Arctic and Alpine Research, Vol. 11, No. 1, 1979, pp. 17-32

SNOW AVALANCHE PATH TERRAIN AND VEGETATION, GLACIER NATIONAL PARK, MONTANA

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ABSTRACT

Snow avalanche paths are major geomorphic features in the Rocky Mountains of Glacier National Park, Montana. They are the most common and geographically widespread form of mass-wasting in the central portion of the park. Field work and aerial-photo studies identified over 800 such paths in the study area. Other mass-wasting phenomena are also common.

Snow avalanche path directions in the study area are concentrated in the southeastern, southern, and northwestern compass octants. The most common type of avalanche path has a bowl-shaped catchment area; a narrow track, often associated with a stream channel; and a tongue-shaped runout zone. Geographically, the avalanche paths are concentrated in the high-relief, high-precipitation, western portions of the study area.

Statistical analysis of the variables which affect avalanche path runout zones revealed that track width accounted for 36% of the variance in runout widths. Runout zone length variations were not adequately explained by any of the terrain variables measured, including those of the starting zone.

Twelve avalanche paths were studied in the field in some detail; these are described. Longitudinal sampling of forest vegetation on these avalanche paths revealed that *Abies lasiocarpa*, *Alnus* spp., and *Acer glabrum* are the most common trees on such sites. Progressing upslope, the number of conifers diminishes, relative to deciduous trees. Ground-cover vegetation is often related to moisture conditions on the avalanche paths.

General vegetative conditions on avalanche paths in the study area indicated frequent avalanching, often at least once per season. Conifers on five avalanche paths were subjected to dendrochronologic analysis in order to accurately determine avalanche frequency. One such path experienced avalanches in 1945, 1950, 1954, 1963, 1965?, 1966, 1972, and 1974. This analysis revealed a lack of slope-to-slope synchroneity relative to periods of avalanche activity.

Avalanche impact pressures and velocities may be determined from damage to trees on and alongside avalanche paths. Impact pressures and velocities for average (impact pressure, 0.21 to 0.28 t m^{-2}; velocity, 3.7 to 4.3 m sec^{-1}) and maximum (impact pressure, 9.6 to 11.9 t m^{-2}; velocity, 25.3 to 28.2 m sec^{-1}) avalanche events were calculated for an avalanche path in the Snyder Lake valley, and are considered typical for the study area.

INTRODUCTION

Glacier National Park is located in the Rocky Mountains of northwestern Montana, where winter precipitation is moderately high, and heavy snows may continue well into June. Dry-snow avalanches may occur throughout the winter (Bradley, 1970); how-

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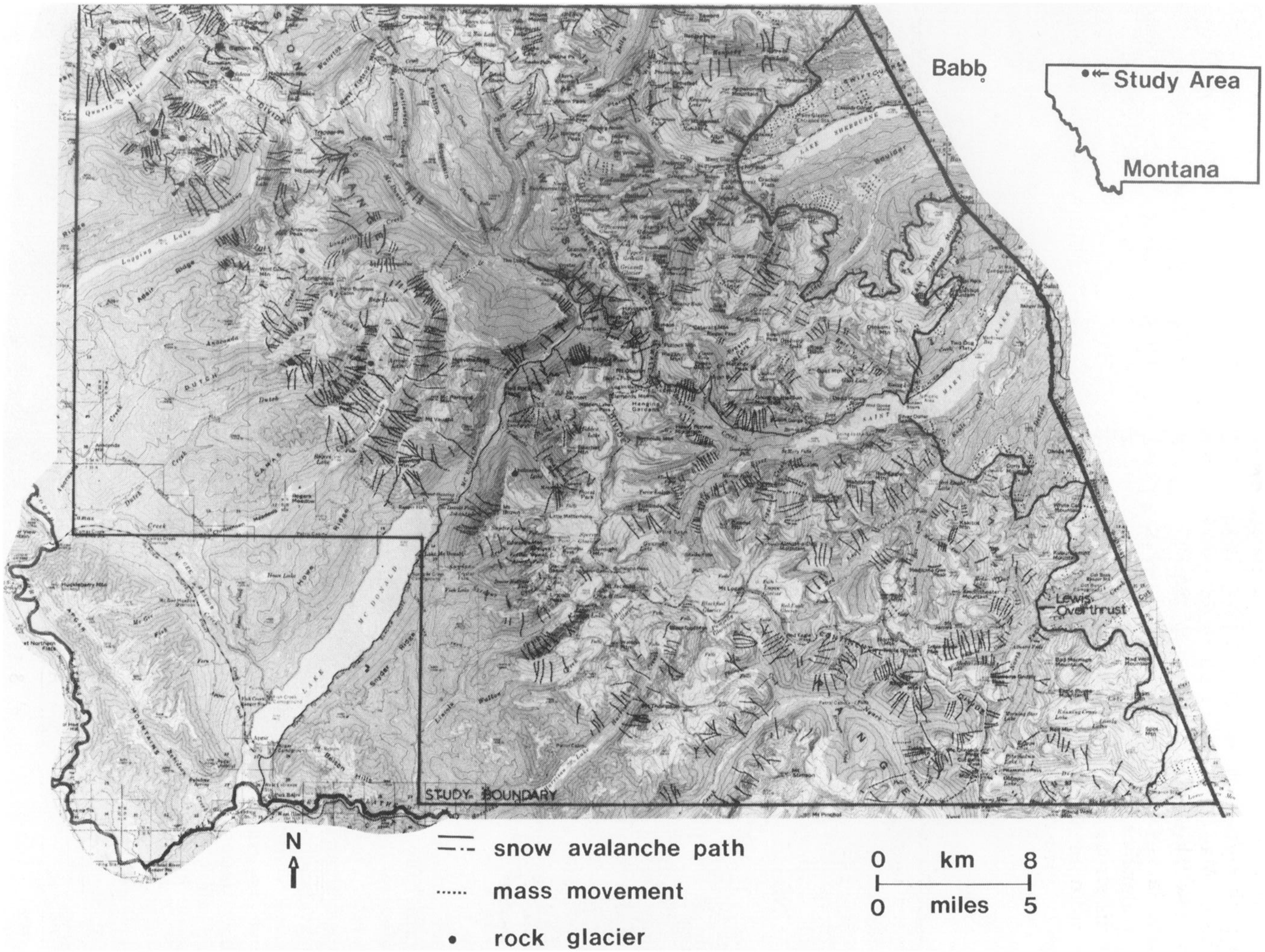

FIGURE 1. Map of the general study area, showing the distribution of the snow avalanche paths and assorted mass-wasting features.

ever, such precipitation conditions, combined with warm, mild spells during the spring months, create especially dangerous avalanche conditions in many areas of the park. Two park employees were killed in an avalanche in May 1953, when up to 43 cm of fresh snow fell within 30 h on old, stabilized snow surfaces (Anonymous, 1953). In addition, avalanches occur every year, with potentially disastrous results, as park workers clear snow from the surface of Going-to-the-Sun Highway, a mountain road which is the major east-west link in the park (Figure 1).

With such well-known conditions documented at park headquarters, I was surprised that no major study of the snow avalanche paths of the park had been carried out. Accordingly, I undertook the task of collecting information dealing with the site distribution and morphology, vegetation, and chronology of snow avalanche paths in the central one-third of the park. This field work and map/aerialphoto interpretation are reported here.

THE STUDY AREA

Glacier National Park is a wilderness park, separated into two approximately equal portions by the Continental Divide, which runs roughly northwest-southeast through the park. The study area (Figure 1), located in the central one-third of the park, encompasses all or portions of seventeen 7-1/2 minute, 1:24,000 U. S. Geological Survey quadrangles.

There are two main mountain ranges in the park. The Livingston Range is the more westerly of the two, extending from the northern border of the study area southeast to the McDonald Creek valley. The Continental Divide follows the Livingston Range in the northern portion of the park and study area, and then shifts to the other main mountain chain, the Lewis Range. The highest peaks in the study area, such as Mt. Stimson (3091.5 m) and Mt. Jackson (3064 m), are in the Lewis Range. The lowest elevation in the study area is Lake McDonald (961 m).

The entire park area was heavily glaciated during the Pleistocene and Holocene, resulting in the spectacular alpine scenery. Most major glacial valleys of the park are oriented northeast-southwest. Finger lakes occupy many of these U-shaped glacial valleys.

There are marked differences in the climatic conditions on the western and eastern sides of the study area, which is bisected by the Continental Divide (Dightman, 1967a; Robinson, 1972). The climate of the park may be broadly classified as continental; however, there are Pacific maritime modifications on the western slopes. Data from West Glacier and Babb (locations shown on Figure 1) are representative of these two climatic regimes (Table 1). Snow accumulations in the high mountain areas of the park may exceed

TABLE 1
Climatic data for West Glacier and Babb, Montana

West Glacier 48°30′N, 113°59′W, 38 yr of record													
Variable	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Temp.	-6.22	-4.11	-0.17	5.44	10.28	13.89	18.10	16.94	11.78	6.05	-0.61	-4.28	5.61
Prec.	78.7	59.4	44.2	43.9	55.9	71.9	36.6	35.3	51.3	67.1	73.9	82.3	699.9

Babb 48°56′N, 113°22′W, 53 yr of record													
Variable	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Temp.	-7.55	-6.39	-2.83	3.44	8.33	11.94	15.67	14.67	10.28	5.83	-0.33	-4.50	4.00
Prec.	23.6	22.1	27.4	41.7	63.5	92.2	48.0	46.2	53.1	30.5	24.6	23.1	496.0

Source: Wernstedt (1972). Data are in °C and mm of precipitation, converted from °F and inches of precipitation.

TABLE 2
Common tree species, eastern slopes of Glacier National Park

Pinus flexilis (limber pine)
Pinus contorta (lodgepole pine)
Abies lasiocarpa (subalpine fir)
Picea engelmannii (Engelmann spruce)
Populus tremuloides (quaking aspen)

TABLE 3
Common tree species, western slopes of Glacier National Park

Pinus ponderosa (ponderosa pine)
Pinus monticola (western white pine)
Abies lasiocarpa (subalpine fir)
Pseudotsuga menziesii (*glauca*) (Douglas-fir)
Abies grandis (grand fir)
Tsuga heterophylla (western hemlock)
Larix occidentalis (western larch)
Picea engelmannii (Engelmann spruce)
Thuja plicata (western red cedar)
Taxus brevifolia (Pacific yew)
Betula papyrifera (*subcordata*) (northwestern paper birch)
Alnus spp. (slide alder)

280 cm yr^{-1} (Dightman, 1967b). Winds are predominantly from the west, resulting in the development of snow cornices on slopes with a southeasterly aspect (which in turn are a result of the orientation of the major glacial valleys). Such cornices are significant factors in avalanche development (Schaerer, 1977).

The vegetation of the study area is complex. The effect of the Continental Divide on the climate creates differences between species on the western and eastern sides of the park (Robinson, 1972). The trees on the eastern slope of the park are similar to those found in the southern Rocky Mountains (Table 2), while those located on the western side of the park are mainly intermountain and Pacific Coast varieties (Table 3).

There is an altitudinal zonation of tree communities in the park (Robinson, 1972), although boundaries between the zones vary due to local factors of site, soil moisture, and soil type (Stanton, 1975). Zones within the present study area include the Canadian zone, which encompasses most of the tree species in the park, except for *Pinus ponderosa* and a few of the high alpine trees; the Hudsonian zone, a narrow belt just below treeline, which is dominated by *Abies lasiocarpa, Larix lyallii,* and *Pinus albicaulis;* and the Arctic-Alpine zone, an area of flowering plants and dwarf shrubs (Robinson, 1972). Generally, treeline is located at 1900 to 2000 m a.s.l.

Avalanches in the study area appear to be largely of the wet-snow variety (historical reports [Anonymous, 1953] and personal observations of avalanche deposits). There does not appear to be much evidence of windblasts associated with powder clouds and dry-snow avalanches in avalanche paths below treeline. However, one avalanche path studied in the field may have been subjected to a large dry powder avalanche, and it is likely that other paths have been similarly affected.

SITE DISTRIBUTION AND MORPHOLOGY OF SNOW AVALANCHE PATHS IN THE STUDY AREA

The large number of snow avalanche paths in the study area obviously pose a potential hazard to winter and spring users of Glacier National Park, as well as having a profound effect on the vegetation, particularly trees. Information on location and morphology of the avalanche paths could assist in delimiting particularly hazardous areas. Such information could be used to infer areas of future avalanche occurrence in locales which have favorable terrain similar to that of actual avalanche paths. Accordingly, data were measured from aerialphotos and maps, and subsequently recorded on 9 of the 17 quadrangles covering the study area, providing a representative sample of over one-half of all avalanche paths in the study area (440 out of approximately 825). Areas in the northern and southern portions of the study area, and on both sides of the Continental Divide, were subjected to data collection, in order to represent the diversity of vegetation and terrain in the park.

Each of the 440 snow avalanche paths sampled was measured for the following information: starting zone highest elevation;

starting zone length; starting zone width; starting zone type, including coalescing, bowl-shaped, or rectilinear (occurring on an open slope); track length; track width; track type (narrow, "neck-shaped," often found in conjunction with a gully or stream channel; or unconfined, open slope); runout zone length; runout zone width; runout zone type (spatulate—wider than long; tongue-shaped—longer than wide; or digitate—formed by the breakup of a runout zone into two or more smaller zones); highest track elevation (height at the top of the track); lowest track elevation; runout zone lowest elevation; and slope aspect. Starting zone, track, and runout zone boundaries were selected on the basis of morphologic criteria, such as steepness of contour lines, and obvious physical boundaries and breaks in slope. Such boundaries were usually easily identifiable on aerial-photos. Starting zone, track, and runout zone areas were computed by multiplying width by length. Slope angles were not measured directly from the maps; however, slope angles were generated by computer using standard algebraic methods (treating the slope angle as the hypotenuse of a right triangle whose horizontal base was lengthwise map distance and whose vertical side was local relief). Several representative longitudinal slope profiles were measured in the field, in order to verify the computer-generated angles, and are discussed in a subsequent section. Presence of associated landforms such as stream channel gullies, debris avalanches, alluvial fans, slush-flow levees, avalanche boulder tongues, etc., was also recorded for each avalanche path.

The geographic distribution of the 825 snow avalanche paths in the study area is shown in Figure 1. There is a concentration in the high-precipitation, high-relief zones of the western parts of the study area. The paucity of avalanche paths in the north-central part of the study area, on Flattop Mountain, may be explained by the topography and structure. Flattop Mountain is a low-relief synclinal plateau which separates the anticlinal ridges of the Livingston and Lewis ranges. This lack of mountainous topography may be combined with a possible "snow-shadow" effect leeward of the Livingston Range. Similarly, the low number of avalanche paths in the eastern portions of the study area may also be attributable to the "snow-shadow" effect caused by the Lewis Range, which produces comparatively low winter precipitation on the eastern slopes of the park (Table 1).

The distribution of snow avalanche paths in the study area does not appear to be dependent on lithology and structure, in contrast to other mass-wasting phenomena in the park (Butler, 1976). Avalanche paths are located on all four of the main Precambrian rock formations of the park.

It is difficult to determine any relationship that may exist between avalanche path distribution and jointing of bedrock. Joints may determine locations of stream gullies, which in turn may exert some control on snow avalanche locations (Eversman, 1968). However, I do not know of any maps of jointing distribution in the park; conclusions are therefore hypothetical.

Analysis of slope aspect of the 440 sample snow avalanche paths revealed a concentration in the northwestern, southeastern, and southern compass octants, as well as a paucity in the northern, northeastern, and eastern octants (Figure 2). The concentration of avalanche paths facing northwest and southeast is directly attributable to the availability of such exposures in the steep-sloped northeast-southwest trending glacial valleys of the park and to prevailing winds which produce cor-

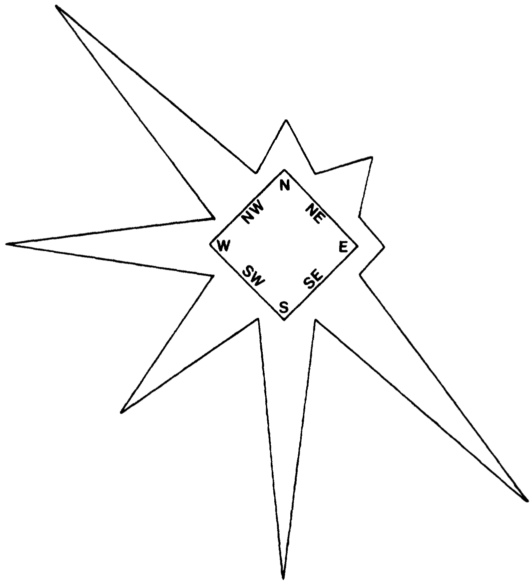

FIGURE 2. Star diagram, illustrating the relative number of snow avalanche paths and their corresponding slope aspects within the study area (based on 440 avalanche paths).

nices on southeast-facing slopes. The peak in the southern octant may seem somewhat anomalous, but is explained by the instability of the snowpack on the slopes where such exposures do exist. This instability is related to the daily temperature regimes in the spring, when available sunshine strikes these slopes, producing unstable and potentially hazardous suncrusts (Bradley, 1970). The general absence of snow avalanche paths in the northern through eastern octants is a result of the shading of such exposures, which limits the development of suncrusts and subsequent instability in the snowpack. Additionally, these slope exposures are generally small in number in the study area; unavailability of slope aspect thus has a significant effect on the appearance of Figure 2. Finally, only east of the Continental Divide do such slope exposures exist to any extent. The subsequent reduction in precipitation on the eastern side of the park also reduces the avalanche potential and hazard.

Landforms associated with the 440 sample avalanche paths are listed in Table 4. Of note is the close association between avalanche paths and stream gullies (312 out of 440). Avalanche boulder tongues (Rapp, 1959) were almost exclusively limited to the base of avalanche paths which terminated above treeline, with debris largely supplied from the Precambrian Siyeh Formation (predominantly limestone and dolomite). Debris avalanches, though not of great number, were nearly always found within the confines of a snow avalanche path. The other landforms listed in Table 4 were locally uncommon or not found in association with avalanche paths.

TABLE 4
Landforms associated with snow avalanche paths in the study area

Landform	Number
Avalanche boulder tongue	65
Avalanche cone	2
Alluvial fan at base of avalanche path	27
Slushflow levee	8
Lake at base of avalanche path	21
Debris avalanche within confines of snow avalanche path	17
Stream channel within confines of snow avalanche path	312
Protalus rampart at base of avalanche chute	2
Rock glacier associated with avalanche path(s)	7

Avalanche paths in the study area most commonly had a bowl-shaped starting zone; a narrow, neck-shaped track (usually associated with a stream channel); and a tongue-shaped runout zone. Table 5 lists the number of avalanche paths (from the sample 440) which fall into each category of starting zone type, track type, and runout zone type.

Measurements from the 440 avalanche paths gave the following statistical means: starting zone highest elevation, 2114 m; runout zone lowest elevation, 1517 m; a local relief, therefore, of 597 m; total path length (computed by adding the starting zone, track, and runout zone lengths), 960 m; and starting zone area, approximately 92,000 m^2.

Statistical analysis of the terrain variables affecting runout zone length and width was carried out in a manner similar to that of Bovis and Mears (1976), because it is in valley bottoms of the park, the location of most avalanche runout zones, that various park facilities and trails are established. Land-use planning within the park would be enhanced by a knowledge of factors which affect the size, and hence the hazard, of avalanche runout zones. The terrain variables tested against runout zone length and width included starting zone width, length, elevation, and area; track width, length, and area; highest track elevation; lowest track elevation; slope aspect; and slope angle. This analysis was based on measurements of 106 sample avalanche paths, taken from the original 440 paths. The 106 paths chosen had clearly defined starting

TABLE 5
Types of starting zones, tracks, and runout zones in the study area

Type	Number
Starting zone type	
Bowl-shaped and coalescing	351
Rectilinear	89
Track type	
Narrow, "neck-shaped"	322
Rectilinear	118
Runout zone type	
Tongue-shaped	285
Spatulate	97
Digitate	58

zone, track, and runout zone characteristics on the topographic maps, and were easily measured.

Results of this analysis revealed that track width alone accounted for 36% of the variation in runout width, as might be expected. No other variable alone accounted for over 25% of the variation in runout width (starting zone width accounted for 21.7% of the variation in runout width). Interestingly, however, no one variable accounted for over 20% of the variation in runout length (distance). Track area accounted for 19.3% of the variation, while starting zone length and width each accounted for approximately 17% of the variation. All other variables, including starting zone area (14.6%), were unable to account individually for more than 15% of the variation in runout length. This is in contrast to the work of Bovis and Mears (1976), who found that starting zone area alone accounted for 65% of the variation in runout distance of avalanches in the mountains of Colorado. However, since different measuring techniques were used in that study, care must be taken in making comparisons of results. In addition, regional differences in climate, terrain, lithology, and structure, as well as other factors, can help to explain these differing results. A third study in another region would likely yield equally different results.

VEGETATION OF SNOW AVALANCHE PATHS

The amount, type, size, condition, and distribution of vegetative cover on snow avalanche paths reveal a wealth of information about past avalanche events. Such factors as extent, depth, impact pressure, velocity, and frequency of past avalanches can be discerned or inferred through close scrutiny of the vegetation on these paths. Forest and tree-species information can be of particular use in reconstructing the history of an avalanche path. Accordingly, the author collected vegetative data from twelve sample avalanche paths in the west-central portion of the study area. The paths sampled (Figure 3) provided a variety of slope exposures, moisture conditions, and vegetative cover and species. Access was also a factor in choosing these sites. Each of the 12 avalanche paths will be briefly described in turn; these discussions will detail site and vegetative conditions, frequency of avalanching, depth of flow (when such information was available), and extent of runout. A general model of vegetative conditions will be presented. Finally, calculations of velocity and impact pressures will also be presented, based on vegetative evidence.

DETAILS OF INDIVIDUAL AVALANCHE PATHS

Each of the twelve sample avalanche paths was assigned an identifying code (Figure 3), and will be referred to as such in the discussions to follow. Each path was subjected to tree-species data collection, utilizing the point-quarter method (Smith, 1966). Longitudinal sampling transects were extended up each path, into the lower portions of the track. At 30-m intervals, tree species were sampled in each of four 25-m^2 (5 × 5m) quadrats, to the left and right, in front of and behind, the quadrats' center. The nearest tree species in each of the four quadrats was recorded. If no tree was found within a sample quadrat, the absence of a tree was recorded. General observations on ground-cover vegetation, moisture conditions, and any unusual circumstances were recorded for each quadrat. Longitudinal slope angles were also measured at each sampling location, using an Abney hand level. Sampling dates varied, but were generally confined within a 3-week period, 25 June to 15 July, so as to avoid ground-cover species differences due to changing-growing seasons and weather conditions. Information on frequency of avalanching was obtained through observation of general vegetative conditions (Schaerer, 1972), dendrogeomorphologic techniques (Potter, 1969; Shroder, 1975, 1978; Burrows and Burrows, 1976; Ives *et al.,* 1976; Shroder *et al.,* 1976), historical information, and conversations with various park personnel.

Avalanche path HR1 has a south-southwesterly aspect. Upper portions were dominated by deciduous tree species, particularly *Alnus* spp., whereas lower portions in the runout zone were characterized by small, dwarfed, damaged conifers, particularly *Abies lasiocarpa* (Table 6 summarizes some general characteristics of each of the sampled paths). The slope was relatively mesic.

Ground-cover vegetation was dominated by various members of the Compositae and Gramineae. Slope angles for this path (Table 7) were similar to those measured on the 11 other sampled paths, and confirmed the accuracy of the slope angles determined algebraically (see previous section). The angles measured included the runout zone and lower portions of the track. These slope angles are similar to those mentioned by Schaerer (1975), and suggest possible similarities in the characteristics of avalanches in Glacier National Park, and the Canadian Rocky and Selkirk mountains.

Tree-ring cores from affected conifers on HR1 revealed avalanching (determined from reaction-wood growth and corrasion scars) in 1971, but were generally inconclusive, due to

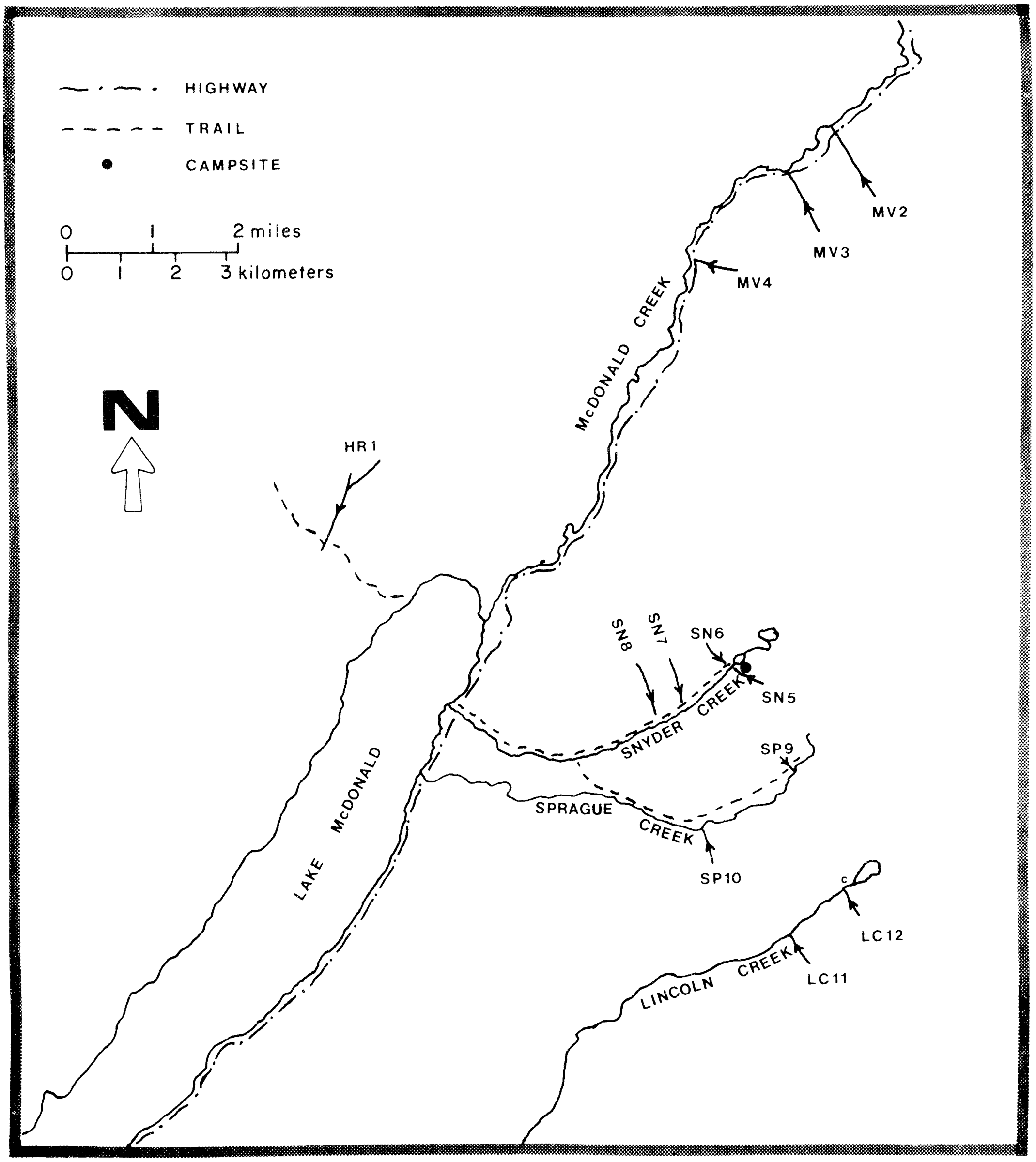

FIGURE 3. Locations of the 12 snow avalanche paths discussed in the text which were subjected to vegetative sampling and slope measurements.

limited sampling. General vegetative conditions (relative dominance of *Alnus* spp.) and photographs in the *Hungry Horse News* (a weekly newspaper from Columbia Falls, Montana) indicate that the path experiences avalanches virtually every year. Some time in the past (probably about 50 yr ago, judging by heights of conifers; see path SN7), a large avalanche event extended downslope much farther than normal, impinging on the mature coniferous forest at the base of the path. Small (up to 4 m tall), relatively undamaged conifers have since repopulated this area at the base, indicating little if any avalanche-induced trauma since their establishment.

Paths MV2 and MV3 are very similar in appearance. Both had a northwesterly aspect and are quite mesic. Ground-cover vegetation was similar (Table 6). *Alnus* spp. were by far the most common trees found on these paths, indicating very frequent, probably yearly, avalanching. *Picea engelmannii* and *Betula papyrifera* were found along the fringes of the runout zones. These two paths reach and cross Going-to-the-Sun-Highway, as is evidenced by damaged trees located across the highway from the main avalanche path. A

TABLE 6
Vegetation of the sampled avalanche paths[a]

Avalanche path	Aspect	Tree-species vegetation	Ground-cover vegetation
HR1	SSW	*Alnus* spp. *Abies lasiocarpa*	Compositae Gramineae
MV2, MV3	NW	*Alnus* spp. *Betula papyrifera* *Picea engelmannii*	Compositae Gramineae *Veratrum viride*
MV4	W	*Acer glabrum* *Crataegus douglasii* *Alnus* spp. *Betula papyrifera*	*Erythronium grandiflorum* (Glacier lily) Assorted mosses and ferns
SN5	NW	*Alnus* spp. *Abies lasiocarpa*	Compositae *Erythronium grandiflorum* *Veratrum viride*
SN6	SE	*Abies lasiocarpa* *Acer glabrum* *Sorbus scopulina*	*Xerophyllum tenax* (Beargrass) *Pachystima myrsinites* Gramineae Compositae *Erythronium grandiflorum* *Castilleja* spp.
SN7, SN8	SE	*Abies lasiocarpa* *Acer glabrum* *Alnus* spp. *Pseudotsuga menziesii* *Sorbus scopulina*	*Xerophyllum tenax* *Erythronium grandiflorum* *Myosotis alpestris*
SP9, SP10	SE NW	*Abies lasiocarpa* *Acer glabrum* *Alnus* spp.	*Xerophyllum tenax* Compositae Gramineae
LC11, LC12	NW	*Alnus* spp.	*Vaccinium membranaceum* Compositae

[a]Species listed do not represent a total inventory of plants located on each individual path; rather, the list is an attempt to identify those which might give some indication as to microclimate and growing conditions. Additionally, the plants listed appear, on a visual basis, to be the most common on the individual paths.

large avalanche reached the road at the base of MV2 in the spring of 1975. I saw freshly damaged trees along the edge of the highway; several spruce and birch trees had been cut by road crews because they had been tilted over a portion of the highway. Snow depth at the edge of the highway was approximately 1.5 m, with fresh tree and rock debris resting on, and ablating into, the surface of the snow. Tree-ring analysis of five cross-cuts and three cores (utilizing reaction-wood growth and suppression-release patterns) taken from trees cut by highway crews revealed past avalanche events had reached the vicinity of the highway in 1955, 1957, 1963?, and 1966.

Avalanche path MV4 is a geomorphologically active site. The *Hungry Horse News* (6 April 1978) states that road crews have dealt with avalanches on Going-to-the-Sun Highway at this site every spring since World War II, except for 3 yr (including 1977 and 1978). Conifers were virtually absent from this path, except where sheltered by the roadcut embankment. Brushy deciduous trees (Table 6) were prolific and extremely thick, making sampling and measurement of slope angles very difficult. This heavy brush cover, with flexible stems bending downslope, attests to the frequency of avalanching (Schaerer, 1972); that is, sturdier deciduous and coniferous trees were precluded from invading the site by heavy and frequent avalanche impact pressures. Fourteen tree-ring cores provided evidence of reaction-wood and suppression-release patterns which confirmed estimates of avalanche frequency.

Avalanche sites in the Snyder Creek valley (SN5 to SN8) were generally more xeric than those along McDonald Creek. They are also generally smaller than their counterparts in the McDonald Creek valley.

Avalanche path SN5, which is oriented northwesterly, has developed a rock cone (Peev, 1966) at its base. Avalanches at this site descend from cliff chutes above, and evidently scour the chutes effectively. Approximately equal numbers of *Alnus* spp. and *Abies lasiocarpa* were sampled. Ground-cover vegetation included many mountain flowers (Table 6). Depth of flow of past avalanche events was determined by the height of trimming and scarring of conifers within the lower reaches of the runout zone and along the trimline. Maximum flow depths have attained 3 to 4 m above ground level. There are indications (lack of scars near the ground) that some past wet snow avalanches have traveled over snow surfaces approximately 1 m deep. This avalanche path is very near the Snyder Lake backcountry campsite; an unusually large avalanche could affect the campsite by dropping or pushing rocks and

TABLE 7

Slope-angle values for twelve avalanche paths measured in the field[a]

HR1	MV2	MV3	MV4	SN5	SN6	SN7	SN8	SP9	SP10	LC11	LC12
10°	9°	8°	17°	9°	9°	14°	13°	8°	10°	13°	11°
12°	12°	10°	20°	8°	6°	19°	16°	11°	14°	16°	15°
16°	13°	11°	18°	9°	11°	21°	18°	15°	19°	20°	15°
19°	16°	14°	23°	14°	19°	21°	19°	18°	19°	23°	17°
23°	19°	17°	26°	16°	24°	23°	21°	19°	21°	23°	19°
25°	23°	17°	28°	17°	22°	23°	24°	22°	24°	25°	21°
25°	24°	19°	29°	20°	23°	24°	25°	24°	24°	28°	21°
26°	25°	22°		23°	24°	24°	25°	25°	27°	29°	22°
28°	25°	23°		25°	27°	24°	26°	27°	26°	29°	25°
29°	26°	24°			28°	24°	28°		28°	33°	27°
	27°	27°			29°	26°	28°		28°		29°
	29°	27°			30°	28°	30°		28°		
	30°	30°			30°	29°	31°		31°		
		31°			29°	30°					
					30°	30°					
					30°						
					31°						

[a]Slope angles listed, measured at 30-m intervals, extend from farthest extent of the runout zone upslope into lower portions of the track.

trees into its perimeter.

The popular trail to Snyder Lake and its campground passes through the runout zone of avalanche path SN6. Access along the trail and to the campsite in the early part of the tourist season could be disrupted by heavy, debris-laden spring avalanches. This avalanche path has a southeasterly aspect, which aids melting of snow deposited by avalanching (however, snow depth in the runout zone on 1 June 1975, was over 1 m). This path was quite xeric by 1 July 1975, when slope angles were measured and vegetation was sampled. Small, stunted *Abies lasiocarpa* exhibiting definite avalanche-induced damage covered much of the runout zone. More frequent avalanching in the upper reaches of the path was evidenced by the phasing out of conifers, which were replaced by flexible-stemmed deciduous trees (Table 6). Ground-cover vegetation reflected the xeric conditions of the slope, both in species (Table 6), and the dessicated nature of many small plants.

Avalanche paths SN7 and SN8 were similar in morphology and vegetation. Both face southeast, and have stream channels near the center of the path. Small, avalanche-damaged *Abies lasiocarpa* and *Pseudotsuga menziesii* were located in the runout zones, with *Acer glabrum, Alnus* spp., and a few *Sorbus scopulina* located farther up in the more geomorphologically active portions of the paths. Both sites were xeric. SN7's maximum depth of flow approached 4 m, based on height of trimmed branches.

Avalanche path SN7 was subjected to a detailed dendrogeomorphologic scrutiny. Twenty-nine cross-cut sections were taken from affected *Abies lasiocarpa* and *Pseudotsuga menziesii*. No apparent differences in manner of response to avalanching occurred between the two species. Datable responses in both species included growth of callous margins over corrasion scars, reaction-wood growth, and suppression-release patterns. Figure 4 shows the age data derived from these trees, using symbology modified from Shroder (1978). Avalanches have reached the sampled conifers near the farthest extent of the runout zone in 1945, 1950, 1954, 1963, 1965?, 1966, 1972, and 1974. The event in the spring of 1963 affected virtually every tree sample. These trees, similar in size and appearance to those found on HR1 and at the bases of other paths, were roughly 45 to 60 yr old and 4 to 6 m tall, indicating a major avalanche event early in this century (allowing 10 to 15 yr for post event establishment of the present conifers). Many trees that had exhibited normal growth patterns up to 1963 were drastically altered, with subsequent extreme eccentricity in growth patterns. This 1963 avalanche was the strongest in the tree-ring record. Scores of very large mature *Pseudotsuga menziesii* and *Abies lasiocarpa* at the base of the runout zone (up to 15 to 20 m tall and 0.6 m in diameter) were destroyed by the avalanche. Their rotting trunks and splintered limbs attest to the strength of that particular avalanche, which came within 50 to 100 m of the Snyder Lake trail.

The dates listed above are certainly minimum figures for periods of avalanching, although data were inconclusive on other past events.

A comparison of these maximum avalanche events with those revealed earlier in this paper for other paths (HR1, MV2, MV4, and SN5, which had a totally inconclusive tree-ring record) did not reveal strong cross-replicating ring patterns which would justify path-to-path comparisons of periods of avalanche activity, although there is some evidence of similar avalanche periods on MV2 and SN7. This finding is similar to that reported by Potter (1969).

Avalanche paths in the Sprague Creek valley (SP9 and SP10) are rather similar to those in the Snyder Creek valley. The sites were fairly xeric, with ground-cover vegetation and tree species similar to that previously reported (Table 6). SP9 crosses the trail to Sperry Chalets, and could disrupt early season usage in the event a large, debris-laden avalanche destroyed portions of the trail.

Numerous avalanche paths extend to the valley bottom in the Lincoln Creek valley (Figure 1). LC11 and LC12 were typical of these. They were oriented northwesterly. Both were almost entirely covered by flexible deciduous trees and shrubs, especially *Alnus* (implying yearly avalanches). Many huckleberry bushes (*Vaccinium membranceum*) were also common, highlighting an important aspect of avalanche paths in Glacier National Park, namely, providing habitat for the threatened grizzly bear (*Ursus arctos*) (Martinka, 1972).

As the previous discussions have made apparent, tree-species distribution on the

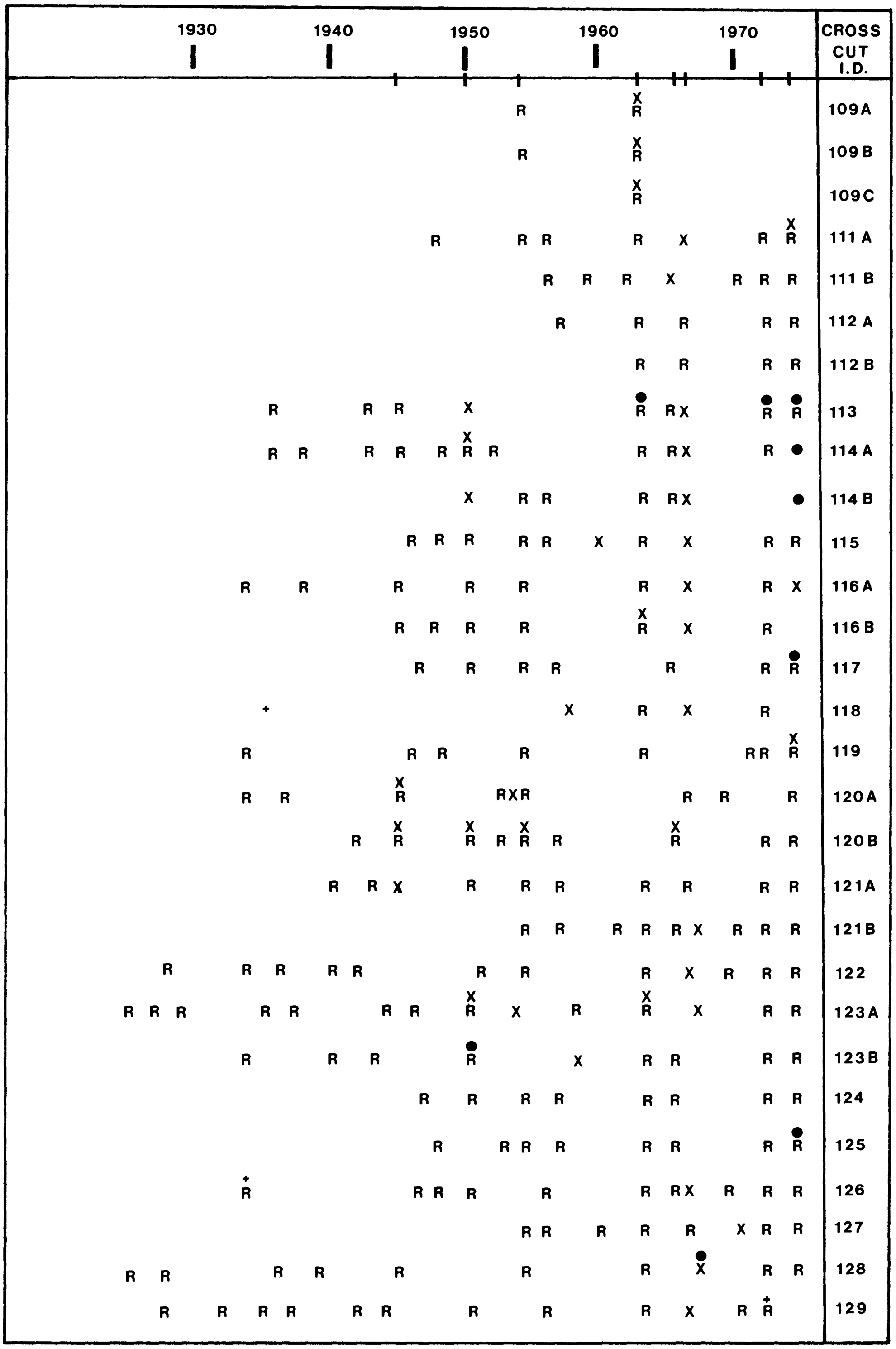

FIGURE 4. Event-response skeleton plot for avalanche path SN7, modified from Shroder (1978), illustrating years of avalanche activity as revealed in tree rings of conifers located within the runout zone. R, reaction-wood growth; X, suppression; +, release; •, initiation of growth of callous margin over corrasion scar.

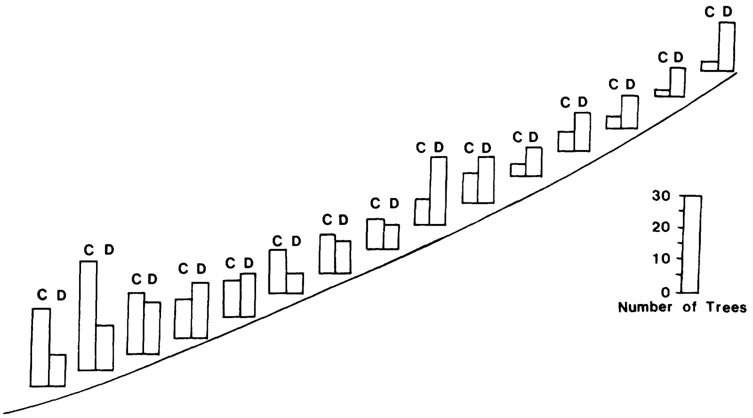

FIGURE 5. Longitudinal profile of typical snow avalanche path runout zone, depicting the locations of coniferous and deciduous trees within the runout zone. Further explanations in text. C, conifers; D, deciduous trees.

sampled avalanche paths frequently exhibit a longitudinal zonation. Conifers, usually *Abies lasiocarpa,* occur at the base of the runout zone where avalanches reach less frequently, and flexible deciduous trees are found farther upslope, where avalanching might occur every year. This relationship is expressed graphically in Figure 5, which is a combination of the coniferous vs. deciduous tree distribution for all 12 sample avalanche paths; that is, it incorporates the data from all 524 sampling quadrats and presents them as if they were all recorded from one idealized, model avalanche path.

Table 8 presents the total number of each tree species sampled, agglomerating the data from each of the 12 sampled avalanche paths. *Abies lasiocarpa* is by far the dominant conifer, accounting for approximately 77% of all conifers sampled. It is also the most common species in the entire sample population, a finding similar to that of Franklin and Mitchell (1967) in the Cascade Range. This result, however, is in direct contradiction to the work of Kessell (1976, and pers. comm., 1975), also carried out in Glacier National Park. Kessell states that the effect of avalanching in the Park is "that of the exclusion of subalpine fir (*Abies lasiocarpa*) within fell-field-slide areas for the more flexible stemmed white bark pine (*Pinus albicaulis*)" (pers. comm., 1975). In light of the present data, and the work of Franklin and Mitchell (1967), Kessell's statement appears too strong, and should be subjected to further field testing and scrutiny.

The two most common deciduous trees on the sample avalanche paths are *Acer glabrum* and *Alnus* spp. (Table 8), found most commonly on mesic and xeric sites, respectively. These results complement those of Martinka (1968), who noted that avalanche paths in Glacier National Park have an alder disclimax as the characteristic plant community at elevations of 1200 to 2000 m. He also stated (Martinka, 1976) that *Acer glabrum* was a characteristic species on such sites, particularly on moister slide paths.

Major variations in ground-cover vegetation were not apparent. However, certain species, notably *Xerophyllum tenax* and *Pachystima myrsinites,* exhibited a preference for xeric sites.

OBSERVATIONS ON IMPACT PRESSURES AND VELOCITIES

Maximum flow depths have apparently reached 3 to 4 m on occasion on the sample avalanche paths. With 4 m as an average depth of flow, the author determined average and maximum avalanche impact pressures for path SN7, a representative example from which much tree data were available.

Procedure followed was as outlined in Mears (1975). Average impact pressure was

TABLE 8
Total number of tree species sampled

Species	Number sampled	% of Total
Abies lasiocarpa (Subalpine fir)	130	36.9
Acer glabrum (Mountain maple)	83	23.5
Alnus spp. (Slide alder)	71	20.1
Taxus brevifolia (Pacific yew)	17	4.8
Sorbus scopulina (Mountain ash)	14	4.0
Betula papyrifera (subcordata) (Northwestern paper birch)	12	3.4
Pseudotsuga menziesii (glauca) (Douglas-fir)	10	2.8
Picea engelmannii (Engelmann spruce)	7	2.0
Crataegus douglasii (Black hawthorn)	3	0.9
Pinus monticola (Western white pine)	3	0.9
Pinus albicaulis (Whitebark pine)	2	0.6
Total	352	100[a]

[a]Due to rounding, actual value is 99.9%. In addition, 172 sampling quadrats had no tree present within their boundaries.

determined using Mears's formula

$$P\max = \frac{\sigma \pi d^2}{25.6 h'^2} \qquad (1)$$

where average diameter (d) of *Abies lasiocarpa* was 11 cm, depth of flow (h') was 4 m, and a modulus of rupture (σ) of $2.36 \times 10^7 < \sigma < 3.03 \times 10^7$ NT m^{-2} ($3500 < \sigma < 4500$ lb in^{-2}) for subalpine fir (Betts, 1919). Thus, average impact pressures on path SN7 (which are considered typical for the other sample paths) were 0.21 to 0.28 t m^{-2} (1 t m^{-2} = 1000 kg m^{-2}; Mears, 1975).

The probable maximum impact pressure on path SN7 was based on data derived from the large Douglas-firs destroyed in the avalanche of 1963, where d = 60 cm, h' = 4 m, and assuming $3.51 \times 10^7 < \sigma < 4.32 \times 10^7$ NT m^{-2} ($5200 < \sigma < 6400$ lb in^{-2}) for Douglas-fir (Betts, 1919). These figures give a maximum impact pressure of 9.6 to 11.9 t m^{-2}.

These impact pressures were translated into avalanche velocity using Mears's formulas (1975), and assuming a density of flow of 300 kg m^{-3} (Schaerer, 1975): maximum velocity for the average avalanche event, 3.7 to 4.3 m s^{-1}; and maximum velocity for the maximum avalanche event, 25.3 to 28.2 m s^{-1}, figures similar to those obtained by Mears in Colorado (Mears, 1975). This maximum event was probably a damp-snow avalanche, although a powder snow avalanche with associated windblast (Voellmy, 1955) cannot be ruled out, particularly when the size of the destroyed Douglas-firs is considered.

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that snow avalanches are significant features affecting the physical landscape in Glacier National Park, Montana. The avalanches have profound effects on the vegetation within and alongside their paths, and are geomorphologically active. A number of avalanches cross or approach major roads, trails, and campsites in the study area, and as such represent potential hazards to human use of park facilities.

Avalanche paths in the study area were concentrated in the southeastern, southern, and northwestern compass octants. Any future developments in the park should avoid these potentially hazardous slope exposures, particularly when located in conjunction with conditions conducive to avalanching (i.e., areas of cornice development, and/or areas with large potential snow-catchment basins associated with funneling stream channels below). Developments should also be avoided where vegetative evidence reveals past avalanche events of major proportions, even if the area is currently considered "safe." Planning should center around the possibility of the large, 100-yr avalanche event, such as occurred on path SN7, rather than the average or norm. It would take only one 100-yr event to create disastrous results. Consequently, the early recognition of 100-yr avalanche runout zones, as discussed by Ives *et al.* (1976), should be of high priority for future planning in the park, and would be of use in planning defensive structures for existing park facilities.

ACKNOWLEDGMENTS

William Marienau served as an excellent field assistant. Additional help in the field was provided by Tom Higgins and Richard Flowers. Personnel of Glacier National Park provided camping facilities and overall logistical support. Research biologist Clifford Martinka and Ranger Jerry Bell were especially helpful. Ray and Marian Butler provided financial assistance. Arthur Mears, Noel Potter, Jr., Jack D. Ives, and an anonymous referee reviewed various drafts of this paper, and offered excellent suggestions and comments. Dr. John F. Shroder, Jr., guided portions of this work in its formative stages.

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