Terrain parameters of avalanche starting zones and their effect on avalanche frequency
by John Andrew Gleason

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Science
Montana State University

Abstract:
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Terrain parameters of the starting zone can explain much of the variance regarding avalanche frequency. The unexplained variance may be due to dynamic snow and weather parameters that were not evaluated in this study.

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A thesis submitted in partial fulfillment
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of

Master of Science

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Earth Science

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

May 1996

APPROVAL

of a thesis submitted by

John Andrew Gleason

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGMENTS

I would like to thank my committee, Bob Brown, Steve Custer, Kathy Hansen, Bill Locke and John Montagne for helping me define and understand the topic of this thesis. Without their guidance I would not have been able to accomplish my goals. I especially would like to thank Steve Custer not only for his academic help, but for his personal guidance in a rough period in my life. John Borkowski was an enormous help with the statistical part of the thesis, and Carol Bittinger was invaluable for her help with the SAS software. I would like to thank the Mountain Research Center for their financial help, without which the summer field sessions would not have been possible. The Big Sky ski patrol helped with valuable information on the avalanche history of the study area and provided lift tickets for me and my assistants. Thanks to my assistants for all the field help. Thanks to Karl Birkeland for his insight into the avalanche enigma and his friendship. Finally, I would like to thank the Department of Earth Sciences for their support both financial and academic.

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ABSTRACT

Characterization of avalanche starting zones has previously been qualitative. A quantitative approach may provide a better understanding of avalanche initiation and location of potential avalanche slopes. The purpose of this research was to characterize and quantify the relationship between terrain parameters of avalanche starting zones and the effect they have on avalanche frequency. Avalanche frequency data for 44 avalanche paths on Lone Mountain in southwest Montana were correlated with data on terrain features of avalanche starting zones. Terrain features tested were: slope angle, altitude, aspect, aspect of the dominant wind direction, path geometry and surface roughness. Over 3500 avalanche events were separated into artificial and natural release groups. For the natural release group the terrain variables slope angle, altitude, aspect and aspect of the dominant wind direction were significantly correlated to avalanche frequency at the 0.10 level using stepwise multiple linear regression(Model r-square 0.47). For the artificial release group the number of explosive events and slope angle were significantly correlated to avalanche frequency (Model r-square 0.67).

Terrain parameters of the starting zone can explain much of the variance regarding avalanche frequency. The unexplained variance may be due to dynamic snow and weather parameters that were not evaluated in this study.

INTRODUCTION

Snow avalanches are hazardous natural events which occur in mountainous regions throughout the world. When avalanches occur in populated areas they can be both deadly and costly. As more people move into mountain environments, the possibility of loss of life and property increases. Annual mortality rates due to avalanches are increasing (Williams, 1993). Snow avalanches are a problem that requires greater attention and deserves increased and sustained funding (National Research Council, 1990). Research on the variables that affect avalanche frequency would therefore prove useful to improve planning and forecasting.

The purpose of this research was to characterize and quantify the relationship between terrain parameters of avalanche starting zones and the effect they have on avalanche frequency. The objective of this study was to compare avalanche frequency data with data on the terrain features of starting zones of avalanche paths in order to determine which terrain parameters best explain avalanche frequency. Characterization of the starting zone has previously been qualitative (Armstrong and others, 1974; Lied and Bakkehoi, 1980; Butler, 1979). A quantitative approach may provide a better understanding of avalanche initiation and location of potential avalanche slopes.

Literature Review

Avalanche starting zones are located where the avalanche initially fractures and starts its movement and typically occur on slopes between 30 and 45 degrees (Butler and Walsh, 1990; LaChapelle, 1985). Perla and Martinelli, (1976) found that the mean slope angle for 194 slab avalanches was 38 degrees with a standard deviation of 5 degrees. Bjornsson (1980) found that the most common starting zones in Iceland occurred in gullies and slopes beneath rock walls between 30 and 40 degrees in slope angle. Armstrong and others (1974) found that starting zones occurred on all types of slopes including open, unconfined slopes and gullies. Lied and Bakkehoi (1980) attempted to classify the topography of the starting zone into five classes in order to calculate avalanche run-out distances based on topographic parameters. The five classes were; cirques, shallow depressions, scars, flat faces and convex slopes in the longitudinal direction (Lied and Bakkehoi, 1980). They pointed out, however, the subjective nature of this classification. Butler (1979) classified starting zones into three types; bowl shaped slopes or cirques, rectilinear or open slopes, and channels or funnels (confined gullies and couloirs). Geomorphologists have attempted to classify hillslope shapes based on profile characteristics and planar form. One system uses a nine-unit classification based on the linear, convex and concave form in both the longitudinal and transverse directions (Ruhe, 1975). The classification systems available are qualitative and don't allow for a quantitative analysis of starting zone characteristics. Based on this gap of knowledge I attempted to quantify starting zone characteristics in order to determine their effect on avalanche frequency.

The initial movement of avalanches is difficult to predict because many factors affect the conditions leading to slope failure. The factors which affect the occurrence of snow avalanches are generally grouped into two categories; dynamic and static variables (Schaerer, 1981). The dynamic parameters include climatic conditions and snowpack variability and the static parameters include terrain conditions of the avalanche path.

The static parameters that influence avalanche occurrence relate to the terrain conditions of the avalanche path. Walsh and others (1990) described these as morphometric terrain variables including; altitude of starting zone, aspect, slope angle, shape of avalanche path, roughness of ground surface, vegetation and bedrock lithology. The effect of relative altitude on avalanche activity depends on the level of the surrounding mountains which influences orographic precipitation and ultimately snow depth. Whether the path is above timberline influences the wind patterns and their influence on slab formation. Reduced wind activity reduces the formation of slab conditions.

The orientation of the slope relative to the wind is important. On lee slopes, increased accumulation occurs and enhances slab formation. The orientation of the slope to the sun affects the temperature of the snowpack. Shady slopes tend to have increased temperature gradient (kinetic) metamorphism because of the colder air temperature (Schaerer, 1981).

The angle of the avalanche path is important. Many researchers divide slope angle into composite parts of the path in order to learn more about starting frequency and run out length (Butler, 1979; Judson and King, 1984; Walsh and others, 1990). Judson and King (1984) examined avalanche frequency across traveled roads, and focused on the starting zone angle. This angle was measured in the first 50 meters of vertical distance in the center of the starting zone. They also selected the angle of the avalanche path above the road as a pertinent parameter. Butler (1979) generated slope angles by computer using algebraic methods and topographic maps. Walsh and others (1990) used a Digital Elevation Model and Geographic Information System techniques to define slope angles and aspects. The variation of the slope angle in the longitudinal direction determines the longitudinal concavity or convexity of a slope (Huber, 1982). This variation influences tensile stresses the snow pack is subjected to and can have an effect on avalanche release.

The shape of the slope influences its ability to collect snow. The concavity or convexity in the transverse profile (cross sectional) direction can influence deposition and depth of snow (Luckman, 1978). Those paths that have a curved horizontal or cross sectional profile such as a bowl or a cirque are able to trap blowing snow from several directions depending on the wind direction (Armstrong and Williams, 1986).

The surface roughness of the starting zone influences the likelihood that a path will produce avalanches. Smooth surfaces are much more likely to produce avalanches than rough irregular terrain with numerous protruding obstacles (Walsh and others, 1990). Smooth slope surfaces such as grass often produce full depth avalanches where the entire snowpack breaks loose and leaves bare ground remaining. In order for rough terrain to release an avalanche, the snow must be deeper than the height of the irregularities which form the roughness. Vegetation, or land cover type, can be used as a measure of surface roughness. Butler and Walsh (1990) used aerial photographs to determine the land cover type of avalanche paths and grouped them into the categories of rock, mixed herbaceous, mixed brush and various species of trees.

The degree to which rock type or lithology influences the location of avalanche paths is not well understood (Butler and Walsh, 1990). The lithology of an area influences the response to brittle deformation such as joints and faults which in turn influences the frequency and size of gullies and couloirs. In Butler and Walsh's (1990) study of Glacier National Park, Montana, a correlation was shown between avalanche path location and the proximity to faults, sills, dikes and structural lineaments. They concluded that avalanche path location is controlled by lithology and structure and by the local avalanche climate. Because most of their work was in a concentrated area, this conclusion cannot be extrapolated to other locations without further research. While lithology may have some control over avalanche path location, the erosional and depositional actions of avalanches themselves can alter the path environment. Avalanche erosion and deposition are significant processes affecting long term stability in alpine terrain (Ackroyd, 1987).

To determine the importance of the parameters which influence avalanche occurrence, location and frequency and list them in a hierarchical fashion would entail a sensitivity analysis with weighted factors based on local avalanche path conditions. This type of analysis has not previously been conducted, however one can formulate some hypotheses based on the current literature.

Armstrong and others (1974) summarized the factors that influence avalanche occurrence including terrain, weather and snow. Four experienced avalanche forecasters working on avalanche evaluation and prediction in the San Juan mountains of Colorado demonstrated the factors they found significant in avalanche occurrence forecasting. The only factor they all agreed on was wind speed and direction, which influences where snow loading will occur. Several other factors were recognized as important such as snow stratigraphy, precipitation intensity, old snow stability and new snow density and crystal type (Armstrong and others, 1974). Starting zone terrain was deemed significant by two of the observers but was not broken down categorically. Although only four avalanche researchers were used for this parameter significance study, the conclusion appears to be that the dynamic or snow related factors are more significant than the terrain parameters. More than 80 percent of all avalanches take place during or just after a storm (Armstrong and Williams, 1986). This led them to conclude that snowfall is the most important of the contributing factors of avalanche formation.

Perla and Martinelli (1976) do not list the parameters affecting avalanche occurrence in any hierarchical fashion. They suggest that the most important factor for snowpack stability evaluation is the knowledge of recent avalanche activity on nearby slopes.

Schaerer (1981) listed parameters and weighted them according to their importance regarding the probability of avalanche release and identification of potential avalanche slopes. He then listed these factors for use in snow stability analysis and gave the generally critical condition of each factor that affects avalanche occurrence. The most critical factor for avalanche occurrence was terrain in the starting zone where slopes are greater than 25 degrees, have an abrupt change of incline and a smooth surface and are on the lee side of the prevailing wind direction. For snow depth, the second most important parameter, the critical conditions were; greater than 30 cm on smooth ground and greater than 60 cm on average ground. Schaerer regards terrain parameters as the most critical factors affecting avalanche occurrence. This conclusion is based on the principle that without the critical terrain conditions, even the most unstable snowpack will not release an avalanche.

Judson and King (1984) found that the average angle of avalanche path and the slope in the first 100 m of the starting zone were strongly correlated with avalanche frequency and could be used to estimate avalanche occurrence in specific regions within their study area. Other factors such as path size and aspect did not correlate to avalanche occurrence in their samples. They suggest that more information is needed in order to analyze all the possible interactions of potential factors involving avalanche occurrence and frequency.

Scale may have a significant effect on the understanding of which factors are applicable or useful at regional, local or site-specific avalanche prone areas. In order to analyze avalanche data on various spatial and temporal scales, some workers are utilizing GIS techniques (Cartwright and others, 1990; Walsh and others, 1990). Walsh and others (1990) used a GIS thematic overlay of avalanche path location and merged it with coverages of attribute data including geologic structure, lithology, topographic orientation and land cover type. This information was used to develop a map of the relative probabilities of bio-physical variables that affect avalanche path location.

The overall conclusion one may draw from the literature regarding the importance of factors that affect avalanche occurrence is that there is no general consensus as to which parameters are most influential for indicating the probability of avalanche release, identifying potential avalanche slopes or quantifying predicted avalanche frequency. Since avalanches cannot occur unless there is appropriate terrain, a study which tests the effects of terrain parameters on avalanche frequency may provide a better understanding of where and when avalanches are expected to occur.

STUDY AREA

The study area is within the Big Sky Ski Area in southwest Montana (Fig. 1). Lone Mountain was chosen as the study area because avalanches are common here and there is a relatively complete record of avalanche frequency data for the area from 1972 to the present. The site is an excellent choice for this type of study because the avalanche paths are found on various aspects and elevations allowing for the spatial analysis of the starting zone to be correlated with the avalanche frequency.

Lone Mountain is a laccolith of Tertiary, porphyritic andesite intruded into a Cretaceous shale sequence (Montagne, 1976; Tysdal~~e~~ and others, 1976). Although most of the exposed surface rock is talus composed of porphyritic andesite, there are areas with horizontal stratigraphy composed of shales and/or hornfels formed by contact metamorphism of shale. Lone Mountain is a horn formed by Quaternary glacial erosion. There are seven active rock glaciers on Lone Mountain (Montagne, 1976). One of the rock glaciers is in the starting zone of two of the paths in this study.

Lone Mountain is in the Madison Range, a north-south trending mountain chain characterized by substantial dry snowfall, low winter temperatures, and strong, variable winds. The snowpack varies annually but is known for extensive depth

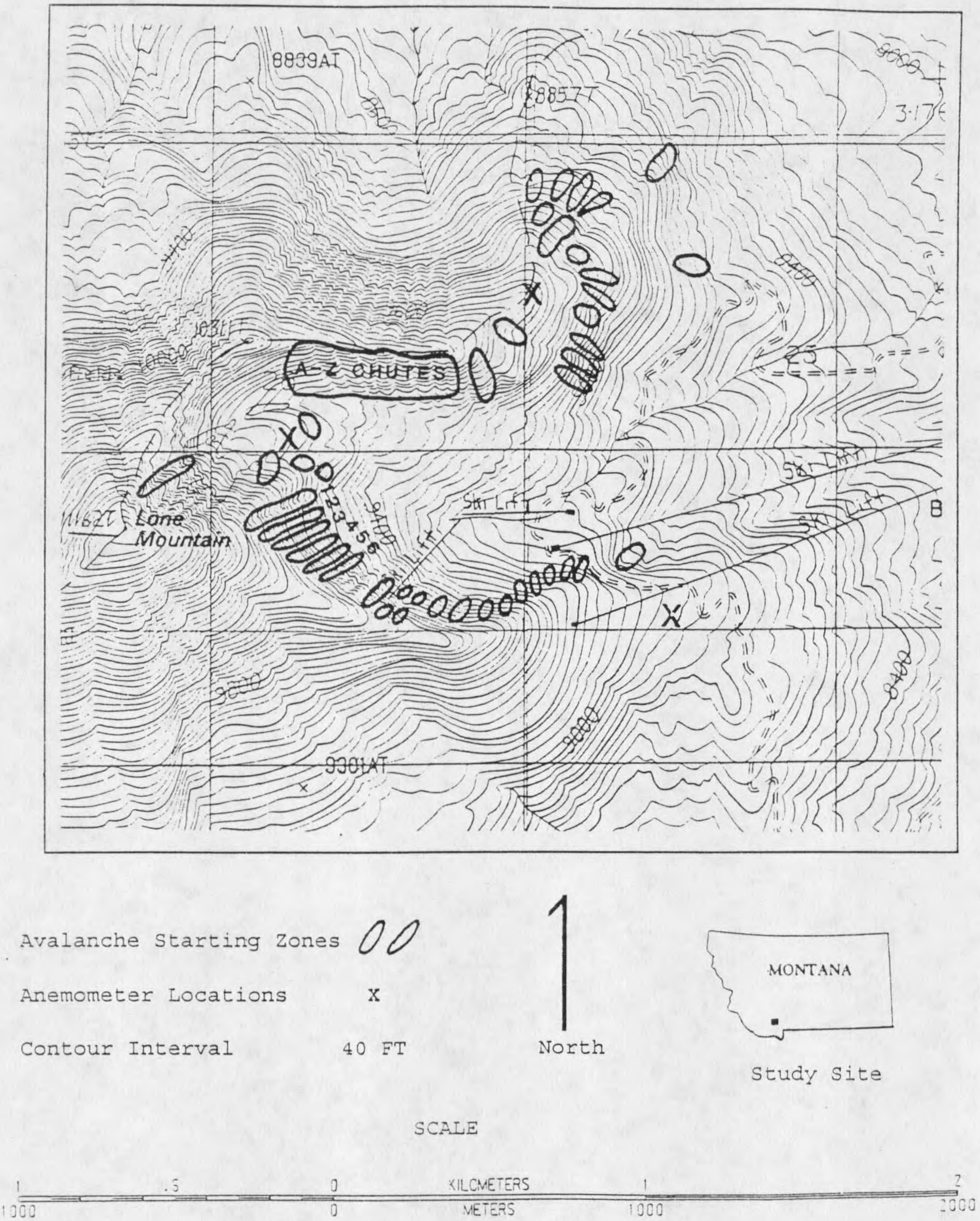

Figure 1. Avalanche path locations and anemometer locations on Lone Mountain. First through Sixth Gullies are numbered 1-6 (Appendix C). Light elliptical lines near the summit of Lone Mountain are snowfields from the original map.

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hoar formation (Ueland, pers. comm., 1992). Average annual snowfall at Big Sky is approximately 650 cm (Ueland, pers. Comm., 1992). Lone Mountain is within the inter-mountain avalanche climate region (LaChapelle, 1966). This region falls between the moderate temperatures and abundant heavy snowfall of the coastal region and the colder temperatures and less abundant, drier snowfall of continental regions.

METHODS

Avalanche Frequency Data

Avalanche frequency data for Big Sky were obtained from the U.S. Forest Service's Westwide Avalanche Network at the Rocky Mountain Experiment Station in Fort Collins, Colorado which collects and stores avalanche data from ski areas throughout the United States. These data are collected as monthly summaries through the U.S. Forest Service avalanche control and occurrence charts. The Big Sky ski area has been compiling this information since 1972.

The raw data consisted of 5159 individual avalanche events. Only avalanches with at least a 15 cm crown line were reported. The data were loaded into a spreadsheet program. Unfortunately with data that is collected by various personnel over twenty years, input is not always consistent. The data needed to be ▒cleaned▒ prior to analysis. When avalanche path names were spelled differently they appeared as separate paths in the data base. Some avalanche path names were changed over the years and had to be corrected in order to insure accurate frequency data. Other problems with the raw data set included column sequence errors and unknown path names. Some of the avalanche path names from the early seventies were unknown by current patrollers. After discarding erroneous and unknown data, a total of 3538 individual avalanche events remained for

44 known avalanche paths, whose starting zones are shown in figure 1.

Field Measurements

The starting zones of each avalanche path were identified using historical avalanche information provided by the Big Sky ski patrol and by direct confirmation by various members of the Big Sky ski patrol (Dixon, pers. comm., 1992, Ueland, pers. comm., 1992). When there was a discrepancy among the experienced patrollers as to the exact location of the starting zones, the area where bombs were typically released was taken as the starting zone. During the summers of 1992 and 1993, the starting zone locations were confirmed by noting debris from the bomb casings. These typically consisted of paper hand charge casings or plastic avalauncher tailfin assemblies.

The avalanche paths in this study area are found on various aspects and at different elevations (Appendix A). Aspect and slope angle measurements of the starting zone were collected using a Brunton compass and inclinometer. Altitudes of each starting zone were measured using a Thommen altimeter. Altitudes were checked for barometric changes by leaving a second altimeter at a known elevation and comparing any change that occurred during the day due to atmospheric pressure fluctuation with the fixed elevation and correcting the starting zone elevation accordingly.

The shape of the starting zone of each avalanche path was measured during the summer field season. The longitudinal shape and the transverse (cross sectional) shape were analyzed in order to determine if the differences between starting zone geometries influenced avalanche frequency. Quantification of the relative concavities and convexities of the starting zones was necessary in order to correlate the geometry with the avalanche frequency. In the longitudinal direction a transit was sighted downslope from the top of the starting zone at the same slope angle as the slide path. The height of the transit above the ground varied because of steep terrain and loose talus, but the lowest possible setting was attempted. A field assistant then walked downslope and held a stadia rod on the ground surface every five meters. The height of the ground surface in relation to the transit was measured by reading the distance above the ground on the stadia rod as determined by the cross hairs on the transit. Determination of the length of the starting zone was problematic and introduced an unknown error into this parameter. The length of the starting zone is often determined by the snowpack and can vary with the size and strength of the particular slab (McClung and Schaerer, 1993). Thus the length of the starting zone may vary between individual avalanche events. Lied and Bakkehoi (1980) found that the stauch wall, or the downslope border of the rupture zone, proved difficult to define. Therefore they used width of starting zone for their terrain study because it was easier to define (Lied and Bakkehoi, 1980). Based on the difficulties with definition of the exact starting zone and the possible error of the measurements, the longitudinal geometry was not included in the analysis.

The transverse profile of each starting zone was determined by measuring the distance across the starting zone with a measuring tape. Due to the gullied nature of the terrain, the width of the starting zones was relatively easy to estimate. The lateral edges were defined at clear breaks of slope or maximum slope change. An Abney level was used to sight across the starting zone from one side at ground level. A field assistant held a stadia rod at the point halfway across the slide path. If the cross section was concave up, the depth from the lateral edge of the starting zone to the midpoint of the path was measured on the stadia rod to the nearest centimeter. If the cross section was convex up, the Abney level was sighted from the midpoint of the cross section to each lateral edge of the starting zone where the stadia rod was being held. If the slope was convex, a negative value was assigned to the depth reading. Three to five transverse profiles were measured for each starting zone and an average depth was calculated.

Weather data was collected by the United States Forest

Service's Westwide Avalanche Network to measure dominant wind directions. Average wind speed and direction were compiled at three locations at Big Sky ski area (Fig. 1). Even though there were operational problems with the anemometers over the years, these data were the only available for the region (Dixon, pers. comm.,1993). The dominant wind direction was calculated by averaging wind directions measured daily every six hours during the winter season since 1982.

The number of explosives used since 1972 was compiled from the files of the Big Sky ski patrol. Each explosive event regardless of the number of explosives used simultaneously was recorded as one bomb event. For example if two hand charges were used at the same time on the same slope it was recorded as one event. The type of explosives used, (hand charge, avalauncher or 75 mm recoilless rifle) was not distinguished for this study because the trigger mechanism for the release of the avalanche events was classified either as artificial or natural.

Data Analysis

The data set, which includes avalanche frequency and terrain parameters for each path, was broken down into subgroups based on the release mechanism of the avalanche events. The first group consists of naturally released avalanches with a total of 309 individual avalanche events for 44 avalanche paths. These were avalanches that released without the influence of explosives or other human activity. The other group consists of artificially released avalanches initiated with explosives or ski cut by ski patrol personnel. This data set has 3229 individual avalanche events for 44 avalanche paths. Avalanche frequency per year was correlated with the terrain parameters in a multiple linear regression model. Avalanche frequency was the dependent variable, while terrain parameters were the independent variables. These included altitude, slope angle, aspect with respect to sun, aspect with respect to the dominant wind direction(wind factor), width and depth of the starting zone, as well as a shape parameter(depth/width). In the artificial release group, the number of explosive events was also analyzed as an independent variable.

The initial data set consisted of the actual number of avalanche events with crown lines of 15 centimeters or greater. These are Class 2 or greater avalanches according to the U.S. Forest Service Avalanche Control and Occurrence Chart used by the Big Sky ski patrol (Perla and Martinelli, 1976). Because the observation of some paths began in different years, the relative frequency of each path was calculated by dividing the total number of avalanche events by the number of recorded years of observation (Appendix A). Each terrain parameter was then plotted in a scatterplot with relative frequency to determine if there was a normal distribution of variables so that a linear regression model could be used to correlate the terrain variable to avalanche frequency. Ninety-five percent confidence intervals are shown by the dashed lines on all scatterplots. Normality was tested using the Shapiro-Wilk test (Appendix B). In cases where there was not a normal distribution, a transformation was performed. The natural log of relative avalanche frequency was used to normalize the dependent variable. The natural log of the number of explosive events was used to normalize the explosive variable.

A non-parametric Spearman correlation coefficient matrix was used to determine the rank of variables before they were transformed to achieve a normal distribution. The Spearman Rho number gives a measure of correlation between multiple variables that may not have a normal distribution (Conover, 1971). A ranking of variables can be determined from the Spearman test by the correlation between the terrain parameters and avalanche frequency (Table 1). Spearman Rho numbers close to negative one and one have higher ranks than numbers closer to zero.

A Pearson correlation coefficient matrix was used to determine correlation between variables after transformation of avalanche frequency (Table 2). The natural log of relative avalanche frequency was used to normalize the distribution so that it could be used in the Pearson correlation matrix and the regression model. The Pearson R number gives a measure of correlation between multiple variables that have a normal distribution. The Pearson R ranges from negative one to one. Negative one has a perfect negative correlation, positive one has a perfect positive correlation and numbers close to zero having little correlation. Values closer to negative one and one suggest covariance between variables.

Table 1. Spearman correlation coefficients (Spearman Rho) for all variables.

	Altitude	Aspect	Slope Angle	Wind Factor	Depth (D)	Width (W)	Shape Factor	Bombs
	Meters	Degrees	Degrees		Meters	Meters	D/W	No.
Altitude	1.0							
Aspect	-0.23	1.0						
Slope Angle	0.31	-0.06	1.0					
Wind Factor	-0.27	0.10	-0.40	1.0				
Depth	-0.0001	-0.03	0.32	-0.37	1.0			
Width	-0.29	-0.09	-0.01	0.08	0.37	1.0		
Shape Factor	0.03	-0.009	0.41	-0.46	0.93	0.16	1.0	
Bombs	0.36	0.24	0.30	-0.56	0.20	-0.13	0.29	1.0
Natural Frequency	0.31	0.28	0.51	-0.41	0.26	-0.004	0.26	0.58
Artificial Frequency	0.32	0.05	0.55	-0.58	0.25	-0.01	0.34	0.73

A simple ranking of variables (Spearman Rho numbers, Pearson correlation coefficients) gives a measure of relative significance of variables but is not as robust as regression. Therefore a stepwise multiple linear regression model was used to test correlation of avalanche frequency as the dependent variable with the terrain parameters as the independent variables at the 0.1 significance level.

Table 2. Pearson correlation coefficients (Pearson R) for all variables.

	Altitude	Aspect	Slope Angle	Wind Factor	Depth (D)	Width (W)	Shape Factor	Ln Bombs
	Meters	Degrees	Degrees		Meters	Meters	D/W	
Altitude	1.0							
Aspect	-0.23	1.0						
Slope Angle	0.36	-0.08	1.0					
Wind Factor	-0.27	0.28	-0.29	1.0				
Depth	0.05	-0.07	0.34	-0.36	1.0			
Width	-0.04	-0.23	-0.01	0.01	0.39	1.0		
Shape Factor	0.08	-0.02	0.42	-0.45	0.92	0.05	1.0	
Ln Bombs	0.42	0.19	0.35	-0.42	0.17	-0.20	0.29	1.0
Ln Natural Frequency	0.44	0.20	0.49	-0.33	0.29	0.03	0.31	0.65
Ln of Artificial Frequency	0.42	0.03	0.52	-0.47	0.19	-0.19	0.31	0.77

In order to gain insight into variables that are correlated to each other using a multiple linear regression model, one has to look at many factors affecting the variables, including P-values, r-squares and the covariance between variables that are significant in the model (Pearson correlation coefficients). Some P-values may be under predicted based on their covariance with other variables in the model. Although there are some problems with regression when there is correlation between variables, valid results can be obtained even when some assumptions are violated (Borkowski, pers comm., 1993).

The analysis was divided into two parts based on the release mechanism of the avalanche event. Separate regressions were run on the naturally occurring avalanches and the artificially released avalanches triggered by explosives or ski cut. The data sets were separated into two populations to determine the effect of the terrain parameters without the influence of artificial avalanche release.

RESULTS AND DISCUSSION

Natural Release Group

The natural release group consisted of those avalanches released without the use of explosives or other human activity to initiate failure. There were 309 naturally released avalanche events in this group. Although the data set is not as large for this group, the terrain parameters can be related directly to avalanche frequency without the artificial influence of explosives.

A stepwise multiple linear regression model using the partial sums of squares method on the SAS software package on the VAX computer at Montana State University was used to correlate avalanche frequency to the terrain parameters of the starting zone (r-square, 0.47, Table 3; Fig. 2-5). Step wise multiple linear regression determines the partial r-square values for each terrain parameter that is significant at the 0.1 level. The adjusted r-square value, 0.35, is close to the actual r-square value for the data set. The adjusted r-square is used to support the r-square as a measure of goodness of fit of the model because the r-square can be driven to one by adding superfluous variables to the model with no improvement in fit (Freund and Littell, 1991). The close similarity between the adjusted and actual r-square values for this data set suggest that the number of variables allows for a realistic explanation of the variance relating terrain parameters to avalanche frequency.

Table 3. Stepwise Regression Table for Natural Release Group (Only variables significant at the 0.1 level are reported.)

Step	Variable	Partial R-square	Model R-square	F-Value	P-Value
1	Slope Angle	0.21	0.21	9.7	0.0
2	Altitude	0.09	0.31	4.7	0.04
3	Aspect	0.11	0.42	6.4	0.02
4	Wind Factor	0.05	0.47	3.0	0.09

Four terrain parameters were significantly correlated to avalanche frequency at the 0.1 significance level; slope angle, altitude, solar aspect and aspect with respect to dominant wind direction (wind factor). The other terrain parameters in the model (depth, width and shape factor), were insignificant with respect to avalanche frequency at the 0.1 level.

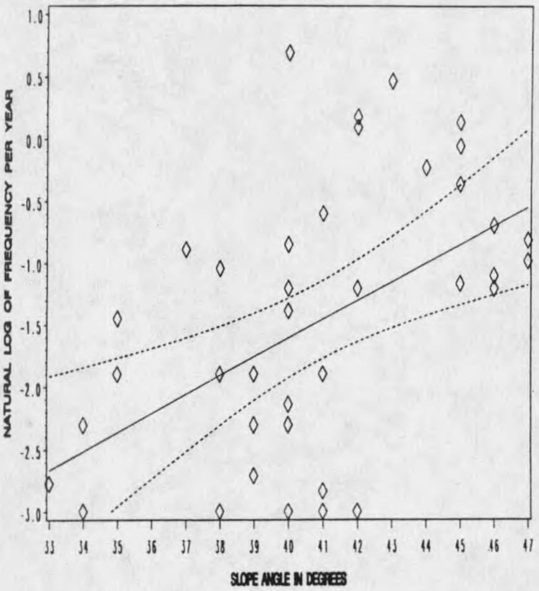

Figure 2. Natural log of avalanche frequency and slope angle. Natural release group. Dashed lines are 95% confidence intervals.

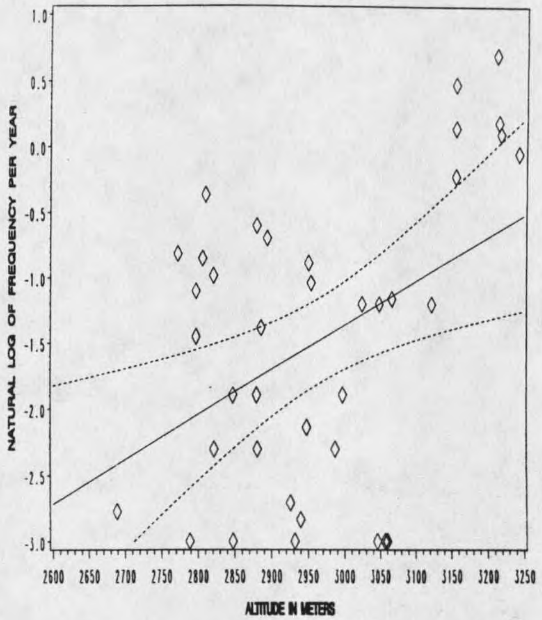

Figure 3. Natural log of avalanche frequency and altitude. Natural release group.

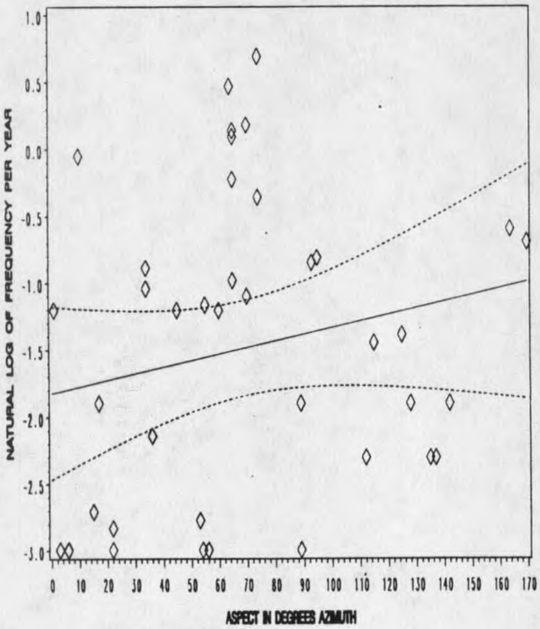

Figure 4. Natural log of avalanche frequency and aspect. Natural release group.

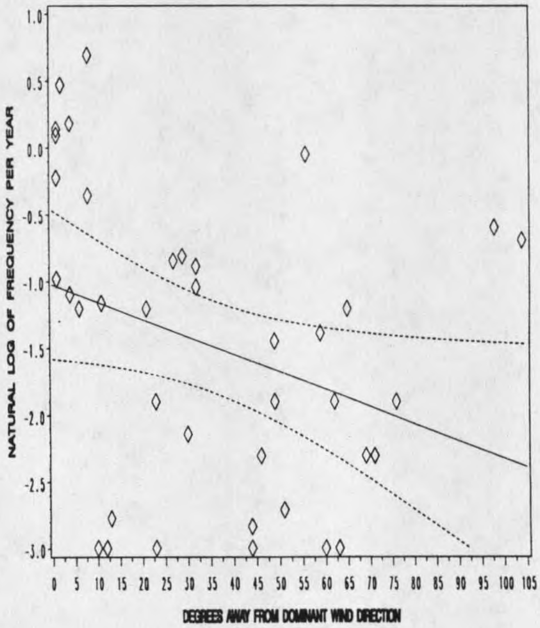

Figure 5. Natural log of avalanche frequency and wind direction (wind factor). Natural release group.

The most significant terrain variable that influenced avalanche frequency for the natural release group was the slope angle of the starting zone (P-value 0.0, Table 3). As slope angle increases, avalanche frequency generally increases due to higher shear stresses within the snowpack. At greater slope angles shear deformation increases resulting in greater shear stresses (Brown and others, 1973). Higher shear stresses result in less stable snowpacks and lead to higher avalanche frequencies.

Avalanche frequencies appear to decrease as the slope angle increases above 43 degrees (Fig. 2). This is consistent with previous studies of frequency verses slope angle where a maximum number of avalanches occurs at a given angle and fewer avalanches occur beyond that mean angle (Perla and Martinelli, 1976). Beyond a critical angle, approximately 43 degrees for the Lone Mountain area, avalanche frequency decreases because snow continually sloughs off steeper slopes, preventing slab formation and decreasing avalanche frequency.

The linear analysis of slope angle may under predict the variance explaining avalanche frequency because the relationship between slope angle and frequency is linear only up to a critical angle of repose where sloughing occurs. The critical angle is predicted to be near 45 degrees, but is uncertain, with up to 5 degrees of deviation (Perla and Martinelli, 1976; LaChapelle, 1985). The slope angles of the starting zones for this study ranged from 33 to 47 degrees. This range does not contain the lower and higher slope angles found in previous studies (Perla, 1977). Thus a linear analysis was performed because the expected relationship to avalanche frequency within the 33 to 47 degree range of slope angles is linear. If starting zones with slope angles higher than 50 degrees were in this data set, then the regression could be separated above and below 45 degrees. For consistency, the slopes steeper than 45 degrees were not removed from the data set. No transform was used in the regression to remove the effect of steeper slopes. Had such a transform been used, the slope of the regression line may have been steeper.

The second most significant terrain variable for the natural release group was altitude of the starting zone (P-value 0.04, Fig. 3). The effect of altitude on avalanche frequency may be due to the deposition of more snow due to orographic uplift, which assumes that precipitation is produced at a rate that is directly proportional to the level at which the air is lifted over a mountain (McClung and Schaerer, 1993). Larger amounts of deposited snow increase stress upon the snowpack and may cause greater instability, thereby increasing avalanche frequency. Because the difference between the highest and lowest starting zones is only 600 m (Appendix A), the effect of orographic precipitation may be negligible. The high significance of altitude may alternatively be due to the highest starting zones being in the lee of the dominant wind direction.

The next terrain parameter to significantly affect avalanche frequency based on the stepwise regression is the solar aspect of the starting zone in degrees azimuth(P-value 0.02). The distribution of this variable was not normal based on the Shapiro-Wilk normality test (Prob>W 0.06, Appendix B). If the Prob>W value is less than the 0.1 significance level, the data do not come from a normal distribution (SAS Institute Inc., 1990). Aspect is not expected to have a normal distribution in a natural system. Various transformations of the aspect variable (natural log, square root, cube root) did not achieve a normal distribution. The distribution was uniform with starting zone aspects ranging from 1 to 170 degrees azimuth (Fig. 4). Uniform distributions can be used in regression analysis but non-parametric analysis is also desirable with non-normal distributions (Myers, 1986). The Spearman rank test is a non-parametric test and ranks aspect as the fourth most significant variable (R-value 0.28) effecting avalanche frequency behind slope, wind factor and altitude (Table 1). Aspect is ranked with lower explanation of the variance than the wind factor in the Spearman test but is more significant using regression analysis. This can be explained by the covariance between terrain parameters. Aspect is not highly correlated to slope angle (Spearman -0.06, Pearson -0.08). The wind factor is covariant to slope angle

(Spearman -0.40, Pearson -0.29) and becomes less significant than aspect in the regression model even though it is ranked higher than aspect in both the Spearman and Pearson correlation tests.

The last terrain parameter to significantly affect avalanche frequency within the stepwise regression model is the aspect with respect to dominant wind direction (wind factor)(P-value 0.09; Table 3). The dominant wind direction is based on data since 1982 from three anemometers on Lone Mountain. The dominant wind direction is from the southwest (237 degrees azimuth). Any slope in the lee of this direction should have significant snow loading. Subtracting 180 degrees from 237 gives a leeward aspect of 57 degrees azimuth, and this number was used as the basis for the parameter used in the model. The highest incidences of avalanche occurrence clustered around the aspect (57 degrees) most influenced by the dominant wind direction (Fig. 4). Therefore, a transformed aspect term was created by subtracting 57 degrees, the aspect most influenced by the wind, from the actual aspect of each starting zone and taking the absolute value of this number. This creates a variable which increases with deviation from the dominant wind direction (Fig. 5). The data show that the frequency of avalanche occurrence generally declines the further the aspect deviates in either direction from the dominant wind direction of 57 degrees.

The stepwise multiple linear regression shows that the wind factor explains only 4.9 percent of the variance (Table 3). The low significance can be partially explained by the covariance the aspect with respect to the dominant wind direction has to slope and altitude. The Pearson correlation coefficient between the wind factor and slope is -0.29, between wind factor and altitude is -0.27 (Table 2). Once slope and altitude are put into the model, wind direction will not be as significant as if it was run without slope and altitude. This is based on the covariance between the variables. Aspect with respect to wind has an R-value of -0.33 in relation to avalanche frequency (Table 3). By itself, the wind factor explains 10 percent of the variance. With slope in the model the wind factor explains only 5 percent of the variance. This shows that aspect with respect to dominant wind direction significantly influences avalanche frequency but is correlated to variables that explain a greater percentage of the variance.

Wind has two effects on the snowpack. Wind direction enhances local snow deposition and wind velocity increases the density of snow (Schaerer, 1981). Wind direction directs cornice formation and deposits snow on leeward slopes. Even if no additional snow is falling, wind blown snow can load a slope to the point of instability. Wind velocity influences local slab avalanche formation by increasing snow crystal destruction thereby increasing the density and the snow's ability to form a cohesive slab layer.

The solar aspect verses frequency data do not explain the effect of solar radiation on the snowpack in the starting zones. Although it is generally thought that more northerly facing slopes will have lower temperatures and therefore more growth of faceted crystals leading to greater instability, the data do not show a significant relationship between avalanche frequency and the angle of incidence of solar radiation. This could be due to a lack of data for a significant number of the south facing avalanche paths at Big Sky. The A through Z Chutes, which are south-facing avalanche paths (Fig. 1) were not included in the data set because individual avalanche events for unique paths were not recorded in the data set. The paths were recorded together as one group whenever any (unknown) number of avalanches occurred on the group of paths. The number of individual avalanches was not recorded and therefore these data could not be used in this study.

Slope angle was compared to aspect and frequency (Fig. 6). Aspect and slope are on the X and Y axis with frequency on the Z axis. The highest frequencies of avalanche occurrence cluster around the starting zones in the lee of the dominant wind direction that have the steepest slope angles. This is an example of how terrain variables interact to influence avalanche frequency. There are some starting zones in the lee of the dominant wind direction that have low frequencies. These paths also have low slope angles. More than one factor in the avalanche equation must be present in order for

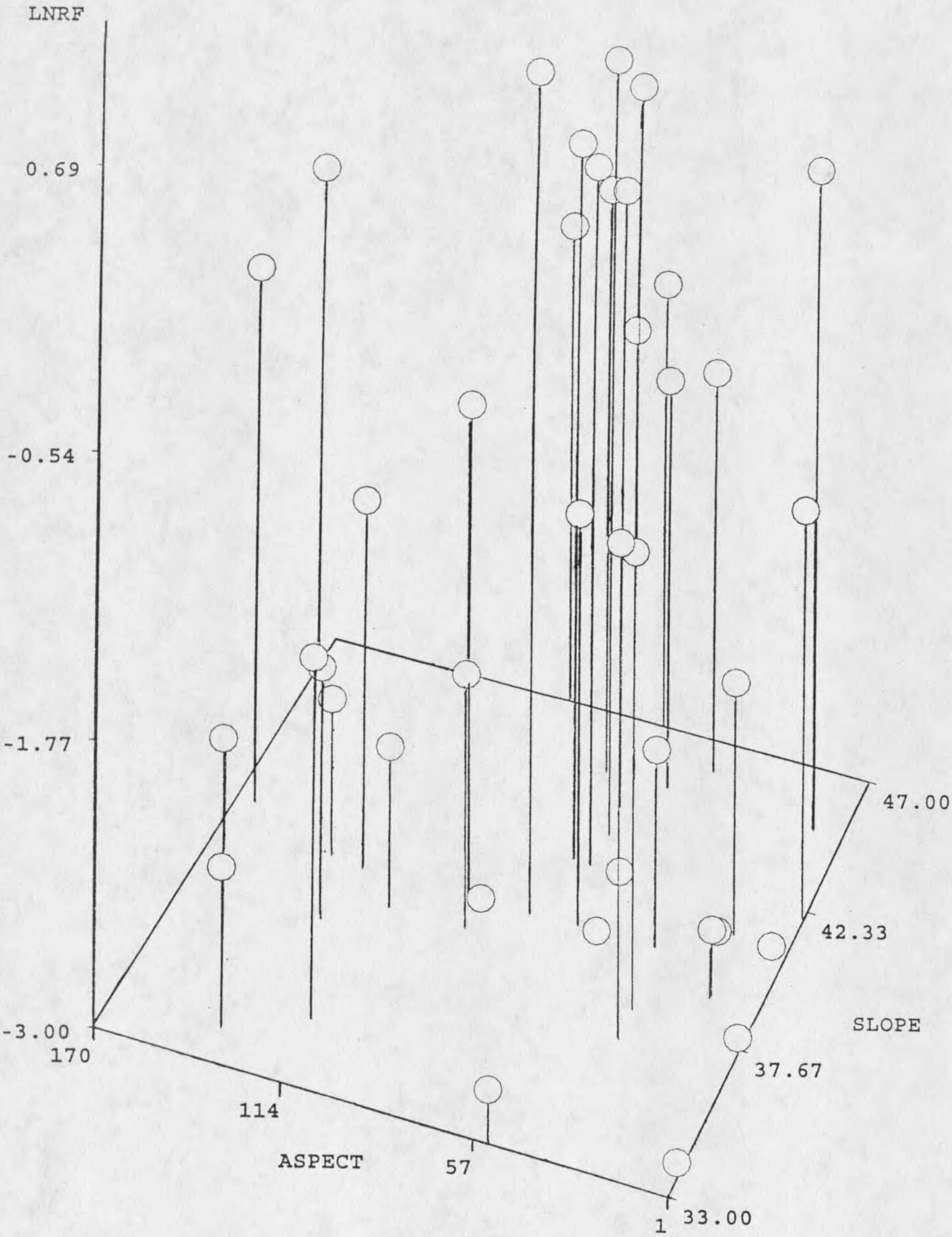

Figure 6. Three parameter plot with the natural log of avalanche frequency per year for the natural release group (LNRF) on the Z axis, solar aspect in degrees azimuth on the x axis and slope angle in degrees are on the Y axis.

instability to occur.

In the Lone Mountain area the starting zones with the highest elevations are also those in the lee of the dominant wind direction. Altitude is correlated to aspect with respect to the dominant wind direction (Pearson R-value -0.27). The correlation between these two parameters could account for the high significance level of altitude because the paths at the highest elevations receive significant wind loading of snow. There is a relationship between altitude and the wind factor (Fig. 7). Avalanche frequency, on the Z axis, is greatest for starting zones with the highest altitudes that are closest to the aspect in the lee of the dominant wind direction. Although there are some outliers in the data set for the three variables, the general trend shows that avalanche frequency increases with starting zones closer to the dominant wind direction that are also at higher elevations.

The data from the natural release group show that there are many terrain variables which affect avalanche frequency. The addition of my data to a larger data set which includes more avalanche paths with varying degrees of steepness, altitude and aspect would provide a better understanding of the influence terrain has on avalanche frequency.

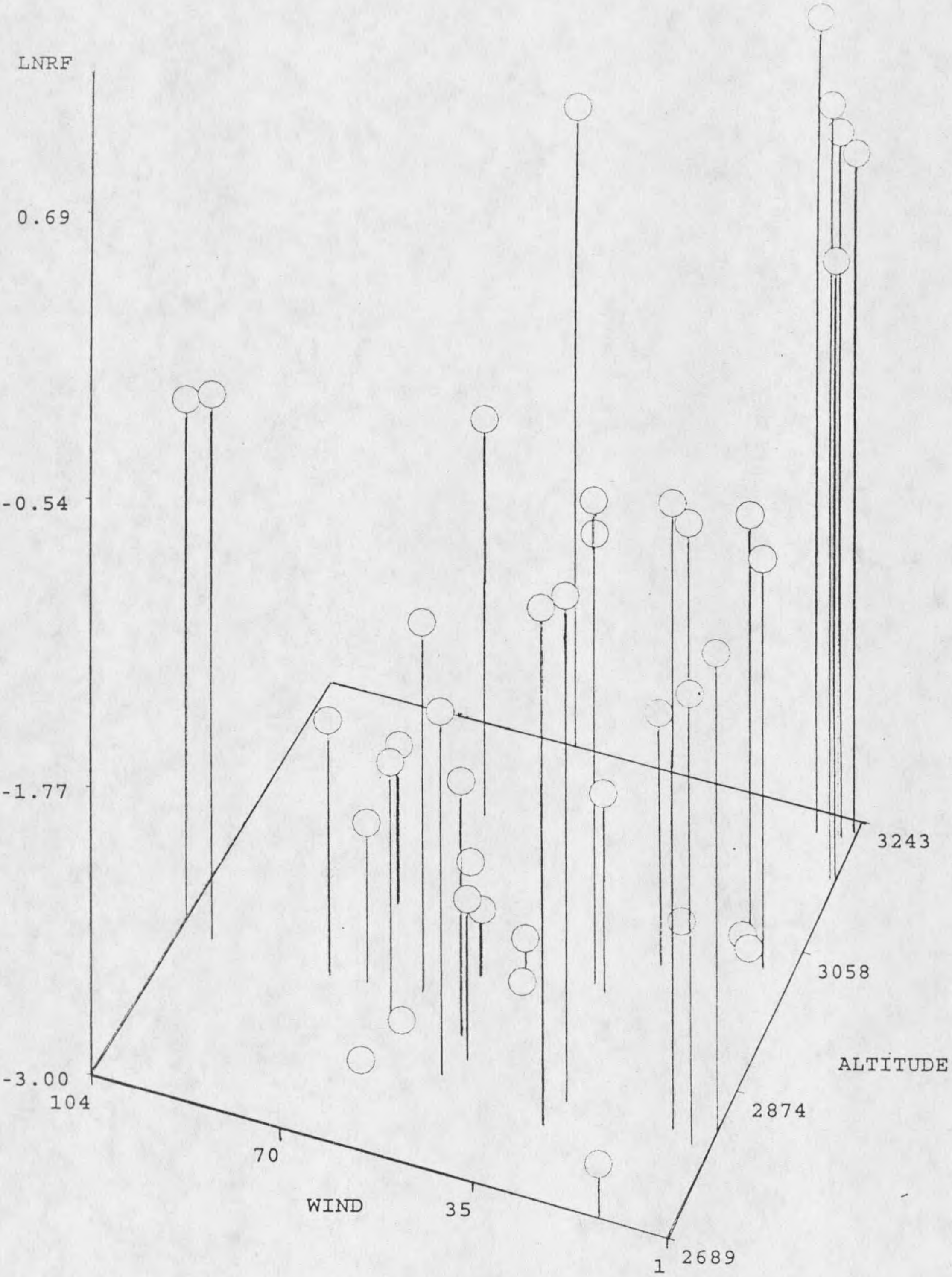

Figure 7. Three parameter plot with the natural log of avalanche frequency per year for the natural release group (LNRF) on the Z axis, altitude in meters on the X axis and the wind factor in degrees on the Y axis.

Artificial Release Group

The artificial release group contains 3229 individual avalanche events that were released by explosive or ski cutting. The natural log of avalanche frequency per year was run as the dependent variable in a stepwise multiple linear regression model. The terrain parameters, which were run as the independent variables in the regression model, include: slope angle, altitude, number of explosive events, aspect with respect to dominant wind direction (wind factor), width and depth of the starting zone in the transverse direction and a shape parameter (depth/width). When an analysis of variance was performed using these variables with a stepwise multiple linear regression model, an r-square value of 0.67 was calculated (Table 4, Figs. 8-10). All other variables were not significant at the 0.1 level and were not included in table 4. The adjusted r-square value, 0.61 is close to the actual r-square value for the data set.

The most significant parameter affecting avalanche frequency in the artificial release group was the natural log of the number of explosive (bomb) events for each avalanche path (P-value 0.0, Table 4). The natural log of the bomb events was used in order to normalize this parameter for use in the regression model. An explosive event is defined as the use of any type of explosive to release an avalanche. The type of explosives used at Big Sky, either currently or in the past, include: 75 mm recoilless rifle, 105 mm recoilless rifle, avalauncher rounds and hand charges.

Table 4. Stepwise Regression Table For Artificial Release Group. (Only variables significant at the 0.1 level are reported.)

Step	Variable	Partial R-square	Model R-square	F-Value	P-Value
1	Ln Bombs	0.58	0.58	54	0.0
2	Slope Angle	0.09	0.67	10	0.0

The scatterplot of relative avalanche frequency and number of explosive events shows a linear relationship between the two variables (Fig. 8). Avalanche frequency generally increases with use of explosives to initiate release. Avalanche frequency does not correlate exactly to the number of bomb events. This is important because the use of explosives will not guarantee an avalanche event. The snowpack must still have some degree of instability for an explosive to initiate release. Even with an unstable snowpack, release is not certain with explosive use. This is important because

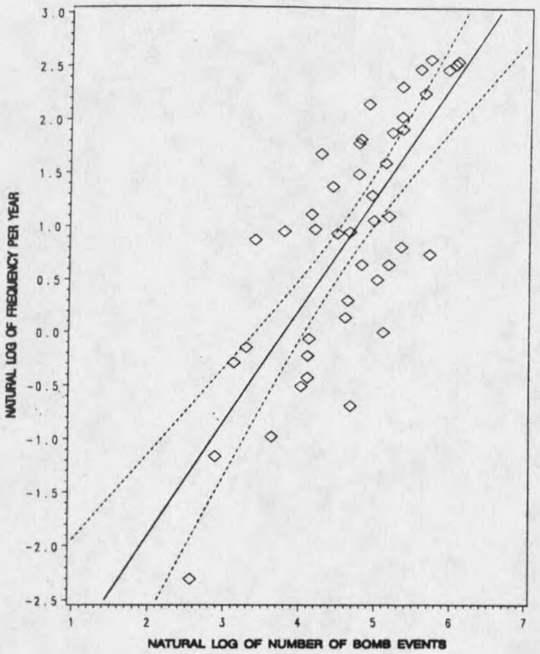

Figure 8. Natural log of avalanche frequency and natural log of bomb events. Artificial release group.

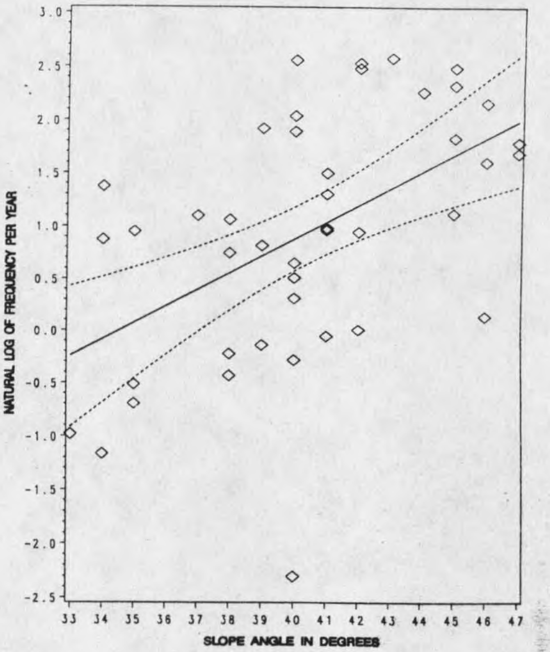

Figure 9. Natural log of avalanche frequency and slope angle. Artificial release group.

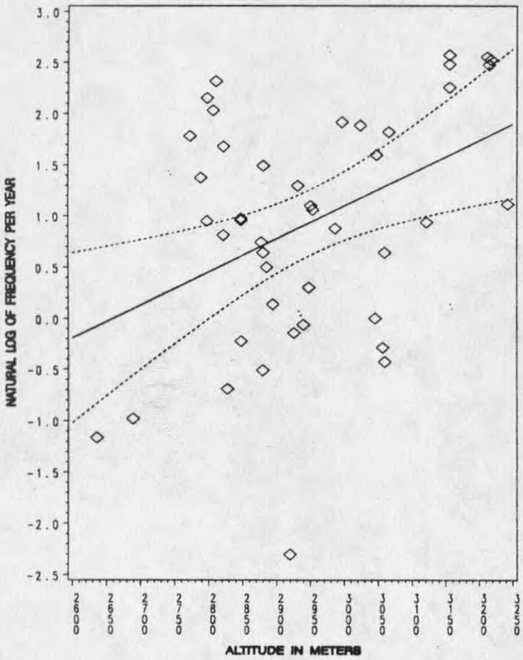

Figure 10. Natural log of avalanche frequency and altitude. Artificial release group.

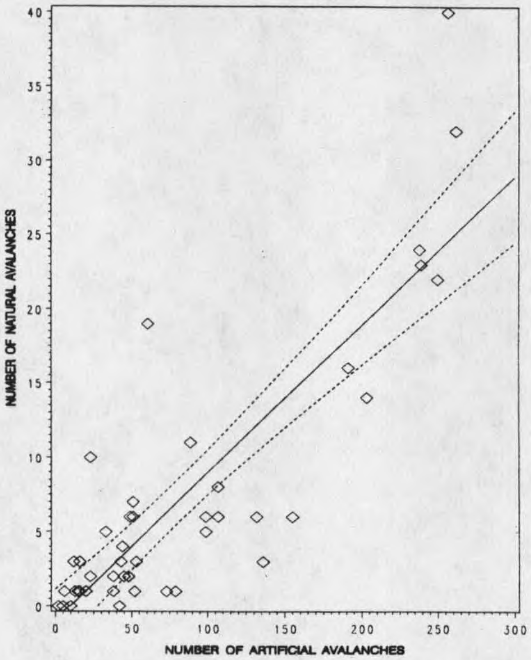

Figure 11. Artificial and natural release avalanche frequencies.

post-control release is possible when explosives fail to initiate release but add more stress to an unstable snowpack (Williams, 1978).

When the number of explosive events was correlated with avalanche frequency, without any terrain parameters in the model, the r-square value was 0.60. When the terrain parameters were run in a regression model without the explosive variable, an R-square value of 0.47 was calculated for the artificial release group. Because the r-square value without the explosive variable remains large, the explosive variable is not independent of the terrain parameters. Therefore the explosive term must be covariant to the other terrain variables. This can also be shown with the Pearson correlation coefficients (Table 2). This may be because ski patrol personnel selected bomb placements where avalanche release was probable based on terrain observations. The locations for these initial placements were identified by observing known starting zones and by trial and error in the early seventies (Ueland, pers. comm., 1992).

Slope angle was the only other significant terrain variable in the artificial release group (P-value 0.0, Table 4). The scatterplot of slope angle verses avalanche frequency suggests a relatively weak linear relationship up to a slope angle of 43 degrees (Fig. 9). At this point the frequency begins to decrease as the slope angle increases. This is consistent with the results from the natural release group where maximum frequency clusters around an average slope angle. Forty three degrees is higher than the mean slope angle of 38 degrees for slab avalanches predicted by Perla, (1977) but is within his predicted standard deviation of 5 degrees. The higher average slope angles on Lone Mountain may be due to skier compaction in the starting zone which could increase overall stability of the snowpack and allow for a higher average slope angle. However, 12 of the 44 starting zones receive no skier traffic. Alternatively, the effects of continuous control by explosives may also affect the stability of the snowpack by constantly releasing any unstable snow.

No other terrain parameters were significant at the 0.1 level for the artificial release group. This is due to the high significance of the number of explosives used, as well as the high covariance of the terrain parameters to the bomb variable.

The scatterplot of avalanche frequency verses altitude shows a weak trend toward a linear relationship (Fig. 10). This weakness is due to a cluster of starting zones around the 2800 meter elevation that have relatively high frequencies. These paths receive significant control work with explosives which accounts for their high avalanche frequency. The high frequencies of these lower elevation starting zones may explain the low significance level for altitude in the artificial release group compared to the natural group.

In the artificial release group the number of bomb events was the most significant variable affecting avalanche frequency. Slope angle of the starting zone also had some influence on avalanche frequency. When the regression on the artificial release group was run without bombs in the model, 47 percent of the variance explaining avalanche frequency occurred. This suggests that the placement of an explosive was based at least in part on terrain variables such as slope angle, aspect and geometry in order to insure release of an avalanche.

Figure 11 is a plot of avalanche frequency for the natural release data set and the artificial release set. Each point represents a specific starting zone. The correlation between the two data sets is apparent in the scatterplot (R-value 0.74). Generally, an avalanche path that has a high rate of release due to artificial methods will also have a high rate of natural release. Factors other than frequency of explosive placement, therefore, influence frequency of avalanche occurrence on Lone Mountain. These factors include the terrain parameters discussed here which in turn influence the snowpack variability between starting zones.

The depth and width of the starting zone in the transverse direction as well as the shape parameter (depth/width) were not significant at the 0.1 level for either the natural and artificial release groups. The low significance may be due to the large variation in the size and shapes of the starting zones on Lone Mountain. This idea was explored in a nested study of six similar starting zones in order to more closely analyze how the geometry of the starting zone could affect avalanche frequency (Appendix C).

CONCLUSIONS

Terrain parameters of avalanche starting zones can explain some of the variance regarding avalanche frequency. The data in this study show that slope angle, altitude, aspect and aspect with respect to dominant wind direction are significant at the 0.1 level when correlated with avalanche frequency in the natural release group (model r-square 0.47). Better prediction was expected for the geometry of the starting zone, but it was not statistically significant. The number of explosive events explains most of the variance for the artificial release group (partial r-square 0.58), but slope angle of the starting zone explained some of the variance (partial r-square 0.09). Because of the covariance between the terrain parameters and the bomb events, the terrain parameters probably exert an influence over avalanche frequency in their relationship to bomb placement. The unexplained variance of avalanche frequency may be due to the dynamic snow and weather parameters, such as snow depth and accumulation patterns that were not evaluated in this study.

The results of this study are statistically significant but marginally predictive. The r-square values are low, which leaves us uncertain of the unknown variance effecting avalanche frequency. Therefore the regression equations (Appendix D) should not be used for predictive purposes.

This project leads to questions for further research.

Terrain analysis of the geometry of the starting zone, using depth and width in the transverse direction, in a place dominated by gullied terrain would lead to a better understanding of the influence this parameter has on avalanche frequency. A better understanding of how concavities in the transverse direction of starting zones affect stability could be gained by measuring shear stress along the top and sides of the concavities with a shear frame.

This study may also have some operational significance for the Big Sky ski area. The bomb data reveals which avalanche paths have low frequencies but a large amount of explosive use. This could help keep the costs of explosives down by looking more closely at the snow pack for these particular paths in order to determine if explosive use is necessary. Avalanche paths that have high avalanche frequencies but a lower use of explosive control could be examined more closely to determine if more explosive control would be prudent for safety reasons.

A recommendation for the collectors of avalanche data would be to insure specific path names for each individual avalanche event. Grouping together simultaneous or sympathetic events renders these data useless for any statistical study. Also, accuracy and consistency in the reporting of path names would lead to easier data interpretation.

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APPENDICES

APPENDIX A. AVALANCHE PATH NAMES AND TERRAIN PARAMETERS.

PATH	FREQUENCY (Total #)	NATURAL RELEASE	WIDTH Meters	DEPTH Meters	SHAPE FACTOR Width/Depth	YEAR
First Gully	257	40	25.9	1.8	14.4	1972
Second Gully	238	24	10.9	1.25	8.8	1972
Third Gully	250	22	9.75	0.65	15	1972
Fourth Gully	239	23	10.9	1.35	8.1	1972
Fifth Gully	191	16	14	-0.55	-25.5	1972
Sixth Gully	262	32	13.4	1.8	7.4	1972
Crons	51	6	10.9	-0.18	-60.9	1972
Ramp Shot	13	1	10.9	0.001	11000	1972
Black Rock RH	38	1	10.9	0.6	18.3	1972
Black Rock Right	99	6	10.9	0.55	19.9	1972
Black Rock LH	20	1	10.9	1.55	7.07	1972
Black Rock Left	132	6	10.9	1.5	7.31	1972
Waterfall	99	5	10.9	1.1	9.97	1972
Jefferson	49	6	10.4	0.51	20.3	1976
Madison	51	7	10.9	0.65	16.8	1975
Gallatin	23	2	25.9	1.8	14.4	1975
Yellowstone	16	1	19.8	0.15	132	1975
Arch Rock	73	1	11.6	0.001	11600	1975
Parkins Paradise	13	1	23.7	1.27	18.7	1977
Exit Chute	2	0	24.9	1.55	16.1	1975
Gondola R	53	3	10.9	0.65	16.9	1972
Gondola L	52	1	11.5	0.85	13.5	1972
Calamity's Road	79	1	14.02	0.15	93.5	1972
Big Couloir	61	19				1972
Forested Knoll	48	2	10.9	0.001	11000	1972
Sure Shot	15	1	10.9	0.1	110	1972
Short Shot	136	3	10.9	0.001	11000	1972
First Pinnacles	23	10				1972
Buttress Gully	89	11	10.9	0.001	11000	1972
First Cache Tree	12	3	10.9	0.001	11000	1972
Second Cache Tree	38	2	14	1.7	8.2	1972
Secong Little Gully	33	5	10.9	0.001	11000	1972
Little Tree	45	2	14	1.05	13.3	1972
High Clearing	10	0	15.2	0.55	27.7	1972
Highway	42	0	9.14	0.3	30.5	1972
Sunset	16	3	9.75	0.3	32.5	1972
BRT South	44	4	15.2	1.6	9.5	1975
Green 17	107	6	17.1	-0.57	-29.9	1978
Peckerhead	43	3	13.4	1.05	12.8	1984
BRT Main Gully	203	14	12.2	2.25	5.42	1972
BRT North Gully	155	6	17.06	1.85	9.22	1972
BRT North Ridge	107	8	12.2	1.2	10.2	1972
Telemarks Tumble	6	1	10.9	0.001	11000	1972
Big Rock Surprise	5	0				1976

APPENDIX A. AVALANCHE PATH NAMES AND TERRAIN PARAMETERS(Continued).

PATH	ASPECT Degrees	SLOPE Degrees	ALTITUDE Meters	WIND FACTOR Degrees	BOMB Total #
First Gully	68	40	3212	2	434
Second Gully	67	42	3215	1	381
Third Gully	65	42	3218	1	421
Fourth Gully	65	45	3156	1	263
Fifth Gully	65	44	3156	1	280
Sixth Gully	64	43	3156	2	301
Crons	1	42	3122	63	89
Ramp Shot	3	38	3060	63	61
Black Rock RH	54	40	3060	12	176
Black Rock Right	45	46	3048	21	167
Black Rock LH	56	42	3046	10	166
Black Rock Left	60	40	3024	6	182
Waterfall	55	45	3066	11	120
Jefferson	34	38	2954	32	144
Madison	34	37	2951	32	176
Gallatin	36	40	2948	30	103
Yellowstone	22	41	2940	44	62
Arch Rock	22	41	2932	44	140
Parkins Paradise	15	39	2926	51	27
Exit Chute	5	40	2920	61	13
Gondola R	17	41	2848	49	66
Gondola L	6	41	2848	60	44
Calamity's Road	3	34	2789	63	83
Big Couloir	10	45	3243	56	63
Forested Knoll	137	34	2987	71	30
Sure Shot	89	40	3057	23	23
Short Shot	89	39	2997	23	209
First Pinnacles	170	46	2895	104	100
Buttress Gully	164	41	2881	98	117
First Cache Tree	142	35	2880	76	56
Second Cache Tree	135	40	2881	69	123
Secong Little Gully	125	40	2886	59	152
Little Tree	112	39	2822	46	208
High Clearing	123	35	2828	57	108
Highway	110	38	2878	44	304
Sunset	128	38	2848	62	61
BRT South	115	35	2798	49	105
Green 17	93	40	2807	27	207
Peckerhead	65	47	2822	1	71
BRT Main Gully	74	45	2811	8	207
BRT North Gully	70	46	2798	4	133
BRT North Ridge	95	47	2773	29	117
Telemarks Tumble	53	33	2689	13	38
Big Rock Surprise	55	34	2636	11	18

APPENDIX B. Shapiro-Wilk Normality Test

(If W (the Shapiro-Wilk value) is less than 0.1, the data do not come from a normal distribution.)

VARIABLE	W	W of transformed variable(Ln)
Altitude	0.1753	
Aspect	0.0611	0.0001
Slope Angle	0.1668	
Wind Factor	0.0060	0.0001
Depth	0.1425	
Width	0.0001	0.0001
Shape	0.2024	
Ln of Bombs	0.2342	
Ln of Natural Frequency	0.1500	
Ln of Artificial Frequency	0.1384	

APPENDIX C. NESTED STUDY

A smaller nested study was conducted on 6 starting zones on Lone Mountain in order to look more closely at the geometry of an avalanche path and how it affects avalanche frequency. The six starting zones were chosen based on their similar aspects, elevations and slope angles. These paths are the first through sixth gullies located on a north-east aspect at 3200 meters (Fig. 1). All starting zones have aspects between 64 and 68 degrees and have slope angles within three degrees of 43 degrees (Table 5). The similarity of the paths allows for an analysis of the geometry of the starting zone which assumes other terrain variables (altitude, aspect and slope angle) are constant.

Table 5. Terrain Parameters of First through Sixth Gullies

Starting Zone	Altitude (Meters)	Aspect (Degrees Azimuth)	Slope Angle (Degrees)
First Gully	3212	68	40
Second Gully	3215	67	42
Third Gully	3218	65	42
Fourth Gully	3156	65	45
Fifth Gully	3156	65	44
Sixth Gully	3156	64	43

The frequency data revealed that all paths had similar frequencies except fifth gully, which had a significantly lower frequency. Field reconnaissance showed that all paths had transverse profiles that were concave up except fifth gully which had a slightly convex transverse profile. A hypothesis was developed that shape in the transverse direction of the starting zone had a significant effect on avalanche frequency. This type of analysis uses exploratory statistics to test a perceived problem during a study. Exploratory statistics are suggestive, not conclusive, but they are a valuable tool which can lead to further research (Borkowski, pers. Comm., 1993). An analysis was performed to test the hypothesis using only the six paths that were found to be similar. The regression was performed using both the artificial and natural release group data to determine if the influence of explosive events affected frequency.

Three shape parameters were used to analyze the shape of the transverse profile. These included: depth and width of the starting zone and a shape parameter, depth divided by width (d/w). These terrain parameters were measured with the same techniques used for all starting zones in the study. Eight to ten profiles per gully were measured and the average geometries were calculated.

The shape parameter in the regression model is the depth of the starting zone divided by width of the starting zone in the transverse direction (depth/width)(Fig. 12). Depth divided by width was chosen as an indicator of the geometry of the transverse profile of the starting zone in order to quantify the shape.

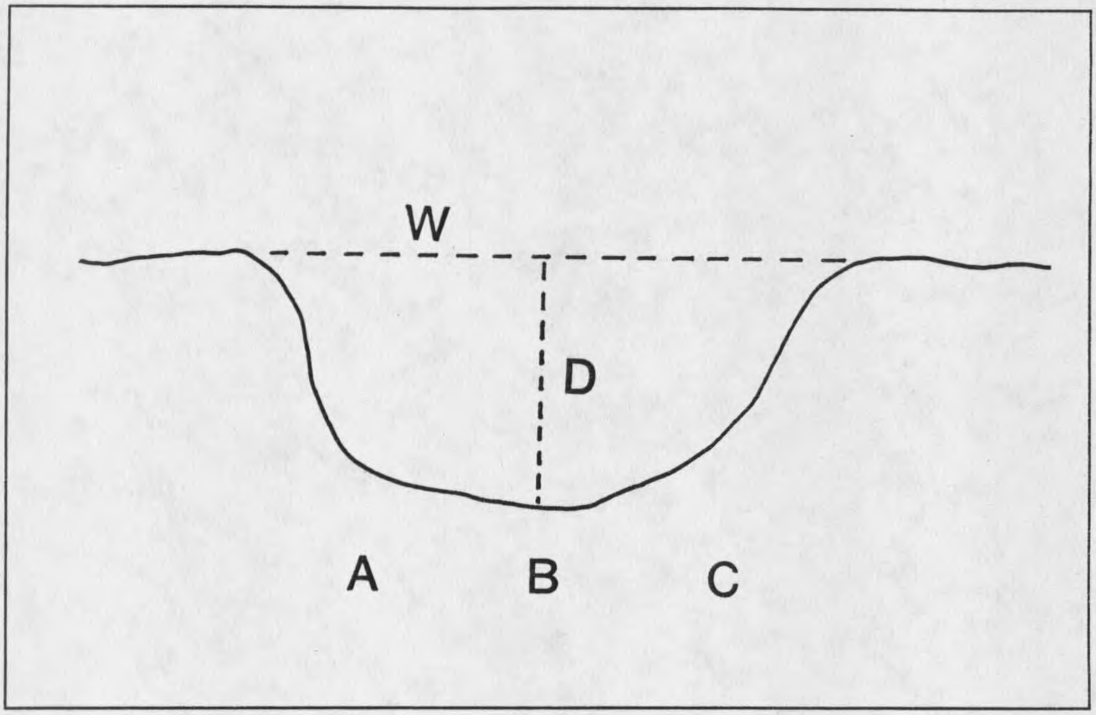

Figure 12. Cross section of starting zone (Transverse direction).W=Width, D=Depth. A, B and C correspond to the regions of the concavity.

A roughness parameter was also used to determine the effect of the roughness of the bed surface of the starting zone on avalanche frequency. Roughness was determined by measuring a 3 m profile of the bed surface in the fall line of the starting zone for each path.

Peak density, the number of peaks at least 10 cm per unit length of profile, was measured with each peak and trough height measured to the nearest centimeter. This data was then run in a model which determines the roughness of ice runways in Antarctica (Lang, 1992). A roughness coefficient between zero and five was determined for each profile. Higher numbers indicate rougher surfaces. Three to five profiles per starting zone were measured and the average roughness was calculated for each path.

Results and Discussion

When the parameters, depth, width, shape (depth/width) and roughness of the starting zone were run in a stepwise regression model with the natural log of natural release frequency per year as the dependent variable, the r-square was 0.99 (Table 6, Figs 13-15). Depth, shape factor and width were significant at the 0.1 level. Roughness was not significant. The terrain parameters altitude, aspect and slope angle were left out of the regression because these variables were controlled and were similar for all paths.

Table 6. Stepwise Regression Table for Natural Release Group Nested Study.

Variable	Partial R-square	Model R-square	P-Value
Depth	0.81	0.81	0.01
Shape Factor	0.17	0.98	0.02
Width	0.18	0.99	0.06

The high r-square value shows that the transverse profile geometry of the starting zone has a significant influence on avalanche frequency for these six avalanche paths on Lone Mountain. The transversely concave paths have significantly higher frequencies than the convex path. The greater loading of concave starting zones leads to a more unstable snowpack resulting in higher frequencies of avalanche release on transversely concave slopes.

For the natural release group the outlier on the plot of frequency verses width (Fig. 13) is first gully which is slightly wider than the other gullies. Figure 14 shows depth in the transverse direction verses frequency. The point with a negative value on the X axis is fifth gully which indicates its convex transverse profile. All other paths have positive values which indicate concave transverse profiles. Larger values on the X axis

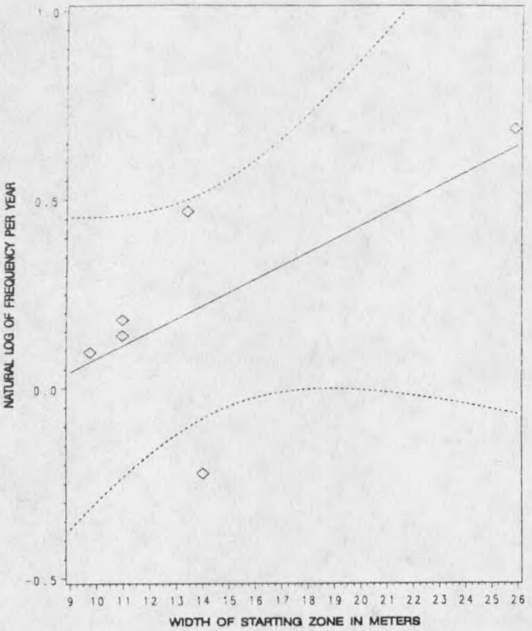

Figure 13. Natural log of avalanche frequency and width of starting zone. Nested study, natural release group.

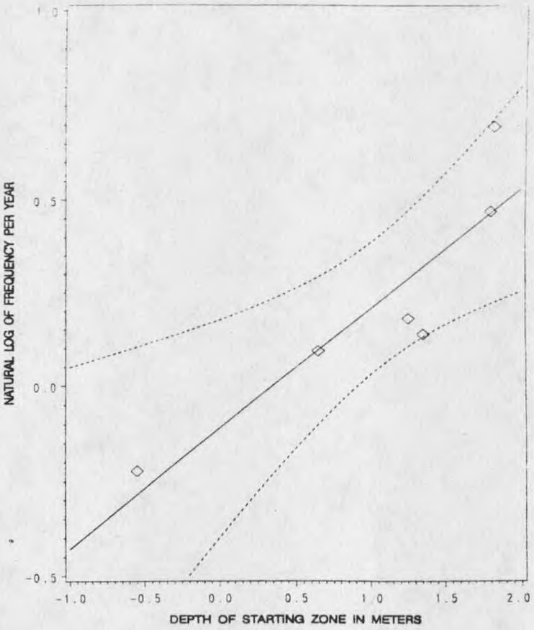

Figure 14. Natural log of avalanche frequency and depth of starting zone. Nested study, natural release group.

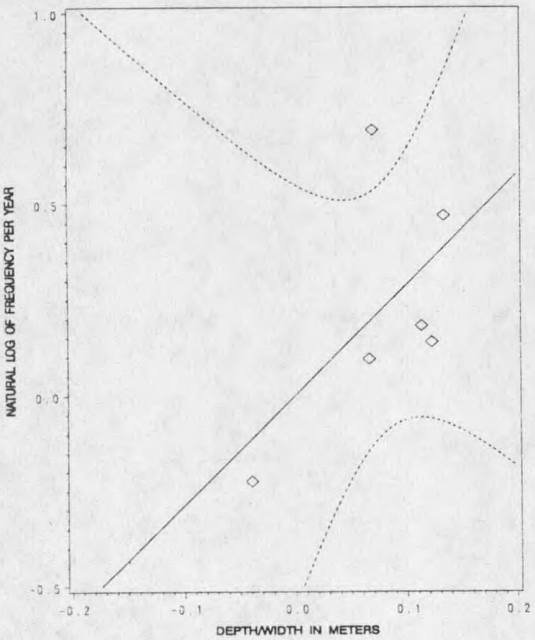

Figure 15. Natural log of avalanche frequency and depth/width (shape factor) of starting zone. Nested study, natural release group.

indicate more concave transverse profiles for paths that have similar widths. The shape parameter is designed to take both width and depth in the transverse direction into account by quantifying shape (Fig. 15). The negative value on the X axis represents fifth gully. The data quantitatively show that the shape of the starting zone in the transverse direction for these six paths influences avalanche frequency.

The depth of the starting zone is an indicator of the concavity or convexity of the shape of the starting zone in the transverse direction when the width is similar between paths. The more concave a starting zone is, the greater the depth value will be. The correlation to avalanche frequency can be explained by the fact that a more concave area will trap more blowing snow by providing a relatively low pressure zone in the concavity. As the wind decelerates it allows snow to deposit in the depression. More wind deposition of snow results in added weight and added shear stress on the snowpack which causes greater overall instability. Convex slopes provide an area of high wind velocity which can often deplete a convex area of its snow and produce low snow depths. Figure 16 shows some starting zones on Lone Mountain in the early fall season where snow has been deposited in the concavities and depleted from the flat and convex areas.

Another explanation of the influence shape has on avalanche frequency may be the slope angle of the sides of the starting zone.

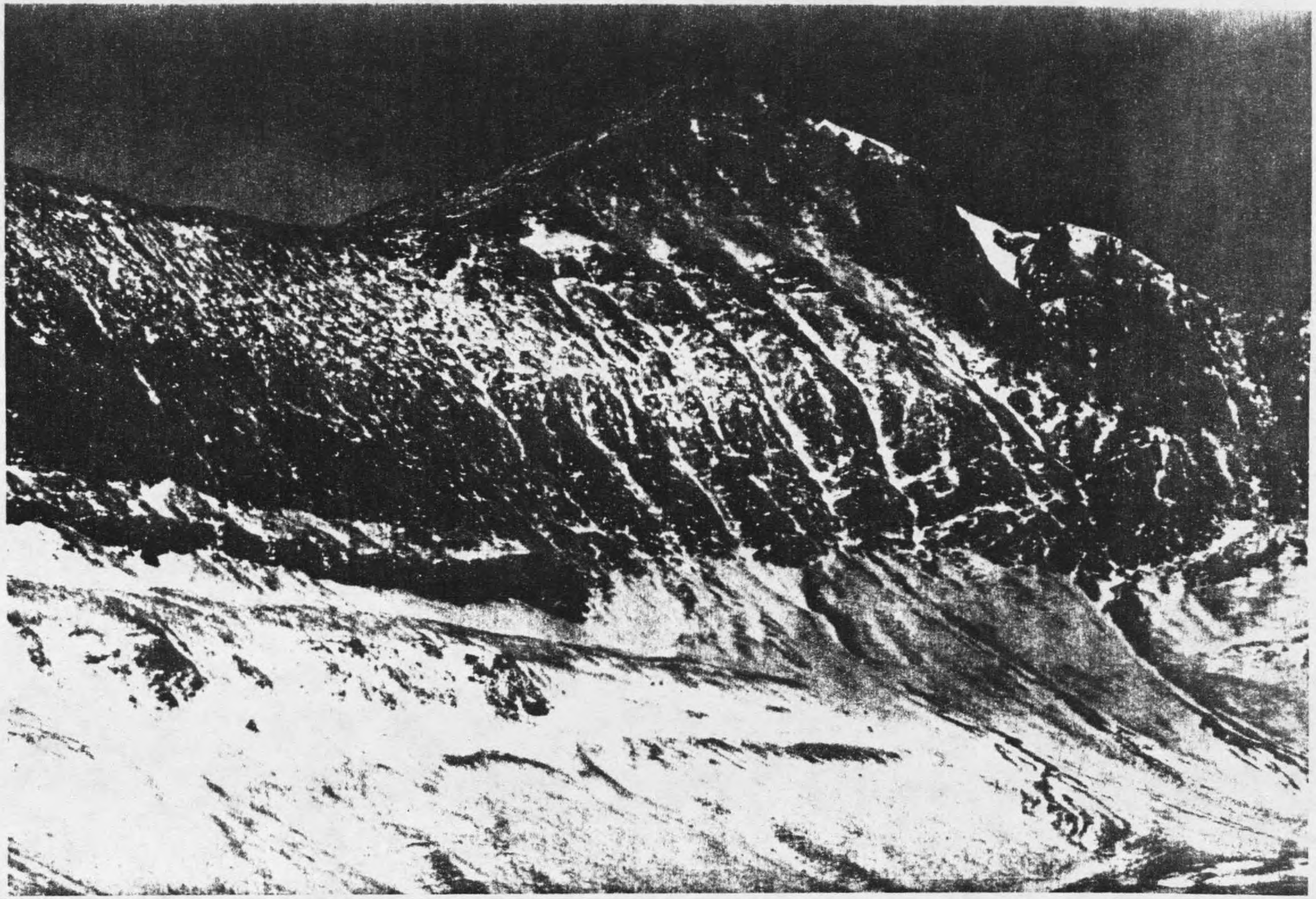

Figure 16. Starting zones facing northeast on Lone Mountain showing snow deposited in transverse concavities after the first snowfall of the season.

A transversely concave starting zone will have regions of varying degrees of steepness. In Figure 12, the sides of the path, regions A and C, will have a steeper slope angle than the middle of the path, region B. Avalanches increase in frequency as slope angle increases due to higher shear stresses and a larger percentage of shear deformation (McClung and Schaerer, 1993). Although no tests were conducted to measure a difference in shear stress between the middle and the sides of starting zones, such a difference is expected and should be tested.

A regression analysis was performed using the artificial release data set to compare the results with the natural release group. The three shape parameters, roughness and the number of explosive events for each starting zone were run in a stepwise regression model as independent variables to determine their effect on frequency (r-square 0.98, Table 7, Figs. 17-20). Depth, roughness and width of the starting zone were the only significant variables at the 0.1 level. The number of explosive events did not have a significant effect on frequency for the nested study. The path with the most bomb events did not have the highest frequency (Fig. 17). The starting zone with the convex transverse profile (Fifth gully) has a total of 280 bomb events. Fourth gully has a lower number of bomb events but a higher frequency. This suggests that the number of explosives used was not a significant factor influencing avalanche frequency for these six paths.

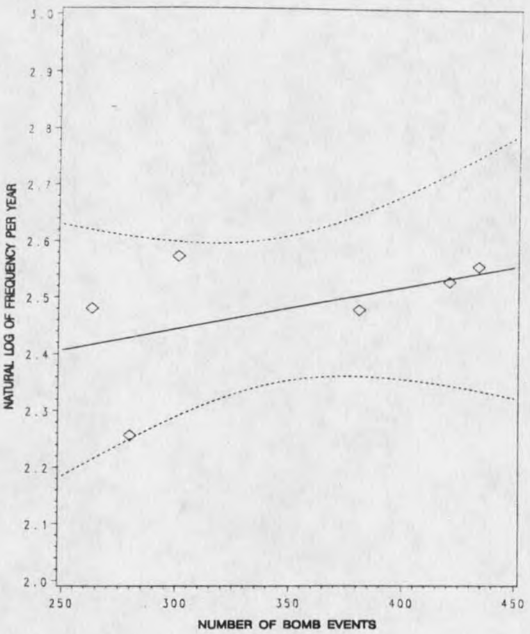

Figure 17. Natural log of avalanche frequency and bomb events. Nested study, artificial release group.

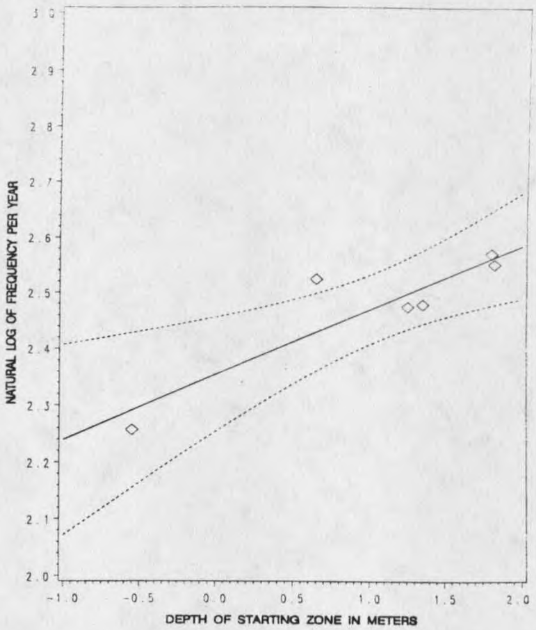

Figure 18. Natural log of avalanche frequency and depth of starting zone. Nested study, artificial release group.

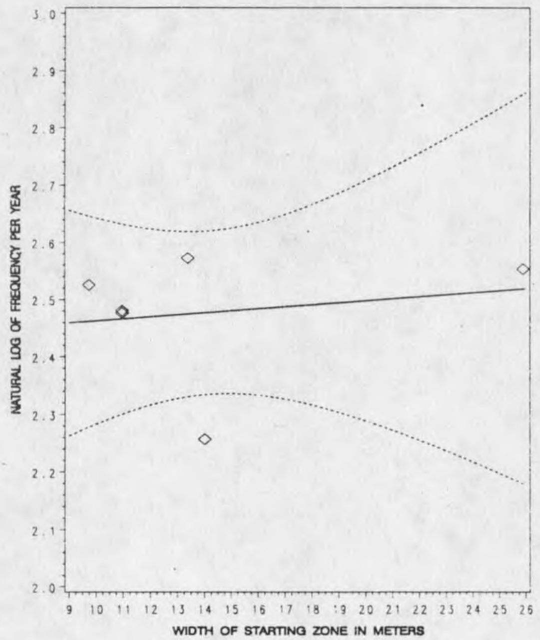

Figure 19. Natural log of avalanche frequency and width of starting zone. Nested study, artificial release group.

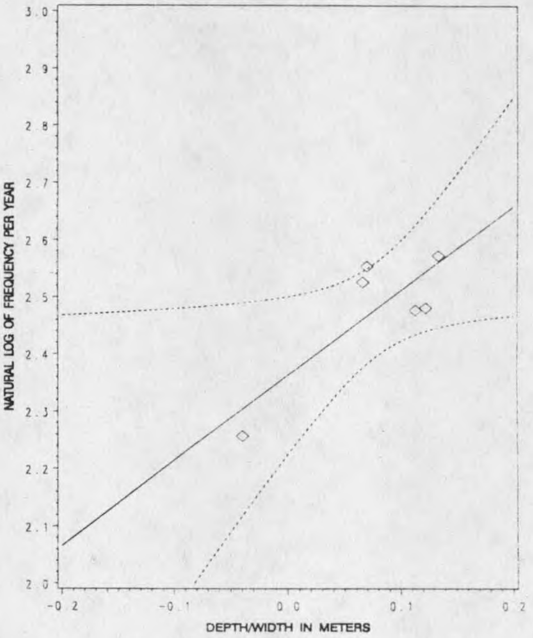

Figure 20. Natural log of avalanche frequency and depth/width (shape factor) of starting zone. Nested study, artificial release group.

The analysis shows that 87 percent of the variance regarding frequency can be explained by the shape parameters for the artificial release group (Table 7). This result demonstrates that transversely concave starting zones have higher frequencies of avalanches than starting zones with transversely convex profiles even when artificial methods are used for release.

Table 7. Stepwise Regression Table for Artificial Release Group - Nested Study.

Variable	Partial R-square	Model R-square	P-Value
Depth	0.82	0.82	0.01
Roughness	0.12	0.94	0.08
Width	0.05	0.99	0.10

The plot of depth verses frequency shows that the convex starting zone (the point with the negative X axis value) also has the lowest frequency for the artificial release group (Fig. 18). The plot of width is similar to the natural release group (Fig. 19). The plot of depth/width verses frequency also shows that the convex path with a negative depth/width value has the lowest frequency (Fig. 20). Even with the use of explosives as the release mechanism for avalanches the relative concavity in the transverse direction influences avalanche frequency.

For the six avalanche starting zones analyzed in the nested study, the geometry of the transverse profile had the most effect on avalanche frequency. Depth in the transverse direction was the most significant parameter for both the natural release group and the artificial release group. Depth is a measure for concavity in the transverse direction that describes how well the starting zone will trap blowing snow. The more snow that accumulates in a starting zone, the higher the shear stresses will be which leads to greater instability of the snow pack and higher avalanche frequency.

In the nested study, which controlled slope angle, elevation and aspect, the transverse profile geometry of the starting zone explained much of the variance regarding avalanche frequency. In both the natural and artificial release groups the transverse profile geometry explained most of the variance in the regression models for avalanche frequency based on the depth and shape factor parameters. These are terrain parameters that have not been previously examined for their influence on avalanche frequency. Although this type of analysis would be restricted to avalanche starting zones that are gullied in shape, it could prove useful in the understanding of avalanche control and forecasting in many areas with confined starting zones. The results of the nested study are suggestive based on the fact that the hypothesis relating the transverse profile geometry to avalanche frequency was developed during the study and was therefore not a priori. The high r-square values suggest that the relationship may be genuine, but can only be validated using data from another study area.

Some of the problems with the study of starting zone geometry at Big Sky include the small number of gullied starting zones, the lack of data from the A-Z chutes, and various other terrain parameters that had more influence on avalanche frequency than geometry. A future study may be useful in an area where more of the terrain parameters, such as aspect and elevation, were similar between starting zones and the terrain was dominated by gullies.

APPENDIX D. Regression Equations

(Yi is the response variable, predicted avalanche frequency.)

Natural Release Group (Table 3)

$$Yi = -12.5 + \text{Altitude}(0.002) + \text{Aspect}(0.009) + \text{Slope}(0.089) + \text{Wind}(-0.011)$$

Artificial Release Group (Table 4)

$$Yi = -7.4 + \text{Slope}(0.101) + \text{LnBombs}(0.912)$$

Nested Study - Natural Release Group (Table 6)

$$Yi = 0.75 + \text{Depth}(1.34) + \text{Width}(-0.057) + \text{Shape}(-14.4)$$

Nested Study - Artificial Release Group (Table 7)

$$Yi = 2.06 + \text{Depth}(0.149) + \text{Width}(-0.004) + \text{Roughness}(0.094)$$