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:
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.

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-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.

Stephan G. Custer ______________________ 5-6-96
Date

Approved for the Department of Earth Science

Andrew W. Marcus ______________________ 5/6/96
Date

Approved for the College of Graduate Studies

Robert L. Brown ______________________ 6/10/96
Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment for a master's degree at Montana State University-Bozeman, I agree that the Library shall make it available to borrowers under the rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature ______________________

Date May 29, 1996

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.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES-Continued

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.

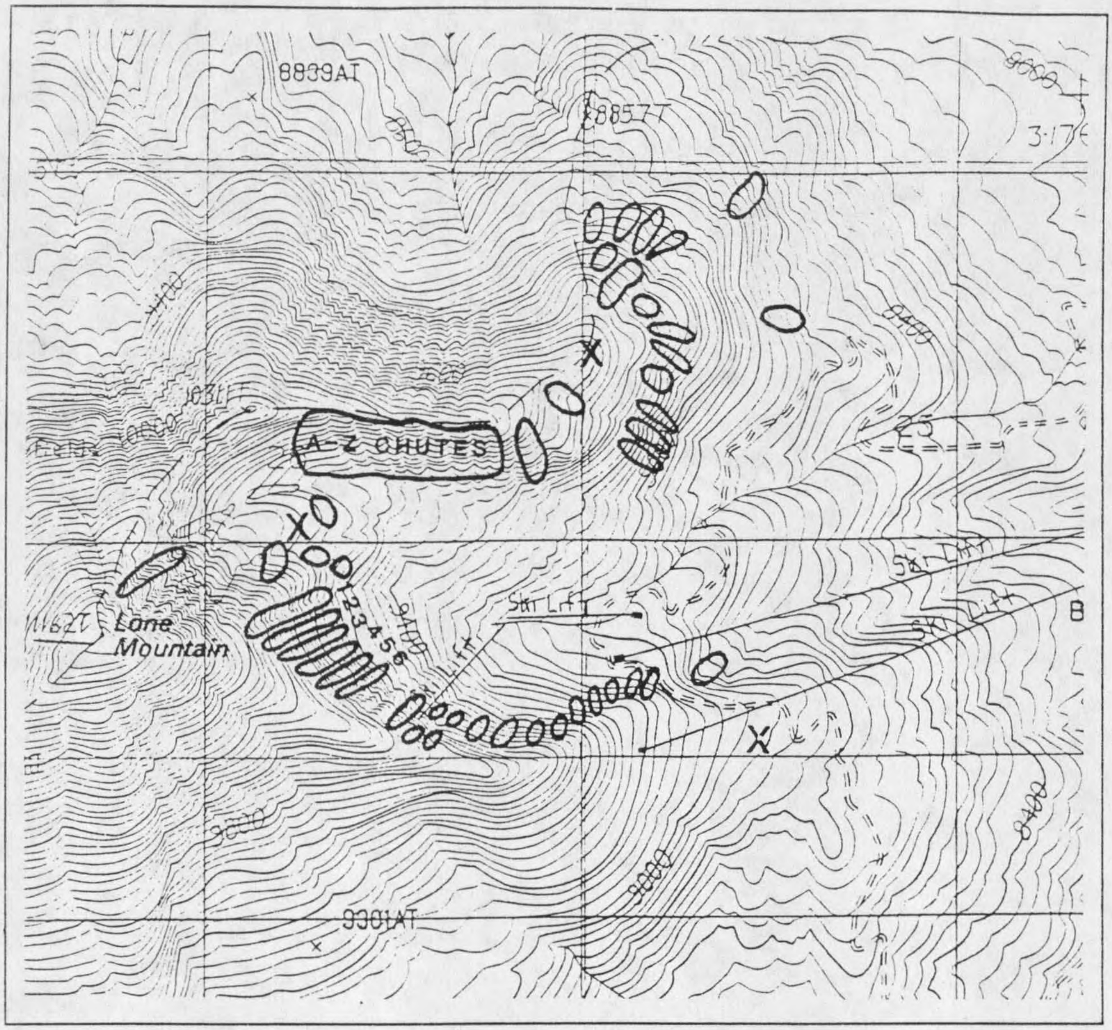
The overall conclusion one may draw from the literature regarding the importance of factors that affect avalanche occurrence is that there is no general consensus as to which parameters are most influential for indicating the probability of avalanche release, identifying potential avalanche slopes or 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; Tysdale 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

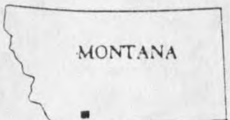


Avalanche Starting Zones 00

Anemometer Locations X

Contour Interval 40 FT

North



Study Site

SCALE

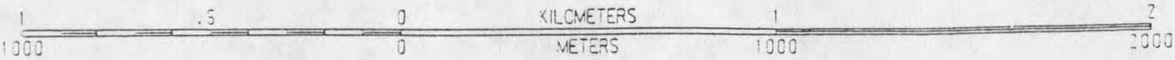


Figure 1. Avalanche path locations and anemometer locations on Lone Mountain. First through Sixth Gullies are numbered 1-6 (Appendix C). Light elliptical lines near the summit of Lone Mountain are snowfields from the original map.

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 Meters	Aspect Degrees	Slope Angle Degrees	Wind Factor	Depth (D) Meters	Width (W) Meters	Shape Factor D/W	Ln Bombs
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.