TERRAIN PARAMETERS OF AVALANCHE STARTING ZONES AND THEIR EFFECT ON AVALANCHE FREQUENCY

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ABSTRACT

Avalanche frequency data for 44 avalanche paths on Lone Mountain in southwest Montana were correlated with data on the terrain features of avalanche starting zones to determine which terrain parameters affect avalanche frequency. Over 3500 individual avalanche events were used in this study. The data were separated into two groups based on artificial and natural release. In the natural release group the parameters that influenced frequency included: altitude, aspect with respect to dominant wind direction, geometry of the starting zone and slope angle. These variables explained 62 percent of the variance correlating the terrain parameters to avalanche frequency. In the artificial release group the significant parameters included: the number of bomb events, altitude, aspect of dominant wind direction and slope angle. These variables explained 83 percent of the variance.

INTRODUCTION

Avalanche frequency data for 44 avalanche paths on Lone Mountain in southwest Montana have been collected by the Big Sky ski area since 1972. Over 3500 individual avalanche events were used in this study. These data were correlated with data on the terrain features of the starting zones of the avalanche paths in order to construct a sensitivity analysis to determine which terrain parameters affect avalanche frequency. The terrain parameters collected in the starting zone include; slope angle, aspect with respect to sun and dominant wind direction, altitude, and geometry of the starting zone. The geometry of the starting zone was calculated based on the concavity or convexity in the transverse direction of the path in order to describe a possible release mechanism for slab avalanches. These variables were correlated using a multiple linear regression model with avalanche frequency as the dependent variable and the terrain parameters as the independent variables. The correlation was broken down into two separate studies based on the release mechanism of the avalanche event,(ie. natural or artificial). Separate regressions were run on the natural and artificial, (explosive or skier induced), avalanche data sets in order to determine the effect of the terrain parameters without the influence of human-induced avalanche release.

LITERATURE REVIEW

The starting zone is typically an area between 30 and 45 degrees in steepness (Butler and Walsh, 1990; LaChapelle, 1985). Perla (1977) 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 et al. (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 subjective topographic classes used were: cirques, shallow depressions, scars, flat faces and convex slopes in the longitudinal direction (Lied and Bakkehoi, 1980). Butler (1979) classified starting zones into three types: bowl shaped slopes or cirques, rectilinear or open, even shaped slopes and channels or funnels which are confined gullies and couloirs. Geomorphologists have attempted to classify hillslopes shapes based on profile

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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 described in the study are qualitative and don't allow for a quantitative analysis of starting zone shape.

The variation of the slope angle in the longitudinal and transverse directions determines the concavity or convexity of a slope (Huber, 1982). This influences tensile strength of the snow pack and can have an affect on avalanche release. The shape of the slope influences its ability to collect snow. The concavity or convexity in the transverse profile direction can influence deposition and depth of snow (Luckman, 1978). Those paths that have a curved transverse 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).

To determine the importance of the parameters which influence avalanche occurrence, location and frequency and list them in a hierarchical fashion requires 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.

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.

Schearer (1981) lists parameters and weights them according to their importance regarding the probability of avalanche release and identification of potential avalanche slopes. He then lists these factors for use in snow stability analysis and gives the generally critical condition of each factor that affects avalanche occurrence. For the most critical factor, 'terrain in starting zone', he sites slopes greater than 25 degrees, abrupt change of incline, smooth surface and lee side of prevailing wind as generally critical conditions for avalanche occurrence. For snow depth, the second most important parameter, the critical conditions are; greater than 30 cm on smooth ground and greater than 60 cm on average ground. This study regards the static parameters of terrain analysis as the most critical factors affecting avalanche occurrence. This is based on the idea 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 meters 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, aspect and starting zone angle 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.

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. Most of the sources indicate a need for further research. There appears to be a gap in knowledge correlating the significance of the static terrain parameters to avalanche occurrence and frequency. By examining all the parameters involved in avalanche processes at different spatial scales, avalanche prediction can become more accurate and reliable.

STUDY AREA

Lone Mountain, located in the Gallatin National Forest in southwest Montana was chosen as the study area because of the relatively complete record of avalanche frequency data since 1972. The study area is located within the Big Sky ski area of Big Sky, Montana. The site is an excellent choice for this type of study because the avalanche paths are found on various different aspects and elevations allowing for the spatial analysis of the starting zones to be correlated with the avalanche frequency.

Lone Mountain is located within 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 hoar formation (Ueland, pers. comm., 1992). Average annual snowfall at Big Sky is 650 cm . Lone Mountain is located within the inter-mountain avalanche climate region (Mock and Kay, 1992). This region corresponds to LaChapelle's (1966) inter-mountain region which climatologically falls between the milder 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 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 monthly 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, which comes in an eighty column format, consisted of 5159 individual avalanche events. Only avalanches with at least a 15 cm. (6 inch) crown line were reported. The data were loaded onto a Quattro Pro spreadsheet program in order to parse as well as clean up the data. Unfortunately with data that is collected by various personnel over twenty years, input is not always consistent. When avalanche path names were spelled a different way they showed up in the data as separate paths. 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 were examined for 44 known avalanche paths.

The starting zones of each avalanche path were located using the information in the data set 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 summer the starting zone locations were confirmed by debris from the bomb casings. These typically consisted of paper hand charge casings or plastic avalauncher tailfin assemblies.

The shape of the starting zone of each avalanche path was calculated during the summer field sessions. A system to quantify the relative concavities and convexities of the starting zones was needed in order to correlate the geometry with the avalanche frequency. 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 were relatively easy to estimate. 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 slope was concave, the depth from the side of the starting zone to the midpoint of the path was measured on the stadia rod to the nearest centimeter. If the slope was convex, the Abney level was sighted from the midpoint to the side of the starting zone where the stadia rod was being held. If the slope was convex, a negative value was assessed to the depth reading. Three to five transverse profiles were measured for each starting zone and an average depth was calculated. The average starting zone width was 13.45 meters with a mode of 10.97 meters.

Weather data was collected by the United States Forest Service's Westwide Avalanche Network. Average wind speed and direction were compiled at three locations at Big Sky ski area.

The number of explosives used was compiled from the files of the Big Sky ski patrol since 1972. 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) was not distinguished for this study because the trigger mechanism for the release of the avalanche events was recorded only as artificial or natural.

RESULTS AND DISCUSSION

The data set, which includes avalanche frequency and terrain parameters for each path, was broken down into sub-groups 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. These were avalanches that released without the influence of explosives or other human activity. The second 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. Relative avalanche frequency was correlated with the terrain parameters in a multiple linear regression model. Avalanche frequency was run as the dependent variable. The terrain parameters were run as independent variables and included; altitude, slope angle, aspect with respect to dominant wind direction, width and depth of the starting zone, as well as a shape parameter which was the log of path depth divided by path width. In the artificial release group, the number of explosive events was also put into the model 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. Each terrain parameter was then plotted in a scattergram with relative frequency to observe 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.

NATURAL RELEASE GROUP

The natural release group consists of those avalanches released without the use of explosives 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 multiple linear regression model was used to correlate avalanche frequency to the terrain parameters of the starting zone. Relative avalanche frequency was used as the dependent variable in the regression model and the terrain parameters were run as independent variables. The terrain parameters of the starting zone used in the model for correlation with avalanche frequency were: slope angle, altitude, aspect with respect to dominant wind direction, width and depth of starting zone, the log of depth divided by width, and a multiple variable term of aspect*width. When all of these terms were run in a multiple linear regression model, an R-square value of 0.626 was achieved(Table 1). The adjusted R-square value was 0.547. This shows that the number of variables used in the model is valid for the explanation of the variance between the terrain parameters and avalanche frequency. The terrain variables are independent of one another based on the low variance inflation values. Variance inflation values range from one to ten, with one being the case where the predictors are completely independent of one another. The variance inflation numbers for this data set are all very close to one, which indicates that the independent variables are not highly correlated to each other.

The most significant terrain variable that influenced avalanche frequency was altitude of starting zone. The scattergram of relative avalanche frequency verses altitude shows that this relationship is based mostly on six individual avalanche paths with high frequencies (Figure 1). These paths are named first through sixth gullies and are located above the Bowl on the northeast

REGRESSION TABLES

NATURAL RELEASE GROUP

R- Square 0.6262
Adjusted R- Square 0.5469

VARIABLE	PROB > |T|	VARIANCE INFLATION
Altitude	0.0006	1.333
Dominant Wind Direction	0.0139	1.719
Aspect*Width	0.0154	1.088
Depth	0.2087	1.501
Width	0.5624	1.26
Slope Angle	0.8792	1.712
Log Shape	0.9609	1.53

ARTIFICIAL RELEASE GROUP

R- Square 0.8368
Adjusted R- Square 0.7992

VARIABLE	PROB > |T|	VARIANCE INFLATION
Bombs	0.0071	457.56
Slope*Bombs	0.0021	485.27
Altitude	0.0851	2.217
Dominant Wind Direction	0.1928	1.358
Slope Angle	0.3241	5.603
Log Shape	0.9808	1.181

ARTIFICIAL RELEASE GROUP

(BOMB EVENTS ONLY)

R- Square 0.8067
Adjusted R- Square 0.7960

(WITHOUT BOMB EVENTS)

R- Square 0.7761
Adjusted R- Square 0.7201

cirque of Lone Mountain. When the data are examined with these paths taken out, altitude is not as significant a variable.

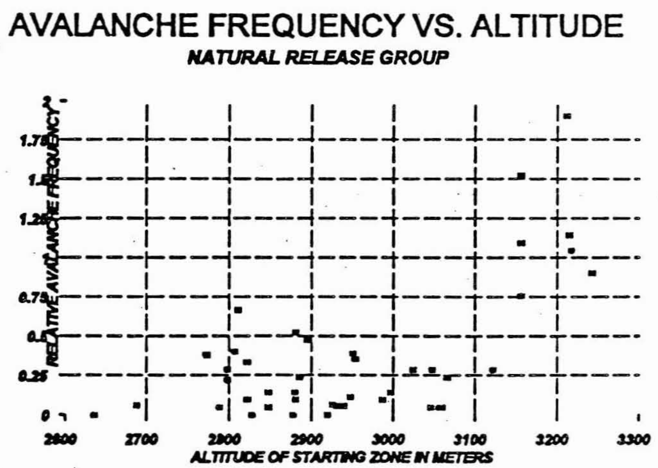

FIGURE 1

The second most significant terrain parameter is aspect with respect to dominant wind direction. The dominant wind direction, based on data from three weather stations on Lone Mountain, was from the southwest (237 degrees azimuth). Any slope in the lee of this direction would have significant snow loading. Subtracting 180 degrees from 237 gives the aspect of the starting zone which is most influenced by the dominant wind direction. This aspect, 57 degrees azimuth, was used as the basis for the parameter used in the model. The actual aspect in degrees azimuth of each starting zone showed a non-linear relationship with avalanche frequency (Figure 2). It was recognized that the highest incidences of avalanche occurrence clustered around the aspect most influencedby the dominant wind direction. Therefore, an aspect term was created by subtracting 57 degrees, the aspect most influenced by the wind, from the actual aspect of each starting zone. This created a variable relative to the dominant wind direction that had a linear relationship with relative avalanche frequency and was used in the model (Figure 3). The model shows that the aspect with respect to dominant wind direction is significant with a T probability estimate parameter of 0.0139. This quantitatively shows that loading due to the wind is a significant factor in avalanche release on Lone Mountain. The data show that the frequency of avalanche occurrence generally declines the further the aspect deviates from the dominant wind direction of

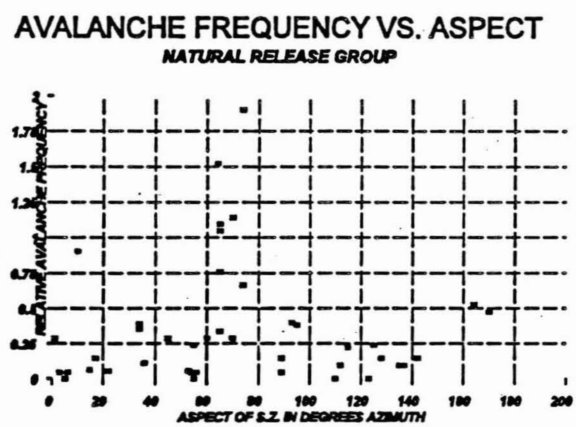

FIGURE 2

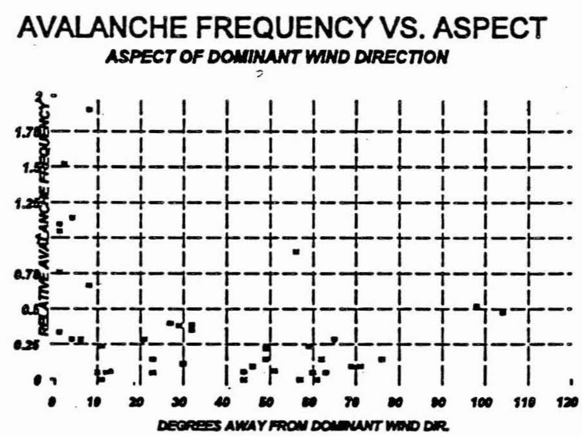

FIGURE 3

The aspect verses frequency data do not explain the effect of solar radiation on the snowpack in the starting zones. Although it is generally regarded that more northerly facing slopes will have colder temperatures and therefore more depth hoar development leading to greater instability, these data do not show a significant relationship relating avalanche frequency with the angle of incidence of solar radiation (Schaerer, 1981). This could be due to a lack of data for a significant number of the southerly facing avalanche paths at Big Sky. Twenty six southerly facing avalanche paths were not included in the data set because individual avalanche events for unique paths were not recorded in the data set. The paths were lumped together as one group whenever an avalanche occurred. The number of individual avalanches was not recorded and therefore these data could not be used in this study.

The third most significant term affecting avalanche frequency is the aspect*width term. This multiple variable term is significant with a T probability value of 0.0154. This term interprets the interaction between the width of the starting zone and its aspect and relates this interaction to avalanche frequency. Width by itself does not significantly affect avalanche frequency (T probability value-0.5624). When width is run as a multiple variable with aspect it does affect avalanche frequency. This is due to the effect wind has on snow loading relative to the width of the starting zone. A larger starting zone has the capability to load more snow and increase instability by adding more shear stress to the snowpack.

The depth of the starting zone is the next most significant parameter affecting avalanche frequency with a T probability value of 0.2087. Although it is not as significant as the three previous parameters, depth is the last variable to have any deterministic significance. 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. The greater the depth value, the more concave a starting zone 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 with more eddy currents and decreased flow velocity. As the wind decelerates it allows snow to deposit as it is blown across 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 do not provide this area of low pressure and wind can often deplete a convex area of its snow.

Another explanation of the influence shape has on avalanche frequency may be the slope angle of the sides of the starting zone. A transversely concave starting zone will have regions of varying degrees of steepness. The sides of the path will have a steeper slope angle than the middle of the path. This difference in slope angle may influence avalanche frequency. Slab 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 strengths between the middle and the sides of starting zones, the results could explain the significance of this parameter. The geometry of the starting zone is shown to influence avalanche frequency although the correlation explains only a small part of the variance.

The effect of slope angle in the starting zone on avalanche frequency was insignificant for the natural release group (Prob. T Value: 0.8792). The scattergram of avalanche frequency verses slope angle shows a non-linear relationship between the variables (Figure 4). Avalanche frequency peaks at 40 degrees then tapers off as the slope angle increases. The frequency does not, however, assume a normal distribution pattern. A smooth curve cannot be approximated for this data, but some conclusions can be formulated. There is a cluster of high frequency starting zones between 40 and 44 degrees. Although this is higher than Perla´s (1977) predicted slope mean of 38 degrees for slab avalanches, it does fall within his estimated standard deviation of five degrees. Avalanche frequencies decrease as the slope angle increases above 42 degrees. 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 1977). Because the correlation between frequency and slope angle is weak for this data set, no conclusions can be drawn that relate avalanche frequency to slope angle for the natural release avalanches on Lone Mountain.

The last parameter in the regression model is Logshape, which is the natural log of depth of the starting zone divided by width of the starting zone. 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 with a meaningful number. Because some of the depth values were zero, depth was divided by width in order that no denominators had a zero value. The scattergram of avalanche frequency verses path shape shows a clustered relationship with three distinct groups along the X axis, logshape (Figure 5). The group at zero represents starting zones with convex transverse profiles. The group clustered around log one represents starting zones with concave transverse profiles. Numbers closer to one have the most concave profile. In other words the ratio of the depth of the profile to the width of the profile is relatively larger as the values approach one. The group clustered around log four represent flat transverse profiles with neither convex nor concave characteristics. Although the non-linearity of this variable results in little statistical significance for this regression model, some conclusions can be drawn from the scattergram. The highest frequencies are found in the concave profile group. This is probably due to the effect of wind loading on concave surfaces. Because there is a large number of lofrequency starting zones in this group, a strong correlation does not exist between avalanche frequency and the geometry of the starting zone. The lowest frequency starting zones are found in the convex group. This may be due to deflation of the snow surface on the rounded features of these starting zones. A strong statistical correlation does not exist, so these conclusions are qualitative.

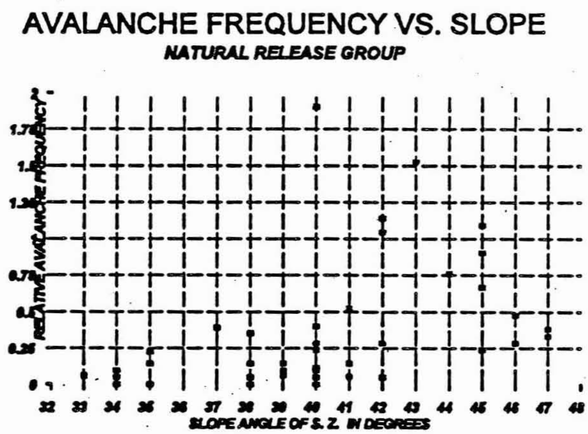

FIGURE 4

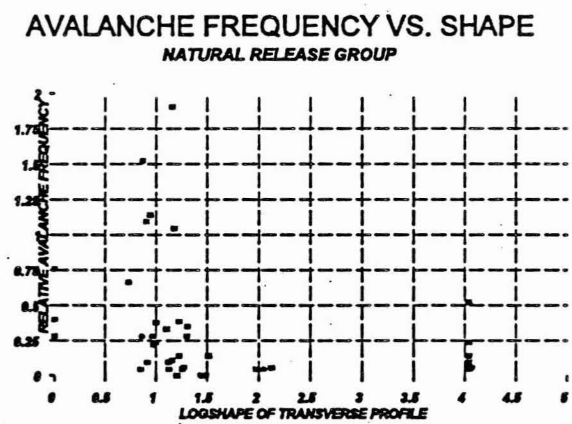

FIGURE 5

The data from the natural release group show that there are many terrain variables which affect avalanche frequency. Although some variables showed little or no significance in their correlations to avalanche frequency, some of the low correlations can be explained by the incompleteness of the data set. Slope angle of the starting zone for example, had little significance in this data set, whereas other workers have found slope angle to be a significant factor in avalanche frequency (Perla, 1977; Schaerer, 1981; Judson and King, 1984;). The addition of these 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.

ARTIFICIAL RELEASE GROUP

The artificial release group contains 3229 individual avalanche events that were released by explosive or ski cutting. Relative avalanche frequency was run as the dependent variable in a multiple linear regression model. The terrain parameters, which were run as the independent variables in the regression equation, include: slope angle, altitude, number of explosive events, aspect and geometry. When an analysis of variance was performed using these variables, an R-square value of 0.8368 was calculated(Table 1). The adjusted R-square value, 0.7992 is close to the actual R-square value for the data set. This is an indictor that an allowable number of variables was used in the regression model. If too many variables are put into a model to increase the R-square value, the adjusted R-square value would drop significantly. The close correlation 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.

The most significant parameter affecting avalanche frequency in the artificial release group was the number of explosive events for each avalanche path (also referred to in this paper as a bomb event). An explosive event is defined by the use of any type of explosives 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. The scattergram of relative avalanche frequency and number of explosive events shows a linear relationship between the two variables, allowing the explosive term to be run in the linear model (Figure 6).

When the number of explosive events was correlated by itself against avalanche frequency the R-square value was 0.80. Without the explosive term in the model an R-square value of 0.7761 was calculated. Because the R-square value without the explosive term remains large, the explosive term is not independent of the terrain parameters. Therefore the explosive term must be covariant to the other terrain variables. This may be due to the intrinsic relationship between the terrain and bomb placement. In other words, the initial bomb placements were located in areas where avalanche release was probable. The locations for these initial placements were found by observing known starting zones and by trial and error in the early seventies (Ueland, pers. comm., 1992).

When slope angle and the number of explosive events are multiplied together to form a multiple variable, the term is relatively significant. This shows that the slope angle is covariant with the number of bomb events, thus the placement of the bomb was originally decided based at least in part on the slope angle.

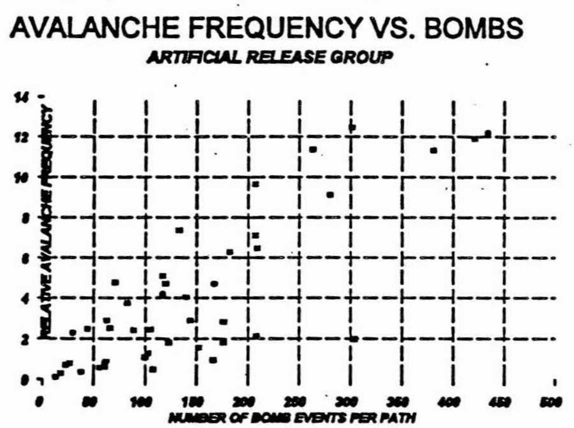

FIGURE 6

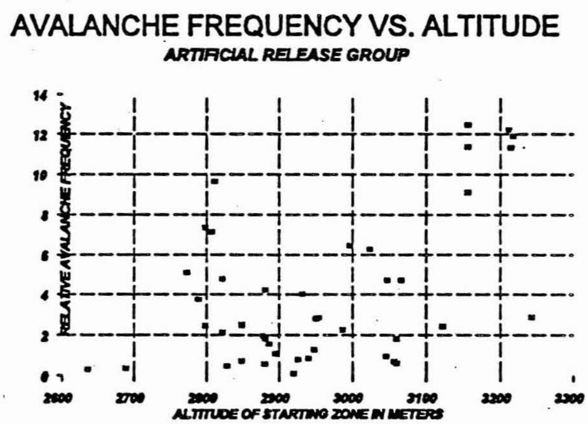

FIGURE 7

The second most significant parameter affecting avalanche frequency is altitude. The scattergram of avalanche frequency verses altitude shows a weak trend toward a linear relationship (Figure 7). This is due to a cluster of starting zones around the 2800 meter elevation that have relatively high frequencies. These paths are located on the Big Rock Tongue found on the Challenger side of the study area. The high significance of the altitude parameter appears to be based on the cluster of six starting zones with the highest frequencies. These are the first through sixth gullies located above the Bowl on the northeast cirque of Lone Mountain. 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 rate at which the air is lifted over a mountain (McClung and Schaerer, 1993).

The third most significant parameter affecting avalanche frequency is the aspect of the starting zone with respect to the dominant wind direction. The aspect parameter does not show a linear relationship to avalanche frequency (Figure 8). This is due to a cluster of high frequencies around 60 degrees azimuth. When the aspects of the starting zones are calculated based on their relationship to the dominant wind direction a linear relationship is found with avalanche frequency and allows the variable to be run in the model (Figure 9). The relatively high significance of this parameter shows that the influence of wind strongly affects avalanche frequency. This is due to the lee slope deposition of wind transported snow.

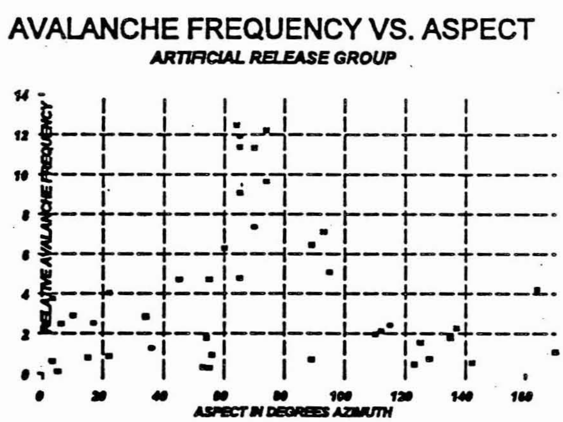

FIGURE 8

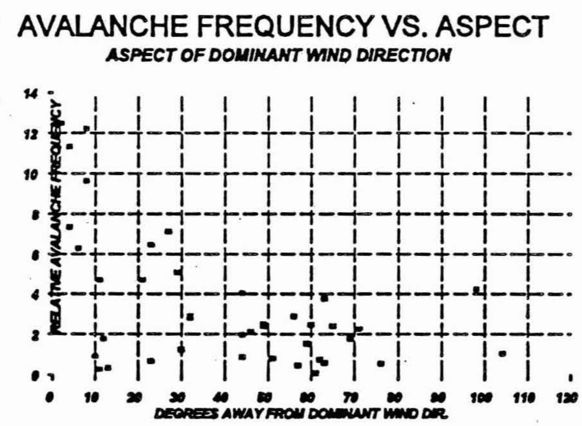

FIGURE 9

The next most significant parameter for the artificial release group is slope angle of the starting zone. The scattergram of slope angle verses avalanche frequency shows a linear relationship up to a slope angle of 40 degrees (Figure 10). At this point the frequency begins to decrease as the slope angle increases. 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. Another explanation may be the effects of continuous control by explosives which may also affect the stability of the snowpack by constantly releasing any unstable snow.

The shape of the starting zone did not significantly affect avalanche frequency for the study area within the artificial release group. This term was calculated by taking the log of depth divided by width of the starting zone. The log of this variable was used to increase the linearity of the variables (Figure 11). When the width and depth parameters were run by themselves in the model, no significant correlation to avalanche frequency was found.

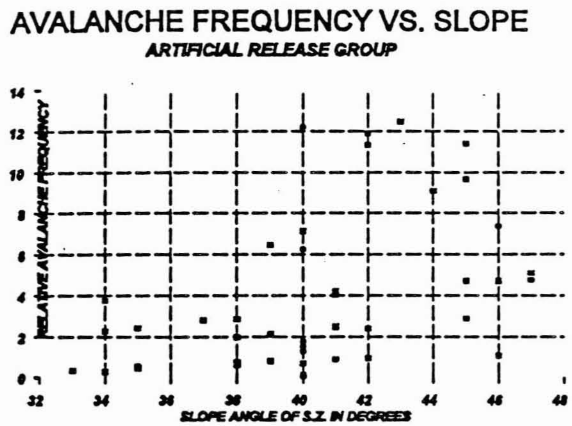

FIGURE 10

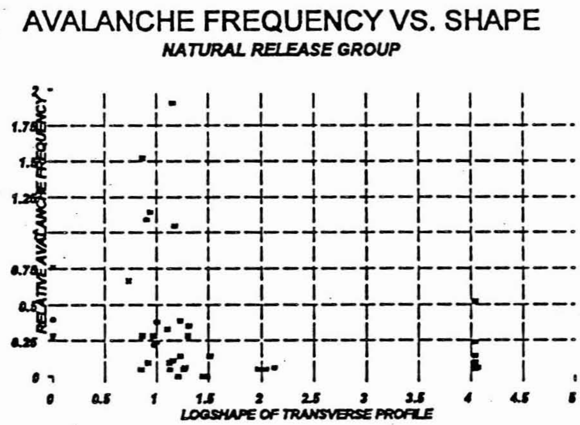

FIGURE 11

In the artificial release group the number of bomb events was the most significant variable affecting avalanche frequency. Certain terrain parameters however, also had some influence on avalanche frequency. This suggests that the placement of an explosive was based on terrain variables such as slope angle and aspect in order to insure release of an avalanche.

CONCLUSION

Terrain parameters of avalanche starting zones can explain a significant part of the variance regarding avalanche frequency. The data in this study show that altitude and aspect with respect to the dominant wind direction are the most significant terrain parameters that influence avalanche frequency in the natural release group. The geometry of the starting zone is not as statistically significant but still explains some of the variance. The number of explosive events explains most of the variance for the artificial release group. Because of the covariation between the terrain parameters and the bomb events, the terrain parameters exert a significant influence over avalanche frequency in their relationship to bomb placement. The unexplained variance of avalanche frequency may be due to dynamic snow and weather parameters that were not part of this regression analysis.

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