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Effects of Terrain on Excessive Travel Distance by Snow Avalanches

Abstract

This study was undertaken to determine the characteristics of snow avalanches most likely to travel excessive distances across low-angle runout zones and perhaps onto opposite slopes. "Excessive" travel attained by snow avalanches is related to low equivalent coefficients of friction and large snow volume. In this study, wet-snow avalanches traveling down deeply incised, "hockey-stick profile" avalanche paths exhibited excessive travel. The equivalent coefficients of friction calculated for these avalanches were similar to those determined for far-traveling avalanches elsewhere. Conditions in the runout zone also affect excess travel, because early successional vegetation is less likely to impede continued avalanche travel than a mature forest environment. Large-volume avalanches produce low coefficients of friction resulting in excessive travel into the low-angle portions of the runout zones where erosion is possible. Land-use planners can utilize these observations in identifying particularly hazardous sites.

Introduction

Mass movements of snow, rock, or weathered surficial debris occasionally flow excessive distances across the landscape, owing to low coefficients of friction and large volumes. In the context of snow avalanches, "excessive" distance can be considered either from a planning perspective, i.e., in excess of the 100-year avalanche runout zone (Ives *et al.* 1976); or in a physically based context, i.e., in excess of normal travel distances given certain terrain parameters (Izumi 1988, Yamada 1989). The latter approach has also been applied in studies of rockfall-avalanches (sturzstroms) (Hsü 1975, Eisbacher 1979) and volcanic debris flows (lahars) (Naranjo and Francis 1987). The distances traveled by such mass movements are indicative of the fundamental physical processes operating on, and influenced by, the landscape.

Snow avalanches in subalpine terrain typically occur within well-delineated paths which pass vertically through the surrounding forested environment, producing distinct swaths of non-forested, supple vegetation (Malanson and Butler 1984, 1986; Butler 1989a; Erschbamer 1989). The transverse and longitudinal boundaries of these avalanche paths mark the zone within which the geomorphic influence of a snow avalanche is typically confined. However, infrequent high-magnitude snow avalanches can extend beyond the longitudinal and transverse margins of the path and into the surrounding forest, uprooting trees and introducing sediment into the slope debris cascade (Butler 1989a, Butler and Malanson 1990). Because these infrequent, spatially extensive avalanches are erosionally active in normally unaffected portions of paths, an understanding of the type and characteristics of avalanches which travel excessive distances is important from both a geomorphic and planning perspective.

The purposes of this paper are to: 1) examine the terrain and avalanche characteristics associated with historical cases of snow avalanches which possessed large volumes, low coefficients of friction, and therefore excessive travel distances in a portion of the northern Rocky Mountains of Montana, U.S.A.; and 2) describe historical cases in which no excessive travel occurred. We compare our results with those from studies in other mountain environments with generally similar avalanche climates.

Background

Excessive travel distance by a snow avalanche is a function of a number of factors: type of avalanche, snow conditions, vegetation encountered along the avalanche track and in the runout-zone, climate, terrain relief, and morphology of the avalanche path (Mears 1979, 1984). It has been held that wet-snow avalanches and avalanches comprising large blocks derived from the fracture of a hard, dry snow slab develop large internal frictional forces among the moving blocks, the avalanche, and the path surface (Mears 1984, p. 82). These large frictional forces cause rapid deceleration in

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the runout zone and relatively short runout distances. Conversely, dry-snow powder avalanches entrain air, become partly fluidized into diffuse aerosols, and possess small internal frictional forces, resulting in dispersal of the avalanche deposit over long distances at the base of the slope. Deceleration and reduced dispersal may result from encountering wet or blocky snow in the travel path, or from interacting with large trees and understory vegetation which dissipate energy quickly (Mears 1984).

Recently, Martinelli (1986), Izumi (1988), Mears (1988, 1989), and McClung *et al.* (1989) have reviewed empirical snow-avalanche runout models based on analysis of terrain variables, particularly those developed by personnel at the Norwegian Geotechnical Institute. Mears (1988, 1989) and McClung *et al.* (1989) examined data on runout distances from four different geographic areas, and demonstrated that the Norwegian approach is not applicable to many of the climates and terrains that produce avalanches in North America. They concluded that the statistical runout equations developed in one mountain area should not be applied to other areas.

Mears (1988) also pointed out a basic problem with physical models for calculating avalanche runout distance: they are dependent on the use of a friction-term value (the coefficient of friction) which varies with terrain and snow type, and which have not been measured. The values for the coefficient of friction are typically estimated, based on the experience of the user. Commonly used values range from 0.1 to 0.5 (Buser and Frutiger 1980, Perla *et al.* 1980).

In the statistical models developed by others and discussed and used by Mears (1988 p. 233, 1989 p. 284) and McClung *et al.* (1989), the vertical relief of the avalanche path (H), has been identified as an important controlling variable (Figure 1). However, because a snow avalanche is not always initiated at the top of the avalanche path, but at some lower elevation, it is more useful to define H as the vertical relief from the top of the breakaway scar. This redefinition of H was earlier employed by Hsü (1975), Eisbacher (1979), and Naranjo and Francis (1987) in their examination of excessive travel distances of sturzstroms and lahars. This approach has also been used in Japanese (Izumi 1988; Yamada 1989) and Norwegian

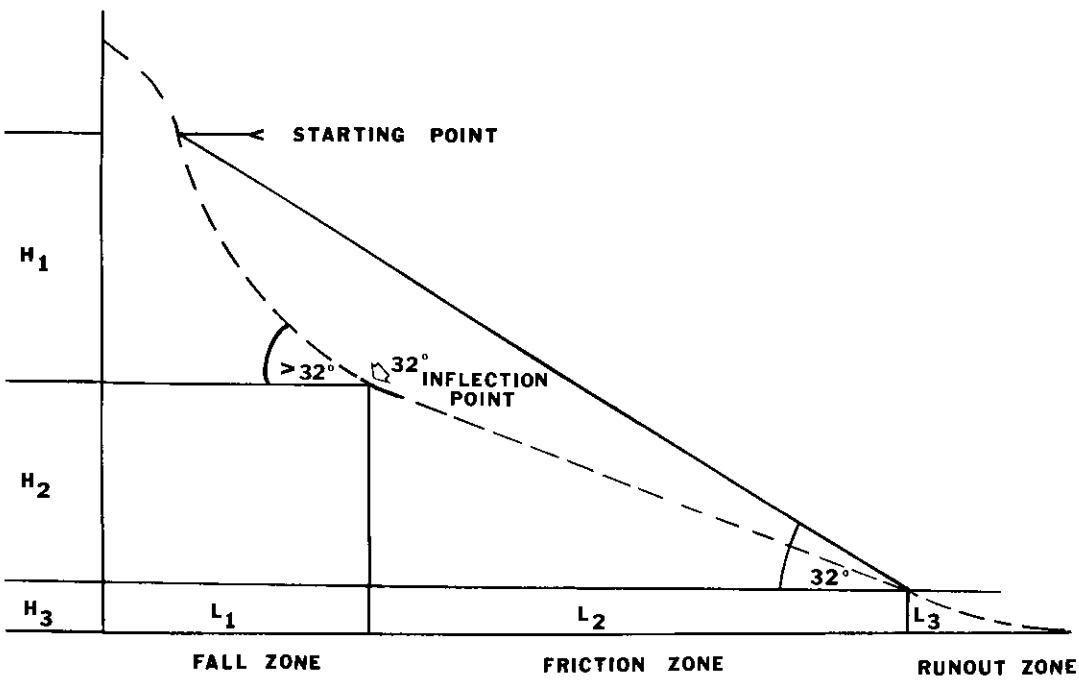

Figure 1. Longitudinal profile of typical snow-avalanche path, with key points and zones as discussed in text. H, height; L, length; dashed line represents hypothetical longitudinal profile of avalanche path.

(Lied and Bakkehøi 1980) studies of snow-avalanche excessive travel distances.

Glenne (1986) and Izumi (1988) defined H as "the vertical avalanche fall height," rather than as the total relief of the avalanche path, and L as the horizontal reach of the avalanche (Figure 1). With these variables, they subsequently calculated the equivalent coefficient of friction (μ) as:

$$\mu = H/L. \quad (1)$$

Excessive travel distance (Le), defined by Hsü (1975, p. 138) as "the horizontal displacement of the tip. . . beyond the distance one expects from a frictional slide down an incline with a normal coefficient of friction of tan 32° (0.62)," may be expressed as:

$$Le = L - H/\tan 32°. \quad (2)$$

The 32° angle, typically utilized in sturzstrom work, has also been experimentally confirmed by Japanese workers for use with snow avalanches (Izumi 1988).

Izumi (1988) utilized Hsü's (1975) definition in a modified form, referring to an "unlubricated slide mass" rather than a "frictional slide." Although Izumi used the term "slide mass," it is assumed that avalanche motion is not necessarily a sliding one, but in all likelihood a turbulent flow (a point emphasized by Glenne, 1986). Izumi illustrated an inverse relationship between avalanche volume and equivalent coefficient of friction, and a direct relationship between volume and excessive travel distance.

Izumi's (1988) results from the study of both wet- and dry-snow avalanches in the maritime mountains of Japan therefore illustrated relationships similar to those from sturzstrom and debris avalanche studies: mass-movements having greater volumes tended to exhibit lower equivalent coefficients of friction, and were more likely to travel long distances. Slab avalanches of dry snow had the lowest coefficients of friction in Izumi's study, and as a group the slab avalanches also had the greatest excessive travel distances. Full depth, dry powder avalanches had intermediate coefficients of friction generally in the range of 0.4 to 0.6; and full depth, wet-snow avalanches had the highest μ values, ranging from 0.4 in one case to the more typical 0.6 to 0.8 range. Excessive travel distance for the dry, full-depth avalanches was limited, typically less than 200 m. Only one wet snow avalanche achieved excessive travel distance. All slab avalanches in Izumi's sample traveled excessive distances, ranging from 100 to 1,800 m.

In review, two aspects of the work on avalanche distances need to be reiterated. First, the concept of "excessive distance" is very important. Mears (1989) referred to "maximum runout distance" of a "design avalanche." His calculation of a runout ratio expressed the concept of excessive distance, and McClung and Lied (1987) and McClung *et al.* (1989) have shown how this concept can be used in a predictive method. Hsü (1975) and Izumi (1988) specified a precise definition of "excessive" as in excess of an expected distance, which itself needs further consideration. For Mears' (1989) formula for runout ratio (RR), it is necessary to measure the horizontal component of path length above and below a 10° slope angle on the path (10° being the presumed angle below which retardation of snow motion occurs; Lied and Bakkehøi 1980). In Hsü's (1975) formula (equation 2), excess length is the total actual length minus the expected length, which in turn is equal to the horizontal length defined by a straight line of 32° slope originating at the top of the slide. It should be noted that the process of locating either of these tangents to the slope may produce error or bias depending on the scale of the source material, whether topographic maps, aerial photographs, or digital elevation models (Walsh *et al.* 1987).

Both definitions embody valuable concepts. In Mears (1989) we find that the excessive distance is a function of the length of a runout zone relative to an upper path or slide zone. For Hsü (1975), the distinction between the two is less arbitrary, with the 32° figure being based on observational and experimental results for sturzstroms, which may be cautiously applied to snow avalanches. Izumi's (1988) "equivalent coefficient of friction" has value as an easily calculated index not requiring overly precise (i.e., larger than 1:24,000-scale) topographic maps or time-consuming field data collection.

Other factors influencing excessive runout are the topographic features of the path itself and the terrain in which the path is located. Runout distance is not affected by conditions in the starting zone, for either a dry or wet-snow avalanche, on unconfined avalanche paths. The angular transition between track and runout zone is significant for identifying paths with the potential for extremely long runout distances (Martinelli 1986, p. 30). Avalanche paths having linear or slightly concave

tracks with abrupt transitions (at point L3 on Figure 1) to nearly flat runout zones have been called "hockey-stick paths" by Martinelli (1986), and avalanches on such paths have tended to run "unusually long distances." The transverse profile across an avalanche path is an important morphological variable that has not been incorporated into mathematical runout models, and should be. On confined (channelized) avalanche paths, released snow is forced through a confined track, therefore increasing velocity and making runout distance dependent on the size of the starting zone, i.e., making runout distance dependent on snow volume (Mears 1979). A recent paper by Nicoletti and Sorriso-Valvo (1991) illustrates how transverse morphologic controls can be incorporated into computations of runout distance for rock avalanche, and offers promise for similar applications in snow-avalanche runout prediction.

The Study Area

Glacier National Park (GNP) is located in northwestern Montana, U.S.A., astride the continental divide. The western half of GNP (Figure 2) has a modified Pacific maritime climate with relatively mild temperatures and heavy, wet snowfall. East of the divide, winters are much colder and windier, and snowfall tends to be drier and light. Pleistocene glaciation produced a steep landscape prone to snow avalanches, and Butler and Malanson (1985a) and Butler (1986a) have illustrated the geographically-widespread occurrences of avalanches in GNP, the types of avalanches that occur, and the climatic conditions that produce them. Slab and point avalanches of wet and dry powder snow have been reported from both sides of the continental divide.

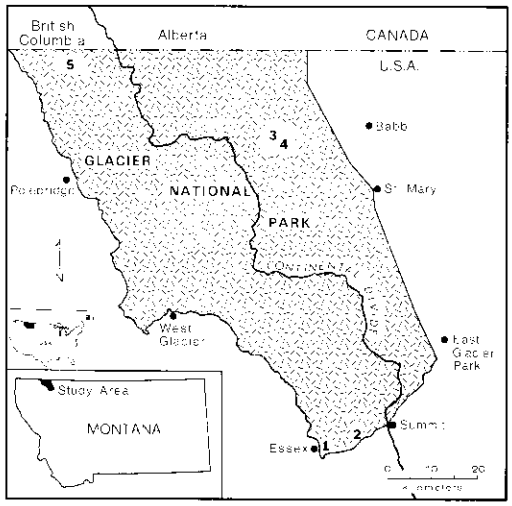

Figure 2. Location of historical snow avalanches discussed in the text. 1, Goat Lick 1979 and 1982 avalanches. 2, Shed 7. 3, Mt. Henkel. 4, Josephine Lake. 5, Kintla Lake.

Analysis

Six cases (Figure 2) of snow avalanches of known type, and with known initiation and termination elevations, are available in published and archival literature from GNP (Anonymous 1946, *Hungry Horse News* 1975, Panebaker 1982, Martinelli 1984, Williams and Armstrong 1984, Butler and Malanson 1985b, Frauson 1979). Data on the volumes of these avalanche deposits were not measured, but can in some cases be reconstructed from the areal extent of avalanche deposits visible on photos, in combination with depth estimates derived from evidence of vegetation damage along path margins.

For each of the six historic cases, H was calculated by subtracting the lowest elevation of the avalanche deposit from the highest known starting elevation. L was calculated by mapping the location of the snow failure zone and the avalanche deposit on U.S.G.S. 1: 24,000-scale topographic maps and measuring the horizontal distance down the center of the path between the upper and lower elevations. Distance measurements are therefore considered accurate to within 20 m. The equivalent coefficient of friction for each case was calculated using equation 1 (Table 1). Le was calculated for each case using equation 2. By comparing Le to μ, we examine the length of an avalanche in terms of its average slope and a slope of 32°. For lower average slopes, i.e., lower coefficients of friction, the distance in excess of a 32° run will be greater for a given path length.

Table 1 also provides information on avalanche characteristics and path terrain. The type of avalanche is recorded for each example. Volume of the snow deposited in the runout zone was estimated in the cases of the Goat Lick (1979 and 1982) and Shed Seven avalanches by mapping the areal extent apparent on photographs in Panebaker (1982), Martinelli (1984), and Williams and Armstrong (1984); and by estimating snow depth either from the known height of objects in the photographs, or from the height of vegetation in the runout zone (Butler and Malanson 1985b). Terrain conditions and type of vegetation within each avalanche path's track and runout zone were examined in the field (Figures 3, 4) for all but the

TABLE 1. Calculation of equivalent coefficient of friction and excessive travel distance for six snow avalanches, Glacier National Park

Path Name	V[1]	H	L	H/L	L_e	Type Avalanche
Goat Lick 1979	2.67	975.4	2529.8	.386	969.0	Wet snow in steep, narrow gully
Goat Lick 1982	1.27	1127.8	2529.8	.446	877.6	Wet snow in steep, narrow gully
Shed 7 1979	0.86	737.6	1724.6	.428	544.1	Wet snow in steep, narrow gully
Mt. Henkel 1979	n.a.	1036.2	2377.4	.436	719.0	Wet snow (with wind?) in steep, narrow gully
Josephine Lake 1975	n.a.	646.2	731.5	.883	−310.8	Dry powder with wind on open slope
Kintla Lake 1946	n.a.	1544.5	2255.5	.685	−235.6	Dry powder with wind in steep, narrow gully

[1]Volume, in $10^5 m^3$.

n.a., not available.

Figure 3. Inner zone of steeply plunging Goat Lick avalanche path.

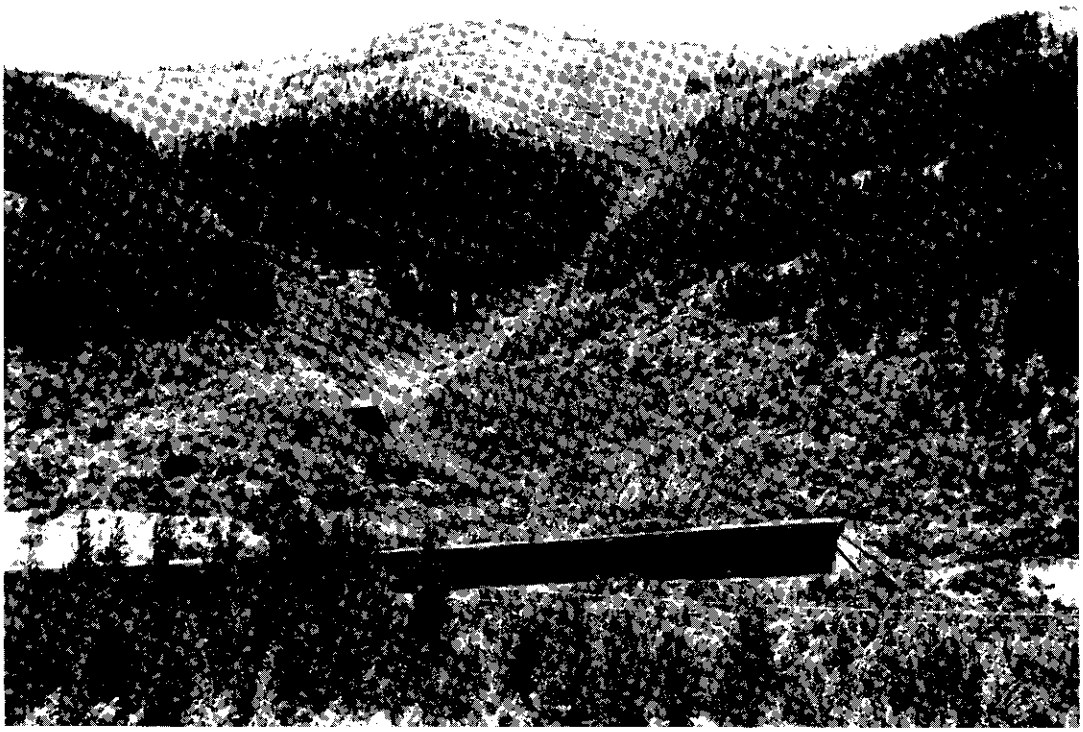

Figure 4. Shed 7 avalanche path, with deeply incised central gully and low, herbaceious vegetation (arrow). Furthest reaches of the runout zone in foreground. Note the snowshed covering the railroad tracks.

Kintla Lake case, which was studied using aerial photographs and a topographic map. Factors particularly affecting the potential for excessive runout were the degree of incision (if any) of a central channel running longitudinally down the path (the "inner zone"), the longitudinal profile of the path (*sensu* Martinelli 1986), and the character of vegetation present, categorized as: inner zone, of primarily herbaceous vegetation such as *Urtica dioica;* flanking zone, of flexible deciduous trees such as *Alnus sinuata, Acer glabrum,* and *Populus tremuloides;* and outer zone, of more widely scattered trees and shrubs such as *Amelanchier alnifolia* (Malanson and Butler 1984, 1986).

Results

Each of the snow-avalanche paths examined has a "hockey-stick path profile" (Martinelli 1986), a steeply plunging upper track with a pronounced break in slope leading to the low-angle runout zone. Of the six cases examined (Table 1), four avalanches possessed relatively low equivalent coefficients of friction (<0.5) compared to those avalanches in this study and Izumi's (1988) which did not travel excess distances. The four avalanches with lower equivalent coefficients of friction attained excessive travel distances of 544-969 m. Volumes exceeded 85,000 (0.85×10^5) m^3 in the three cases for which reconstruction of depositional volume was possible.

These data compare favorably with Izumi's (1988) results. He illustrated that avalanches larger than 1×10^5 m^3 experienced excessive travel distance. However, all such avalanches in his sample were slab avalanches of dry snow. The wet-snow avalanches he examined rarely exceeded 0.3×10^5 m^3 in volume, and thus uniformly high equivalent coefficients of friction (> 0.58 in all but one case) and did not experience excessive travel.

In contrast to Izumi's (1988) findings, all avalanches in our study which possessed low coefficients of friction and excessive travel distance were wet-snow avalanches. The Glacier Park wet-snow

avalanches occurred in deeply-incised, steeply plunging paths with well-defined inner zones of low herbaceous vegetation (Figure 3). These conditions apparently precluded significant energy dissipation along the lateral margins of flow, so that the low friction and continued high energy levels favored excessive travel in the runout zone. A similar conclusion for rock avalanches was recently reported by Nicoletti and Sorriso-Valvo (1991).

The transverse shape of an avalanche path also seems to be important. A dry-snow avalanche incorporating air can have considerable depth so the relative proportion of the avalanche contacting the ground will be small, even on a flat slope. In wet-snow avalanches, however, this ratio of volume to contact will be low unless the flow is channelized by local terrain features.

Conditions in the runout zone in each case of excessive travel also favored continued movement. In the two Goat Lick avalanches, the snow discharged onto the floodplain of the Middle Fork of the Flathead River, where vegetation is sparse to non-existent. The Shed 7 avalanche encountered young conifers where power line maintenance had removed the mature vegetation (Figure 4); and the Mt. Henkel avalanche debouched into a post-fire successional grove of young aspen (*Populus tremuloides*).

The two avalanches which did not experience excessive travel had high equivalent coefficients of friction (Table 1), in the same range as those described by Izumi (1988) which did not undergo excessive travel. Both our cases involved dry-powder avalanches with accompanying windblast. The Josephine Lake avalanche (Table 1) occurred on an open, unconfined slope, i.e., it did not travel down a deeply incised gully in the center of the avalanche path. The lack of confinement in a central gully may allow energy to dissipate along an avalanche's lateral margin, leading to an increase in friction and a shorter travel distance. Although volume information was not available for this avalanche, it possessed sufficient strength to demolish a boat-storage shed at the base of the path, possibly a result of the associated windblast (*Hungry Horse News* 28 February 1975).

The other case of avalanching without excessive travel, at Kintla Lake (Table 1), did occur on a path with the requisite terrain conditions for excessive travel; a steeply plunging and deeply incised central gully with low herbaceous vegetation in the inner zone. However, the low-angle runout zone was limited in extent, and the avalanche entered a mature coniferous forest near the head of that zone (Anonymous 1946). Entry into the forest, causing increased friction during flow plus uprooting and destruction of the trees, dissipated the energy that might otherwise have propelled the avalanche farther into the runout zone.

Discussion

The number of avalanches examined in this study is low, mainly because of the limited number of on-site observations of starting elevation. However, tree-ring data reveal that far-traveled avalanches also reached the longitudinal peripheries of the Goat Lick path in the winters of 1971-72, 1964-65, 1962-63, 1956-57, 1949-50, 1944-45, 1936-37, 1934-35, and 1924-25 (Butler and Malanson 1985a); and that avalanches reached the outer edges of the Shed Seven runout zone in the winters of 1975-76, 1973-74, 1971-72, and 1968-69. Frauson (1979) also described another snow avalanche with excessive travel distance at the Mt. Henkel path, also occurring in 1979; unfortunately, no data were available concerning starting elevation. These additional examples reveal that snow avalanches frequently have traveled long distances in Glacier Park.

Rainfall associated with a rise in temperature is the most common climatic trigger of snow avalanches in GNP, and wet-snow avalanches are the most common type (Butler 1986a). Historical data corroborate that most cases of excessive travel at the Goat Lick and Shed Seven paths were wet-snow avalanches (see Butler 1986b, for details).

Given the results of this and other studies, a general model of avalanche movement and energy is desirable. We propose some directions for such a task that can be easily applied by land-use planners without intensive labor requirements associated with on-site monitoring. In Figure 1, we show the longitudinal profile of a typical avalanche path, with several key locations noted. The path is divided into three portions: the part 32° and steeper (Izumi 1988) (H1 and L1); the part below that point but above the point defined by an average 32° slope (H2 and L2); and the runout zone (H3 and L3). We can refer to these as the fall zone, the friction zone, and the runout zone. The motion of an avalanche will be generated during the fall on the slope steeper than 32°; this

energy will mostly be dissipated in the friction zone; and the extent to which it is not fully dissipated in the friction zone will be expressed in the length of the runout zone. Thus excessive distance is, as expressed by McClung and Lied (1984, 1987) and Mears (1989), a function of the ratio of the lengths of two portions of the path. We suggest, however, that it is the upper two sections of the path that are important in determining the excessive distance traveled (that distance which exceeds the calculated value for an average slope of 32°). The excessive distance is, then, a direct function of H1, and an indirect function of H2. Also, the coefficients of the function(s) may differ for the portions of the slope above and below H2. The exact function need not be specified here because, as noted in most studies, other factors must also be taken into account.

Glenne (1986) summarized many of these factors relative to a smooth longitudinal surface: they include weather and snowpack, melting, and the changes in mass of the avalanche along the path (the friction of moving snow is also a function of its mass and volume). We have emphasized the importance of local terrain and vegetation. We note that the transverse topography and vegetation of a path may affect the friction, because of changes in the area of surface contact relative to the mass and volume of the avalanche. Variation in the longitudinal topography and vegetation, beyond the effects of a large stand of trees at the bottom of a slide, must also be considered. For example, our Shed 7 path, and many others in Glacier Park, the Rocky Mountains in general, and in Europe, pass over a snowshed (gallery) which will cause a fast-moving flow to become airborne for at least a short distance. Abrupt profile interruptions to a generally concave "hockey-stick" profile could also cause snow acceleration or deceleration, depending on the shape (convex or concave) and steepness of the interruptions.

Conclusions

Our data reveal that many wet-snow avalanches can travel excessive distances with low equivalent coefficients of friction. Our data do not preclude the possibilities that slab and dry-snow avalanches may also travel excessive distances, as described by Izumi (1988) and Yamada (1989) for Japanese avalanches; however, our limited historical sample reveals no such cases. In the northern Rocky Mountains, excessive travel distances develop where large-volume avalanches are released on "hockey-stick profile" paths which are deeply incised. A flume-like terrain works in concert with low-stature, flexible vegetation of the inner zone to provide minimal frictional resistance to the passage of the snow; and movement continues into low-angle runout zones where vegetation is limited in areal extent and height. Where avalanches do not travel in confined paths, and/or where they encounter mature forest in the runout zone, excessive travel is unlikely.

These findings have several geomorphic implications. Effective scouring of the below-snow surface will be limited to the transverse (Butler and Malanson 1985a, Butler 1989a) and distal margins of avalanche paths. Inner zones of steeply plunging avalanche paths subject primarily to wet-snow avalanches are not likely to experience significant avalanche erosion. As pointed out elsewhere (Butler and Malanson 1990), these flume-like snow-avalanche paths seem to be relict landforms.

In the outer margins of avalanche runout zones, forest may be entered and trees uprooted (Butler and Malanson 1990). Deposition of dense wet-snow avalanches can also block creeks and rivers, producing temporary dams which ultimately fail and release jokulhlaup-like outburst floods of surprisingly high peak discharges (Butler 1989b).

Land-use planners can utilize the information presented in this paper to identify particularly dangerous sites. Excessive travel likelihood can be quickly calculated by determining the equivalent coefficient of friction using $\mu = H/L$. The necessary data for such calculations are quickly and easily extracted from topographic maps and maps of avalanche path location (Butler and Walsh 1990), in concert with descriptions of past avalanches. Even if historical data are absent, runout zones and slopes opposite avalanche paths that are most likely to be impacted by excessive travel can be identified on the basis of path topography; "hockey-stick profile" paths (easily discernible from topographic maps) with deeply incised central gullies (also easily identified on maps) present the greatest danger. Limiting development on, immediately across from, and downvalley from such paths seems the most prudent course for planners seeking to apply our observations.

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