only four lakeshore sample sites of the 300 set failed to record any deposition between 1968 and 1981 and most sites away from the basal transect had deposition in every year (99% of site years 1969-81 for the upper sites, 89% for the middle sites, Appendix I). The depositional patterns in all three summary diagrams indicate that large avalanches on the major cones (D and F, Fig. 13) are major contributors of debris to the lower slopes. The main year to year variation in depositional activity is the downslope extent and location of the runout zones from these avalanches. More than 50% of the lower sites were covered in 1970, 1973, 1974, 1980 and 1981 (both 1970 and 1974 exceed 84%) and only two years have less than 30% (1978, 16%; 1972, 29%). The lowest probabilities and amounts of deposition are for sites along the lakeshore and the area downvalley of the protalus rampart, both of which are peripheral to the lowest flanks of Cone D. The higher mean accumulation values immediately downvalley of the protalus rampart are the result of a single dirty avalanche in this area in 1969 (Luckman, 1971).

Examination of spring snow cover and observations of sample site accumulations suggest that rock debris is fairly

FIGURE 11. Ablating remnants of a dirty avalanche at the apex of Cone E, Surprise II, 16 August 1971. This deposit, shaped like an inverted Y in plan view, extended over 50 m from the cliff and contained 15-30 m^3 of debris. A remnant of the winter snow cover, 1.5-2.0 m thick, is preserved beneath this deposit and exposed in the grey bluff behind sample boulder 100 (centre foreground, at the 160 m contour of Fig. 13).

Restes d'ablation d'une avalanche survenue à l'extrémité du cône E, Surprise II, le 16 août 1971. Ce dépôt, en forme de Y inversé vu en plan, s'étend sur plus de 50 m à partir de l'escarpement et contient de 15 à 30 m^3 de débris. Un vestige du couvert de neige, de 1,5 à 2 m d'épaisseur, repose sous les dépôts et est à découvert sur le versant gris derrière le bloc témoin n° 100 (premier plan au centre à la courbe de niveau de 160 m de la fig. 13).

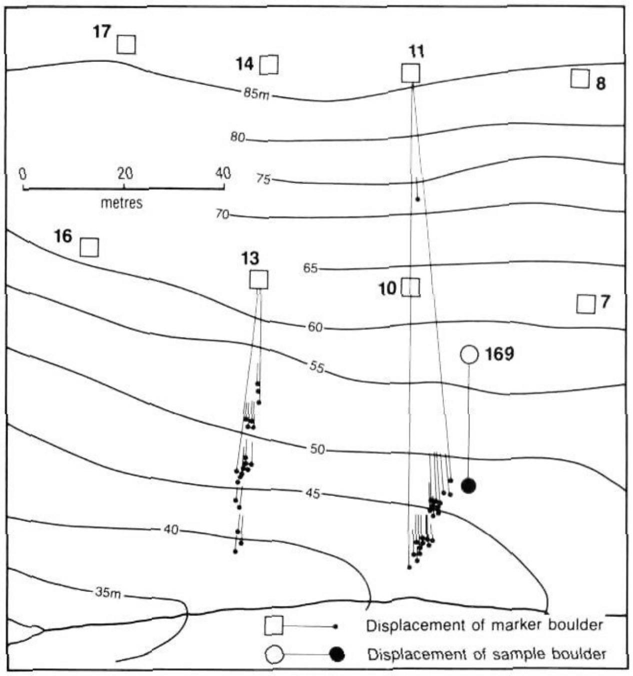


FIGURE 12. Movement of marker boulders eroded from squares at Surprise II in 1970. This figure shows part of the lower two rows of squares and drammatically illustrates the selective nature of avalanche erosion in some cases. The boulders from the destroyed squares must have been transported en masse. None of the other squares shown were damaged and accumulation in square 10 (over which 21/22 boulders and the polyethylene from square 11 must have passed) was only 95 cm³ (0.04 mm).

Déplacement des blocs témoins érodés à partir des carrés, Surprise II, 1970. Cette figure montre une partie des deux rangées de carrés et illustrent clairement la nature sélective de l'érosion par les avalanches dans certains cas. Les blocs en provenance des carrés détruits ont dû être transportés en groupe. Aucun autre des autres carrés n'a été endommagé et l'accumulation qui s'est faite sur le carré n° 10 (sur lequel ont passé 21 ou 22 blocs et le polyéthylène du carré n° 11) n'étaient que de 95 cm³ (0,04 mm).

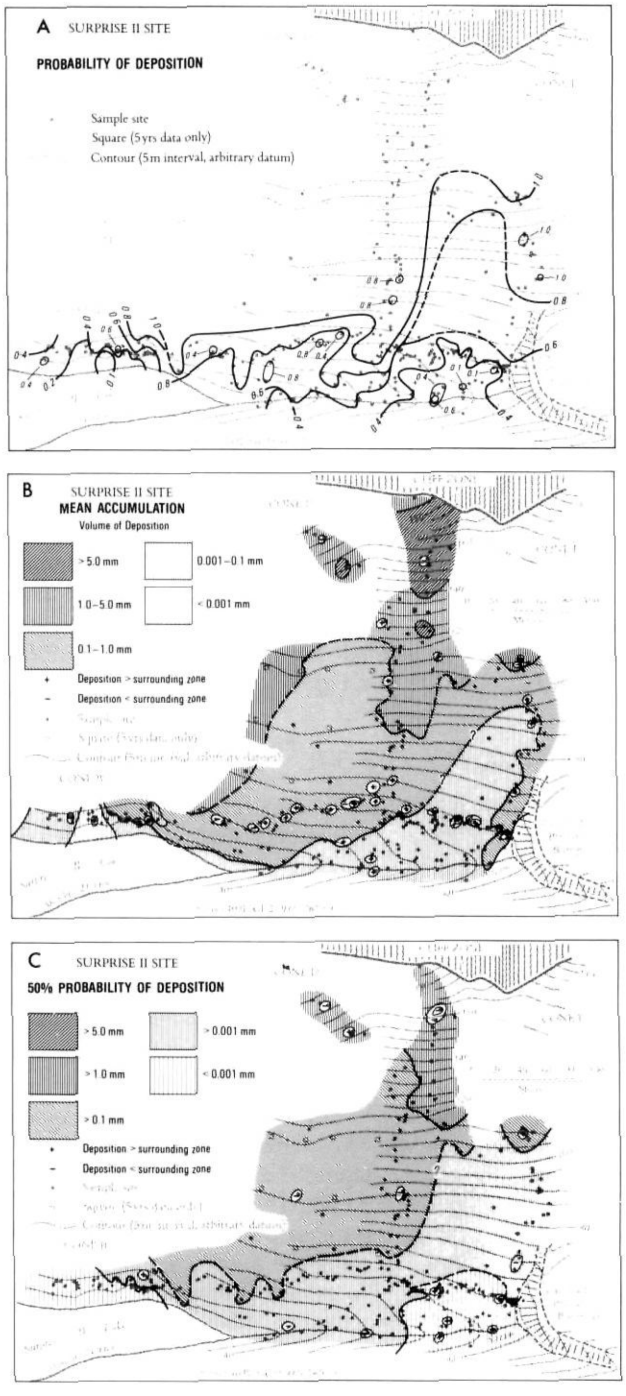


FIGURE 13. Depositional Patterns at the Surprise II site (1968-78).

Patrons de mise en place des dépôts, site de Surprise II (1968-1978).

evenly mixed throughout the avalanche snow at this site and sharp variations in debris concentration, such as those produced by avalanche erosion at other sites, are not common. The erosion of squares, the 1969 avalanche deposit (Luckman, 1971, Fig. 7) and spot estimates from avalanche snow of up to 70 mm mean debris thickness all suggest that erosional incorporation of talus does occur at Surprise II but on a smaller scale than at Tumblin' Creek. Most of the deposition appears to be associated with the spatially extensive, dirty avalanches carrying debris from the cliff zone. This may however be a sampling artefact: as with rockfall estimates, the limited area of deposits resulting from avalanche erosion means that it is much less likely to be sampled than spatially extensive, uniform deposits from larger avalanches.

The 50% probability and mean accumulation patterns show similar decreases in the volume of deposition downslope. As many of these sample sites have deposition in every year and most of the debris appears to be derived from the cliff zone, the most likely cause of this gradient is a greater number of depositional events per year on the upper slopes. Basal slopes are only affected by the largest avalanches, perhaps 0-2 times a year, whereas the top of the slope is the site of many depositional events (Fig. 10). Consistent differences in accumulation patterns such as those shown in Figure 13 have to reflect differences which recur annually. The longer avalanche season at Surprise II and the significantly higher number of depositional events recorded in its snowcover are both contributory factors in this pattern.

Figure 13 (mean accumulation) and Figure 14 show a small number of residual high values scattered over the lowest sites. These are single large boulders that are most likely from rockfalls onto snow that slide or roll to the base of the slope. Such boulders may also mire in soft snow near the point of impact. The lack of such high depositional amounts for sites in mid-slope is due, in part, to this bimodal distribution of rockfall deposition on the slope.

The mean accumulation values (Fig. 13B) and cumulative frequency distributions shown in Figure 14 suggest that the upper half of the slope receives between 1-2.5 mm accumulation per year, the "middle sites" *ca* 0.1-1.0 mm/yr and the basal slopes somewhat less from avalanche deposition. Downslope redistribution of this debris may take place by surface sliding, rockfall impact, debris flow and avalanche erosion but the steep, unstable surface of these upper slopes suggest it is presently actively accreting. The primary role of avalanches at this site appears to be depositional, delivering considerable amounts of finer debris to the lower slopes of the talus. Examination of grain-size characteristics of these slopes reveals little evidence of the well developed sorting patterns developed at other sites dominated by avalanche erosion (Luckman, 1978a, Fig. 4).

EASTERN VALLEY SIDE SITE

The eastern side of Surprise Valley is dominated by a bed of massive limestone, 20-30 m thick that dips westwards at *ca* 40-50° and outcrops as dipslope slabs on the upper half of the slope. The ridgecrest is formed on the underlying shales which are dissected by a series of funnel-shaped gullies that pinch out downslope as they cross the limestone (Luckman, 1978a, Fig. 2). Avalanches originate in the open shale basins or on the smooth slab surfaces and run to the valley floor.

The Eastern Valley Side Site is unique in Surprise. It is the lower part of a narrow avalanche boulder tongue that extends across vegetated talus into forest (Fig. 15). The feature is about 1-3 m thick, gently convex-upwards in cross profile and composed of platy slabs of limestone from the outcrop upslope. The tongue has a mean slope of 19° reaching maximum angles of 30° at the upper part of the sampled area. The plan irregularities of the lower tongue are due to minor topographic features on the slope. A network of 138 sample boulders and 3 squares were set up at this site. Three squares set in the adjacent avalanche track were abandoned in 1969.

Results

This site is clearly dominated by avalanche activity but the tongue is affected by two adjacent avalanche tracks. The main ("south") track and debris source runs down the tongue but avalanches often terminate at a slight bedrock bench, downslope of the "bulge" at the 45 m contour. Avalanches coming down an adjacent track, north of the tongue, may run onto the tongue below the 70 m contour and continue to the base. Both tracks originate from the same starting zone and are only separated by a 20-30 m wide strip of vegetation (see Luckman, 1978a, Fig. 2).

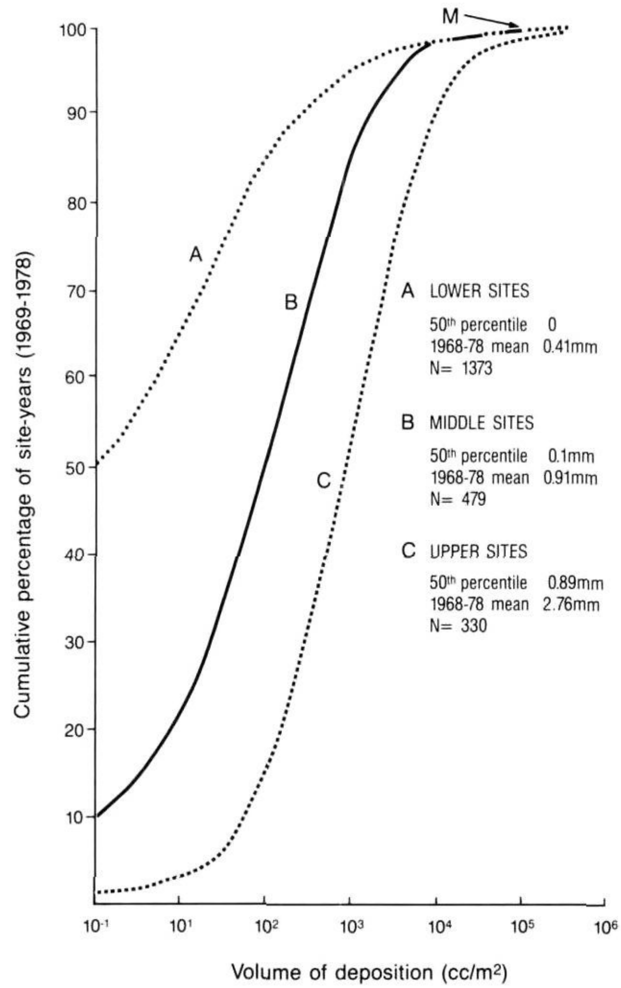


FIGURE 14. Cumulative frequency curves for annual volume of accumulation on sample sites at Surprise II, 1968-1978 (cm^3/m^2). These three curves illustrate the major differences in both the frequency and magnitude of depositional amounts in the upper, middle and lowest sections of the talus at this site. The arrow indicates the maximum value of the Middle Sites (curve B).

Courbes de fréquence cumulative du volume annuel d'accumulation sur les sites témoins de Surprise II, 1968-1978 (cm^3/m^2). Ces trois courbes illustrent les principales différences à la fois de la fréquence et de l'importance des quantités de dépôts dans les parties supérieures, moyennes et basses du talus à ce site. La flèche montre la valeur maximale atteinte aux sites moyens (courbe B).

Avalanches ran to the base of the tongue in 1968 and severely damaged trees up to 50 m downslope in 1971, 1974 and 1977. In 1974 avalanches destroyed mature timber in several other tracks on the eastern valley side carrying trees onto or across the main valley floor. A small dirty snowpatch remaining at the base of the tongue in July 1978 contained an estimated 0.3-0.5 m^3 of rock debris and several broken trees. Avalanche erosion on the upper part of the tongue occurred in 1971 when 10 of the highest 18 sample boulders (above the 77 m "contour") were buried or transported as much as 140 m downslope (Luckman, 1978a, Fig. 1). A line of painted boulders set to monitor creep between the highest boulder sites was also destroyed in 1971 (Table III). In 1977

FIGURE 15. The Eastern Valley Side site from the west, 26 July 1968. The point A marks the upslope end of the sample site network.

Le site de Eastern Valley Side vue de l'ouest, le 26 juillet 1968. La lettre A indique la fin de la pente ascendante du réseau de sites témoins.

another 8 sites, mainly from the 55-60 m area, were buried or eroded and two sample boulders upslope were striated by debris moving over their surface.

Depositional patterns for the 1969-1976 years are given in Luckman (1978a, Fig. 1). Summary data for 1969-81 are shown in Figure 16. The main differences between years are the amount of erosion in the upper track and the downtrack runout distances. Avalanches run down the "south" track in most years (though deposition was limited in 1970, 1976 and 1981) but only run to the base of the tongue once every 2-3 years. The 50% probability summary clearly outlines the "south" track while the probability summary picks up increasing distances of downtrack runout (and deposition) with less frequent events. The probability of deposition shows a relatively simple decrease with distance downtrack. The mean accumulation summary is similar to the probability diagram because of the smaller volumes of deposition at this site. As almost all of the debris in the tongue is derived from erosion of loose material from the upper slopes it is not surprising that two of the three years with heaviest deposition are associated with evidence of erosion in the upper part of the sampled area

TABLE III

Movement of painted boulders from a line across the Eastern Valley Side Site, Surprise Valley, Alberta

Measurement date	Displacement (m)				Boulders lost
	0	<0.1	0.1-1.0	>1.0	
10.8.68	39	(boulders set)			
24.5.69	30	4	3	1	1
18.7.70	28	3	3	0	5
21.8.71	8	displacement up to 70 m downslope			

The only boulders remaining were at the two ends of the line, adjacent to sample boulders at the edge of the tongue. Displacements in 1969 and 1970 are probably due to creep. The line was at the "130 m" contour (Fig. 16).

(1971 and 1977). Depositional amounts in this area are probably underestimated by the sparse network of surviving sample sites.

Similar avalanche tracks occur in many places along the eastern valley side slope but this is the only avalanche boulder tongue. The significant control in its location appears to be *the availability of a sufficient quantity of loose debris* by weathering in the track or starting zone for avalanche transport to build the tongue on the lower slopes. At other sites, *e.g.* Old Nip (below), this debris is provided by pre-existing talus surfaces.

STRIKE VALLEY SITE

The Strike Valley site is at the head of a small valley excavated along the outcrop of the Banff formation. Its eastern side is a debris-mantled bedrock slope developed on the lowermost shale units overlying the Palliser dipslope. The western flank is a straight scree developed beneath 300-500 m high cliffs of Mississippian limestones. A shallow embayment in these cliffs is the source area for a major avalanche track which runs to the base of the talus and continues down the axis of the valley (Fig. 17). Most of the talus is blocky rockfall material with small avalanche boulder tongues superimposed in a few localities.

A transect of 63 boulder sites was set up in 1968 from the small col/bench at the head of the valley (Fig. 18). Although this sampling network is far from ideal it has yielded considerable information about avalanches at this site.

Results

(a) Col area

These 13 sites are on a small bench at the head of the valley below a long 25-40° debris-mantled shale slope. Avalanche deposition occurred in 1973 and 1981 but volumes of deposition are small and in most years there was no accumulation at these sites (Appendix I).

(b) Avalanche track

The idiosyncratic sampling network at this site may be subdivided into three areas, a transect across the upper ava-

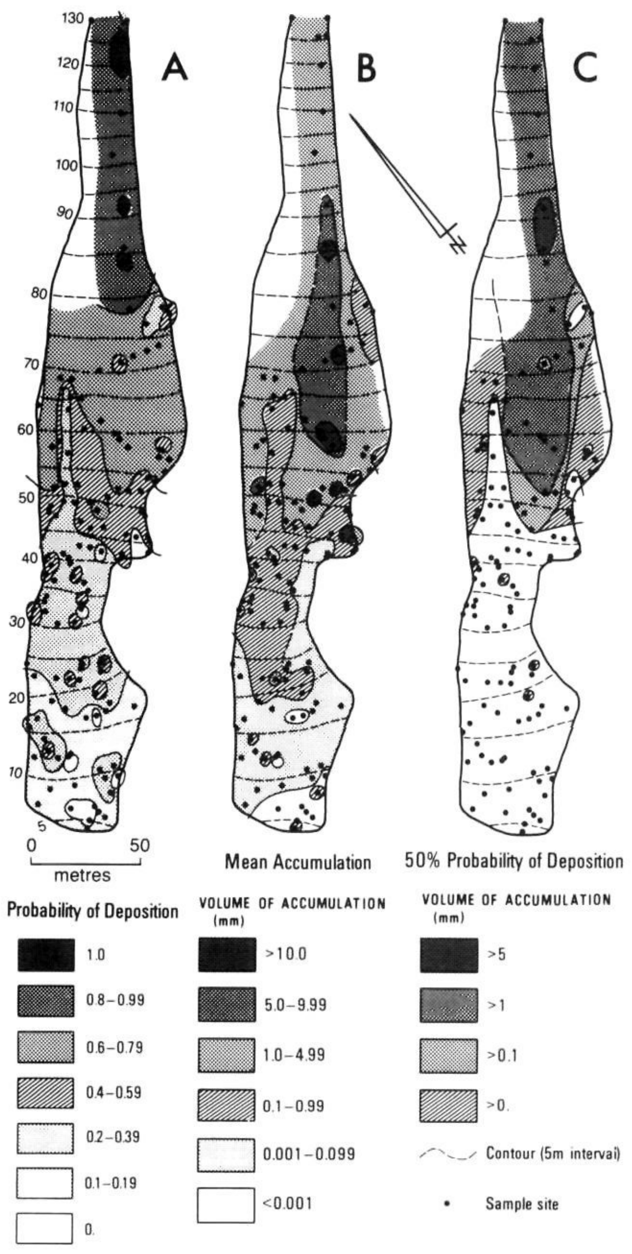


FIGURE 16. Depositional Patterns at the Eastern Valley Side site, 1968-78.

Patrons de mise en place des dépôts du site de Eastern Valley Side, 1968-1978.

FIGURE 17. Strike Valley site from the north (Old Nip), 18 June 1968. A large dirty avalanche deposit occupies the avalanche track studied.

Le site de Strike Valley vu du nord (Old Nip), le 18 juin 1968. Un important dépôt de matériaux d'avalanche occupe le couloir d'avalanche étudié.

lanche track, a downslope segment and the lower avalanche track (see Appendix I). The higher depositional probabilities and amounts of the upper track are clearly visible in Figure 18. Avalanches run down this track in most years but the extent and volume of deposition appears to be dependent on erosion of loose debris within the track. Significant avalanche erosion took place at this site in the first few years and these results will be discussed in some detail.

In 1968 a large dirty avalanche ran down the main track (Fig. 17), terminating near the residual snowpatch of Figure 18 and eroding the upper part of the talus. The character of deposition in 1969 indicated considerable avalanche erosion took place upslope of the upper transect. Many sites were completely debris-covered (one site, completely buried in 1969, was relocated in 1977!) and one boulder site was moved over 20 m downslope by avalanche erosion. The heaviest deposition was confined to the upper sampling transect and deposition on the lower sites was only a few scattered fragments and single boulders on two separate sites.

On July 11, 1970 the lower sites were covered by a residual snowpatch of 1500-2000 m^2 which was littered with large boulders ranging up to 1.38 m^3 (2.0 $\times$ 1.3 $\times$ 0.7 m) in size (Fig. 19, the remnants of this snowpatch in mid-August are shown on Fig. 18). Inventory of this debris indicated 10-15 m^3 of debris was present on the snow, equivalent to a mean accumulation of 5.-7.5 mm over the snowpatch. A snow deposit of similar character and extent was examined in August 1971 yielding an estimated volume of 11 m^3 with two boulders of over 1.50 m^3. Most of this debris was concentrated on *ca* 400 m^2 of snowpatch close to boulder 52 (at *ca* the 43 m contour) indicating a mean depositional thickness of approximately 27 mm. In both years the snowpatch debris consisted of large boulders mixed throughout relatively clean snow with only small amounts of fines (Fig. 19). Six boulders $>$0.005 m^3 were deposited on boulder sites in the lower transect in 1970 and two more in 1971 including one of 1.03 m^3 on boulder 52 (Fig. 3F). Without prior observation of the snowpatch such large, isolated values would likely be interpreted as rockfall and appear to inflate the means for these two years. However the comparability of boulder and snowpatch estimates for the lower transect (6.69:5-7.5 in 1970; 66.6:27.0 in 1971) suggest that the means from the boulder sites are the right order of magnitude. Although both types of estimate indicate greater depositional volumes in 1971, the deposition in 1970 was much more extensive and covered the whole length of the sampling network.

The coarseness of these deposits suggests avalanche erosion of boulders in the middle and lower parts of the track. Because of the configuration of the track, avalanches run

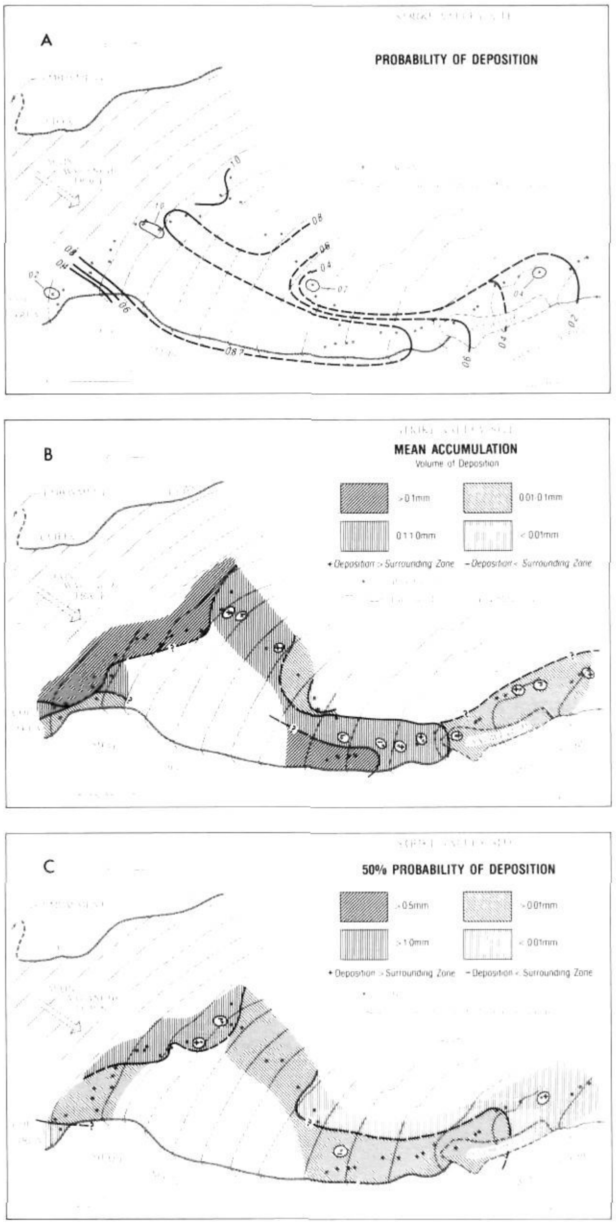


FIGURE 18. Depositional patterns at the Strike Valley (Avalanche) site, 1968-78, Surprise Valley, Alberta.

Patrons de mise en place des dépôts du site de Strike Valley (Avalanche), 1968-1978.

along the basal fringe of the talus and may therefore incorporate basal material more easily than at other sites. The only direct evidence of erosion is that, in 1970, boulder 24 (0.31 m^3, 1.5 × 0.6 × 0.45 m) was moved *ca* 150 m downslope from the 150 m "contour" to the sampled snowpatch at the 57 m "contour" and, in 1971, part of boulder 49 (at the 60 m "contour") was moved over 20 m downtrack. However the presence of isolated large boulders in the avalanche deposits of this site emphasizes the dangers of inferring process from the characteristics of deposition on a single site: large single boulders cannot be assumed to be from rockfalls unless there isn't any evidence of avalanching from snow cover observations or adjacent sample sites.

FIGURE 19. Avalanched debris on a residual snowpatch, Strike Valley, 11 July, 1970. This is the coarsest avalanche deposit observed in Surprise. Note the relative absence of fines. The avalanches at this site run down-valley across the basal fringe of the talus.

Débris d'avalanche sur une plaque de neige résiduelle, Strike Valley, le 11 juillet 1970. Il s'agit des débris les plus grossiers observés à Surprise Valley. À noter la relative absence de débris fins. À ce site, les avalanches se produisent vers l'aval au travers de la bordure inférieure du talus.

Although the depositional pattern of the lower track indicates that avalanches ran into this zone in most succeeding years (except for 1975 and possibly 1978) these avalanches carried little debris: only 3 site-years had >1000 cc between 1971 and 1981 (Appendix I). The upper sites show similar trends although depositional amounts are generally higher and more consistent. The marked erosion and deposition in the first four years (1968-1971) is not repeated in the next 10 providing an excellent demonstration of the difficulty of extrapolating from a short term data base.

The summary data for this site (Fig. 18) clearly show the differences in the frequency and volume of deposition between the avalanche track and the adjacent rockfall dominated talus. However, although avalanche deposition is more frequent, the 50% probability depositional rates are lower than other sites because, over the 13 year period, most of the avalanches at this site were relatively clean.

(c) Creep studies

In July 1968 an experimental site was established to monitor surface creep at a location without rockfall or avalanche disturbance on the shale slope facing the Strike Valley site (see Figs. 17 and 20). A red line, *ca* 5 cm wide was spray-painted across the slope and 47 local shale fragments (up to 20 cm "a" axis and painted white) placed on the line. The surface consisted of shale fragments and fines, *ca* 20-30 cm thick, overlying bedrock on a 29-32° slope. Poorly developed stone stripes also occurred.

Between 26 July and 10 August five stones moved as much as 5 cm from the line probably due to overland flow following heavy rainfall. By the following spring (Fig. 20) the painted line had disintegrated and the debris and white stones were spread 0-50 cm downslope. Although measurements were discontinued at this time, these results indicate that the

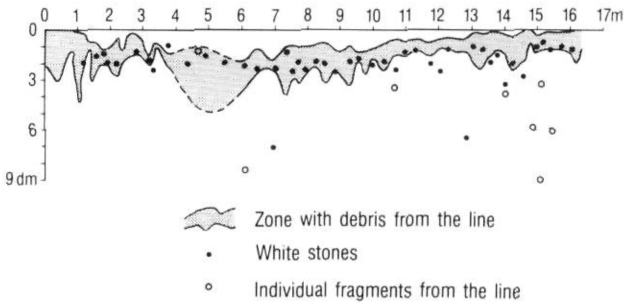


FIGURE 20. Movement of debris from a painted line at Strike Valley between 26 July, 1968 and 31 May, 1969. For explanation see text.

Le transport des débris à partir d'une ligne peinte à Strike Valley, entre le 26 juillet 1968 et le 31 mai 1969. Voir l'explication dans le texte.

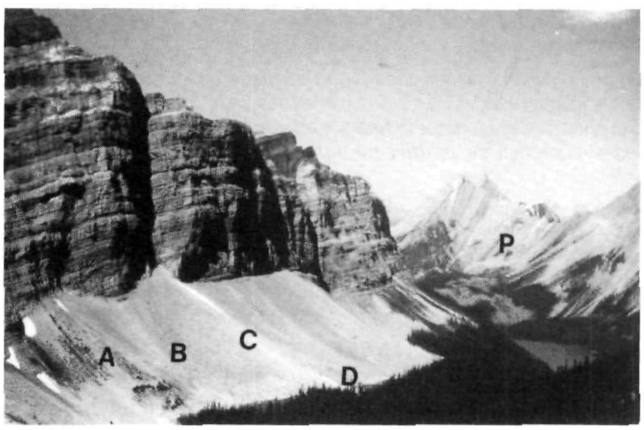


FIGURE 21. Old Nip site from Strike Valley (south). The ON2 site is the light coloured avalanche track at A, the ON1 site is a profile from A-B-C, and the avalanche boulder tongue is the light coloured area below D. The Palliser site (Fig. 22) is visible at P.

Le site de Old Nip vu de Strike Valley (au sud). Le couloir d'avalanche pâle indiqué par la lettre A représente le site ON2, le site ON1 est une coupe à partir de A-B-C, et la partie pâle sous la lettre D est une langue de blocs d'avalanche.

upper slopes of many talus slopes in Surprise, which consist of a similar mixture of fines and smaller rock fragments, may undergo considerable frost creep and possibly solifluction where fines are present at or near the surface.

OLD NIP SITE

The Old Nip Site is about 1 km downvalley of Strike Valley in a similar geological setting. However, at Old Nip the strata are almost horizontal and the valley broadens to a well marked bench backed by vertical cliffs 300-500 m high (Fig. 21). The cliff is straight in plan and flanked by well developed sheet talus slopes up to 300 m long. The Old Nip Cone lies below the only embayment in the cliff. Limited rockfall inventory data (Luckman, 1976) indicate the site is not very active at the present time. Several avalanche tracks cross these talus slopes and a well defined small, avalanche boulder tongue has developed on the northern flank of the cone (Luckman, 1971, Fig. 11). The lack of source areas for avalanches in these cliffs suggests the avalanches are triggered by cornice falls onto an unstable snow-cover on the talus. Avalanche snow was examined at the base of this avalanche track in 1968, 1969 and 1970 when the upper slopes and rockfall cone were snow-free. Snow blocks in the avalanche debris at the base of the avalanche boulder tongue in 1969 indicate that the snow cover of the talus slope had failed by slab avalanching. This evidence, plus the results discussed below indicates that avalanche modification of these talus slopes occurs as a result of avalanches triggered in the snow cover of the talus itself and that slab avalanches, as well as spring snow avalanches, may be of considerable geomorphic significance (Rapp, 1960; Gardner, 1970).

The sample site network at Old Nip consists of a transect of boulders and 2 squares across an avalanche track, straight talus and the rockfall cone (Fig. 21). A lower transect of nine squares at the base of the talus showed little deposition and most of these sites were abandoned except for those at the avalanche boulder tongue. Seven additional squares were set on this tongue in 1969.

Results

To simplify the interpretation and discussion of results from the several environments sampled at this site, the data are divided into four groups which are discussed separately.

(a) Avalanche boulder tongue (ABT)

This is a small classic avalanche boulder tongue (Luckman 1978a, Fig. 3) developed by snow avalanches reworking the northern flank of the rockfall cone. Coarse, loose debris on the cone has been swept downslope and built out a small, flat-topped debris tongue. The lower tongue has a surface gradient of 16-24° and is bordered by a low 30-35° bluff, *ca* 2 m high. Three squares at the base of the tongue (one on it and one on either side) were monitored from 1968-1978. Squares were set higher on the tongue in 1969, damaged by avalanche erosion and not reset after 1971 (see Appendix I).

The sampling network and erosional patterns for 1969-1971 are shown in Luckman (1977, Fig. 8). In these first three years avalanche erosion took place on the flat raised surface of the tongue and debris (including marker boulders) was deposited on the lower tongue and on the apron of debris immediately downslope. Some of the marker boulders moved in 1970 were moved further downslope in 1971. Evidence from undamaged squares, both upslope of eroded areas and between eroded squares and marker boulders derived from them, indicates that erosion of the slope surface was very localised. Debris movement patterns indicate that the flat upper surface of the tongue is basically erosional in origin and debris incorporated into the avalanches is redistributed downslope or deposited beyond the steep frontal slope of the tongue. A scatter of debris beyond this slope merely indicates the extent of the largest avalanches and the most probable direction of progradation of the tongue. There is no evidence of erosion or significant deposition on the lower sites between 1971 and 1978 but moderate deposition occurred higher on the tongue in 1973 and 1974 (see Appendix I).

(b) Old Nip Site 2(ON2) and Boulder 1

This site consists of 24 boulders within an area of 500-700 m^2 in a second avalanche track, about 200 m south of the Old Nip cone (Fig. 21). Sample boulders at this site are relatively small because of the lack of larger material: only 3 exceed 0.5 m^2 and 11 are less than 0.15 m^2. Nevertheless the amounts deposited are entirely consistent with results from other avalanche sites although volumes are somewhat lower because of the generally small size of material available upslope. Approximately 60% of the site years show accumulation (Appendix I) with significant avalanche deposition in 1971, 1974, 1976-78 and 1980.

Boulder 1 has an area of 1.85 m^2, is flush with the upslope talus surface and lies about 15 m upslope of the top site of ON2 in the same avalanche track. Avalanche erosion in 1969 demolished a square placed several metres upslope, covering the boulder with 16.23 mm of debris and scattering marker boulders up to 40 m downslope amongst the sample sites of the ON2 series. Two fragments of polyethelene yielded accumulation estimates of 0.89 and 1.87 mm that are considerably higher than estimates from the sample boulders (mean 0.04 mm). A square at the foot of this slope was monitored from 1968-1973 and only recorded deposition from the 1969 avalanche. There is little consistency between depositional volumes on Boulder 1 and the ON2 boulders downslope despite sharing a common avalanche source (Appendix I). These discrepancies probably reflect local differences in patterns of avalanche erosion and deposition within the track.

(c) Old Nip Site 1 (ON1)

ON1 is a transect of boulders contouring from Boulder 1 across the sheet talus and cone to the avalanche track on its north side (A,B,C; Fig. 21). The cone is a simple rockfall cone, average gradient of 35°, consisting of very coarse blocks (-6 to $-7\ \phi$ nominal diameter, Luckman, 1973). Although 30% of the site-years show accumulation, most of these are small rock chips and fragments: the bulk of this deposition is on the straight talus including avalanched coarser debris in 1971, 1974 and 1980 and a large rockfall boulder of 0.33 m^3 in 1980. The only significant deposition on the cone was two large single boulders in 1972. The scattered material is probably rockfall chips or pebble-fall debris, possibly redistributed downslope by small surface avalanches.

PALLISER SITE

The lower part of Surprise Valley is blocked by a large rockslide deposit which covers 3-4 km^2 and exceeds 250 m in thickness. This large dipslope failure occurred along several distinct steeply-inclined (40-50°) bedding plane surfaces and probably took place shortly after deglaciation (Luckman, 1973, 1981). The Palliser site consists of three adjacent, single lithology talus slopes developed below the rockslide scar (Fig. 22). Scree No. 1 is a straight, rockfall talus, about 150 m long, average inclination 31°, below a simple 40-50° dipslope cliff in the sandy and silty limestones of the Sassenach formation (Devonian). The Palliser and Small Cones are fed from major joint and bedding plane surfaces of the Palliser limestone (Devonian) in the rockslide scar. The larger Palliser Cone is flanked on one side by a massive vertical cliff, is 350 m long with an average inclination of 32°. Avalanches run out over both cones and the Palliser Cone has a marked basal concavity (26° in its lower third) with a marked sorting gradient of surface debris due to avalanche activity (Luckman, 1978a, Fig. 4).

The original sampling network consisted of a transect of 108 boulders and 18 squares along the base of these three talus slopes with a higher transect of 5 squares. Additional, higher sites were set in 1969 (Fig. 23). Most squares perished or were destroyed by avalanche erosion after two years. The results from this site are reported in four sections because of differences in the nature and frequency of depositional activity.

Scree No. 1

These sample sites consist of a basal transect of 8 squares and 14 boulders. Snow avalanches following the storm of August 4-5, 1969 (see below) account for over 91% of the deposition at this site (77% for boulder sites alone). At other times deposition consisted of scattered single fragments or boulders, over half of which was a single block deposited in 1981. One square was destroyed by rockfall impact in 1970.

The storm of August 4-5th 1969 was a depression of the "cold low" type which intensified as it crossed the Cordillera and deposited up to 180 mm of rain on the eastern ranges and foothills of the Rockies (Janz and Storr, 1977, Appendix F). Over 33 cm of snow were deposited on camp at Surprise Lake and much larger amounts elsewhere (55 cm at Maligne Lake, S. M. Elder, pers. communication, 1969). Large wet snow avalanches began during the storm and continued

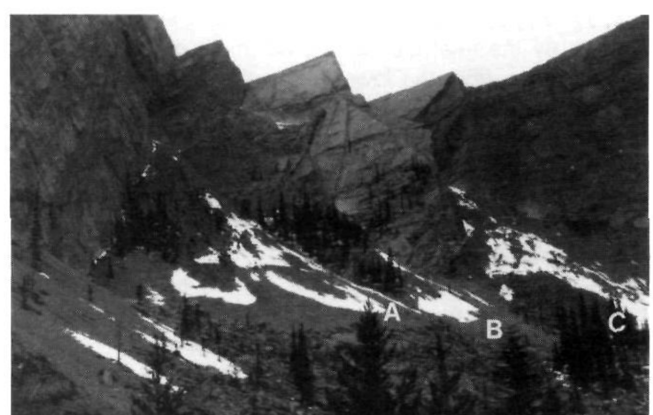


FIGURE 22. The Palliser site from the west, 8 August, 1969. The labelled sites are Palliser Middle (A), Small Cone (B) and Scree No. 1 (C). The Palliser Lower and Runnel sites run westwards (left) along the base of the Palliser cone but are obscured by the landslide debris. The snow deposits mark the downslope limits of avalanches on the cones during the August 1969 storm.

Le site de Palliser vue de l'ouest, le 8 août 1969. Les sites indiqués par des lettres sont Palliser Middle (A), Small Cone (B) et Scree n° 1 (C). Les sites de Palliser Lower et de Runnel vont vers l'ouest (vers la gauche) le long de la base du Palliser Cone, mais sont cachés par les débris d'éboulis. Les dépôts de neige indiquent les limites de la pente descendante atteintes par les avalanches survenues durant la tempête du mois d'août 1969.

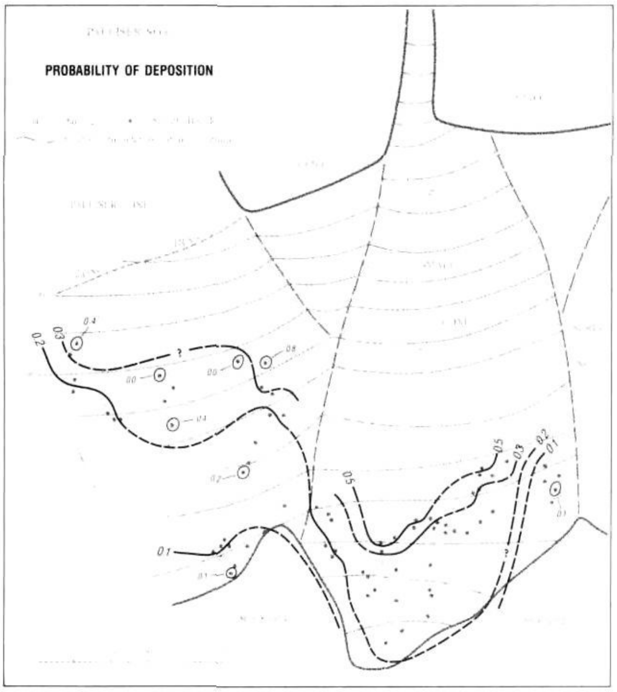


FIGURE 23. Probability of deposition at the Palliser/Small Cone sites, 1968-78. Only the lower third of the eastern half of the Palliser Cone is shown (Palliser Middle site) plus a few of the easternmost sample boulders of the basal transect (Palliser Lower).

Probabilité d'accumulation aux sites de Palliser et Small Cone, 1968-1978. On ne voit que le tiers inférieur de la moitié est du Palliser Cone (site de Palliser Middle) ainsi que certains des blocs témoins les plus orientaux du transect de base (Palliser Lower).

through the rapid melt of the next few days (Luckman, 1976, Fig. 1). By the afternoon of the 6th most of the snow had already gone from the lower slabs above the talus though avalanches and rockfalls triggered by falling blocks of snow were still moving considerable debris onto the talus. In several places the snow cover of the upper talus slopes had avalanched onto the lower slopes or into the rockslide deposits. These avalanche deposits were examined on August 8th. The majority were composed of fairly clean snow but in places the wet avalanches had scoured the talus surface and incorporated considerable debris. All sample sites were covered by avalanche snow and sampling on August 24 revealed that all of the boulders and 4 of the squares had accumulations ranging from .035-64.8 mm in thickness, all of which was derived by erosion of the lower talus slope. One of the squares at the base of the talus was partially destroyed and seven marker boulders (average 3500 cc) were moved an average of 7.3 m into the rockslide debris beyond the talus. Investigation of surface grain-size characteristics at this site prior to the storm (Luckman, 1973) demonstrated the paucity of "perched boulders" (characteristic of avalanching, see Luckman 1978a) at the base of this talus. The marked difference in appearance of these sites before and after the avalanche event, plus the absence of similar depositional patterns over the next 12 years, confirm that avalanche activity was unusual at this site. Avalanches generated by this storm were observed at other sites in Surprise but none of the other sample site networks had significant accumulation.

Small Cone

The Small Cone receives avalanches and rockfall debris funnelled from a large area of cliff. The sample sites are almost all located in the basal 20% of the slope (Fig. 23) and depositional amounts are strongly correlated with the extent of avalanches. Significant avalanche activity occurred in 1969, 1971, 1972 and 1974 whereas negligible deposition occurred in all other years except for 1979-80 when the deposits appeared to be fragments from a rockfall. Fresh boulders of 0.15 m^3 and 0.18 m^3 (both greater than the 1968-81 total accumulation) were noted upslope of sample sites in 1978 and 1980, respectively. In 1969 avalanche erosion destroyed the uppermost two squares, scattering marker boulders to the 60 m "contour" (up to 100 m downslope) but only one boulder site downslope showed deposition. The upper square was again destroyed in 1971, the boulders deposited 35-50 m downslope and fresh debris moved into the rockpile beyond the talus. The heavy deposition of 1972 must also have been accompanied by avalanche erosion of the upper and middle slopes as marker boulders (from destroyed squares) were moved into the sampling transect and three were redeposited on sample boulder sites. The 1974 avalanche contained little rock debris but seven sites had a cover of twigs (from the apex of the talus cone) and the avalanche damaged the trees in the rockpile. A small avalanche also ran down the east flank of the Palliser cone in 1977.

The mapped probabilities of deposition basically reflect the extent of these avalanches with almost half the sites showing deposition in two years and only the highest sites showing deposition in more than three years. The small quantities of debris in avalanches at this site suggest these probabilities are underestimates: the data demonstrate significant avalanche erosion in at least 3 years between 1968-1978.

Palliser Cone

The Palliser Cone is over 375 m long with an average inclination of 32°. The sample sites are all on the basal third of slope where the mean gradient is 26° and are subdivided into three groups; a basal transect, Palliser Middle (Fig. 23) and the Palliser Runnel. The latter site is a small area at the western edge of the cone adjacent to the base of a small straight scree below the vertical cliff. These sites show consistent accumulation of small rock chips (.002-.017 mm/yr, 56% of site years >0, Appendix I), possibly from small relatively clean avalanches on the cone or adjacent talus sheet. By contrast, on the "lower" transect of the main cone 90% of the site years have no accumulation and 93% of the total accumulation is a boulder of 0.13 m^3 deposited in 1977. Other boulders of 0.78, 0.15 (both 1972) and 0.13 m^3 (1974) were noted near sample sites. In 1974 avalanche deposition at the base of the slope included 8 trees, 2-8 m in length (some complete with roots), that must have been transported 150 m or more downslope. Although 2-3 m^3 of soil was attached to the tree roots, deposition on the sample sites was slight except for a few twigs. The middle boulder sites were set in 1969 and only cover the eastern half of the cone (Fig. 23). They show higher probabilities and amounts of deposition than the lower sites and both avalanche and rockfall events can be identified. In 1969 one square was demolished by a rockfall boulder of *ca* 0.15 m^3. A small dirty avalanche ran down the cone in August 1969 but no deposition was recorded. In 1971 the highest squares (above the goat trail) were destroyed by avalanches and the marker boulders moved up to 50 m downslope. Although there was considerable deposition on the squares near the 85 m "contour" (Fig. 22) deposition on the boulder sites was insignificant. The squares were abandoned after 1971 but, as most of the marker boulders were still in place in 1978, they indicate that relatively little erosion occurred in this area over this seven year period. Parts of the sample site network was covered by avalanches in 1973, 1974, 1976 and 1977 but most sites only had deposition for two years in the 1969-1978 period.

The sample site network at the Palliser site was not optimal: avalanche erosion demolished most of the upper squares in the first few years and the lower transects were beyond the range of avalanche deposition in most years. Between 1978 and 1980 two debris flow channels were active on the Palliser Cone and levees from the larger flow deposited 3-5 m^3 material in the Palliser Runnel area. Four small flows occurred in the uppermost section of Scree No. 1.

ENTRANCE SITE

The Entrance Screes are the lowest site sampled in Surprise (Table I), well below treeline, and consist of a series of talus sheets (*sensu* Church *et al.*, 1979) and shallow cones below a vertical cliff of Pekisko limestone (Fig. 24). Due to its low elevation and southerly aspect this site is the first to melt out in the spring and the relatively low, straight cliffs do not generate avalanches. Sample sites were set up in two areas. The upper sites are at the top of a straight section of talus less than 5 m from the base of a 30-50 m high vertical cliff. The lower sites are on the basal third and at the base of a cone further east where the cliff is higher with 60-90 m of degraded Banff formation below the Pekisko cliff.

Results

Eight boulders at the upper site were monitored over the entire period (two were lost before July 1969) and showed consistent accumulation of small rock chips (104-837 cm^3/yr). The annual means (Appendix I) largely reflect the size of the largest fragment measured but only 16% of the site-years had zero accumulation. These small values probably reflect the small sample site area, a slight overhang and a low snowcover duration. However, deposition on two squares set in 1969 at the apex of a small cone, 30 m west of the upper sites, was greater than the 1968-81 total on the sample boulders and in 1981 several boulders of 0.5 m^3 fell from the base of the cliff and were deposited adjacent to the sample boulders.

The lower sample sites had little accumulation: 85% of the site years were zero and only four years had deposition on more than 3 (of 28) sample sites. The nature of deposition in 1971, 1974 and 1976 suggests avalanche activity, probably originating on the Banff slopes or on the talus itself. Most of the material collected was relatively small: only 4 boulders greater than 1000 cc were measured during the entire sampling programme. However, individual fresh boulders of 1.9 m^3 (1976) and 3 m^3 (1981) were noted near basal sample sites and a moderate cliff fall, estimated to be *ca* 10-20 m^3, occurred between the two sampled areas in 1974-1975 (possibly triggered by the rainstorm in August 1975).

FIGURE 24. Entrance Screes from the East, 29 June 1970. The Entrance Upper sites are at A and the Lower sites occupy the area between B and C.

Entrance Screes vue de l'est, le 29 juin 1970. Les sites appelés Entrance Upper sont situés en A et les sites appelés Lower occupe l'espace entre B et C.

Three painted lines, 15-20 m long and 2-5 cm wide, were set up on these slopes in August, 1968. Although this project was abandoned in 1969 due to measurement problems, observations in August 1980 give a general impression of small scale processes on these slopes. The uppermost line set on coarse debris (>10 cm a axis) near the top of the talus was virtually intact after 12 years with 80-90% of the line still in place and maximum displacements of *ca* 30 cm. Line 3, painted across similar material with a lobe of fines (<1-2 cc) had disappeared on the fines. These observations (and others at the Palliser site) suggest frost action (particularly frost creep) is significant where fine material is exposed at the talus surface whereas coarser surfaces are much more stable in the absence of rockfall or avalanche impact effects.

DISCUSSION

COMPARISON BETWEEN SITES

During the study period less than 4% (43/1059) of the sample boulders had no accumulation and almost half (19) of these were at the Palliser site. Every site monitored provided evidence of snow avalanche activity on the talus in at least one year[1]. The major differences between sites are in the

1. The only exceptions are Entrance Upper and possibly Palliser Runnel. However absence of avalanche deposits does not necessarily indicate an absence of avalanche activity: avalanches may have involved only clean snow or terminated upslope of the sampled zone (*e.g.*, Fig. 22).

nature, magnitude and frequency of avalanche activity. Systematic comparison between sites may be based on three parameters, mean accumulation data (Table IV), percentage of sites with accumulation and percentage of sites with >1 mm debris thickness (Figure 25). The data summarised in Figure 25 give a good indication of the extent and quantity of avalanche deposition over the study period. On the basis of these data the sites may be broadly categorised into five major groups.

(i) Sites close to the base of vertical cliffs with frequent deposition (mean probability 0.5-0.9) of small fragments and rock chips (Entrance Upper, Palliser Runnel). Total amounts of deposition are very small, usually <0.10 mm/yr. The source of the debris at the Palliser site could be rockfall or relatively debris poor avalanches: the Entrance Upper site is rockfall dominated.

(ii) Basal sites with infrequent deposition (mean probabilities 0.1-0.2), rockfall dominated but with occasional avalanche deposition (Entrance Lower, Palliser Lower, Scree No. 1).

(iii) Lower slope sites similar to (ii) but with significant avalanche deposition and/or erosion in some years (Small Cone, Palliser Middle). Mean probability of deposition ranges from 0.2-0.3.

(iv) Midslope sites with rockfall and avalanche activity in some years (or parts) of the site (TC1-3, ON1, SV top). Mean depositional rates are variable but average 0.5-2.5 mm/yr (mean probabilities 0.3-0.5) except for SV Top.

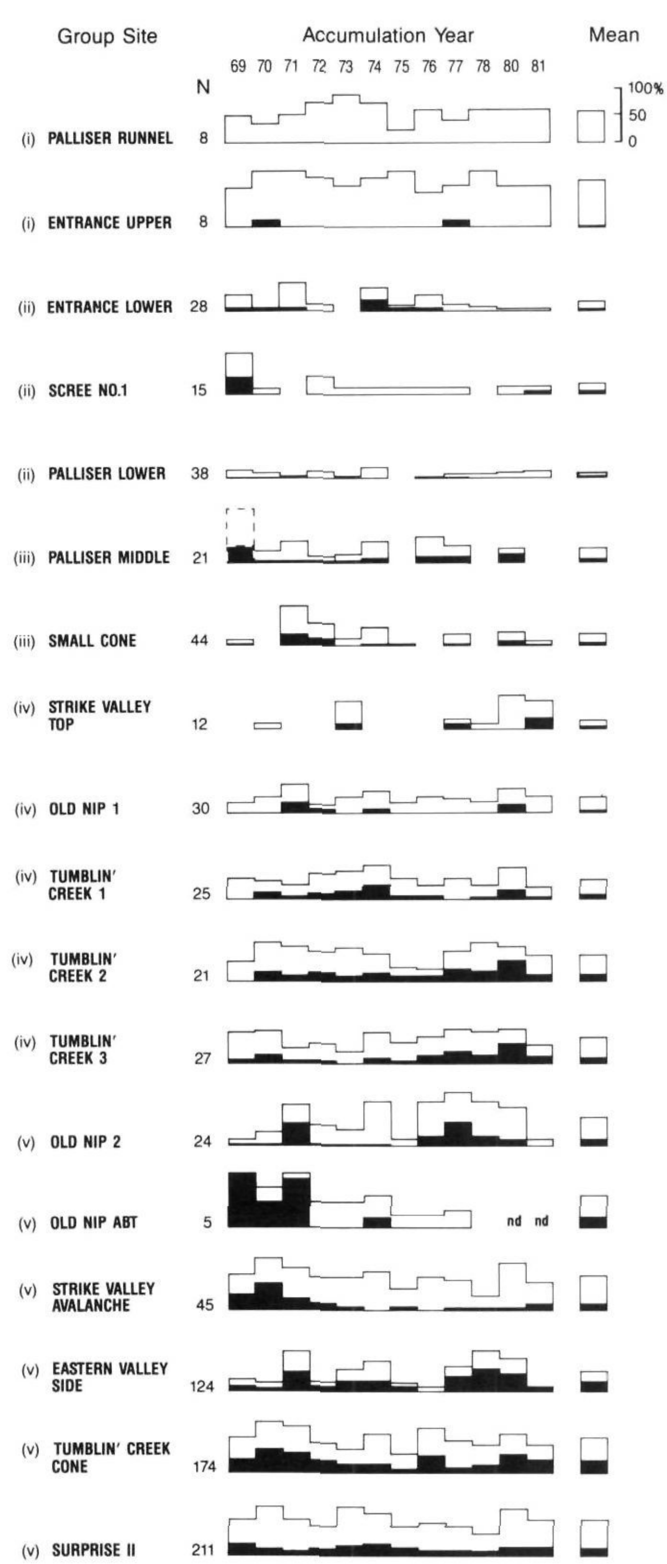
(v) Avalanche sites with deposition in most years and significant erosion of the talus in some years (ON2, ON ABT, EVS, Strike Valley, Surprise II and Tumblin'Creek Cone). Deposition occurs on most sample sites on the upper and middle slopes (mean probabilities >0.5) and averages 1-4.00 mm/year with individual annual means up to 10-15 mm/yr. Depositional amounts on the lower slopes depend on avalanche size, frequency and erosion upslope but average 0.25-2.25 *mm/yr. At the most active sites avalanche erosion* may occur about one year in two (Tumblin' Creek Cone).

TABLE IV

Annual mean thickness of deposition (mm) for sites in Surprise Valley, 1969-1981

Site	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980*	1981	**Mean**	Group
Palliser Runnel	.01	.02	.01	**.03**	.01	.02	.00	.01	.00	.01	.00	.01	**.01**	1
Entrance Upper	**.54**	.34	.11	.08	.09	.09	.06	.07	.40	.08	.04	.04	**.23**	1
Entrance Lower	.05	.01	.16	.01	0	**.54**	.17	.35	.01	.00	.01	.00	**.10**	2
Scree No. 1	**1.27**	0	0	.02	.00	.00	.02	.00	.01	0	.08	.25	**.29**	2
Palliser Lower	.14	.20	.00	.02	.00	.01	0	.00	**6.65**	.00	.02	.01	**.51**	2
Palliser Middle	2.55	.30	2.48	1.23	.67	.63	.00	.24	.73	0	**4.04**	0	**1.25**	3
Small Cone	.69	.00	1.21	**4.92**	.04	.08	.00	0	.14	.00	.88	.18	**.66**	3
SV Top	0	.00	0	0	**.94**	0	0	0	.24	.01	.01	.53	**.17**	4
ON1	.01	.02	4.38	.59	.01	.97	.00	.01	.02	.00	**9.30**	.03	**1.90**	4
TC1	.07	.33	.25	.15	**3.08**	.71	1.28	.19	.04	.45	.30	1.19	**.63**	4
TC2	.09	3.23	1.68	11.00	.31	.48	.21	.81	**12.30**	1.97	1.73	.39	**2.54**	4
TC3	.32	.32	.17	.12	.08	1.19	.24	**6.33**	1.25	5.39	1.78	4.95	**1.91**	4
ON2	.04	.05	3.08	.15	1.06	.15	.02	.59	**3.79**	.91	.52	.02	**.71**	5
ON B1	**16.20**	.41	.81	.25	.00	.02	.05	2.59	1.87	4.81	.22	11.10	**2.95**	5
ON ABT	**6.31**	1.91	2.13	.01	.16	.10	.00	.01	.07	0	—	—	**1.09**	5
SV Avalanche	3.92	4.85	**29.50**	.71	.42	.05	.22	.06	.03	.96	.66	.86	**3.22**	5
EVS	.24	.18	**3.91**	.63	1.31	.79	.41	.04	2.65	2.73	.81	.20	**1.12**	5
TCC	2.54	5.70	**7.62**	5.11	4.60	1.78	.59	3.81	1.87	1.03	2.38	2.64	**3.33**	5
S2	**2.08**	.97	.94	.58	1.16	1.24	.58	.71	.57	1.05	.53	.28	**.82**	5
Subdivisions of major avalanche sites														
EVS <50 m	.09	.08	.72	.00	.41	.14	.00	0	.22	**1.02**	.85	.00	**.30**	
EVS >50 m	.46	.29	**7.33**	1.30	2.67	1.48	.82	.09	5.38	4.77	.75	.43	**2.20**	
SV Lower	2.73	6.59	**66.60**	.02	.01	.01	.07	.03	.01	.00	1.26	.75	**5.57**	
SV Upper	**5.73**	4.72	2.19	.62	.96	.09	.37	.03	.07	.25	.04	1.31	**1.65**	
SV Down	**3.49**	1.63	.01	2.14	.37	.06	.19	.15	.01	.03	.02	.36	**.65**	
SII Lower	**1.38**	1.13	.19	.07	.70	.24	.14	.41	.19	.10	.34	.18	**.39**	
SII Middle	.88	.71	.41	.54	1.28	1.51	.52	.36	.48	**3.93**	.19	.12	**.83**	
SII Upper	**6.26**	1.01	4.97	2.71	1.80	2.58	2.24	2.29	2.16	2.18	1.53	.63	**2.45**	
TCC <60 m	2.15	**8.34**	7.88	.32	.99	1.95	.27	6.33	1.91	.20	1.42	1.44	**2.88**	
TCC >60 m	2.93	1.44	7.03	**14.08**	11.30	1.51	1.07	1.61	1.82	2.09	3.84	4.43	**4.08**	

Notes: Units are mm thickness of deposition. All values are rounded; 0.00 = <0.0049; 0 = no accumulation.
For definitions see Appendix I.
Highlighted values are the maximum for the site.
*2 year mean



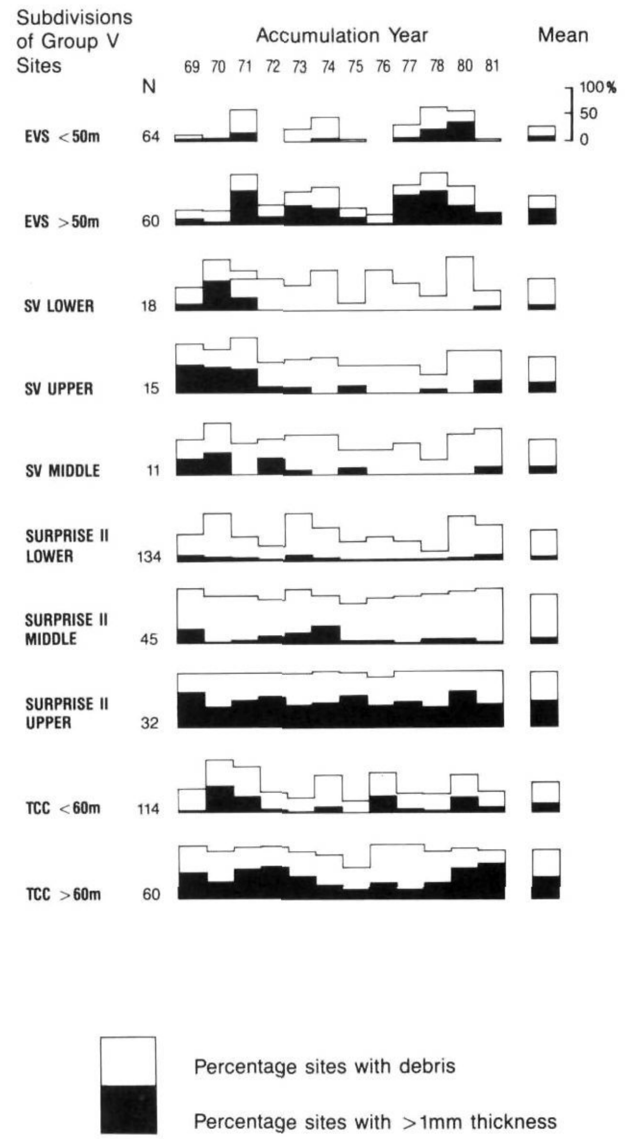


FIGURE 25. Annual variation in the spatial extent and volume of deposition on sample sites at Surprise Valley, 1968-81. The left-hand side of the figure shows data for the principal sites whereas the right side of the figure shows subdivisions of the major avalanche sites by zone. Note that the 1980 data are for a two year accumulation period. Full data are given in Appendix I. N = mean number of sample sites per year (1969-81).

Variation annuelle de l'étendue et du volume de l'accumulation sur les sites témoins à Surprise Valley, 1968-1981. À gauche, on fournit les données sur les principaux sites; à droite, on montre les subdivisions des principaux sites d'avalanche par zone. À noter que les données de 1980 représentent une période de deux ans d'accumulation. Les données complètes apparaissent à l'appendice I. N = nombre moyen de sites témoins par année (1969-1981).

Assuming that the percentage of sample sites with accumulation is proportional to avalanche deposition and extent, the data shown in Figure 25 may be used to evaluate year to year variation in avalanche deposition at a site. The greatest year to year variation predictably occurs at basal sites that are subject to periodic avalanche deposition (*e.g.* Small Cone, EVS lower, Fig. 25) or at sites which lack well defined avalanche tracks (*e.g.* Entrance Lower). Sample site networks on upper slopes or close to the cliff (*e.g.* Entrance Upper, Surprise II Upper) have provided much more consistent results with 50-100% of sample sites receiving deposition in each year.

Common temporal variation in the pattern of avalanche activity between sites over the 13-year period is more difficult to identify. Available published sources that might be used to present a broader regional picture of avalanche conditions are limited (Table V). The avalanche frequency data available for sites along the Banff-Jasper Highway (50-100 km south of Surprise) are not a homogeneous time series (see Table V) and the limited snowfall data for Maligne (the closest station to Surprise) are poorly correlated with the longer record from Jasper (Luckman, 1973). These meagre data do suggest a considerable range in both snowfall amounts and avalanche activity over the 13-year period of study in Surprise. However the summary data for avalanche depositional activity in Surprise (Fig. 25, Tables 4 and 5) show little synchroneity between sites. Apart from 1980, which represents accumulation over a two-year period, only two years show a consistent signal. Most sites show greater avalanche activity and extent in 1974 which also has the highest snowfall at Jasper and largest number of avalanches onto the Icefields Parkway. However 1975, which has the second highest number of avalanches onto the highway and much lower Jasper snowfall, has very low amounts of avalanche deposition at almost every site in Surprise. In other years the high variability in relative importance of avalanche activity between sites suggests that the principal controls of avalanche deposition are more strongly linked to local factors (*e.g.* the elevation, size, aspect and morphology of the starting zone or track, local extent or depth of snowcover) than regional, climatically-controlled factors. This high variability in results from different sites in different years cautions against extrapolation from short term data bases: compare, for example, the results from Strike Valley and the Eastern Valley Side in 1969 and 1970 with each other and the remainder of their records.

The sharp decrease in the number of sites showing evidence of avalanche erosion after 1971 (Table V) is, in large part, due to the abandonment of the sample square network on the upper slopes at several sites. Nevertheless there is some evidence that greater volumes of avalanche deposition (and erosion) are associated with low snowfall winters (1969, 1970, 1977, 1978) and light depositional years occur with large snowfall amounts (1972, 1976, 1981 but not 1971 or 1974). Unfortunately the lack of systematic methods for measuring erosion or adequate snow data for these sites prohibits more effective testing of this relationship.

EVALUATION OF GEOMORPHIC PROCESSES

An initial goal of this project was to provide quantitative estimates of the relative contributions of different mass wasting processes to talus slope development in Surprise. However,

TABLE V

Temporal variation in snowfall and avalanche activity. Jasper National Park, 1967-1981

	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
A. Regional Data															
Winter snowfall Jasper (cm)	170	150	105	86	220	225	146	268	121	163	104	107	129	178	229
Winter snowfall Maligne (cm)	340	424	196	241	323	—	—	—	—	—	—	—	—	—	—
Avalanches, Icefields Parkway[a]	—	—	—	—	59	30	45	221	134	67	78	79	70	38	44
B. Surprise Valley Data (number of sites in each period)															
Sites with avalanche erosion[b]		(2)	6	4	6	1	1	2	1	1	2	1	—	3	1
Sites with above average debris cover[c]			9	8	11	6	7	15	1	6	8	5	—	14	5
Year of maximum debris cover[c]			1½	3	3½	0	2	2	0	1	2	1	—	1	0
Sites with above average accumulation > 1 mm[c]			5	7	7	6	4	5	1	5	7	5	—	10	6
Year of maximum amount > 1 mm[c]			3	1	2½	0	0	2	0	0	1	1	—	3½	1
Year of maximum mean accumulation			5	0	3	2	2	1	0	1	3	0	—	2	0

N.B. 1967 = 1966-7 winter period

Notes: [a] Parks Canada Data reworked from Zweck von Zweckenberg (1979) and Young (1984). Large differences between 1974, 1975 and other years are in part a function of data collection techniques.

[b] Based on erosion of squares and marker boulders, snow observations and debris accumulation patterns.

[c] Based on data shown graphically in Fig. 25. An 'above average' year exceeds the *site* mean for the period of record. N = 17 (Entrance Upper excluded). In determining maximum years tied results were counted as ½.

initial observations indicated that rockfall amounts were seriously under-estimated because of the basal location of many sample sites, the sampling methods used and the problem of differentiating mixed deposits. In addition, avalanche incorporation of talus material made it impossible to establish the immediate source of avalanche-transported debris. Although these factors prohibit precise quantitative answers, these questions may be addressed in a more qualitative appraisal of the available data.

ROLE OF SNOW AVALANCHES

The most dynamic sites at Surprise are those dominated by snow avalanches and therefore the principal result of this study has been to demonstrate the role and significance of snow avalanches in alpine talus slope development. These results confirm that (a) avalanche activity on the talus may be erosional or depositional; (b) the erosional and depositional zones vary and overlap from year to year; (c) the debris in avalanches may be derived from the cliff zone or talus surface; (d) avalanches may be initiated in the snow cover of the talus slope itself and (e) slab avalanches may be significant geomorphic agents at these sites. Avalanches moving over the talus may incorporate individual boulders up to 1.5 m^3 and deposit as much as 50 m^3 of rock debris.

Detailed maps have been created for five slopes to show the probability of deposition and mean accumulation values over a ten year period (Figs. 8, 13, 16, 18 and 23). All five sites are within or include active avalanche tracks and the depositional patterns are primarily the result of deposition from avalanche snow. Although gradients vary, all of these maps show that the probability of deposition decreases downslope (downtrack) and that higher volumes of deposition occur more frequently towards the cliff or avalanche source area. However erosion and downslope redistribution of talus material by snow avalanches also occurs, particularly on the upper and middle slopes. This erosion may be extensive (*e.g.* Fig. 6) or very selective (Fig. 12) and ranges in frequency from one year in two at the most active site to one year in four-six at other avalanche sites. Depositional patterns at these avalanche sites indicate several years when mean accumulation values in the lower part of the track exceed those on the upper slopes (Table IV). The number of years in which this reversal occurs (5 at TCC, 3 at Strike Valley, 2 at Surprise II and 1 at EVS) is roughly proportional to observations of the frequency and intensity of avalanche erosion at these sites. Avalanche reworking of the talus surface of the Tumblin' Creek Cone has resulted in a mean accumulation pattern that shows almost no downslope gradient in the central part of the cone. Over the 1968-1981 period mean accumulation values for the upper and middle sections of these avalanche slopes average 1-4 mm/yr with maximum yearly values of 10-15 mm/yr. Probability data indicate that deposition occurs on sample sites in these areas in most years and exceeds 1 mm/yr one year in two. However net accretion rates on these slopes may be somewhat lower than these figures, depending on the magnitude and frequency of avalanche erosion. Deposition on the lower slopes depends on runout distances and upslope avalanche erosion. Average rates of net accretion are up to 5 mm/yr over the 1968-81 period.

Where avalanche tracks and/or runout zones are well defined, this avalanche erosion and reworking of the slope surface can produce a marked sorting gradient in surface materials and avalanche boulder tongues may develop in the runout zone downslope (Luckman, 1978a). Where avalanche tracks are not confined and/or avalanches are less frequent, distinctive morphological evidence of avalanche activity may be lacking but avalanches occasionally deposit debris on the lower slope system, in some cases by erosion from upslope (*e.g.* Scree No. 1). Both avalanches and rockfall contribute considerable amounts of relatively small material (fines to 100 cc) to the lower parts of talus slopes, most of which becomes matrix between much larger (rockfall?) debris.

ROCKFALLS

Small area, point samples in the basal sections of talus slopes are not an effective sampling strategy to estimate the volume of rockfall (see Luckman, 1978b). The results presented in Table IV considerably underestimate the frequency and volumes of rockfall deposition at these sites. Inventory studies in Surprise in 1969 indicated 231 rockfalls in 347 hours of observation with mean rockfall frequencies of *ca* 0.2 and 1.0 rockfalls/hour at the Old Nip and Scree No. 1 sites (Luckman, 1976). Most of these were small pebble falls that came to rest on the upper talus slopes but, during the same summer, 3 separate boulders of 2-3 m^3 were deposited at or beyond the basal fringe of talus slopes (Luckman, 1973, Table 4.5). Crude estimates of depositional probabilities for rockfalls may be derived from those basal sites without significant avalanche input (Table VI). These probabilities range from 0.01-0.005 per site year and in most cases could be doubled if "near misses" (fresh boulders directly upslope of sample sites) were included. Although these numbers appear very small it should be noted that sampling networks covered perhaps 0.1-0.01% of the basal zone of the talus slopes at these sites. Extrapolation of these data would suggest several rockfalls per year onto the basal slopes.

Despite the paucity of data it seems likely that the total volume of debris added to these slopes by rockfall over the study period considerably exceeded all avalanche transport except possibly at the EVS site. Only three rockfall events were identified on the Tumblin' Creek Cone (Table VI) but their combined volume exceeds the total from all 2084 site-years of measured accumulation. The same is true of the two largest rockfall boulders at Surprise II (identified by slide tracks on dirty snow). Most of the talus slope material at these sites is contributed by rockfall: although avalanches input significant quantities of debris, their primary role is probably the downslope redistribution of loose surface debris originally derived by rockfall.

DEBRIS FLOWS

Debris flows are not a major component in debris slope development in Surprise although there is morphological evidence of former flows at some sites (*e.g.* Fig. 9; Luckman, 1978a, Fig. 3). The primary cause of debris flows in Surprise appears to be localised intense precipitation events where drainage from the cliff zone locally saturates and mobilises

TABLE VI

Rockfall and debris flow events in Surprise Valley, Alberta

a) Rockfall events at selected sites

Site	Site-years	Rockfalls[a] On	Rockfalls[a] Adjacent	Probability[b]
Entrance Lower	364	4	3	.011
Old Nip Lower	353	3[c]	0	.009
Palliser Lower	489	3	4	.006
Scree No. 1	198	1	0	.005
Tumblin' Creek Sites	—	—	5[d]	—

Notes: [a] These rockfalls were defined as single boulders >10^3 cc resting on or immediately adjacent to sample sites with no evidence of avalanche deposition from adjacent sites.
[b] Probability calculated as rockfalls on sample sites divided by total site years (including 1979)
[c] Depositional events in 1971 and 1974 are interpreted as avalanche based on depositional pattern and grain size characteristics.
[d] TC Cone 1.5-2 m^3, 1972; 0.9 m^3, 1973; 1 m^3, 1980: TC2 Site 10-15 m^3, 1969: TC3 Site 100-150 m^3, 1976.

b) Debris flow events

Date	Comment
Aug. 4-6, 1969	Precipitation as snow in Surprise, no debris flows generated. Significant debris flow activity occurred further east (see Luckman 1981)
Aug. 1, 1975	Surprise II(?), Hoodoo Valley and other sites adjacent to Palliser area (see Luckman 1981)
1976, 1977	Single, small flows at Surprise II in each year.
1979-1980	Fresh flows on TC Cone, TC3, Palliser Cone, Scree No. 1

the upper part of the talus. Two events of this type have been recorded. On August 1, 1975 an intense thunderstorm, centered over the lower end of the valley, generated flows that blocked the highway to Maligne Lake, created large debris flows on the Hoodoo Valley Screes (Luckman, 1981, Photo 10) and a single flow at Surprise II (Luckman, 1981). A similar storm in 1979 or 1980 probably created the fresh flows seen on the Palliser, Scree No. 1 and Tumblin' Creek Sites in 1980. Small debris flows were also generated near the Surprise II site in 1976 and 1977. The storm of August 4-5, 1969 produced maximum 24-hour precipitation at Jasper (over 50 years of record) and generated debris flows further east where the precipitation fell as rain. Based on these data, debris flow generating events probably occur in Surprise Valley once every 3-5 years, but because of the localised nature of the precipitation event, the recurrence interval at any one site may be much larger.

Isolated observations and experiments with painted lines indicate that, where fines are present at or near the talus surface, frost creep and related processes may be active on these slopes (Fig. 20, Table III).

CONCLUSION

This paper has presented detailed case studies of depositional patterns and volumes on talus slopes. These studies demonstrate that few talus slopes in these alpine environments are without some snow avalanche activity and that, where cliff-zone topography focusses avalanches onto talus slopes below, snow avalanches may add and rework significant volumes of debris on these slopes. However, even on the most active avalanche sites it appears that rockfalls usually provide the greatest volume of debris input to the talus slope and that the most visible avalanche effects involve redistribution of surface talus materials. Each of the slopes studied in Surprise Valley contributes facets to this study and it is difficult to generalise the results in simple quantitative terms: the wide year-to-year and site-to-site variability in depositional amounts and patterns emphasises the dominance of mainly local site controls on the geomorphic activity of avalanches in any given year at any site. The results of the complete period of record confirm and amplify many of the conclusions drawn from the initial results (Luckman, 1971, 1972a) and other, concurrent, studies (*e.g.* Gardner, 1983) but they also illustrate the dangers of extrapolation from limited spatial or temporal samples. At the other extreme it is difficult to place these results in a long-term, magnitude-frequency context except to state that, at least for avalanche features, the debris volumes measured and processes documented during this study are sufficient to have produced the present avalanche landforms at these sites during the Holocene. Evaluation of rockfall rates requires a more extensive spatial and/or temporal sampling programme than that attempted here.

ACKNOWLEDGEMENTS

This project was begun as part of a doctoral programme at McMaster University and I would like to thank Brian McCann and Derek Ford for their encouragement, advice and support in those early years. Financial support has come at various times from McMaster University, University of Western Ontario, National Research Council of Canada and the Natural Sciences and Engineering Research Council of Canada, Many individuals have trekked with me into Surprise to assist in this study and I would like to acknowledge the following for their contributions in the field: D. C. Ford, M. C. Brown, M. Boon, P. Fuller, D. Stanifield, T. M. L. Wigley and J. Secombe (1968); Gary Pilkington (1968-69); S. B. McCann, M. Church, J. Ryder, D. Monocello and C. Evans (1969); my wife Helen (1969-71); R. V. Maher, G. Brewster and M. F. Goodchild (1971); H. von Gaza (1972); B. Bird (1973); K. J. Crockett (1974, 1976); F. Mark (1975); M. S. Kearney and A. B. Beaudoin (1976), E. Zweck von Zweckenberg (1977); D. Crann (1977-78); F. F. Dalley (1978, 1980); G. Frazer (1981); and last, but by no means least, Mac Elder, formerly warden at Maligne Lake, and his wife Cathy for those critical pack horses, considerable assistance and hospitality over the first half of this project. Parks Canada, Jasper also provided logistical support and facilities in the first few years of the project and the Geography Department, University of Edinburgh allowed generous use of their computing facilities in 1979-80. Derry Graves, Gordon

Shields and other members of the Cartographic Section, U.W.O. drew the maps. Sidney White, Jim Gardner and two anonymous referees made useful comments on the manuscript. Finally, it is fitting that the most precious gem in Surprise Valley should be named for my wife Helen, who has contributed in many ways in all phases of this project.

REFERENCES

Atmospheric Environment Service (A.E.S.), 1982. Canadian Climate Normals, Volume 2, Temperature 1951-80. Environment Canada. p. 721-748.

Caine, T. N., 1974. The geomorphic processes of the alpine environment, *In* J. D. Ives and R. G. Barry, ed., Arctic and Alpine Environments, Methuen, London.

Caine, T. N., 1976. The influence of snow and increased snowfall on contemporary geomorphic processes in alpine areas, p. 145-200. *In* H. W. Steinhoff and J. D. Ives, ed., Ecological Impacts of Snowpack Augmentation in the San Juan Mountains, Colorado. Final Report, Colorado State University Publication, Fort Collins.

Church, M., Stock, R. F. and Ryder, J. M., 1979. Contemporary sedimentary environments on Baffin Island, N.W.T., Canada: debris slope accumulations. Arctic and Alpine Research, 11: 371-402.

Elder, S. M., 1972. Personal communication. Chief Park Warden, Pacific Rim National Park, Ucluelet, British Columbia.

Ford, D. C., 1979. A review of alpine karst in the southern Rocky Mountains of Canada. Bulletin of the National Speleological Society of America, 41: 53-65.

Gardner, J. S., 1970. Geomorphic significance of avalanches in the Lake Louise area, Alberta, Canada. Arctic and Alpine Research, 2: 135-144.

——— 1973. Morphology and sediment characteristics of mountain debris slopes in the Lake Louise area, Alberta. Zeitschrift für Geomorphologie, 15: 390-403.

——— 1979. The movement of material on debris slopes in the Canadian Rocky Mountains. Zeitschrift für Geomorphologie, 23: 45-67.

——— 1983. Accretion rates on some debris slopes in the Mt. Rae Area, Canadian Rocky Mountains. Earth Surface Processes and Landforms, 8: 347-355.

Gardner, J. S., Smith, D. J. and Desloges, J. R., 1983. Dynamic Geomorphology of the Mt. Rae Area: A High Mountain Region in Southwestern Alberta. University of Waterloo, Department of Geography, Publication Series No. 19, 237 p.

Gray, J. T., 1973. Geomorphic effects of avalanches and rockfalls on steep mountain slopes in the central Yukon Territory, p. 107-117. *In* B. D. Fahey and R. D. Thompson, ed., Research in Polar and Alpine Geomorphology; Proceedings of the Third Guelph Symposium on Geomorphology. Geoabstracts, Norwich.

Janz, B. and Storr, D., 1977. The Climate of the Contiguous Mountain Parks. Environment Canada, Application and Consultation Division, Meteorological Applications Branch, Project Report No. 30, 324 p.

Kotarba, A., Klapa, M., Midriak, R., Petras, J. and Skroda, J., 1979. Field experiments on high mountain slopes of the Tatra Mts. Studia Geomorphologica Carpatho-Balcanica, XIII: 132-148.

Luckman, B. H., 1971. The role of snow avalanches in the evolution of alpine talus slopes, p. 93-100. *In* Slopes — Form and Process, Institute of British Geographers, Special Publication No. 3.

——— 1972a. Some observations on the erosion of talus slopes by snow avalanches in Surprise Valley, Jasper National Park, Alberta, p. 85-92. *In* H. O. Slaymaker and H. J. McPherson, ed., Mountain Geomorphology, Tantalus Press, Vancouver.

——— 1972b. Debris accumulation on talus slopes in Surprise Valley, p. 36-38. *In* W. P. Adams and F. M. Helleiner, ed., International Geography, Vol. 1. University of Toronto Press.

——— 1973. Scree slope characteristics and associated processes in Surprise Valley, Jasper National Park, Alberta. Ph.D. thesis, McMaster University, 499 p.

——— 1975. Drop stones resulting from snow avalanche deposition on lake ice. Journal of Glaciology, 14, 70: 186-188.

——— 1976. Rockfalls and rockfall inventory data: some observations from Surprise Valley, Jasper National Park, Canada. Earth Surface Processes, 1: 287-298.

——— 1977. The geomorphic activity of snow avalanches. Geografiska Annaler, 59A: 31-48.

——— 1978a. Geomorphic work of snow avalanches in the Canadian Rocky Mountains. Arctic and Alpine Research, 10: 261-276.

——— 1978b. Measurement of debris accumulation on alpine talus slopes. Zeitschrift für Geomorphologie, Supp. 29: 117-129.

——— 1981. The geomorphology of the Alberta Rocky Mountains: A review and commentary. Zeitschrift für Geomorphologie, Supp. 37: 91-119.

Mountjoy, E. W., 1964. Rocky Mountain Front Ranges between Rocky River and Medicine Lake, Jasper National Park, Alberta, p. 1-13. *In* Edmonton Geological Society, 6th Annual Field Trip Guidebook, August 1964.

Rapp, A., 1959. Avalanche boulder tongues in Lappland, descriptions of little-known forms of periglacial debris accumulations. Geografiska Annaler, 41: 34-48.

——— 1960. Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia. Geografiska Annaler, 42: 65-200.

Rapp, A. and Fairbridge, R. W., 1968. Talus fan or cone, p. 1106-1109. *In* R. W. Fairbridge, ed., Encyclopaedia of Geomorphology. Van Nostrand Reinhold, New York.

White, S. E., 1981. Alpine mass movement forms (noncatastrophic): Classification, description and significance. Arctic and Alpine Research, 13: 127-137.

Young, R. B., 1984. Temporal variations in snow avalanche activity along the Icefields Parkway. Unpublished Report, Department of Geography, University of Western Ontario.

Zweck von Zweckenburg, E., 1979. Snow avalanche activity along the Ice fields Parkway. B. A. Report, Department of Geography, University of Western Ontario.

APPENDIX I

This appendix contains summary data for accumulation at all the sites studied in Surprise. Note that the term **site** is used to refer to a group of sample sites, *e.g.*, Scree No. 1, whereas **sample site** refers to individual collection sites (*i.e.*, **sample boulders** or squares). **Marker boulders** (usually 1-300 mm 'a' axis) were used to anchor squares in place and are identified by painted markings. **Painted boulders** are derived from experimental lines set up on the slope.

For each site results are given in a standard format. **Set** indicates the number of sample boulders (b) and squares (s) originally set up (see Luckman, 1979, Table 1). A few sample sites excluded are designated by nr. The **area** (m^2) and **volumes** (m^3) given are for the complete 13-year period. The figures in brackets include data from sample squares.

Mean accumulation values are reported as an averaged depth in millimetres. Zero indicates no accumulation on the sites whereas .000 is <0.00049 mm. Sample sites that were missed in a previous year (*e.g.*, they were snow covered) are not assigned to the annual total for the collection year. However, these amounts are included in the total accumulation for the sample sites and averaged into sample site means and site means for the total period of record.

Annual means are the total volume of accumulation for the year divided by the total surface area sampled. Note that the 1980 mean is an annual mean averaged over a two-year period. **Site means** are the total accumulation at the site divided by the total area sampled.

Number of (sample) sites refers to both boulders and squares with the number of squares reported in brackets. Where major differences in site means etc. occur between boulder and square sample sites data including results from squares are given in brackets (*e.g.*, Palliser Lower).

> **1 cc** is the number of sample sites with more than 1 cc accumulation regardless of surface area. The mean is the percentage of all sample site-years divided by total sample site-years.

> **1 mm** is the number of sites with > 1 mm accumulation per unit area.

max % is the percentage of total accumulation at a site in a given year that is accounted for by the maximum volume on any sample site in that year. The mean is the percentage of total accumulation over the 13-year period that is attributable to the maximum single sample site-year.

EASTERN VALLEY SIDE SITE

EASTERN VALLEY SIDE (EVS): Set 137b,6s(3nr) Area 543.2 (557.1) m^2 Volume .651 (.651) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	.234	.211	3.91	.631	1.31	.789	.414	.041	2.65	2.73	.814	.196	1.17
	(.235	.176)											(1.12)
Sites	140(3)	139(3)	125	126	123	124	125	125	117	115	116	109	1484
> 1 cc	27(1)	23	89	22	48	67	20	12	54	85	70	11	35.7%
> 1 mm	11	7	43	11	20	22	10	1	31	43	37	9	16.6%
max %	25	42	17	37	60	29	41	76	10	37	11	43	5.9%

EVS UPPER (>"50 m contour"): Area 255.0 m^2 Volume 0.56 m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	0.46	0.29	7.33	1.30	2.67	1.48	0.82	0.09	5.38	4.77	0.75	0.43	2.20
Sites	73	72	61	62	60	60	61	61	53	51	53	47	714
> 1 cc	20	19	54	22	35	40	19	12	37	47	36	10	49.2%
> 1 mm	9	3	35	11	20	19	10	1	28	30	17	9	19.2%

EVS LOWER (<"50 m contour"): Area 302.0 m^2 Volume 0.09 m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	0.09	0.08	0.72	zero	0.41	0.14	0.00	zero	0.22	1.02	0.85	0.00	0.30
Sites	67	67	64	64	63	64	64	64	64	64	63	62	770
> 1 cc	7	4	35	0	13	27	1	0	17	38	34	1	23.1%
> 1 mm	2	4	8	0	0	3	0	0	3	13	20	0	6.9%

ENTRANCE SITE

UPPER SITES: Set 10b,3s Area 32.3 (36.9) m^2 Volume .004 (.009) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	.218	.337	.108	.080	.089	.087	.059	.067	.399	.084	.039	.042	.127
	(.540)												(.234)
Sites	10(2)	8	8	8	8	8	8	8	8	8	8	8	98
> 1 cc	7(2)	8	8	7	6	7	8	5	6	8	6	6	83.7%
> 1 mm		1							1				2.0%
max %	76	43	73	37	45	57	52	73	75	76	49	74	44.7%

LOWER SITES: Set 28b,1s Area 170.4 (172.8) m² Volume .017 (.017) m³

Mean	.054 (.046)	.006	.157	.006	zero	.537	.167	.345	.009	.000	.006	.000	.100 (.098)
Sites	28(29)	28	28	28	28	28	28	28	28	28	28	28	336
> 1 cc	8	1	14	3	0	12	3	8	3	2	1	1	15.4%
> 1 mm	1	1	1			5	2	1					3.3%
max %	97	100	79	68	—	29	76	99	54	50	100	100	26.5%

OLD NIP SITE

ROCKFALL SITE (ON1): Set 31b,1s(6nr) Area 246.2 (250.9) m² Volume .468 (.469) m³

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	.002 (.013	.009 .021)	4.38	.587	.009	.973	.002	.007	.017	.003	9.30	.032	1.87 (1.90)
Sites	31(1)	31(1)	30	30	30	30	30	30	30	30	27	27	356
> 1 cc	6(1)	9(1)	16	5	9	13	6	8	8	7	11	9	30.3%
>1 mm			7	2		3					4		4.5%
max %	89	62	27	57	67	56	68	43	84	42	94	77	70.0%

AVALANCHE SITES: ABT Set 10s Area 112.3 m² Volume .122 m³
B1 Set 1b,1s Area 24.1 m² Volume .069 m³
ON2 Set 24b Area 63.6 m² Volume .053 m³

ABT	(6.31	1.91	2.13	.008	.162	.104	.000	.008	.072	zero			1.09)
ABT (3sq)	(6.31	4.60	2.66	zero	.000	.000	.000	.009	.072	zero			1.36)
Sites	3	8	8	6	6	5	4	4	3	3			50
> 1 cc	3	6	8	3	3	3	1	1	1				60.0%
> 1 mm	3	3	7			1							26.0%
max %	83	80	23	75	99	99	100	100	100				38.6%
B1	16.2	.405	.805	.250	.004	.017	.052	2.59	1.87	4.81	.221	11.1	2.95
ON2	.041	.051	3.08	.145	1.06	.150	.022	.591	3.79	.912	.516	.015	.707
Sites	24	24	24	24	24	24	24	24	24	24	23	23	286
> 1 cc	3	6	18	9	7	19	3	19	23	19	16	3	50.8%
> 1 mm	1	1	10	1	1	1		3	10	4	3		12.3%
max %	96	28	62	73	99	20	77	33	56	40	66	93	19.6%

PALLISER SITE

PALLISER CONE-MIDDLE: Set 22b,11s Area 63.4 (100.6) m² Volume .058 (.122) m³

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	zero (2.55	.617 0.30	.024 2.48	.474 1.23)	.672	.626	.002	.235	.734	zero	4.04	zero	.911 (1.25)
Sites	3(3)	31(10)	26(5)	22(1)	21	19	19	19	19	19	18	18	234
> 1 cc	3(3)	8(6)	11(5)	3(1)	4	8	1	9	6	0	5	0	24.7%
> 1 mm	1	1	1	1	1	2		2	2		3		6.0%
max %	99	36	74	74	93	77	100	34	79	—	58	—	28.3%

PALLISER CONE-LOWER: Set 40b,5s Area 254.2 (275.1) m² Volume .140 (.140) m³

Mean	.219 (.136	.138 .203)	.004	.018	.000	.013	zero	.003	6.65	.000	.018	.013	.551 (.510)
Sites	41(5)	41(4)	37	37	37	37	37	37	37	37	37	37	452
> 1 cc	7(2)	5(1)	2	5	1	8	0	1	3	3	4	5	9.7%
> 1 mm	1	1							1		1		0.9%
max %	99	96	66	55	100	41	—	100	100	33	98	62	92.8%

PALLISER RUNNEL: Set 8b,1s Area 55.5 (60.2) m² Volume .012 (.032) m³

Mean	.066 (.005	.005 .017)	.010	.029	.009	.015	.002	.007	.004	.007	.004	.007	.009 (.009)
Sites	9(1)	9(1)	8	8	8	8	8	8	8	8	8	8	98
> 1 cc	4(1)	3(1)	4	6	7	6	2	5	3	5	5	5	56.1%
> 1 mm													0.0%
max %	53	81	69	40	25	51	67	54	45	66	77	33	10.3%

SMALL CONE: Set 46b,4s Area 161.8 (185.5) m² Volume .119 (.123) m³

Mean	.900	.000	1.27	4.92	.040	.082	.000	zero	.137	.001	.883	.178	.761
	(.691	.000	1.21)										(.664)
Sites	48(4)	50(5)	45(1)	44	44	43	43	43	43	43	43	43	533
> 1 cc	7(2)	1(1)	33(1)	18	7	15	2	0	9	2	11	4	20.4%
> 1 mm	2(1)		11	8		1			1		4	1	5.3%
max %	98	96	31	63	47	19	51	—	63	81	54	99	32.0%

SCREE No. 1: Set 14b,8s Area 74.9 (116.7) m² Volume .012 (.034) m³

Mean	.000	zero	zero	.021	.002	.004	.017	.001	.014	zero	.077	.253	.036
	(.056	.031	zero	.020)									(.041)
	1.60	(August 1969) All subsequent entries include August											.158
	(1.27)	" "											.293
Sites	22(8)	21(7)	16(2)	15(1)	14	13	13	14	14	14	14	14	184
> 1 cc	16(6)	2(2)	0	5(1)	2	2	2	2	2	0	2	2	20.9%
> 1 mm	6(4)											1	3.8%
max %	34	94	—	46	92	62	97	71	69	—	100	100	12.2%

STRIKE VALLEY SITE

TOP: Set 13b Area 81.9 m² Volume .013 m³

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	zero	.000	zero	zero	.936	zero	zero	zero	.244	.008	.007	.533	.165
Sites	13	13	13	13	12	12	11	11	12	12	10	10	142
> 1 cc		1			6				2	1	6	5	14.7%
> 1 mm					1				1			2	2.8%
max %	—	100	—	—	94	—	—	—	82	100	94	55	42.0%

AVALANCHE: Set 49b Area 494.1 m² Volume 1.589 m³

Mean	3.92	4.85	29.5	0.71	0.42	0.05	0.22	0.06	0.03	0.96	0.66	0.86	3.22
excluding #52			(1.13)										(1.21)
Sites	46	45	46	46	46	39	39	45	45	45	45	44	540
> 1 cc	30	42	35	28	28	28	16	27	25	12	38	22	62.6%
> 1 mm	13	22	10	5	3		3		1	1	2	6	11.0%
max %	25	18	96	41	70	52	42	56	42	80	89	38	64.5%

UPPER TRACK: Set 19b Area 162.4 m² Volume .268 m³

Mean	5.73	4.72	2.19	0.62	0.96	0.09	0.37	0.03	0.07	0.25	0.04	1.31	1.65
Sites	16	15	16	16	16	14	14	16	16	16	17	17	189
> 1 cc	14	12	16	9	10	9	7	8	8	5	13	13	65.6%
> 1 mm	8	7	7	2	2		2			1		4	17.5%
max %	23	24	29	92	89	81	73	80	52	89	17	50	25.0%

LOWER TRACK: Set 19b Area 224.6 m² Volume 1.251 m³

Mean	2.73	6.59	66.6	0.02	0.01	0.01	0.07	0.03	0.01	0.00	1.26	0.75	5.57
Sites	19	19	19	19	19	14	14	18	18	18	18	17	212
> 1 cc	8	17	13	11	9	10	2	13	9	5	17	6	56.6%
> 1 mm	2	20	4									1	9.0%
max %	82	30	99	66	66	43	99	42	29	31	95	99	82.5%

DOWNSLOPE TRANSECT: Set 11b Area 107.1 m² Volume .070 m³

Mean	3.49	1.63	0.01	2.14	0.37	0.06	0.19	0.15	0.01	0.03	0.02	0.36	0.65
Sites	11	11	11	11	11	11	11	11	11	11	11	11	132
> 1 cc	7	10	6	7	8	8	5	5	6	3	8	9	62.1%
> 1 mm	3	4		3	1		1					1	9.8%
max %	52	64	52	60	82	41	94	96	49	99	44	90	22.3%

SURPRISE II SITE

ALL SAMPLE SITES: Set 265b,35s Area 1390.0 (1689.9) m^2 Volume 1.149 (1.337) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	2.08	0.97	0.94	0.58	1.16	1.24	0.58	0.71	0.57	1.05	0.53	0.28	0.79
													(0.82)
Sites	170	262	233	254	199	186	226	213	209	230	241	107	2530
> 1 cc	109	230	149	129	171	138	119	120	111	92	202	69	64.8%
> 1 mm	35	30	23	32	36	36	25	19	18	17	34	15	12.7%
max %	22	18	20	30	14	17	13	25	21	53	24	14	4.5%

LOWER SITES: Set 83b,11s Area 934.1 (1034.8) m^2 Volume .361 (.405) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	1.38	1.13	0.19	0.07	0.69	0.24	0.14	0.41	0.19	0.10	0.34	0.18	0.40
													(0.39)
Sites	118	166	138	161	107	100	143	143	140	157	166	64	1603
	(11	9	1	1	1		1	(50 site-years but not single years)					
> 1 cc	57	143	62	47	90	59	50	59	47	26	128	39	50.3%
> 1 mm	12	14	7	5	10	4	4	4	3	1	8	4	4.7%
max %	43	29	89	91	42	73	66	58	38	97	57	29	11.9%

MIDDLE SITES: Set 41b,20s Area 216.5 (412.9) m^2 Volume .205 (.341) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	0.88	1.26	0.13	1.04	1.41	2.30	0.18	0.35	0.20	3.93	0.19	0.12	0.95
		(0.71	0.41	0.54	1.28	1.51	0.52	0.36	0.48)				(0.83)
Sites	21	58	59	58	57	53	50	41	41	41	41	21	541
	(2	17	18	17	16	12	9	1	1)				
> 1 cc	21	50	51	47	57	47	37	35	36	37	40	21	88.9%
		(16	18	15	16	12	6	1	1)				
> 1 mm	6	2	4	9	12	18	3	3	2	4	4	1	12.7%
max %	19	53	43	17	28	33	44	39	64	90	26	23	17.7%

UPPER SITES: Set 41b,4s Area 239.1 (240.9) m^2 Volume .583 (.590) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	6.26	1.01	4.97	2.71	1.80	2.58	2.24	2.29	2.16	2.18	1.53	0.63	2.45
Sites	31(2)	38	36	35	35	33	33	29	28	32	34	22	386
> 1 cc	31	38	36	35	34	32	32	26	28	32	34	22	99.0%
> 1 mm	19	14	18	18	14	14	18	12	13	12	22	9	46.9%
max %	28	39	27	50	27	40	20	47	33	40	18	23	2.7%

TUMBLIN' CREEK

TUMBLIN' CREEK CONE (TCC): Set 278b,19s Area 947.8 (1069.8) m^2 Volume 3.209 (3.566) m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	2.54	5.70	7.62	5.11	4.60	1.78	0.59	3.81	1.87	1.03	2.38	2.64	3.39
													(3.33)
Sites	91	253	184	158	157	199	195	148	149	177	187	186	2084
	(7	17	9	7	5	7	2)						
> 1 cc	59	229	156	86	69	141	66	121	89	90	135	96	64.2%
> 1 mm	20	107	65	33	21	32	13	42	16	22	65	45	23.1%
max %	26	21	13	26	21	29	25	35	48	17	12	22	4.2%

TCC UPPER (>"60 m contour"): Area 401.6 m^2 Volume 1.63 m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	2.93	1.44	7.03	14.08	11.30	1.51	1.07	1.61	1.82	2.09	3.84	4.43	4.08
Sites	38	82	51	50	48	71	71	62	62	61	60	59	715
> 1 cc	36	69	47	46	40	56	40	59	59	51	53	50	84.7%
> 1 mm	17	25	27	28	19	17	11	17	11	17	32	36	35.9%

TCC LOWER (<"60 m contour"): Area 668.6 m^2 Volumne 1.93 m^3

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1980	1981	MEAN
Mean	2.15	8.34	7.88	0.32	0.99	1.95	0.27	6.33	1.91	0.20	1.42	1.44	2.88
Sites	53	171	133	108	109	128	124	86	87	116	127	127	1369
> 1 cc	23	160	109	40	29	85	26	62	30	39	82	46	53.4%
> 1 mm	3	82	38	5	2	15	2	25	5	5	33	9	16.4%

SITE 1 (TC1): Set 27b	Area 183.3 m²		Volume .115 m³										
Mean	0.07	0.33	0.25	0.15	3.08	0.71	1.28	0.19	0.04	0.45	0.30	1.19	0.63
Sites	27	27	26	25	26	25	25	25	25	25	25	22	303
> 1 cc	9	8	6	11	12	15	9	6	9	6	14	5	35.6%
> 1 mm		2	1	2	3	6	1	1		1	4	1	7.3%
max %	60	47	83	47	93	44	98	97	49	96	56	96	36.8%
SITE 2 (TC2): Set 26b	Area 104.9 m²		Volume .227 m³										
Mean	0.09	3.23	1.68	11.0	0.31	0.48	0.21	0.81	12.3	1.97	1.73	0.39	2.54
Sites	22	23	21	19	20	22	23	21	18	21	23	23	256
> 1 cc	8	16	13	10	12	11	6	5	10	15	15	11	50.8%
> 1 mm		4	2	3	2	3	2	2	4	4	9	3	14.8%
max %	54	61	86	66	57	55	81	73	80	73	62	64	24.6%
SITE 3 (TC3): Set 32b,5s	Area 161.5 (174.4) m²			Volume .326 (.332) m³									
Mean	0.32	0.32	0.17	0.12	0.08	1.19	0.24	6.33	1.25	5.39	1.78	4.95	2.02 (1.91)
Sites	34(3)	27(2)	24(2)	22	27	28	30	29	28	27	29	24	329
> 1 cc	19	16	7	8	7	16	12	15	19	17	19	9	49.8%
> 1 mm	2	4	1	1		3	2	5	7	5	10	4	13.4%
max %	40	34	63	59	47	72	56	63	27	68	62	33	16.5%