



The spatial variability of snow resistance on potential avalanche slopes
by Karl Wessel Birkeland

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences

Montana State University

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Abstract:

Since snow avalanches are believed to release from zones of localized weakness, knowledge of snow strength patterns is important for determination of slope stability and for the application of effective avalanche control measures. No previous studies have mapped snow strength over an entire inclined snow slab. In this study, the spatial variability of snow resistance (an index of snow strength) and depth were measured and compared with terrain features on two inclined slopes in Montana during two winter field seasons. An instrument that indexes snow strength by measuring snow resistance was refined, allowing the strength of an entire snow slab to be characterized in a short time. Measurements of depth and resistance were taken at 1 m intervals across and down the slopes. The spatial pattern of trees appears to affect the pattern of snow depth at the first site, where a significant linear relationship was found between snow depth and average snow resistance during both years of study (p-values $< 1 \times 10^{-6}$). When data sets were reduced to lessen the effects of spatial autocorrelation, the relationship between snow depth and average resistance continued to be significant (p-values $< 7 \times 10^{-3}$). These results suggest that localized snow depth variations may be important in snow strength genesis. Although a linear relationship existed at that site, low r values for the two years ($r^2 < 0.357$) indicate additional factors may be critically relevant. A second site with greater complexity of terrain features and less localized wind drifting did not show a linear relationship between depth and average resistance. Complicated patterns of resistance at that site demonstrate that many factors contribute to snow resistance. In particular, the snow over rocks was found to have significantly weaker resistance than adjacent areas which were not over rocks (p-value $< 1 \times 10^{-6}$). Results may provide predictive information of weak zone locations in snow slabs, which would improve avalanche forecasting and control techniques.

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

June, 1990

N378
B5344

ii

APPROVAL

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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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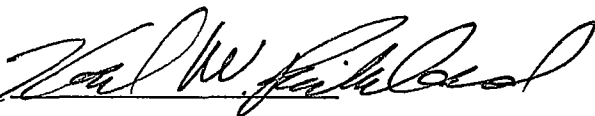
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ACKNOWLEDGEMENTS

I would like to acknowledge the support of my graduate committee, Katherine Hansen-Bristow, Robert Brown, Stephen Custer, John Montagne, Jeff Banfield, and Joe Ashley. Of the above, Kathy, Bob, and Jeff deserve my special thanks for their input and encouragement throughout the project. My fellow graduate students provided encouragement and suggestions, especially Janet Hardy, my fellow snow studies student. I would like to thank William Quimby (Department of Mathematical Sciences, Montana State University) for consultations regarding spatial statistics, and Carol Bittinger (Computing Services, Montana State University) for help with some of the graphics. Several individuals helped with field work, especially Doug Williams, Paul Tackett, and John Sperry. John Amend, Allan Overcast, and Bruce Ivey (Department of Chemistry, Montana State University) developed the microprocessor that was used for the Digital Resistograph. Bridger Bowl Ski Area provided discounted season passes and tickets for field assistants, and the Bridger Bowl Ski Patrol provided logistical support. Much of this work was supported under a National Science Foundation Graduate Fellowship, and additional financial support was provided by the Office of the Vice President for Research at Montana State University, Sigma Xi, the Montana Technological Development Trust, and the Montana State University Research and Development Institute. Finally, I would like to acknowledge the support of my parents, Peter and Suzanne Birkeland, and my sister, Robin Birkeland, who have provided me with the confidence to make goals and achieve them.

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ABSTRACT

Since snow avalanches are believed to release from zones of localized weakness, knowledge of snow strength patterns is important for determination of slope stability and for the application of effective avalanche control measures. No previous studies have mapped snow strength over an entire inclined snow slab. In this study, the spatial variability of snow resistance (an index of snow strength) and depth were measured and compared with terrain features on two inclined slopes in Montana during two winter field seasons. An instrument that indexes snow strength by measuring snow resistance was refined, allowing the strength of an entire snow slab to be characterized in a short time. Measurements of depth and resistance were taken at 1 m intervals across and down the slopes. The spatial pattern of trees appears to affect the pattern of snow depth at the first site, where a significant linear relationship was found between snow depth and average snow resistance during both years of study (p -values $< 1 \times 10^{-6}$). When data sets were reduced to lessen the effects of spatial autocorrelation, the relationship between snow depth and average resistance continued to be significant (p -values $< 7 \times 10^{-3}$). These results suggest that localized snow depth variations may be important in snow strength genesis. Although a linear relationship existed at that site, low r^2 values for the two years ($r^2 < 0.357$) indicate additional factors may be critically relevant. A second site with greater complexity of terrain features and less localized wind drifting did not show a linear relationship between depth and average resistance. Complicated patterns of resistance at that site demonstrate that many factors contribute to snow resistance. In particular, the snow over rocks was found to have significantly weaker resistance than adjacent areas which were not over rocks (p -value $< 1 \times 10^{-6}$). Results may provide predictive information of weak zone locations in snow slabs, which would improve avalanche forecasting and control techniques.

CHAPTER 1

INTRODUCTION

The purpose of the study was to identify and quantify general strength characteristics of potential avalanche slabs and to compare areas of relative strength or weakness with geographic features. Researchers have proposed that localized weak areas (described as having weak shear strength) within a slab fail initially, triggering full slab failure and resulting in an avalanche (Gubler and Armstrong, 1983; Smith and Sommerfeld, 1985; Gubler and Bader, 1989). If failure of such weak zones is a prerequisite for avalanche initiation, then locating these areas becomes critical. Patterns of snow resistance (an index of snow strength) within potential avalanche slabs in continental climates may be related to vegetation and rock outcrop patterns, and with wind patterns related to both ridges and trees. The objectives of this study were: 1) to determine if snow resistance variations across a slab can be identified and measured, and 2) to compare geographic features (specifically, rocks and trees) of the study area with measured intervals of snow resistance of the entire inclined snow slab. Characterization of potential avalanche slabs using resistance may eventually lead to increased knowledge of the distribution of weak areas on a slope. Knowing weak zone distribution would, in turn, aid in avalanche forecasting and control. The contribution of weak zones to avalanche initiation is important based on what is known about snow failure under differing strain rates. Snow strength decreases with increasing strain rate (Brown, 1977; Narita, 1980). Strain rates induced by new snowfall, a skier, or an explosive have been shown to be relatively slow when compared to rapid strain rate increases applied by

fracture propagation from a localized failure in the snowpack (Gubler and Armstrong, 1983). Typical strain rates in snowcover resulting from snowfall have orders of magnitude of 10^{-6} /second and rates associated with explosives are on the order of 10^{-3} /second, while strain rates resulting from fracture propagation approach 1/second (Gubler and Armstrong, 1983). Thus, certain areas of a slope that would fail in response to strain rates caused by fracture propagation initiating at a localized weak area may not fail under strain rates applied by the traditional avalanche control measures of using explosives or ski cutting.

The above results are important in terms of avalanche control work. Use of control techniques may not be effective unless applied to weak areas of the snow. Placing explosives in locally stronger areas may give a false sense of security about slope stability. Improper placement of explosives has been advanced as a major cause of "post-control release" avalanches (avalanches which run minutes to hours after avalanche control measures have been applied) (Williams, 1978). Since currently there is little available data, and therefore no method for predicting exactly where a weak area may occur, aerial detonation of explosives has been promoted for use in avalanche control. Aerial blasts impact the largest possible area of a snowpack, thus increasing the chance of impacting a weak area and causing initial failure to occur (Gubler, 1977). Field observations indicate that aerial explosions do cause a greater percentage of snow from avalanche starting zones to release than do in-snow blasts on adjacent slopes, presumably because the aerial blasts are impacting more weak areas of the snowpack (Juergens, 1984). Further, the use of aerial explosions for avalanche control in Switzerland has reduced the incidence of post-control release avalanches (Gubler and Armstrong, 1983). Using aerial explosives to impact every region of every starting zone,

however, is neither feasible nor economic. The present study may provide important information about the location of varying strength patterns in inclined snow slabs, eventually aiding in the prediction of weak zone locations and the improvement of avalanche forecasting and control techniques.

Previous Studies

Previous studies have verified the existence of weak zones in snowpacks. Acoustic emissions data have demonstrated localized failure, and measurements of strain rates in snowcover have provided convincing evidence for weak zone failure being the mechanism for avalanche initiation. In addition, in-situ field measurements of snow shear strength on avalanche crowns and multiple Rutschblock tests (Föhn, 1987) have shown snowpack strength variability.

As a snowpack fails, certain distinguishable noise emissions can be detected with geophones. Studies utilizing these acoustic emissions have been done in various regions, including Montana, Colorado, and Switzerland. In a review of these investigations, Sommerfeld and Gubler (1983) concluded that the radii of areas of initial dislocation (or failure) were 0.1 to 1.0 m. This indicated that small (0.03 to 3.1 m^2) weak areas were where initial failure appeared to be taking place.

Recent measurements of strain rates in snowcover have provided additional evidence for weak zone failure as the only plausible mechanism for avalanche release. Field observations indicate that quick brittle failure is the predominant mechanism during avalanche release (Sommerfeld, 1969). However, localized strain rates in natural inclined snow covers rarely exceed 10^{-4} /second (Gubler and Bader, 1989), and strain rates in excess of 10^{-4} /second are required for brittle failure (Smith and Sommerfeld, 1985). Thus,

during the initiation of a natural avalanche small weak areas must be experiencing ductile failure (which takes place at strain rates less than 10^{-4} /second (Narita, 1980)). As that ductile failure spreads, the strain rates at the tip of the fracture are increased until they exceed 10^{-4} /second, sending the snow slab into the observed widespread brittle failure and resulting in an avalanche (Gubler and Bader, 1989).

The first attempts at in-situ field measurement of localized strength variability in snow slabs were made in New Zealand by Conway and Abrahamson (1984a, 1988) utilizing a shear strength test. Shear strength, the resistance of the snow slab to being pulled off its bed surface, is measured by isolating a column of snow, inserting a shear frame, and pulling on the frame with a force gauge. With this test the above authors measured strength variability across crown-faces of recently avalanched slopes and found weaker and stronger areas. Subsequent work suggested that a "deficit", or weak area along a crown of a recent avalanche can vary in length from 2.9 to 7 m (Conway and Abrahamson, 1988). Research by Föhn (1988) conducted in Switzerland using the same strength test also indicated snow strength variability, although the fluctuations measured were two to four times smaller than those reported previously for similar sized-slopes. Föhn (1988) concluded that reduced fluctuations might be due to climatological factors (the stronger winds at the New Zealand site may have increased variability) or to measurement technique (Föhn modified the shear frame test to eliminate bending modes of failure and threw out outliers in the data). In conclusion, Föhn (1988) hypothesized that larger and/or more numerous weak areas were necessary for avalanche initiation than had been previously proposed.

Wind deposition has been proposed as a mechanism which is responsible for weak zone development. Conway and Abrahamson (1984a) hypothesized that variations

in depth due to patterns of wind deposition may be a primary factor in shear strength variability along the crown of recently avalanched slopes, and suggested such variations might change weak layer thickness and gravitational forces along a slope. Föhn (1988) found that areas characterized by low shear strength values had 30 to 40% lower slab depths than adjacent stronger areas.

Weak zone measurements in previous studies (Conway and Abrahamson, 1984a, 1988; Föhn, 1988) were performed using a shear frame test. Conway and Abrahamson (1984a) took an average of 12 measurements at each site, Föhn (1988) took between 20 and 39 measurements per site, and data were gathered at the crown wall and flanks of the avalanched slopes. Shear tests are time consuming, allowing relatively few measurements to be taken at each site, and can be susceptible to human error (Perla, 1983). Concern also arises because snow at the crown of a recently avalanched slope is disturbed by the avalanche, and the resultant metamorphism may affect the measurements taken. Further, no data were collected on potentially weaker areas that may have existed within the slab before avalanche initiation.

In an attempt to collect data over an entire undisturbed slab, Föhn (1988) utilized over 100 Swiss soldiers to execute Rutschblocks (a test utilizing a large shear column which is loaded by a skier (Föhn, 1987)) across and down an entire slope. Some strength variability was demonstrated in slabs, however these tests may have been prone to human error since the large number of people taking part in the test may have made consistency between measurements difficult. Further, each test required an area of about 3 m², and tests were made 10 to 15 meters apart. Distances between measurements may have been too large to delineate small-scale strength differences in the snowpack. Testing the entire snow slab with many closely-spaced measurements would be more

beneficial.

While the existence of weaker areas of the snowpack has been substantiated, and some measurements made of their length along the crowns of recently avalanched slopes, little data have been gathered pertaining to their cause or their spatial variability within potential avalanche slopes. Conway and Abrahamson (1984a) hypothesized that snow strength variations might be caused by wind deposition patterns of snow. Their study was conducted on a glacier and wind effects were a likely contributor to weak zone formation because the surface on which the snow was deposited was relatively homogeneous. Important potential variables for weak area formation on more heterogeneous surfaces, such as the effects of rocks and vegetation, were not addressed. Personal observations while working as a ski patroller, and the observations of others (Brown, pers. comm., 1990; Custer, pers. comm., 1990; Dixon, pers. comm., 1990; Elliot, pers. comm., 1990), indicate regions around trees and rock are often weaker than surrounding areas, and rock and trees have been loosely tied to areas of stress concentrations in snow (Schaerer, 1981). One might surmise that geographic features such as rocks and trees might affect weak zone patterns, but this has yet to be tested.

Snow studies in Montana in the late 1960's and early 1970's correlated variability in resistance (a snow strength index) of snowpack to location of early season snow using sample intervals of 15 m or more (C.C. Bradley, pers. comm., 1988). Areas retaining early season snowcover (i.e., north-facing slopes and areas under trees) were found to be more susceptible to basal weakness due to increased temperature gradient metamorphism. To date, there are no other studies correlating specific snow characteristics to geographic features.

Although studies indicate that strength variability does exist in snowpack, and

several lines of evidence indicate that weak zones within snow slabs are critical for avalanche initiation, nothing is known about the spatial distribution of weak zones on a slope, or what might be influencing the formation of such weaker and stronger areas within a snow slab. The objectives of this study are to characterize the strength of an entire inclined snow slab, and to compare those strength patterns with geographic features at the site. An analysis of snow strength patterns may provide information on weak zone location and genesis.

CHAPTER 2

FIELD AREA

Two sites near Bozeman, Montana, and in close proximity to Bridger Bowl Ski Area, were chosen for study. Average annual snowfall at Bridger Bowl Ski Area (located 19 km northeast of Bozeman (Figure 1)) is approximately 675 cm. Data indicate that Bridger Bowl ranked fourth amongst United States ski areas in terms of avalanche activity in 1988-89 (U.S. Forest Service, 1989). As defined by Haas and White (1975), southwest Montana is located in the Intermountain or Middle Alpine avalanche region of the United States. This region is characterized by fairly substantial winter precipitation, low winter temperatures, varying winds, dry snow, and a changeable snowpack depending on the given winter. Snow covers vary from shallow, unstable snowpacks with depth hoar formation and climax avalanches to more stable snowpacks with extensive surface avalanches.

Air temperature, precipitation, and snowfall data, collected at a nearby National Oceanic and Atmospheric Administration (NOAA) weather station for the two seasons studied, indicate two contrasting winter years (Tables 1, 2 and 3). In 1988-89 the season was characterized by above average (106% of normal) total precipitation, with above normal amounts in November, February and March, and below normal amounts in December and January. Perhaps the most significant weather event of the season occurred in February, when a large arctic air mass moved into the region for two weeks. Extremely low temperatures from this air mass were reflected in a -12.4°C average temperature for the month (7.8°C below normal). Besides that event, temperatures were

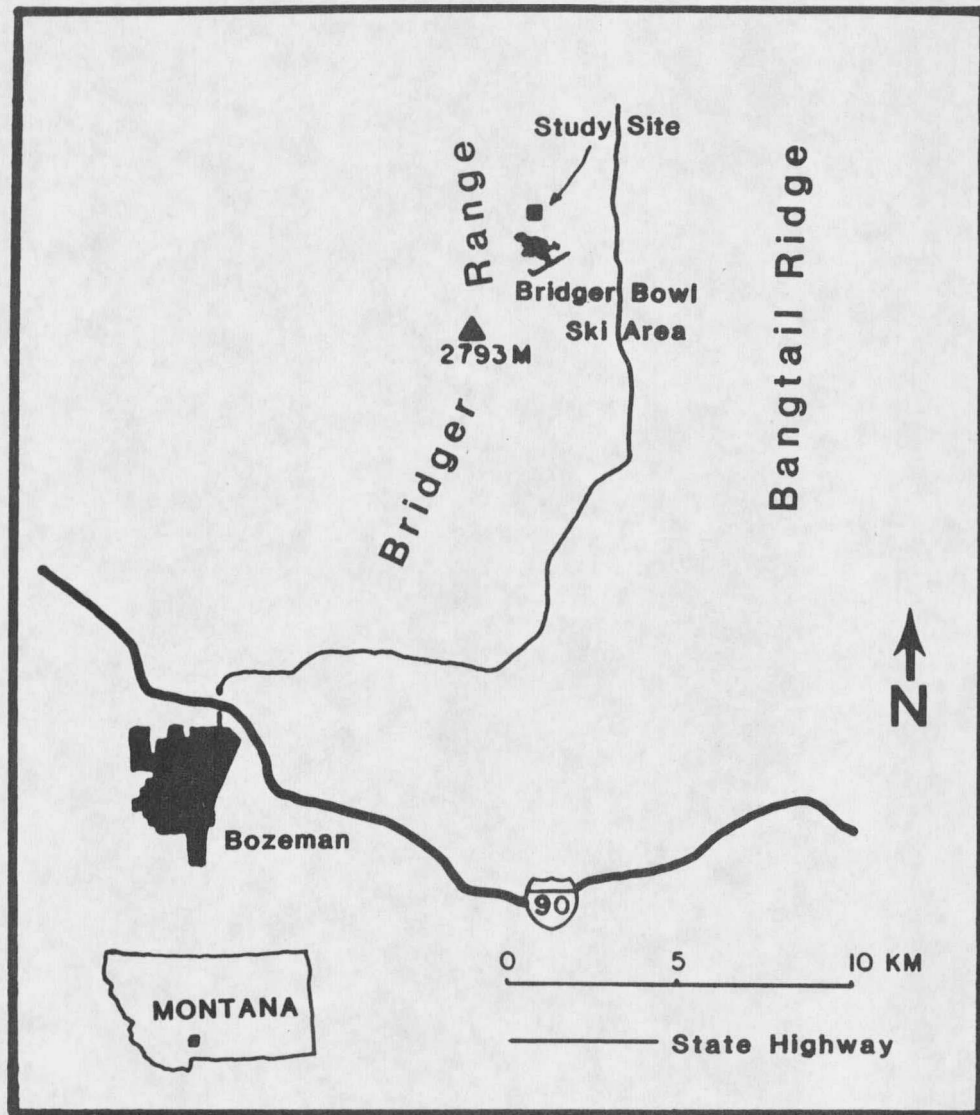


FIGURE 1: The study sites are located directly north of Bridger Bowl Ski Area, which is located 19 km northeast of Bozeman, Montana in the Bridger Range.

TABLE 1: Precipitation data from the Bozeman 12 NE National Oceanic and Atmospheric Administration climate station, 1800 m elevation. Deviations from average are based on the 38-year period from 1952-1989.

Month	Precipitation (cm of water)			
	1988-89	Deviation from avg.	1989-90	Deviation from avg.
November	9.3	2.9	12.5	6.1
December	4.3	-2.3	7.5	0.9
January	6.3	-1.0	5.8	-1.5
February	5.0	-0.5	2.3	-3.2
March	9.8	2.9	7.1	0.2
Total	34.7	2.0	35.2	2.5

TABLE 2: Temperature data from the Bozeman 12 NE National Oceanic and Atmospheric Administration climate station, 1800 m elevation. Deviations from average are based on the 38-year period from 1952-1989.

Month	Temperature (°C)			
	1988-89	Deviation from avg.	1989-90	Deviation from avg.
November	-2.1	-0.3	0.8	2.6
December	-5.4	-0.3	-5.2	-0.1
January	-4.7	2.5	-3.3	3.9
February	-12.4	-7.8	-5.2	-0.6
March	-2.4	0.9	-2.1	1.3

within 2.5° C of normal, with November and December being slightly lower, and January and March being higher, than normal (Table 2). Snowfall was heaviest in March (138 cm), while monthly totals between 70 and 110 cm fell for the previous four months (Table 3).

TABLE 3: Snowfall data from the Bozeman 12 NE National Oceanic and Atmospheric Administration climate station, 1800 m elevation. Averages were not available for these data.

Month	Snowfall (cm)	
	1988-89	1989-90
November	80.3	82.8
December	72.4	147.1
January	109.7	57.4
February	94.2	52.8
March	138.9	112.5
Total	495.5	452.6

The 1989-90 season had characteristics that differed from those of the 1988-89 season. Total precipitation was again slightly greater than average (108% of normal), but the distribution of the precipitation was different. Above average precipitation fell in November and December, with below normal amounts in January and February and a near normal amount in March (Table 1). The most significant weather event was probably the large amount of snow that fell in December, 1989. A unique storm pattern became established which combined a high pressure system off the Washington coast with a low pressure system near the Gulf of Alaska. This pattern channelled storms directly into the Bozeman area from the north. Two contrasting air masses, one warm and one cold, converged over Bozeman, and heavy snow resulted. By the end of December, 77 cm more snow had fallen at the NOAA climate station than at the same time during the previous season. However, after December the snowfall decreased considerably in January and February, and then increased slightly in March again (Table 3). Temperatures were warmer than the previous year, with above average temperatures in

November, January and March, and only slightly below normal temperatures in December and February (Table 2).

Winds are frequent at Bridger Bowl Ski Area, and are generally from the north or south at mid- and lower-mountain elevations (below 2350 m). The Bridger Range is oriented north-south, and winds are funneled between the Bridgers and the Bangtail Ridge through Bridger Canyon. Thus, storms coming out of the northwest and southwest result in winds out of the north and south, respectively. Wind data collected at mid-mountain (2150 m) at Bridger Bowl Ski Area illustrate this wind pattern for both field seasons (Figure 2). During both years southerly winds were dominant. This pattern was especially evident during the 1989-90 season. In 1988-89 northerly winds were also common, though southerly and southeasterly winds still predominated. Maximum winds for both seasons were from the south, with a top wind velocity reported for the two seasons of 136 kilometers per hour on January 25th, 1990.

The two study sites (referred to as the Bradley Meadows and Bridger Bowl sites) were chosen because of their ease and safety of access, and because they have similar aspects, elevations, and slope angles (Table 4). The similarity of these slope characteristics, which can be substantial contributors to avalanche formation (Perla and Martinelli, 1975), reduced the variability between sites. The spatial distribution of rock outcrops, vegetation, wind exposure, and shading, however, does vary between the two areas, and allowed a comparison of study sites based on those factors. The two sites are located directly north and outside of the Bridger Bowl Ski Area boundary, thereby eliminating skier traffic. They are also small enough to reduce exposure to potential avalanche hazard during sampling.

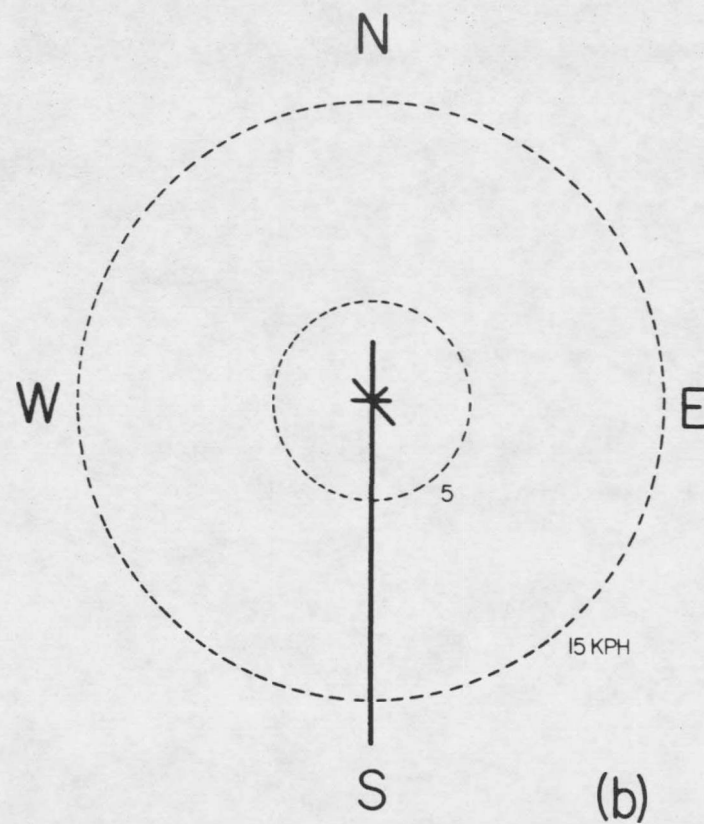
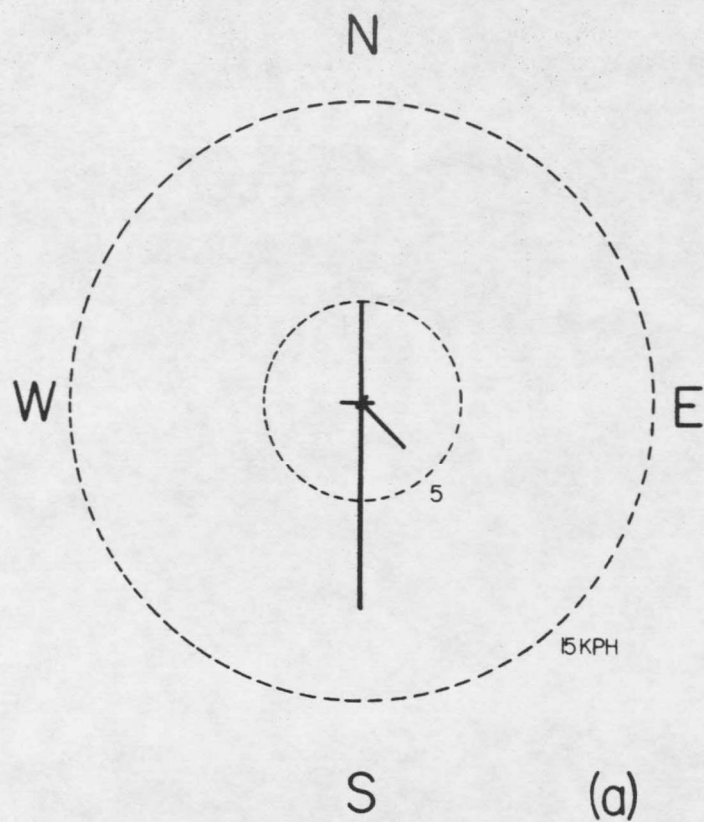


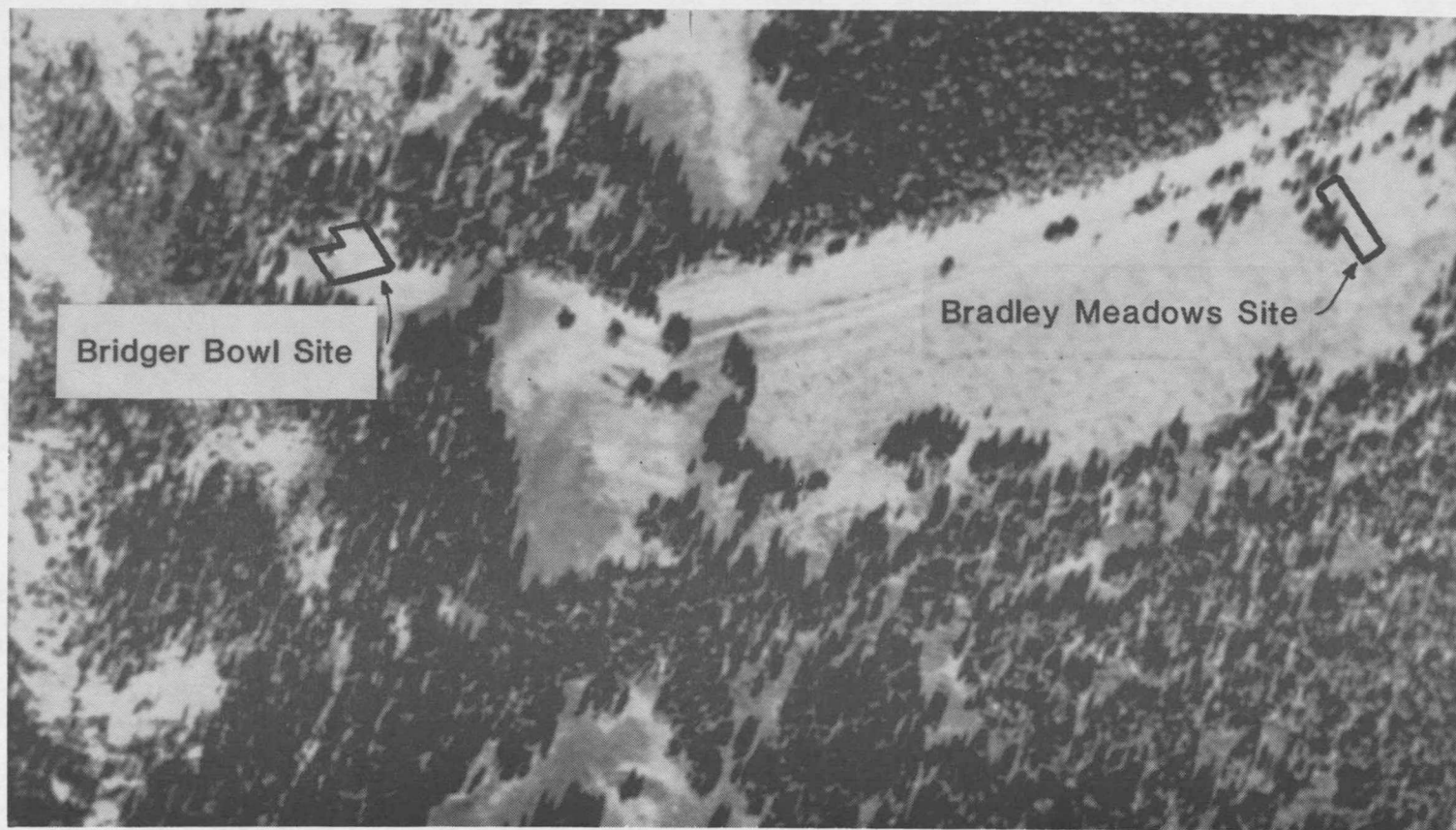
FIGURE 2: Winds were primarily out of the south both seasons, as demonstrated by directional diagrams of total wind (in kilometers per hour) observed at mid-mountain at Bridger Bowl Ski Area in 1988-89 (a) and 1989-90 (b).

TABLE 4: Geographic variability at both study areas.

Slope Characteristics	Bradley Meadows	Bridger Bowl
<u>Similarities</u>		
Aspect	60° East of North	80° East of North
Elevation	2300 m	2300 m
Slope angle	34°	32 to 36°
<u>Differences</u>		
Wind exposure	Exposed	Sheltered
Trees	A few stands around the site, up to 24 m tall.	A few stands within the site, and many trees surrounding the site, up to 22 m tall.
Rock outcrops	No rock outcrops	One significant rock outcrop (approx. 64 m ²).
Substrate	Predominantly grass-covered soil, some small rocks (less than 1 m ²).	Soil, with some large boulders (up to 8 m ²) interspersed throughout.

A fairly extensive amount of information is known about the Bridger Bowl site, as it has been used for several past studies (Dent and Lang, 1979; Lang and Dent, 1979; Grady, 1982; Grady, *et al.*, 1982; Brown and Hansen, 1985). This site has greater on-site variation than the Bradley Meadows site (Table 4), with several trees, a steep (slope angle of approximately 44°) rock outcrop, and many large loose rocks, some as big as three meters in diameter. The area is also surrounded by tall (up to 22 m) trees (Figure 3). This site was not rectangular. Since data analyses were greatly facilitated by rectangular site shape, this site was broken into two rectangular sub-areas which were called Bridger 1 and Bridger 2, respectively.

The Bradley Meadows site is located about one quarter of a mile north of the



0 m 500 m N →

FIGURE 3: This aerial photograph of the two study sites shows the exposure of the Bradley Meadows site to south and southeast winds, and the relatively protected location of the Bridger Bowl sites.

Bridger Bowl site, on the northern end of an area locally referred to as "Bradley Meadows". This site is much more exposed to wind than the Bridger Bowl site, and the primary geographic feature which might affect snowpack variation are trees along part of the southern edge (Figure 3). The substrate, unlike that of the Bridger Bowl site, is mostly soil covered with grasses and some small (less than 1 m²) rocks (Table 4).

CHAPTER 3

METHODS

Previous Methods of Snow Strength Measurement

Methods of measuring snow strength have been previously developed for tensile and shear strengths, and for measuring general strength indices. Tensile strength, the strength of the snow as it is being pulled apart, is commonly measured in-situ by digging a snowpit, isolating a layer, and pulling on it with a force gauge (Perla, 1969; McClung, 1979; Conway and Abrahamson, 1984a; Rosso, 1986; Jamieson and Johnston, 1988). Shear strength measurements, assessments of the strength of the snow across the potential failure plane, have recently been cited as the most important measurement for avalanche studies (Föhn, 1988; Gubler and Bader, 1989). Inter-layer shear boundaries are where initial failure planes develop. Such initial failure puts rapid stress on surrounding areas which, in turn, causes widespread failure and results in avalanches (Gubler and Bader, 1989). To collect shear strength measurements a snowpit is dug, and the weak layer of interest is identified. The shear frame is then inserted into the snowpack above the suspected weak layer and is pulled with a force gauge. Shear measurements are sensitive, however, to shear frame geometry, rate-of-pull, and shear frame mass (Perla and Beck, 1983). In previous studies only twenty-five to fifty measurements were taken in a day due to the lengthy nature of the procedure (Conway and Abrahamson, 1984a; Föhn, 1988). A composite strength index, which measures a complicated combination of tensile, shear and compressive snow strengths, can be

measured by pushing a probe through the snow. The most widely used instrument for measurement of a strength index is the Swiss Rammsonde, or ram penetrometer. Data collection of each profile may take fifteen minutes (Dowd, 1984).

Current Instrument Development

All of the previous methods are very time consuming, preventing the collection of the numerous data points required to describe the strength characteristics of an entire snow slab before changes in the snowpack occur. Therefore, a Digital Resistograph (DR) was used for this study. The DR was an appropriate instrument for this study because: 1) it measures a snow strength index, which allows the characterization of snow strength variability on a slope, 2) each measurement takes less than a minute, allowing many data points to be collected, 3) it is comparable to the ram penetrometer (Dowd and Brown, 1986; Brown and Birkeland, in preparation), an instrument widely used in avalanche studies (Perla and Martinelli, 1975), and 4) the data are collected in a form that can be easily loaded onto, and analyzed with, a computer.

The DR has been developed and refined at Montana State University. Originally, a mechanical resistograph was developed by Dr. Charles Bradley (former Montana State University Professor in the Earth Sciences Department) in the early 1960's. The resistograph consisted of a probe with a horizontal blade on the bottom that was pushed into the snow, rotated ninety degrees, and withdrawn. Resistance to the upward pull was balanced by a spring, and fluctuations in resistance in the snowpack were recorded on a scribe on the top of the probe (Bradley, 1966). The resistograph proved to be a quick way to acquire an index of snow strength. However, it is difficult to collect, store and analyze large data sets with the resistograph since each data point is represented by a

piece of paper with a graph on it. Additionally, computer analyses of the data requires that each graph be digitized. Such problems precluded the use of the mechanical resistograph for this study.

Duaine Bowles (formerly a technician at Montana State University) attempted to improve on Bradley's resistograph by designing a device to take a continuous electronic measurement of an index of snow strength (Dowd, 1984). Though never completed, this device was the basis from which Tim Dowd (a Montana State University engineering graduate student) designed and built the first microprocessor-based resistograph for the measurement of a snow strength index.

Dowd's device, called a Digital Thermo-Resistograph (DTR), consisted of: 1) a probe equipped with a sixty degree cone and load cell, 2) an optically-interrupted, light-emanating, diode position detector, and 3) a microprocessor that was connected by wires to both the probe and position detector. Temperature transducers were to be eventually added, but were never operational. To operate the instrument, inputs from the probe and position detector were plugged into the microprocessor and the probe was pushed through the snow to the ground. Information gathered could be instantly analyzed visually on a liquid crystal display (LCD) screen on the microprocessor. Up to twenty-five two meter deep profiles could be stored in memory to later be plotted on an X-Y plotter (Dowd and Brown, 1986). Dowd's device had many advantages over previous methods for indexing snow strength. The primary benefit was increased measurement efficiency (each measurement took less than a minute). It was also shown that DTR readings were comparable to the widely used ram penetrometer (Dowd and Brown, 1986). In addition, the DTR provided an instantaneous view of the snowpack on its LCD screen, allowing for in-field analyses.

Still, problems exist which preclude the use of the DTR in its present form for this project. Limited memory allowed only twenty-five profiles to be stored at a time. Permitting for time required for site access, sampling, returning to a warm building where the X-Y plotter could be stored, plotting up the graphs, and returning to the field, a maximum of only seventy-five profiles could be collected in one day. Thirteen and a half days would be required to sample the Bridger 2 site (the largest site). One alternative approach was to reduce the site size, but personal observations made while working as a ski patroller indicated sampling a site this large would be necessary to detect variability across a slope. Because of these problems, improvements on Dowd's DTR were made with the assistance of Dr. John Amend and his associates in the Montana State University Chemistry Department. Amend's team had developed a data logger which could be used to collect data at remote sites and store the data in electronically-erasable, programmable, read-only memory (EEPROM) modules. Software had been developed which allowed data to be loaded directly onto a personal computer. Instead of attempting to try to increase the memory of the current DTR, the probe and depth sensor of the Dowd DTR were interfaced with the Amend data logger.

The Amend data logger required slight modifications for continuous data collection in a cold environment. Advanced, high speed, complementary metal oxide semiconductor (CMOS) chips were used for minimum power dissipation and maximum battery life. The CMOS chips used were extended temperature versions (for use between -30° and $+70^{\circ}$ C), allowing operation in all weather conditions. Data were stored in EEPROM memory modules. Each module had eight EEPROM chips with 8,192 bytes of memory per chip for a total of 65,536 bytes per module, allowing the storage of 160 two meter deep profiles per module. Three memory modules were taken into the field to increase

available memory to 480 two meter deep profiles. Memory capacity was more than adequate as the maximum number of profiles collected in one day was 450 profiles. New improvements to the microprocessor will eventually increase the memory to 640 two meter deep profiles per module. Software developed allowed easy downloading of digital data onto a personal computer where they were stored in files in ASCII format, ready for analyses.

The enhanced device solved the problems of quick data acquisition and easy data analyses. This new device changes the possibilities for data collection in snow. Now a large sample can be collected in a relatively short period of time, before significant snowpack changes take place, and the massive amount of data collected can be readily analyzed on a computer. There are still, however, shortcomings with the present instrument. The instrument provides an index of snow strength. How that index precisely relates to other strength indices, i.e. the ram penetrometer, has yet to be determined. Nevertheless, strong visual correlations between the two instruments has been made (Dowd and Brown, 1986), and measurements have been undertaken to more precisely define that relationship (Brown and Birkeland, in preparation). Further, it is unclear what relationship there may be between spatial patterns of resistance and shear strength patterns, which are believed to be critical for avalanche release. In spite of the problems associated with measuring a strength index using a ram penetrometer or the DR, avalanche workers continue to gather this data because it provides valuable information on specific layers within the snowpack that can be used as part of an avalanche forecast.

Site Preparation and Mapping

Study sites chosen were prepared for sampling in October and November of 1988.

Area perimeters were measured with a fiberglass coated surveyor's tape, and were marked every ten meters with 60-70 cm long pieces of six millimeter diameter rebar inserted into the ground. Approximately 30 cm of rebar were left above ground, and a 2.5 m long piece of bamboo was wired to the rebar for accurate location after snowfall. Although some bamboo poles were broken off by snow creep in the spring of the first field season, the rebar remained undisturbed. The broken bamboo poles were replaced before the second field season.

Study areas were chosen in locations that were unlikely to be skied because of local topography and limited skier traffic. However, steps were taken to further discourage skier access, which would have resulted in biased data from an age hardening of the snow. Study sites were roped-off with a yellow polypropylene rope marked with surveyor's flagging, and cardboard signs were added to the rope to inform people that the area was being used for snow studies and was not to be disturbed. Ski tracks were never observed within any of the sites.

Geographic features of the sites were mapped in July of 1989. Features mapped were selected based on previous personal field observations made while working as a ski patroller, observations of others (Brown, pers. comm., 1990; Custer, pers. comm. 1990; Dixon, pers. comm., 1990; Elliot, pers. comm., 1990), and the minimal available literature (Shaerer, 1981). These observations indicated that factors such as changes in slope, rock outcrops, vegetation, and wind drifts might be responsible for some of the strength variability observed in snow. To measure the topography of the sites, a survey tape was stretched uphill between two points on the perimeter of the study area. By standing at one point and sighting with a level onto the tape upslope, and knowing the height to the observer's eye, a measurement was obtained which allowed the elevation

at the tape to be calculated. These measurements were repeated up the slope to the top of the study site, and this line of measurements was repeated every five meters across the site. Topographic data were used to generate three dimensional perspective plots for each site on the computer.

Trees and rock bands were located by measuring from the study area perimeter to the feature with a tape measure. Height of trees inside and in close proximity to each study area was measured by taking an angle to the top of the tree with a Brunton compass at a known distance from the tree (Compton, 1962). A map of geographic features was made for each site by drafting features onto three dimensional slope maps. These were used to assist in determining the influence of the various features on snow resistance.

Collection of DR Data

Due to disturbance created by sampling the study sites, each site could only be sampled once a season. Factors taken into account to determine sampling dates were: 1) the existence of a well developed, typically mid-season snowpack with discernable weaker and stronger layers (which was identified by digging a snowpit), 2) a weather pattern indicating relative stability (little chance for warming, wind, precipitation, or other factors that would cause rapid snowpack changes) over the time required for sampling a specific site (two to four days), and 3) a working Digital Resistograph (DR).

Once a time period was selected, a field assistant was employed and sampling began. Upon arriving at the site, the bamboo and rebar at the corners of the area to be sampled were located. It was necessary to dig down to the rebar to accurately locate points because snow creep had tilted the bamboo poles downhill. In a few cases the

poles had been tilted so far downhill that they became buried and were difficult to locate. Care was taken in locating the points so as not to disturb the snow within the site. After locating the corners, a surveyor's tape was stretched out from the top of the slope to the bottom, the tape was tied off on either end with skis and poles, and sampling commenced.

Resistance data were collected with a Digital Resistograph (DR), which was described in more detail earlier. Operation of the DR, while simple, was expedited by two people. One person was needed to push the probe through the snow, and a second person was required to carry and operate the microprocessor. Before any sampling took place, the person operating the probe pushed it through the snow on several trial runs. This allowed the operator to 'feel' the layers to be encountered, increasing the smoothness and accuracy of operation when pushing the probe through the snow for actual data collection. When a point was sampled, the person doing the probing set the depth sensor down on the snow at the selected site, inserted the probe into the sensor, indicated readiness, and the second person pushed the start button. After pushing the probe through to the ground as smoothly as possible, the probe operator would say "Stop" and the microprocessor operator pushed the stop button. One problem experienced with the DR was that the tip occasionally became clogged with dirt and ice and had to be cleaned. An inaccurate reading resulted when it was not cleaned properly.

Variability measurements were taken during sampling to track any drift in the instrument or snow conditions. A small site (approximately 2 m²) was chosen near the top of the study site for each day of sampling, and one "control" profile was sampled there for every downslope column of points sampled. These "control" profiles were graphed and compared to each other to check for changes in the snowpack or the

instrument over the course of the day.

Sampling took place from the top to the bottom of the slope for each column. Columns were first sampled from bottom to top to minimize disturbance of points not yet sampled. However, this method was extremely time consuming and physically exhausting, especially when sampling weak snow. Sampling from top to bottom could be done without disturbance as long as care was taken to avoid knocking snow down on points below. A DR measurement was taken at 1 m intervals down the slope, the tape was then moved one meter across the slope, a test variability measurement taken, and another downslope column of measurements collected. For each sample point, instantaneous measurements of resistance were taken by the DR at five millimeters depth intervals. The numbers could then be graphed to produce a resistance profile.

The decision to collect profiles in a one by one meter grid was made based on previous studies which showed the existence of localized shear weak zones. Prior field measurements appeared to indicate that such weak zones along avalanche crowns can be as localized as 2.9 meters in length (Conway and Abrahamson, 1984a; 1988), acoustic emissions data indicate initial failure planes can be as localized as 0.1 to 3.1 m² in areal extent (Sommerfeld and Gubler, 1983), and models predict that such weak zone areas can be 1.0 m² in size (Gubler and Bader, 1989).

Because snowpack is a dynamic material, capable of large changes in a relatively short period given the proper conditions, sampling was conducted as rapidly as possible during periods of relative meteorologic stability. Observations of air temperature, winds, and cloud cover were made at the completion of each column of measurements. Each site took two to four days to sample depending on the size of the site. Sampling was stopped if a dramatic and unforeseen change in the snowpack took place. An example

of this occurred at the Bradley Meadows site in 1988-89. Measurements at that site were discontinued after two days when an unexpected storm produced 69 cm of snow at nearby Bridger Bowl after two days of sampling.

Data Analyses

Each snow profile varied from 32 to 230 cm in depth and, therefore, included 64 to 260 data points (the DR was programmed to take an instantaneous reading of the resistance every 0.5 cm). There were 300 to 1100 snow profiles sampled per site. These enormous data sets were analyzed on the Montana State University computer network using the MicroVAXII computer in the Department of Mathematical Sciences. The terminal used to access this computer ran off a VAXstation 2000 computer, and everything operated under an Ultrix V2.3 operating system. In order to increase efficiency, an X-Window V10 windowing system was used to log onto several ports of the computer at once. Data analyses were often slow, indicating the potential need for a more powerful computer for future studies.

Once loaded onto the computer, some errors that were introduced during input into the MicroVAXII had to be corrected. MicroEMACS 3.9e (Lawrence, 1987) was used to correct and edit the data. The primary error was erroneously split numbers, which were corrected with search and replace functions in MicroEMACS. In addition, each double carriage return which separated profiles in the data was replaced with an "NA", which was more easily recognized by the data analysis environment to be used.

Once data were cleaned and the NA's added in MicroEMACS, data were loaded into "S" (a programming environment for data analyses and graphics) on the MicroVAXII (Becker, et al., 1988). A function was designed by Dr. Jeff Banfield (Department of

Mathematical Sciences, Montana State University) that loaded the data into "S" in a matrix, with each profile occupying one position in the matrix (Appendix). At this point the data were ready for analyses.

A problem that had to be remedied before data were analyzed was that the load cell on the probe did not give a constant starting point reading from day to day (i.e., changes in temperature, etc., affected initial readings). Such day-to-day changes in the load cell, however, did not affect differences between readings in a specific profile since readings by the load cell are linearly related to the load exerted on the probe, irrespective of the initial readings. To compare all readings equally, the DR was programmed to take three readings one tenth of a second apart immediately after the start button was pushed. Such readings, taken while the probe was at rest, provided a "zero" for that particular profile. A function was written in "S" that took each profile separately, found the minimum value for that profile, and subtracted that minimum value from the remaining numbers in the profile (Appendix). This function zeroed all profiles so that they could be compared with one another.

Graphically comparing individual profiles is important when analyzing a snowpack. Such plots are used to initially discern the snowcover characteristics in specific areas and to visually track weak and strong layers across and down the slope. A function was therefore designed in "S" that plotted each profile (Appendix). Profile graphs were used to identify erroneous data points where the DR had possibly clogged with snow and dirt and was apparently working improperly (these points were easily identifiable since their profiles showed straight lines instead of discrete layers like the rest of the plots). These points were eliminated for statistical tests, and average values of the points around them were inserted into matrices for graphics.

Of particular interest to this study was the spatial distribution of resistance on a potential avalanche slope. Given the profiles discussed above, mapping resistance was a difficult task. Mapping the profiles required at least four dimensions since the location of the sample point (with an X and a Y component) had to be established in addition to the depth and resistance information of the profiles. Additional work could have been done to try to display these data, possibly with the aid of a Geographic Information System, but that was beyond the scope of this project. Additional analyses of profile data would be useful, but was beyond the scope of this project. Such analyses are planned for the future. For our purposes, data were collapsed into average resistances which could then be mapped in three dimensions. To observe the spatial distribution of resistance a function was written that calculated average resistance values from each list of numbers for a given profile, and loaded that value into another matrix (Appendix). Use of the averaged value was appropriate because it eliminated bias that might have occurred due to differences in depth from point to point. A three-dimensional perspective plot was created to get a general idea of the spatial variability of the data, and to visually assess patterns. Specific graphics techniques were used to generate maps showing resistance patterns since data were variable. An interpolation function built into "S" (Akima, 1978) was used to create a denser matrix, with an additional point interpolated between each two data points. These data were then smoothed using a two dimensional smoothing process which simply replaced points with the average of all surrounding points, determined by the desired span. Smoothing spans varied depending on the variability at the specific site. In general, a smoothing span was increased until overall snow resistance characteristics could be discerned, while still leaving some variability evident. A row of zeroes was then put on the uphill and downhill sides of the plot to give

perspective, and a three dimensional perspective plot was created using "S".

Once overall resistance maps were created, the factors affecting those patterns were investigated. Based on personal experience and previous studies, one important contributing factor to snow resistance variations was hypothesized to be snow depth. Thin snowpacks are often weaker, and Föhn (1988) reported that areas with weak shear strength had 30 to 40% lower slab depth values. Three-dimensional perspective plots of snow depth were generated in the same way resistance maps were created. A function was written that computed the depth of each profile by using the number of instantaneous resistance measurements taken, and depth values were then placed into a matrix (Appendix A). Interpolative and smoothing functions were then applied to the data, and maps of snow depth were created. Smoothing spans required for depths were generally less for a specific plot than those for resistance due to the reduced variability within the depth data. The same smoothing span employed for resistance was used so that data maps would be comparable.

Simple linear regression was used to determine the extent of the correlation between snow depth and average snow resistance. A problem exists with applying regression analysis to spatial data. Regression assumes that the data collected are independent observations. However, tests indicated that these data were spatially related within the region of the study sites (i.e., each sample point is related to surrounding points), and therefore the observations were not strictly independent. Thus, the p-values reported are underestimated by an indeterminate amount. This is a common problem with the analysis of spatial data, and a completely satisfactory method of quantifying the correlation between spatially related data has yet to be discovered (Cliff and Ord, 1981; Quimby, pers. comm., 1990). Still, regression is considered a "robust" statistical

technique whereby meaningful results can be obtained even when some assumptions are violated (Balling, pers. comm., 1990). Despite its drawbacks, regression appeared to be the best available method to efficiently analyze the data. To decrease the effects of autocorrelation caused by the spatial relationship, data sets were analyzed both in their original form and in a form where data sets were reduced from between 300 to 600 observations to 30 to 40 observations. Reduction in the data sets was accomplished by taking the values in approximately every 5th row and column, and using these to run the regression.

Field observations also indicated that certain geographic features, such as trees and rocks, might have influenced snow resistance. Maps of geographic features were visually compared with resistance maps to see if any patterns were obvious for both years. Further, the second season's data were used to determine the relationship between rocks, trees, and resistance at the Bridger sites. Sample points over a rock or under a tree were identified, and multiple regressions were run for both rocks and depth versus resistance, and trees and depth versus resistance. Such an analysis controls for depth and allows the analysis to focus on the effect of the geographic feature. A large number of "bad" data points, attributable to clogging of the probe, precluded the use of multiple regression analysis for the first year's data at the Bridger sites, and the absence of rocks or trees within the site made using this test unnecessary at the Bradley Meadows site. To see if there was a "zone of influence" within which rocks and trees would affect the resistance, additional multiple regression analyses were run to compare resistance values near rocks with those that were not near rocks.

Collection of Climate Data

Air temperature, precipitation, and snowfall data were obtained from the Bozeman 12 NE National Oceanic and Atmospheric Administration climate station. The station is at an elevation of 1800 m approximately 4 km southeast of the study sites. Averages reported are 38-year averages for the station.

Wind data were obtained from records kept by the Bridger Bowl Ski Patrol for winds at mid-mountain (2150 m). Observations of wind direction and velocity were made at 9 AM, noon, and 4 PM daily. Observations were made with an anemometer, and were what the current lift operator believed was the best estimate of the wind velocity and direction. Unfortunately, these data were not complete. However, they did help to characterize the nature of the winds at the site over the two field seasons. A number which represented "total wind" for each direction in kilometers per hour was calculated with this wind data by multiplying the percentage of observations that the wind was blowing out of each direction by the average wind velocity observed for that direction. Average velocity was calculated by taking the mean of all the observations from a particular location. Thus, the "total wind" not only represents how often the wind was blowing out of each direction, but also how strong the wind was, giving a representation of the potential for wind transport of snow from each direction.

Collection of Shear Strength Data

Shear strength data were collected for one day during the second year of this project by Doug Williams (undergraduate student in Computer Science at Montana State University) to see what relationship, if any, existed between variations in average resistance and variations in shear strength. The data were collected at specific locations

immediately adjacent to one of the study sites at the same time resistance data were being collected with the DR. These collection sites corresponded to hypothesized weaker and stronger areas of that slope. To collect the data a snowpit was dug and the weakest shear in the snowpack was located using a shovel shear test (Föhn, 1988). The weakest shear was the same for all areas tested, and was located approximately 5 cm below the surface. A 400 cm² shear frame was inserted into the snow above that layer, and the shear frame was pulled with a force gauge. Time allowed for failure was kept short (less than five seconds) to insure that failure was brittle. A total of six pits were dug, each 10 m apart up the slope. Three shear frame measurements were taken in each pit. Averages of these data were graphed, and the downslope patterns of shear strength were compared to downslope patterns of resistance data that were collected the same day.

CHAPTER 4

RESULTS AND DISCUSSION

The digital resistograph was effective for rapid acquisition and analyses of spatial snow depth and resistance data. Up to 450 profiles were sampled in one day. Resistance data and snow depth data at each sample point were developed into resistance profiles. Measurements taken close together demonstrated repeatability in the collection of resistance profiles (Brown and Birkeland, in preparation). Conversely, between points on the study sites the instrument showed differences in resistance profiles (Figure 4), which allowed the detection of the resistance variability of the slope. Print copies of all profiles sampled are available from the Montana State University library, or from Katherine Hansen-Bristow (Department of Earth Sciences, Montana State University).

In this study, only average resistance was analyzed. Using average values caused the loss of important information, but a detailed analysis of the profiles was determined to be beyond the scope of this project. Such an analysis of these profile data, which will attempt to track weak and strong layers around the slope, is planned for the future.

Snow Depth for 1988-89 and 1989-90

Snow depth data gathered from two winter seasons at the sites show discernable variations (Table 5). Differences between averages, tested with a Student's t-test, were significant at the 0.001 level. The average snow depth observed at the Bradley Meadows site was greater in 1988-89 than 1989-90. However, the standard deviation of the data was greater in 1989-90, indicating increased depth variability that year. Increased

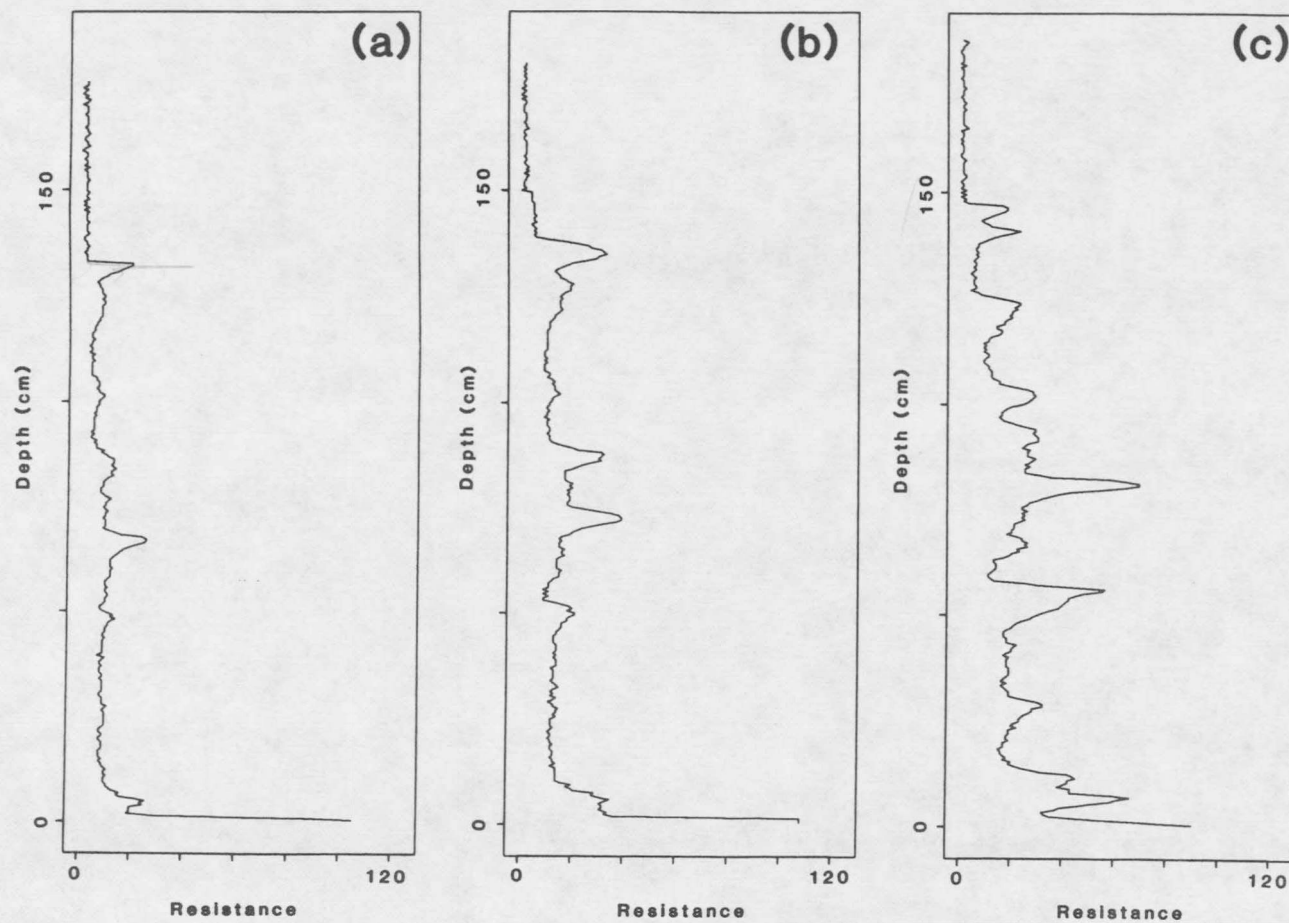


FIGURE 4: Three resistance plots from data collected within 10 m at the Bradley Meadows site in 1989, show examples of low (a), medium (b), and high (c) resistance. These profiles demonstrate that the DR is capable of detecting resistance variability.

TABLE 5: Maximum, minimum, mean, and standard deviation for snow depth (cm) at the time of sampling for the Bradley Meadows, Bridger 1, and Bridger 2 sites.

Site, Year	Sampling Dates	Number (n)	Snow Depth (cm)			
			Maximum	Minimum	Mean	Standard deviation
<u>Bradley Meadows</u>						
1988-89	2/25 to 2/26	358	198	102	147.3	19.0
1989-90	3/10	300	186	66	122.6	27.3
<u>Bridger 1</u>						
1988-89	3/4	274	228	80	157.8	29.9
1989-90	1/13	319	172	42	128.1	16.2
<u>Bridger 2</u>						
1988-89	3/5 to 3/7	657	232	76	165.9	28.2
1989-90	1/14 to 1/15	616	161	32	119.8	15.6

variability may be attributable to the increased southerly winds observed at the site in 1989-90 (Figure 2) which would have redistributed the snow. The effects of wind will be further explored later in this chapter.

At the Bridger sites the snow depth was also greater the first year than it was the second year. This is attributable to the amount of snow that had fallen by the time of the two sampling dates. By the time of sampling, 306 cm of snow had fallen at the nearby climate station the first season, while 259 cm of snow had fallen by the second year's sampling date. The standard deviation at the Bridger sites also decreased from 1988-89

to 1989-90, indicating less variability at the site. It is unclear why variability was less the second season.

Average Snow Resistance for 1988-89 and 1989-90

Average snow resistance values also show discernable variations (Table 6). Differences between averages discussed below, tested with a Student's t-test, were also all significant at the 0.001 level. Average resistance increased slightly from 1988-89 to 1989-90 at the Bradley Meadows site, while its standard deviation decreased. Both average resistance and its standard deviation at the Bridger sites were smaller in 1988-89 than 1989-90. Though smaller standard deviations may be due to less overall variability in resistance, they may be due, at least in part, to improved data collection techniques used in the second year which eliminated many "bad" data points (attributable to clogging of the probe by excessive ice and dirt) observed the first year.

Variability Due to the Instrument

As with any field measurement, operation and reliability of the DR was not perfect. Closely spaced (within 2 m²) measurements were taken at specific locations while sampling to determine the amount of variability due to the instrument. Such tests indicated that the standard deviation of average resistance measurements was on the order of 3 to 4 resistance numbers for closely spaced measurements. Since these results are from measurements taken between sampling columns, they may not be entirely accurate. Relocation of exactly where to take the measurements such that they would be closely spaced, but would not be over the top of previous measurements, was difficult. Results from additional reliability tests with the instrument, whereby measurements were

TABLE 6: Maximum, minimum, mean, and standard deviation for average snow resistance (resistance numbers) at the time of sampling for the Bradley Meadows, Bridger 1, and Bridger 2 sites.

Site, Year	Sampling Dates	Number (n)	Average Snow Resistance			
			Maximum	Minimum	Mean	Standard deviation
<u>Bradley Meadows</u>						
1988-89	2/25 to 2/26	358	31.0	1.26	12.7	5.54
1989-90	3/10	300	29.0	4.84	15.4	4.25
<u>Bridger 1</u>						
1988-89	3/4	274	37.8	1.19	14.1	8.13
1989-90	1/13	319	29.1	3.24	9.0	3.72
<u>Bridger 2</u>						
1988-89	3/5 to 3/7	657	38.9	1.21	14.4	8.34
1989-90	1/14 to 1/15	616	28.8	1.05	12.8	5.31

taken at the same time in a closely spaced grid, will soon be analyzed (Brown and Birkeland, in preparation). In any event, it appears that the contribution of the instrument to the standard deviation may be on the order of 3 to 4 resistance numbers. Such a lack of probe precision makes it harder to differentiate weak relationships, and r^2 values computed in regression analyses may be lowered. However, reduced measurement precision does not invalidate the relationships which are found, and, despite the variability due to the instrument, sites still show discernable patterns of snow resistance.

Bradley Meadows SiteGeographic Features

The predominant geographic features observable at the Bradley Meadows study site (Figure 5) are the trees located both upslope (to the southwest) and along the southeastern side of the site. The largest group (located on the southeast side of the site at about mid-slope) includes trees as tall as 17 m. The site is exposed to wind, as evidenced by wind-induced snow drifting and scouring observed in adjacent areas during both winters. During a particularly windy storm in the winter of 1988-89, a rock outcrop 200 meters south of the study area was blown free of snow. Drift patterns indicated that the predominant wind direction during this event had been from the south or southeast. Following that storm, the study area displayed evidence of wind disturbance (i.e., sastrugi (ripples) on the surface of the snow), but no areas were blown free of snow. Drifting within the study site was observed during both winters.

Snow Depth and Average Snow
Resistance, 1988-89

Visual observations of the site recorded at the time of sampling and the computer drawn three-dimensional perspective plot both indicate a discernable pattern of snow depth (Figure 6). Starting at the top of the slope, depth initially decreased downslope (to point (b)), increased to a maximum near mid-slope (at point (a)), then decreased downhill again until increasing slightly before the bottom of the slope (at point (c)). A second pattern of variation in snow depth can be seen across the slope. Going from southeast to northwest, depth increased to a maximum, decreased slightly, and then increased again, producing a wave-like pattern.

An average snow resistance map (Figure 7) generated from the data for the

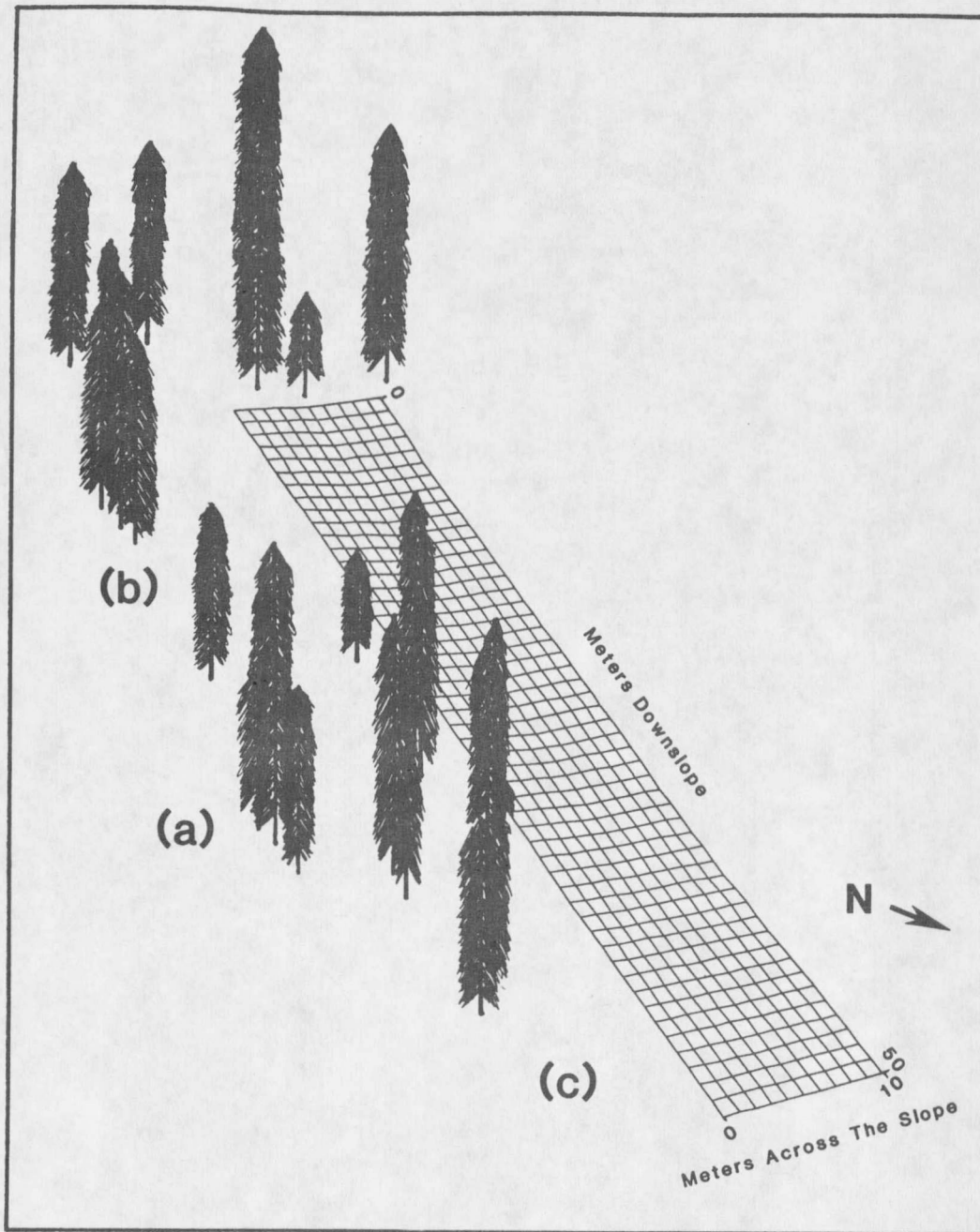


FIGURE 5: The Bradley Meadows site is associated with trees to the southeast and east. The largest group of trees is found at mid-slope (point (a)). A gap in the trees is found at point (b). Point (c) indicates an area unprotected by trees. The site is shown in the grid pattern, which was generated with topographic data.

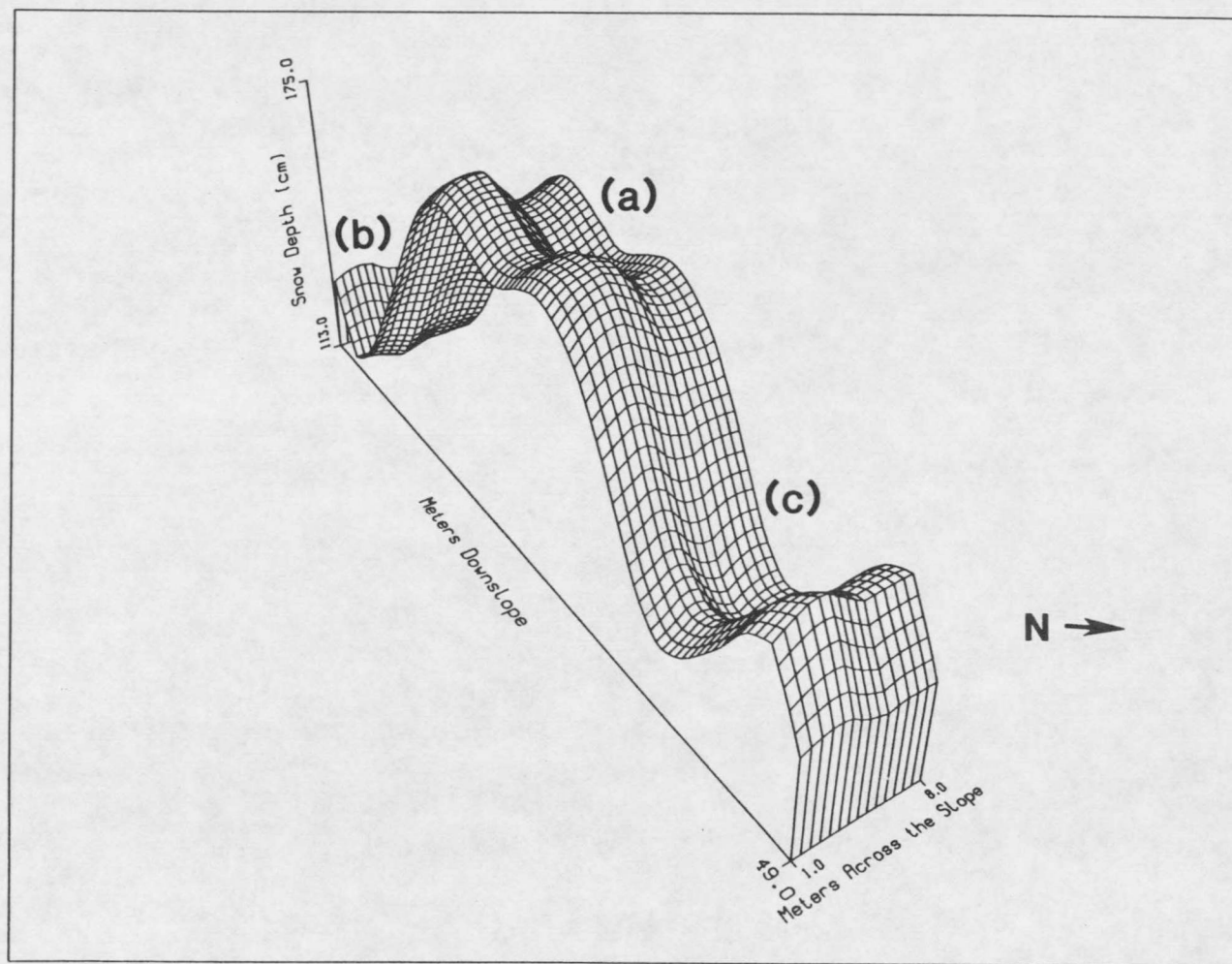


FIGURE 6: A three-dimensional perspective plot of snow depth for the Bradley Meadows site in 1989 shows depth variations over the site. Point (a) indicates a snow drift, while points (b) and (c) indicate areas of wind scour.

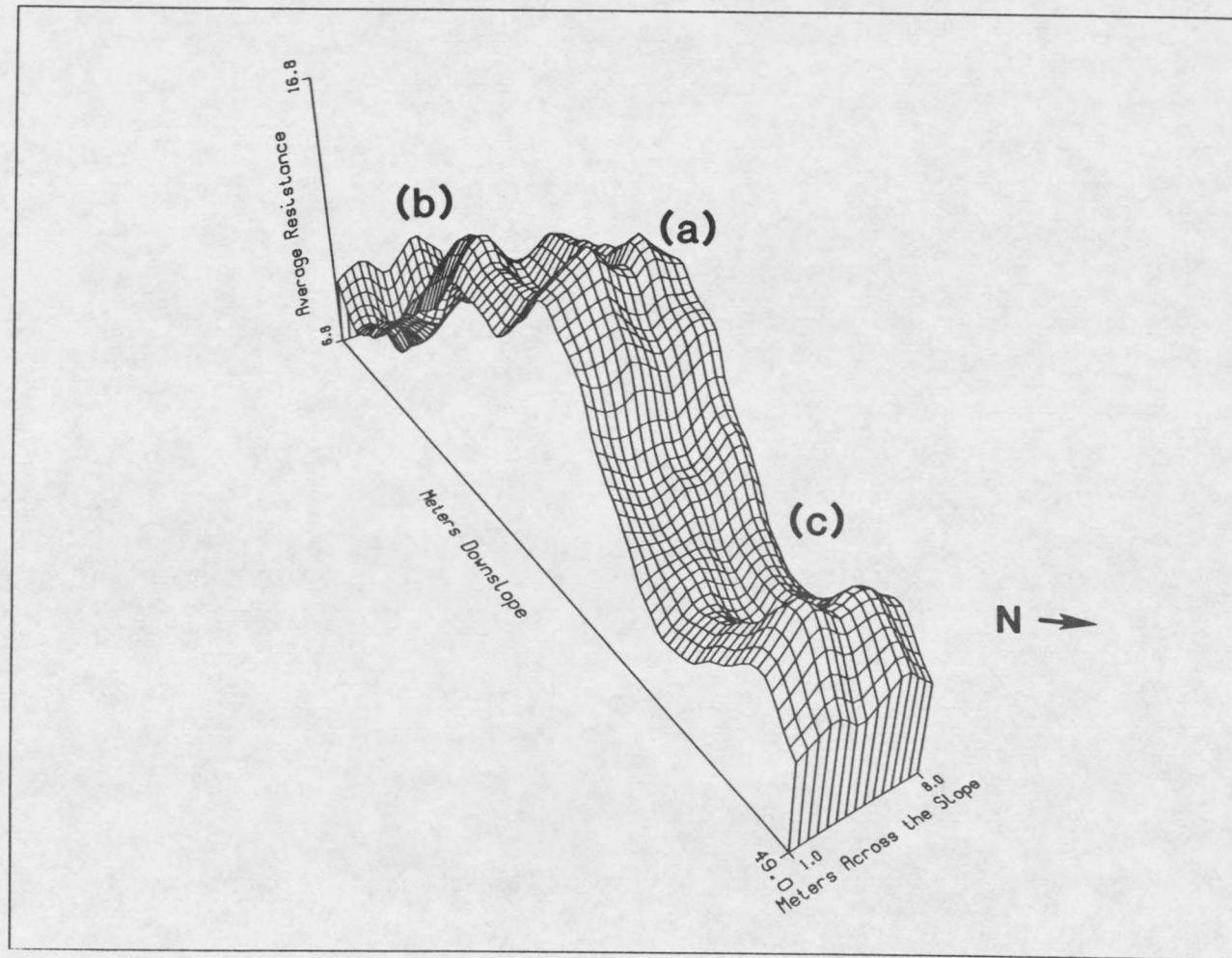


FIGURE 7: A three-dimensional perspective plot of average snow resistance for the Bradley Meadows site in 1989 shows average resistance variations over the site. Point (a) indicates an area of greater resistance, while points (b) and (c) indicate areas of less resistance.

site shows patterns similar to those found for depth. Average resistance initially decreased downslope (to point (b)), increased to a maximum at about mid-slope (point (a)), and then decreased to point (c) before increasing slightly before the end of the slope. A wave-like pattern across the slope, similar to that seen in the depth map (Figure 6), is also evident.

Comparison of Geographic Features, Depth, and Resistance, 1988-89

Comparison of geographic features (Figure 5) and snow depth (Figure 6) maps for the Bradley Meadows site allowed the development of preliminary correlations. Snow depth patterns within the study area during the 1988-89 winter appear to be affected by wind patterns around adjacent trees. Storm events came predominantly from the southwest during 1988-89 (Elliot, pers. comm., 1990); these storms resulted in south or southeast winds at the study site due to the funnelling effect of Bridger Canyon (similar to the winds observed at mid-mountain at Bridger Bowl Ski Area (Figure 2)), and deposited snow to the leeward side of the largest group of trees (point (a) in Figures 5 and 6). On the upper part of the slope there is a gap in the trees (point (b) in Figure 5) which apparently allowed an increase in wind speed and scour, decreasing snow depth (point (b) in Figure 6). Similarly, at the bottom of the slope the lack of trees resulted in more wind scour and a general decrease in snow depth (point (c) in Figures 5 and 6), although there is a small area of increased depth at the bottom of the slope. Another possible explanation is that the trees, a three-dimensional surface feature, caused wind patterns that created a horseshoe vortex and resulted in a downwind pattern of two areas of decreased depth separated by a drift (see Kind, 1981, p. 344). Such a horseshoe vortex would produce an area of increased depth as was observed at the bottom of the

slope.

A comparison of snow depth (Figure 6) and average snow resistance (Figure 7) maps for 1988-89 at the site shows several similarities. As described separately above, both depth and average resistance had similar downslope patterns. Subtle variations in depth across the slope also seem to coincide with variations in resistance. These patterns suggest that snow resistance was related to snow depth. Simple linear regression indicates a significant relationship between depth and average resistance ($p\text{-value} < 1 \times 10^{-6}$) (Figure 8). However, the predictive value of the relationship is low ($r^2 = 0.357$), indicating that depth at this site could, at best, explain only 36% of the variation within the resistance data. There are several possible reasons why the predictability of this relationship is low. Many natural factors may affect average snow resistance, such as the rate, timing, temperature, and storm conditions of snow deposition, the amount of radiation and/or shading the snow has received, and the history of the snowpack over the season (depths, temperatures, etc.). Further, as discussed earlier, variability due to the DR may lower the r^2 .

As explained in Chapter 3, there is a problem with applying linear regression to these data since they are spatially related. To better check the validity of the $p\text{-value}$ for the relationship between depth and average resistance at the Bradley Meadows site in 1988-89, the original data set was reduced from over 358 observations to 39 observations by taking the data in every fifth row down the slope and every fifth column across the slope, thus creating a matrix 13 rows down and 3 columns across. This reduced data set continued to demonstrate a significant relationship between depth and average resistance ($p\text{-value} = 7 \times 10^{-3}$) (Figure 9), reinforcing the conclusions previously drawn.

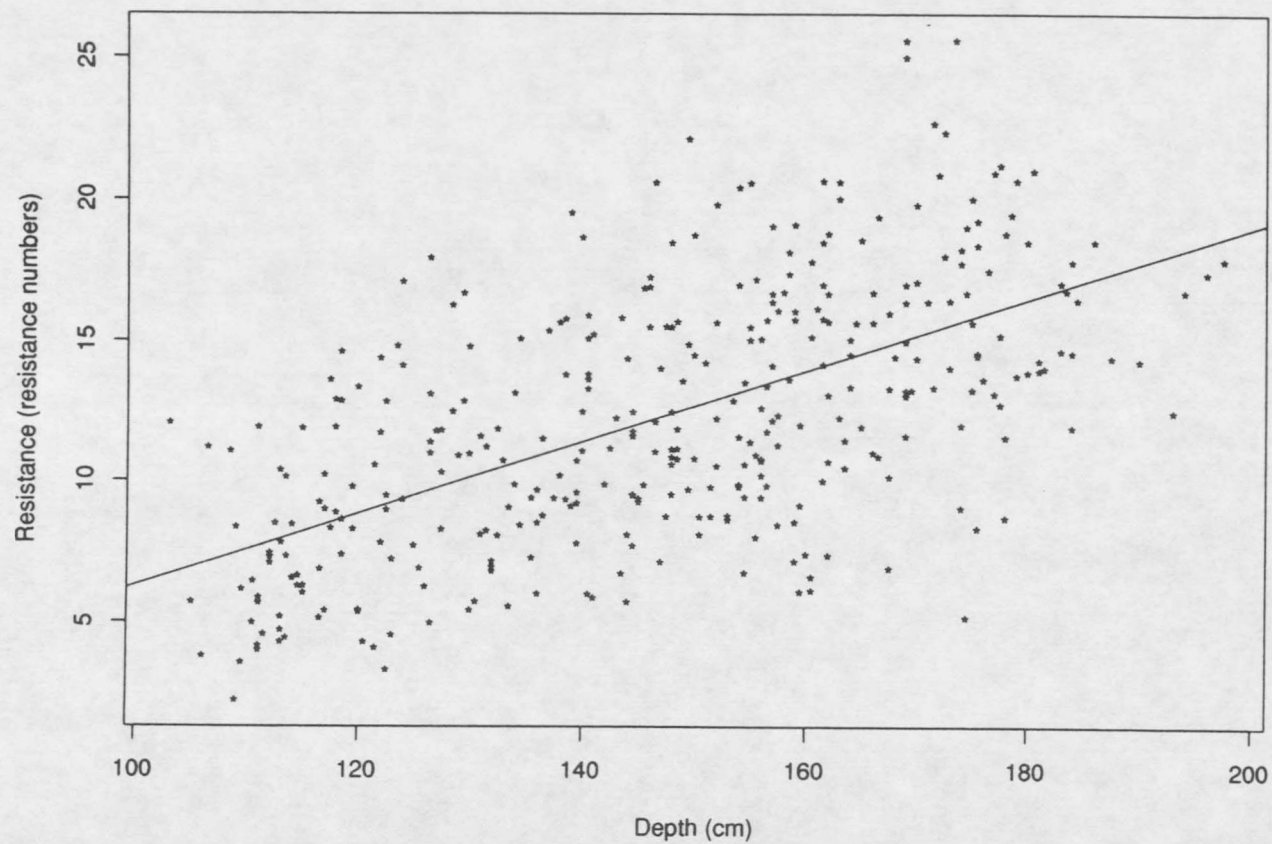


FIGURE 8: A simple linear regression shows a significant relationship between snow depth and average resistance at the Bradley Meadows site in 1989 (p -value $< 10^{-6}$). However, the predictive value of the relationship is low ($r^2 = 0.357$).

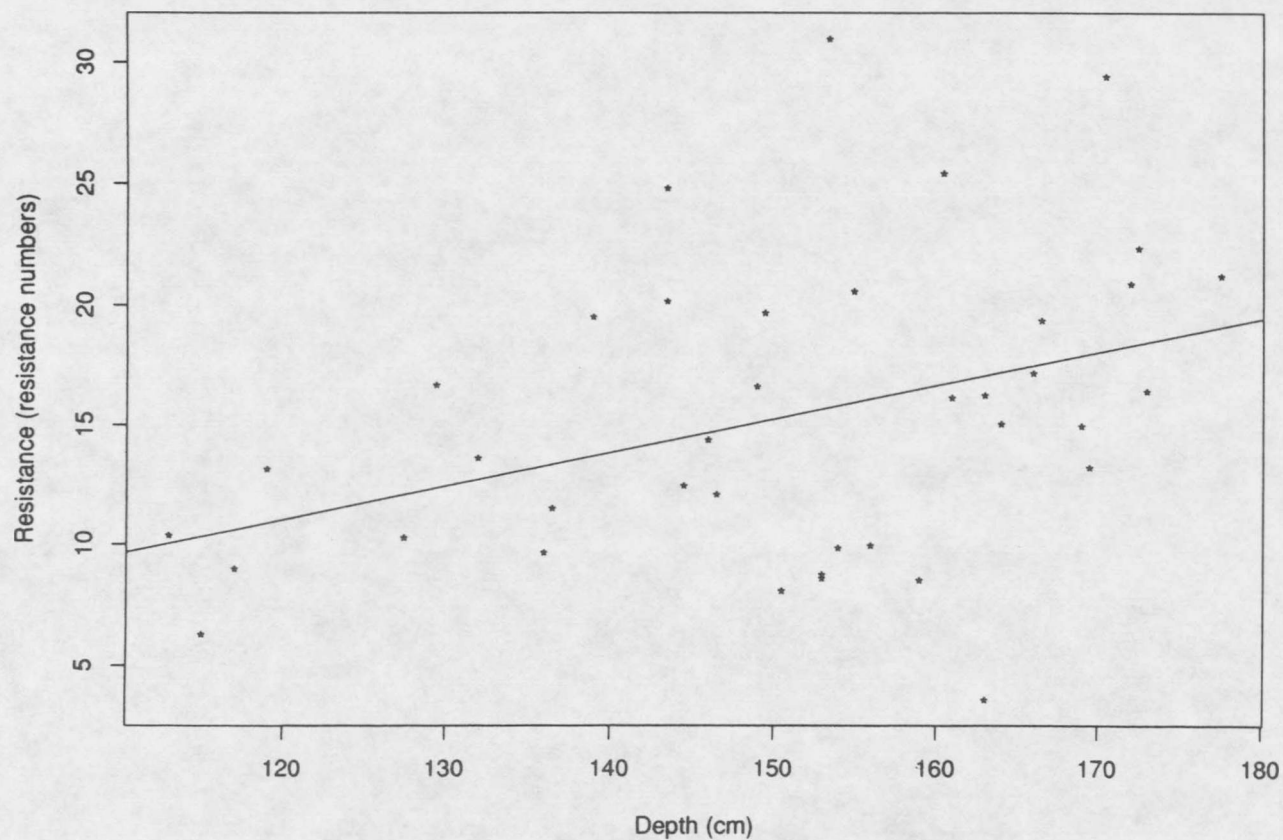


FIGURE 9: A simple linear regression with a reduced data set (reduced from $n = 358$ to $n = 39$) continues to show a significant relationship between snow depth and average resistance ($p\text{-value} = 7 \times 10^{-3}$), and a low predictive value of that relationship ($r^2 = 0.151$) at the Bradley Meadows site in 1989.

Snow Depth and Average Snow
Resistance, 1989-90

The snow depth map generated for 1989-90 shows a similar pattern to that described for the previous year (Figure 10). Maps for the two seasons are not the same width because problems with the DR the second season prevented complete sampling of the site. Going downslope, depth initially increased before decreasing to a local minima (point (b)), increased to a maximum at about mid-slope (point (a)), and decreased again before increasing slightly at the end of the slope (point (c)). Going across the slope there was an increase and then a decrease in depth. This wave-like pattern appears to be similar to that observed across the slope the previous year, but it is sharper.

The map generated for average snow resistance (Figure 11) shows similar patterns to those described for depth (Figure 10). Going downslope resistance initially increased before decreasing (point (b)), increasing to a maximum at about mid-slope (point (a)), and, with one small increase, decreasing to a minimum at the end of the slope (point (c)). Across the slope there was a general increase to a maximum just past mid-way across the slope and then a decrease. The similarity between snow depth and average resistance maps again mirrors the results of the previous season.

Comparison of Geographic Features,
Depth, and Resistance, 1989-90

Snow depth patterns observed at the Bradley Meadows site in 1989-90 (Figure 10) were similar to those observed in 1988-89 (Figure 6), reinforcing the hypothesis that snow depth patterns within the site were affected by wind patterns around adjacent trees. Like the previous season, storm events which were associated with strong winds this season

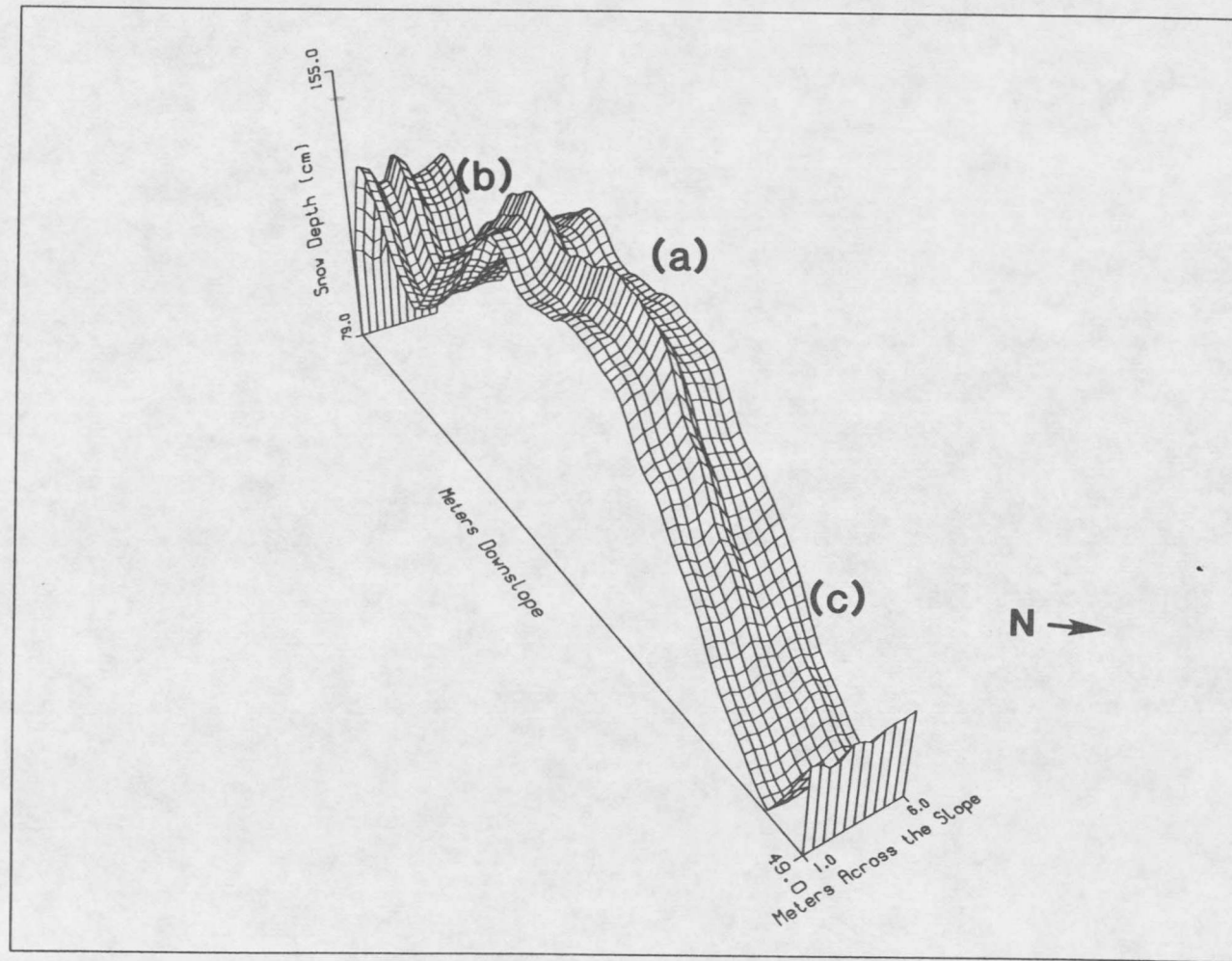


FIGURE 10: A three-dimensional perspective plot of snow depth for the Bradley Meadows site in 1990 shows depth variations over the site. Point (a) indicates a snow drift, while points (b) and (c) indicate areas of wind scour. Depth patterns are similar to those observed in 1989.

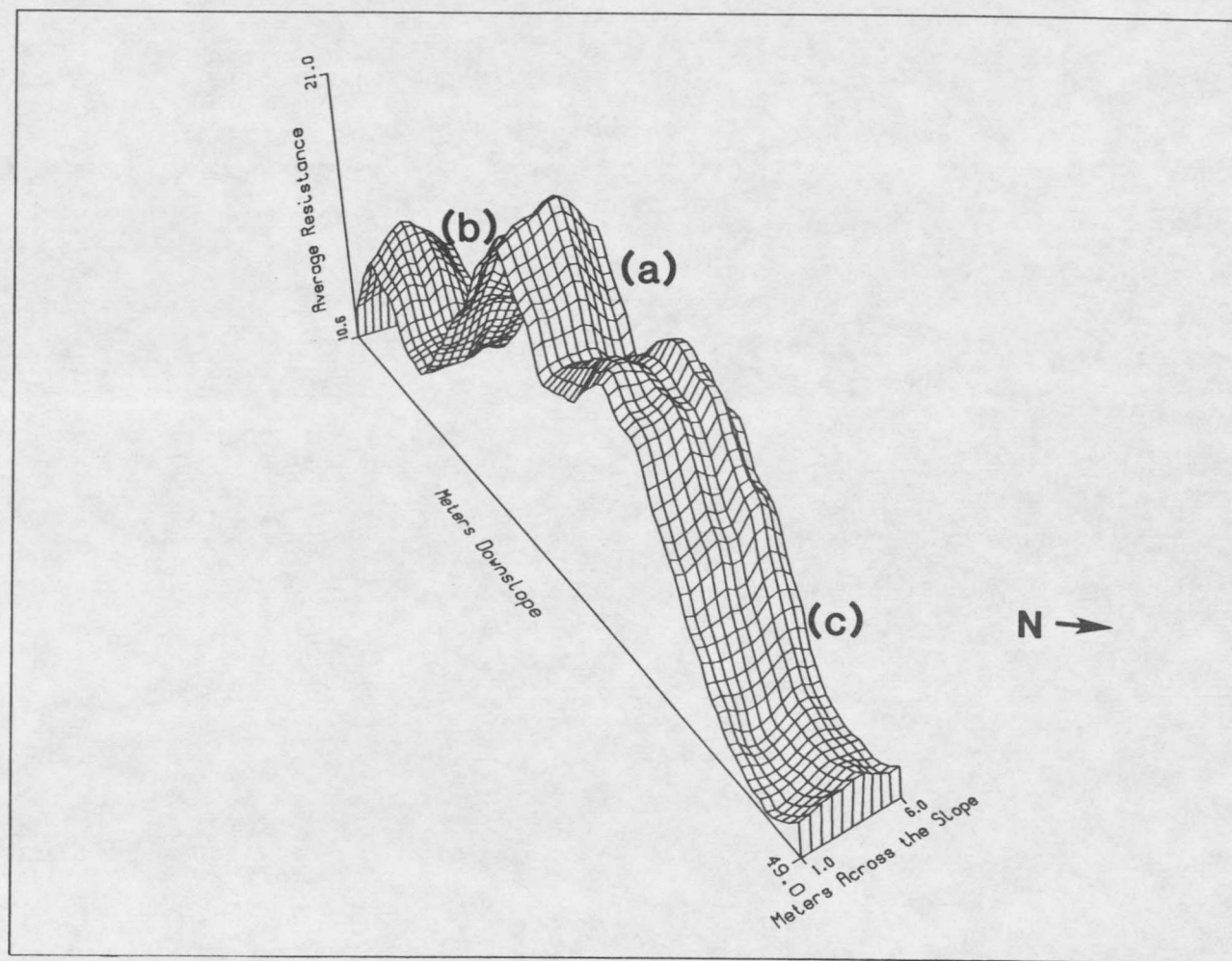


FIGURE 11: A three-dimensional perspective plot of average snow resistance for the Bradley Meadows site in 1990 shows average resistance variations over the site. Point (a) indicates an area of greater resistance, while points (b) and (c) indicate areas of less resistance. The general pattern observed is similar to that observed in 1989.

were predominantly from the southwest, resulting in south to southeast winds at the study site (similar to those observed at mid-mountain at Bridger Bowl Ski Area (Figure 2)). As a result, a large snow drift again formed on the leeward side of the largest group of trees (point (a) in Figures 5 and 10). Gaps or openings between the trees may have produced wind scour which reduced the snow depth at both the top and the bottom of the slope (points (b) and (c) in Figures 5 and 10). Alternatively, the trees may have served to create a horseshoe vortex (see Kind, 1981, p. 344), which would have created the observed snow depth patterns.

As with the previous year, visual similarities in the snow depth and average resistance maps (Figures 10 and 11) suggest a possible correlation. A linear regression for the 1989-90 data showed a significant relationship ($p\text{-value} < 1 \times 10^{-6}$) (Figure 12), although the predictive value of the relationship was again low ($r^2 = 0.204$). These results are consistent with the low $p\text{-value}$ and low r^2 that were observed the previous season.

As discussed previously, the spatial relationship of the data caused the assumption made in regression that we are dealing with independent observations to be violated. This results in autocorrelation and artificially reduces the $p\text{-value}$. To better check the validity of the results, the data set was reduced from 294 observations to 33 by utilizing the data from only three columns across and every fifth column down the slope. The reduced data set continued to show a significant relationship ($p\text{-value} = 6 \times 10^{-4}$) (Figure 13). This $p\text{-value}$ is one order of magnitude smaller than that of the previous year.

The similar results for two seasons of field data at this site are interesting. Patterns of snow depth and resistance at this site appears to repeat from year to year,

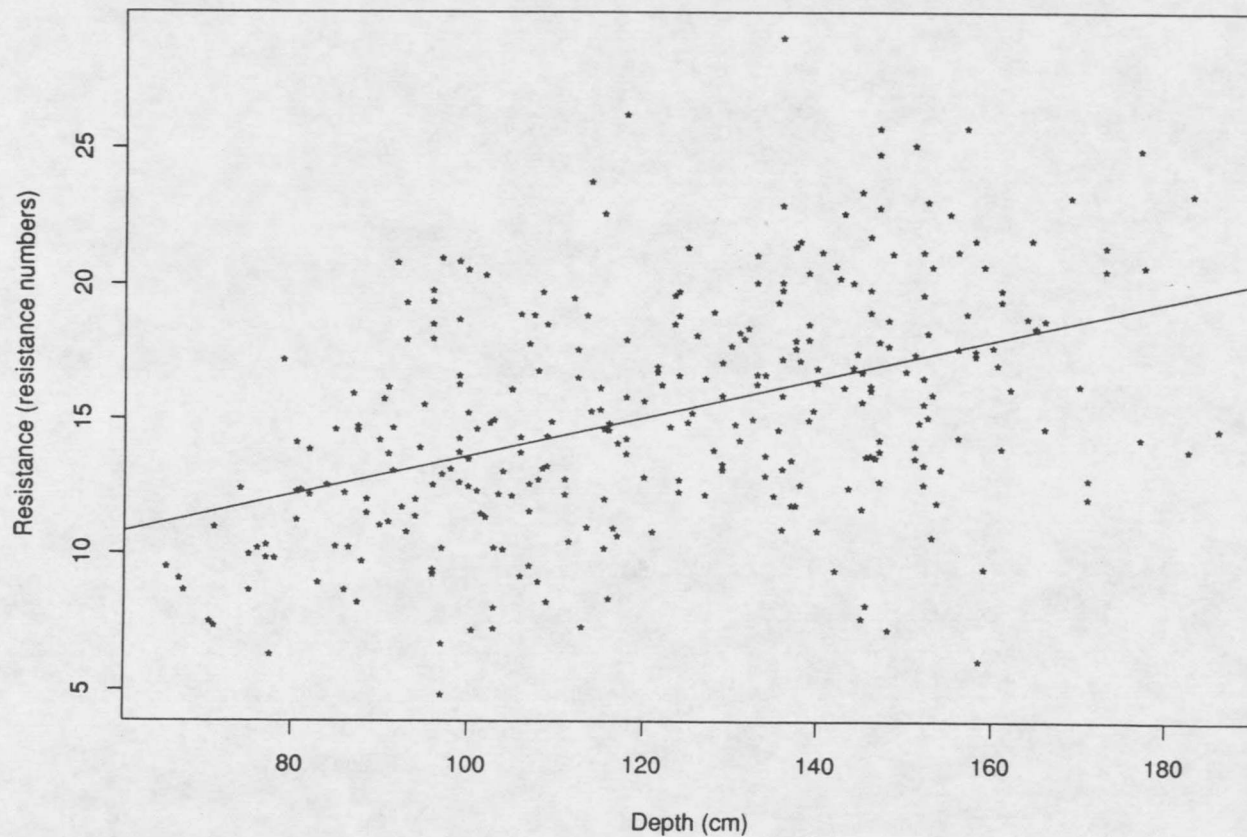


FIGURE 12: A simple linear regression shows a significant relationship between snow depth and average resistance at the Bradley Meadows site in 1990 ($p\text{-value} < 10^{-6}$). However, the predictive value of the relationship is low ($r^2 = 0.204$). This relationship is the same as was observed in 1989.

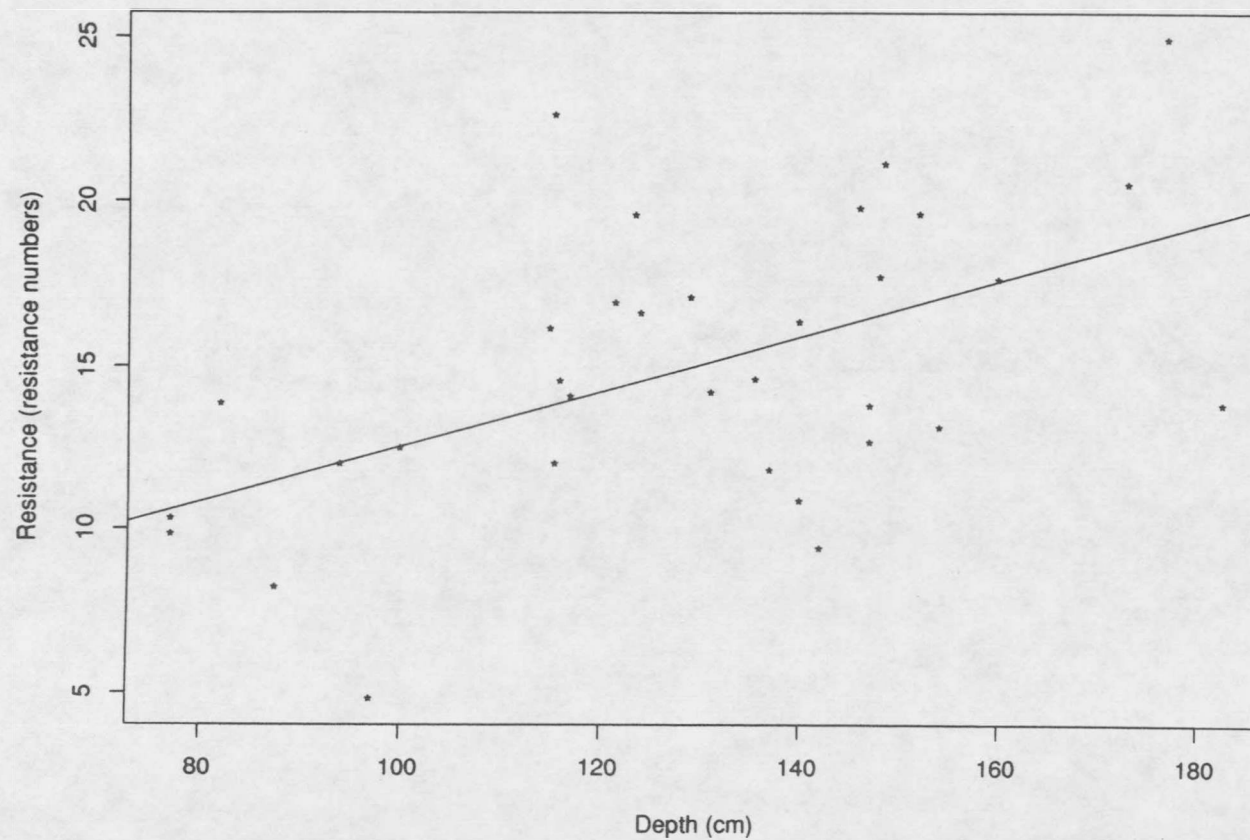


FIGURE 13: A simple linear regression with a reduced data set (reduced from $n = 300$ to $n = 33$) continues to show a significant relationship between snow depth and average resistance ($p\text{-value} = 6 \times 10^{-4}$), and a low predictive value of the relationship ($r^2 = 0.288$) at the Bradley Meadows site in 1990. This is the same relationship as was observed in 1989.

indicating that it may be possible to begin to predict what type of depth and resistance patterns will develop at the site. Perhaps similar patterns might be observed in other wind exposed areas subject to drifting snow and locally variable snow depth. Such predictions may eventually enable avalanche workers to predict strength patterns on slopes given the location of geographic features and knowledge of the local climatic conditions for that particular year.

Relationship of Shear Strength Patterns and Resistance Patterns, 1989-90

Shear strength data were collected 7 m northwest of the site at the same time depth and resistance data were being gathered. Going from the top of the slope to the bottom, average shear strength decreased, increased to a maximum, and then decreased to a minimum at the bottom of the slope (Figure 14). There is a great deal of scatter in this preliminary data. However, the data do suggest that there may be some relationship between gross downslope patterns of shear strength and downslope patterns of average resistance (which also decreased, increased to a maximum and then decreased to a minimum going downslope (Figure 11)) at this site. A more comprehensive study of this possible relationship is warranted. If such a relationship could be demonstrated, the digital resistograph could be then be used to quickly identify areas of potential shear weakness, which would be helpful for avalanche forecasting and control.

Bridger Bowl Site

Geographic features within the Bridger Bowl Site were more pronounced and included several areas of rocks, some trees, and a fallen log within the site. Many trees

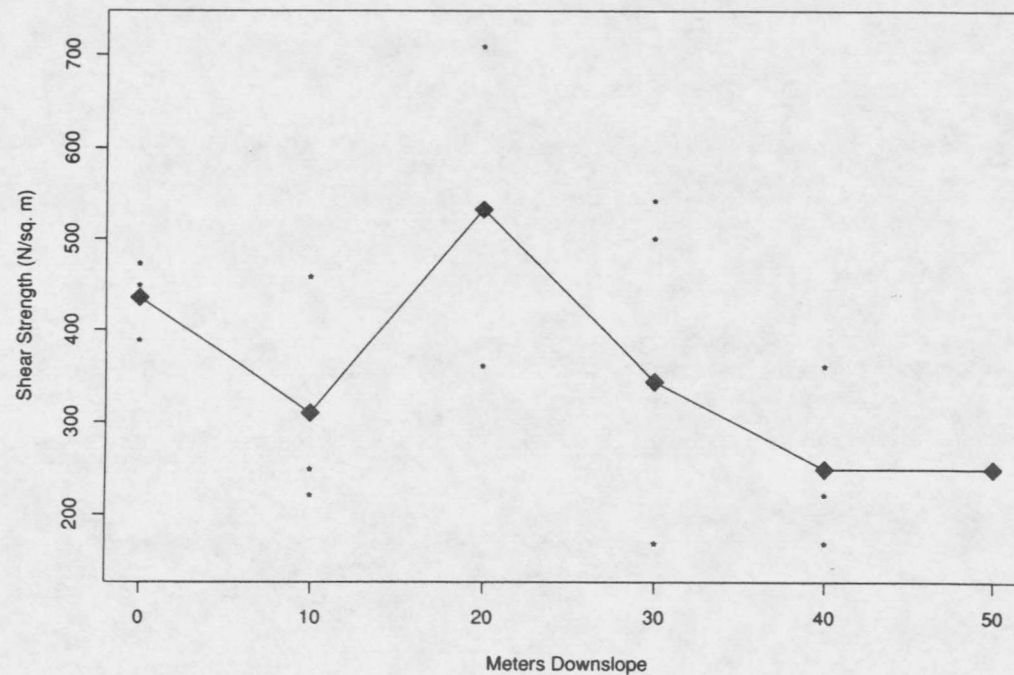


FIGURE 14: Going from the top of the slope to the bottom, average shear strength initially decreased, increased to a maximum, and then decreased to a minimum at the end of the slope. Three shear strength measurements were taken in six snow pits, each spaced 10 m apart. Individual measurements are shown by asterisks, and averages for the three values are shown by the shaded diamonds. Though there is a great deal of scatter in these preliminary data, they suggest a possible relationship with average resistance measured at this site (Figure 10).

surround the site (Figure 15). As outlined in Chapter 2, the Bridger Bowl Site was divided into two rectangles, referred to as "Bridger 1" and "Bridger 2", to facilitate the use of the graphics environment "S" for data analyses. Bridger 1 was completely sampled in one day, and Bridger 2 was sampled on the two following days, during both years. Separate site, depth, and average resistance maps were generated for each of these two areas.

Bridger 1

Geographic Features

The primary geographic features at Bridger 1 are the presence of trees within and around the study area (Figure 16). Toward the bottom of the slope there are two stands of trees, one where the tallest tree in the stand is about 9 m tall (point (a)) and the other where the tallest tree is about 15 m tall (point (b)). There is also a group of five trees (two large and three small ones) located near the top of the site (point (c)). The largest in this group is about 12 m tall. The slope is fairly uniform, and the substrate is mostly soil with some small (less than 0.5 m²) rocks and one fallen log (point (d)).

Snow Depth and Average Snow Resistance, 1988-89

Variations detected in snow depth (Figure 17 and Table 5) include a low point due to the immediate sheltering influence of a tree (located at point (b)). Starting at the top, depth generally decreased going downslope before increasing slightly and then decreasing again in a wave-like pattern. Going across the slope (from south to north) depth variability was again wave-like, as it generally increased, decreased, and then increased again.

Average resistance was quite varied within the site (Table 6) and the map of

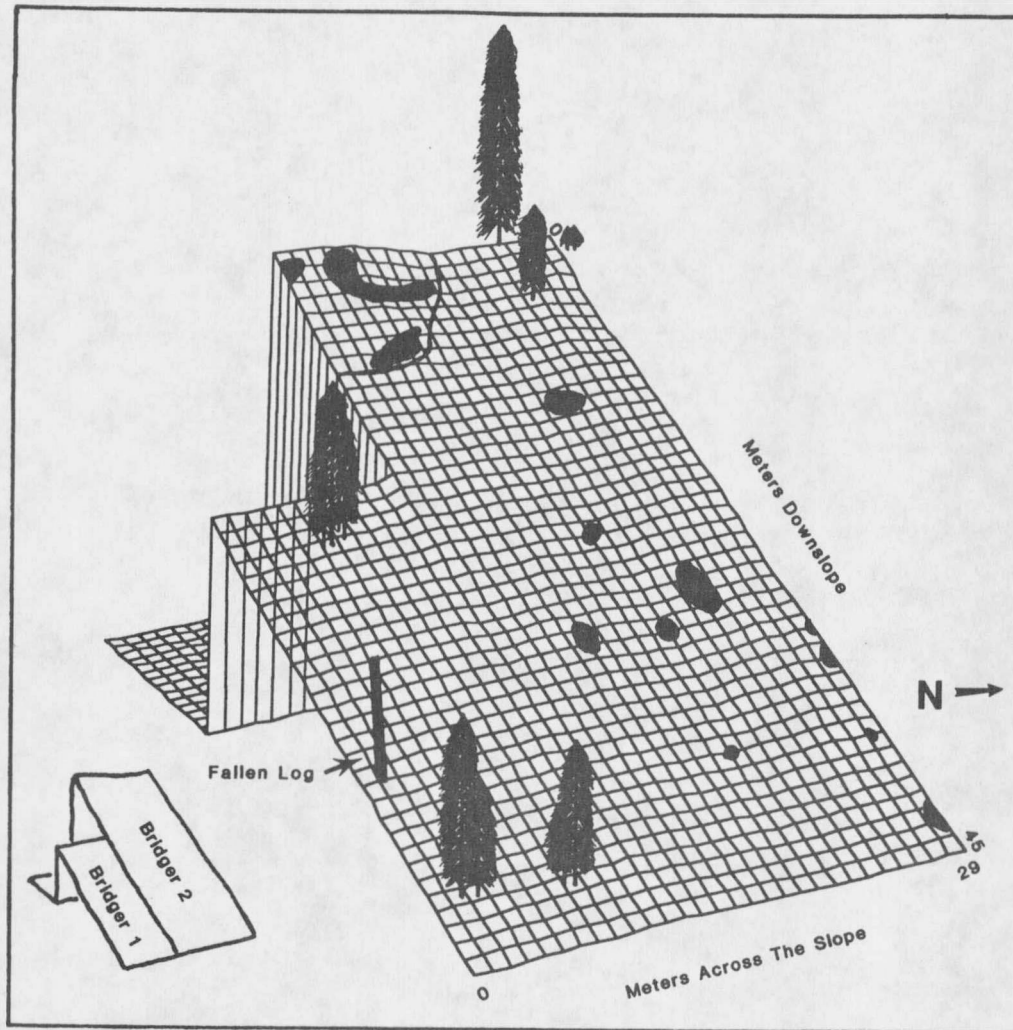


FIGURE 15: The map of the Bridger Bowl Site shows significant geographic variability. The grid represents the site, and was generated with topographic data. Rocks are represented by shaded areas.

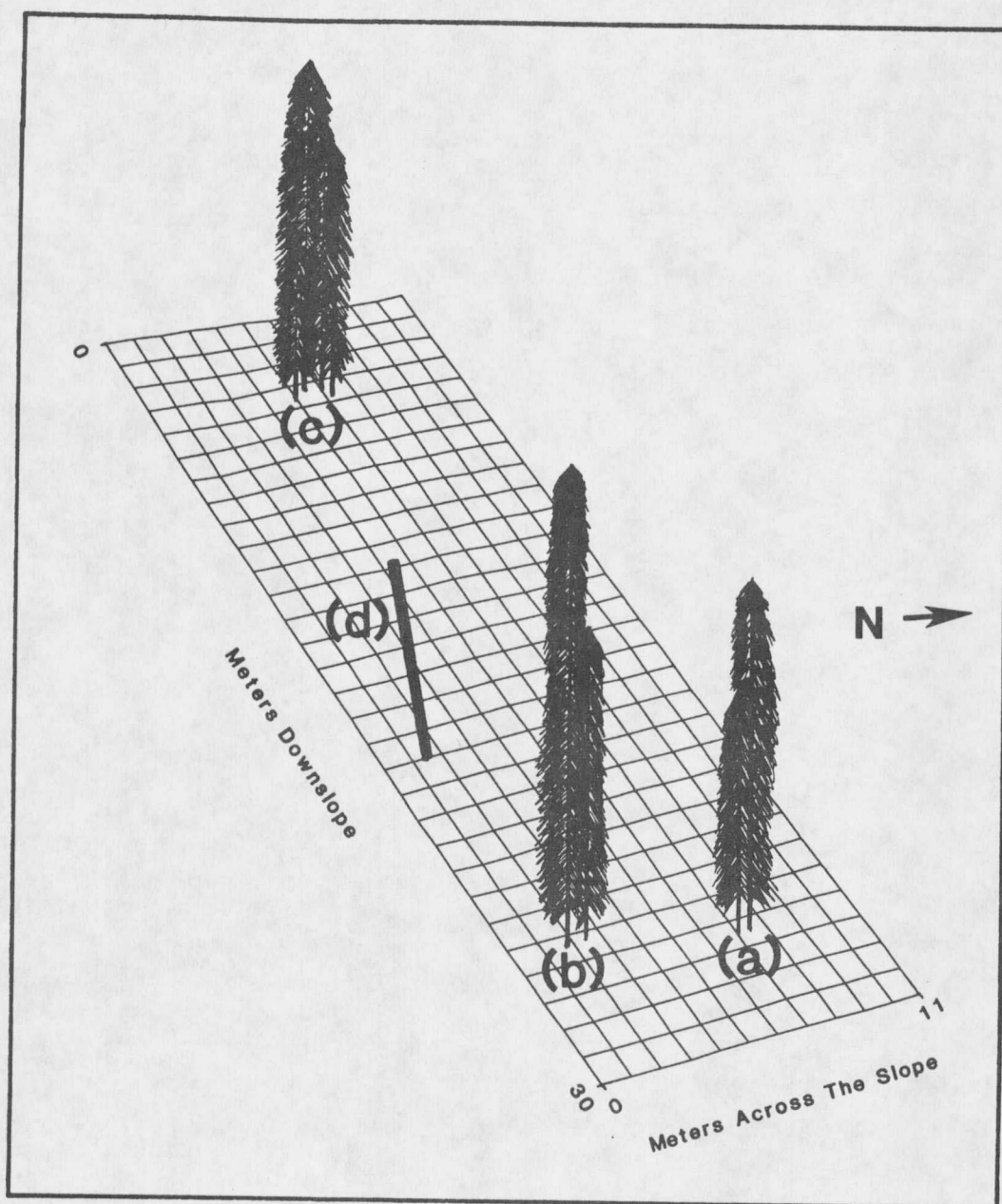


FIGURE 16: Geographic variability observed within the Bridger 1 site included trees (points (a), (b), and (c)) and a fallen log (point (d)).

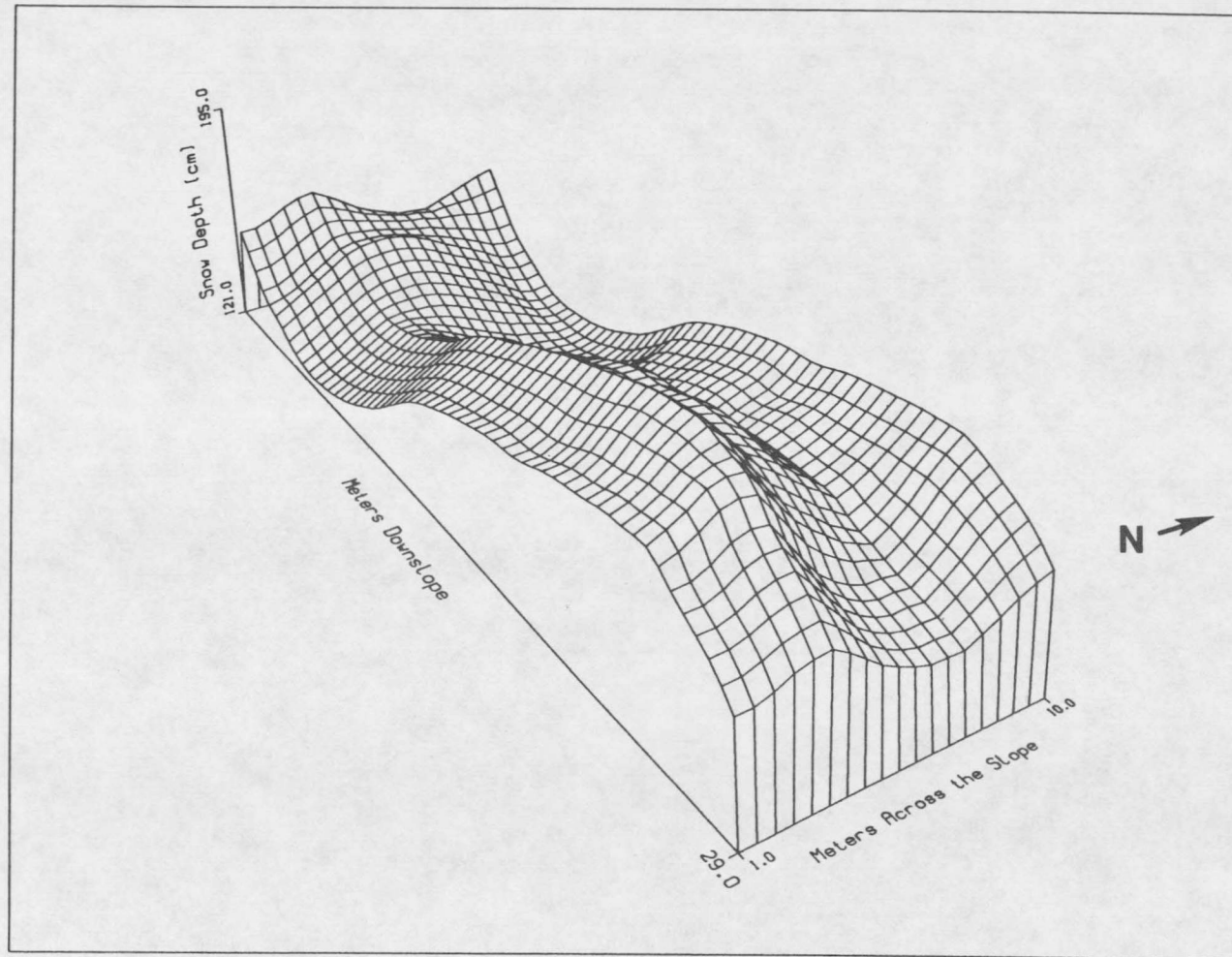


FIGURE 17: A three-dimensional perspective plot of snow depth for the Bridger 1 site in 1989 shows depth variations over the site. Snow appears to be deposited in a wave-like pattern both across and down the slope.

average resistance does not show as clear a pattern as was observed for snow depth (Figure 18). However, resistance did appear to generally decrease, increase, and then decrease again going from upslope to downslope. Going across the slope from south to north, two areas of increasing resistance at the top and bottom of the slope were apparent, along with one area (at midslope) that illustrated no large change, but rather small incremental changes.

Comparison of Geographic Features,
Depth, and Resistance, 1988-89

Snow depth was not strongly visually related to the location of different geographic features (Figures 16 and 18), perhaps because this site is relatively protected from strong surface winds by trees (some as tall as 22 m). This protection prevented local drifting around small groups of trees which would have influenced local snow depths.

Geographic features mapped at Bridger 1 (Figure 16) do not visually appear to be related to average resistance (Figure 18). Field observations made while sampling indicated that areas immediately around trees were generally shallower and weaker than adjacent areas. However, the shallow and weak nature of these locations was observed to be localized to within one meter of the trees and did not show up as trends in the average resistance data. Sampling under trees within the site was extremely difficult due to branches and soft snow, and it is possible that such complications may have prevented the collection of accurate data at these locations. The presence of the log under the snow (point (d) in Figure 16) was not observed as having a perceptible effect on the overlying snow's average resistance.

Like geographic features, snow depth was also not correlated to resistance at

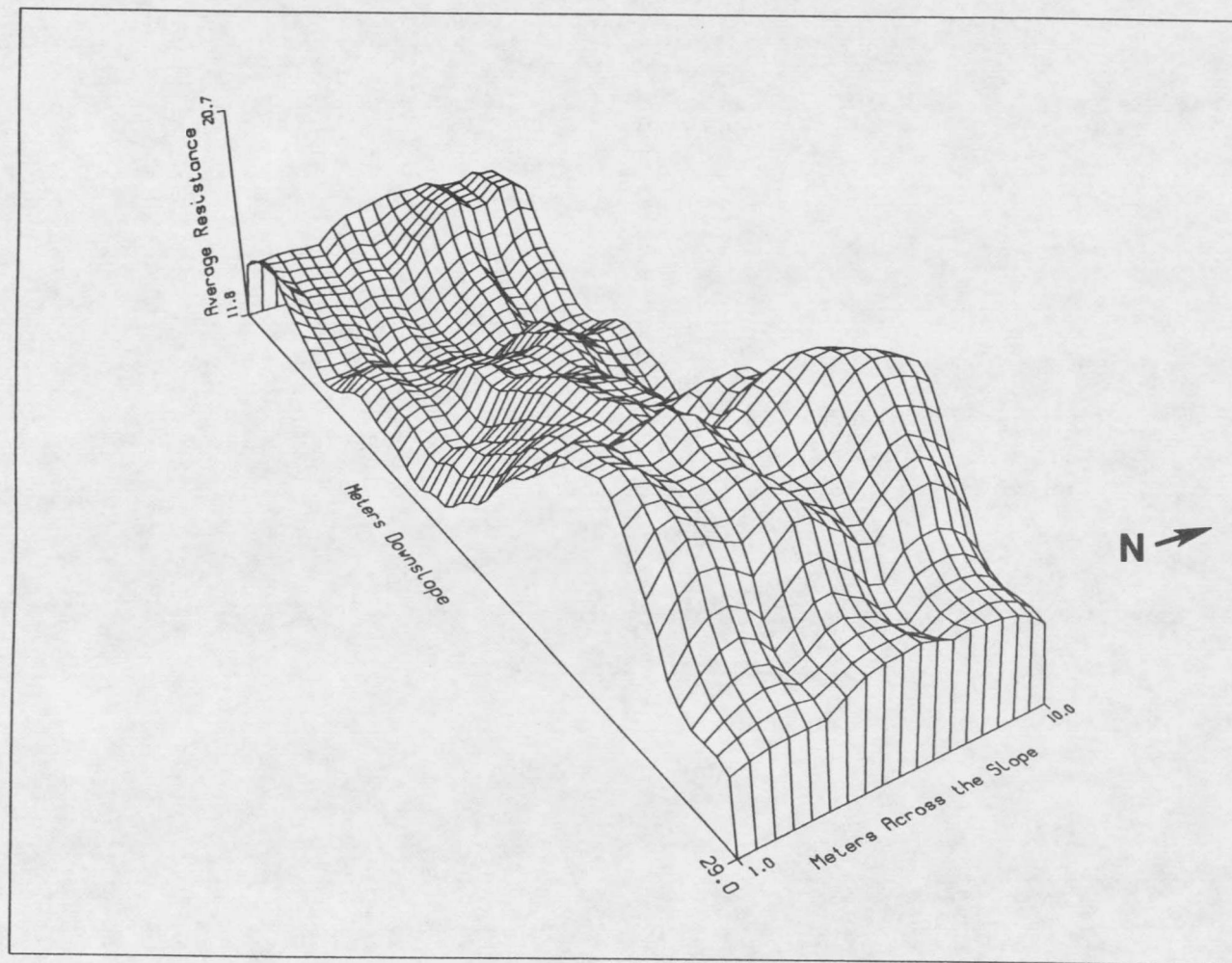


FIGURE 18: A three-dimensional perspective plot of average snow resistance for the Bridger 1 site in 1989 shows average resistance variations over the site.

this site. Although a very rough similarity between depth and average resistance was indicated in the area about two-thirds of the way down the slope (Figures 17 and 18), a simple linear regression showed this relationship was insignificant ($p\text{-value} = 0.4438$) (Figure 19).

Snow Depth and Average Snow Resistance, 1989-90

Snow depth variability was evident again in 1989-90 (Table 5; Figure 20). The minimum depth was observed under the same group of trees as the previous season ((b) in Figure 16). Going downslope from the top of the slope, depth generally increased slightly, decreased to a minimum toward the bottom of the slope, and then increased slightly again (Figure 20). There were minimal variations in depth going across the slope, in contrast to the wave-like pattern observed in 1988-89 (Figures 17 and 20).

Variability in average resistance (Table 6) did not show a clear, definable pattern (Figure 21), but did suggest that average resistance decreased a small amount before increasing to a maxima going from south to north across the site. Patterns of average snow resistance for the site were different from 1988-89 (Figures 18 and 21). Both seasons showed variable resistance, but the resistance patterns observed in 1989-90 were smoother than those for the previous year. This is likely due to the more careful collection of data the latter year, which resulting in a decrease in the number of data points which had to be eliminated due to clogging of the probe with ice and mud, and led to a decrease in the standard deviation in the data (Table 6).

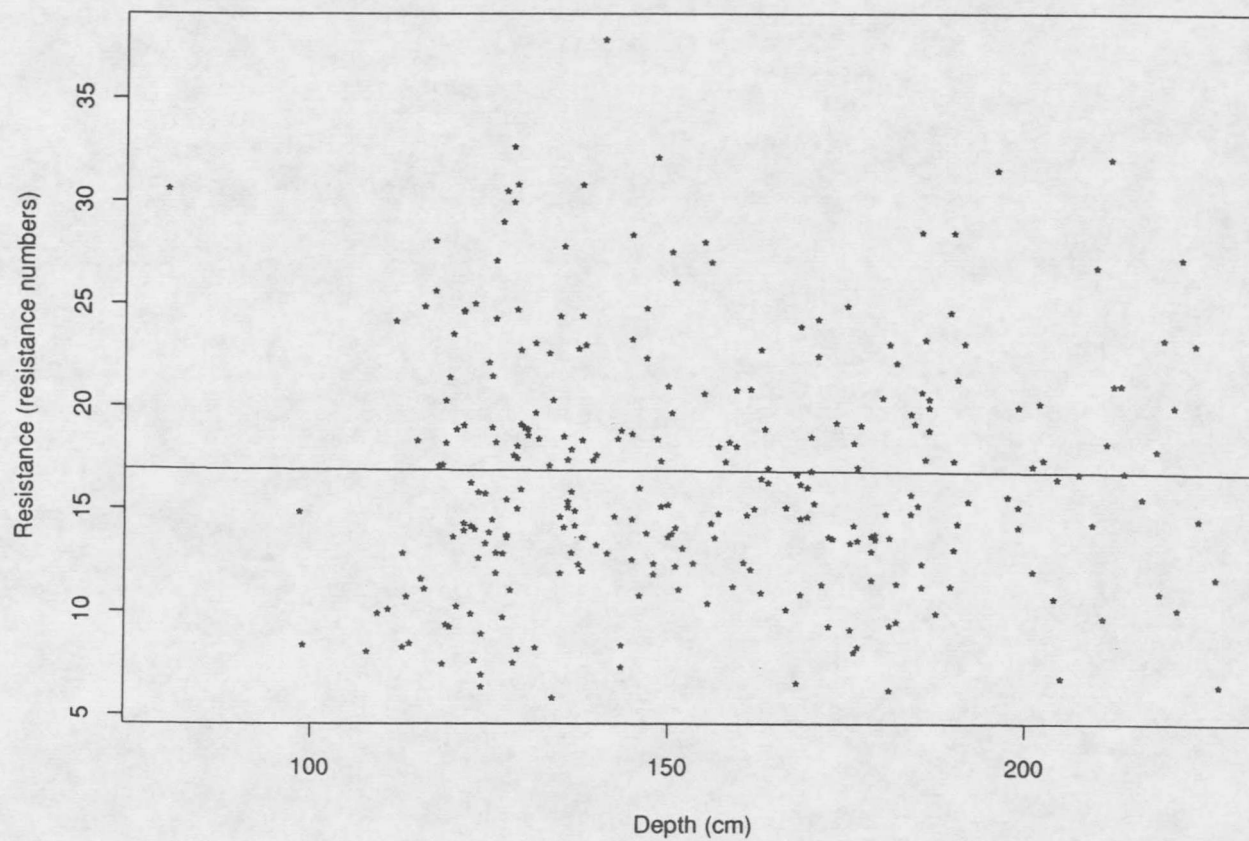


FIGURE 19: A simple linear regression between snow depth and average resistance at the Bridger 1 site in 1989 was insignificant (p -value = 0.4438).

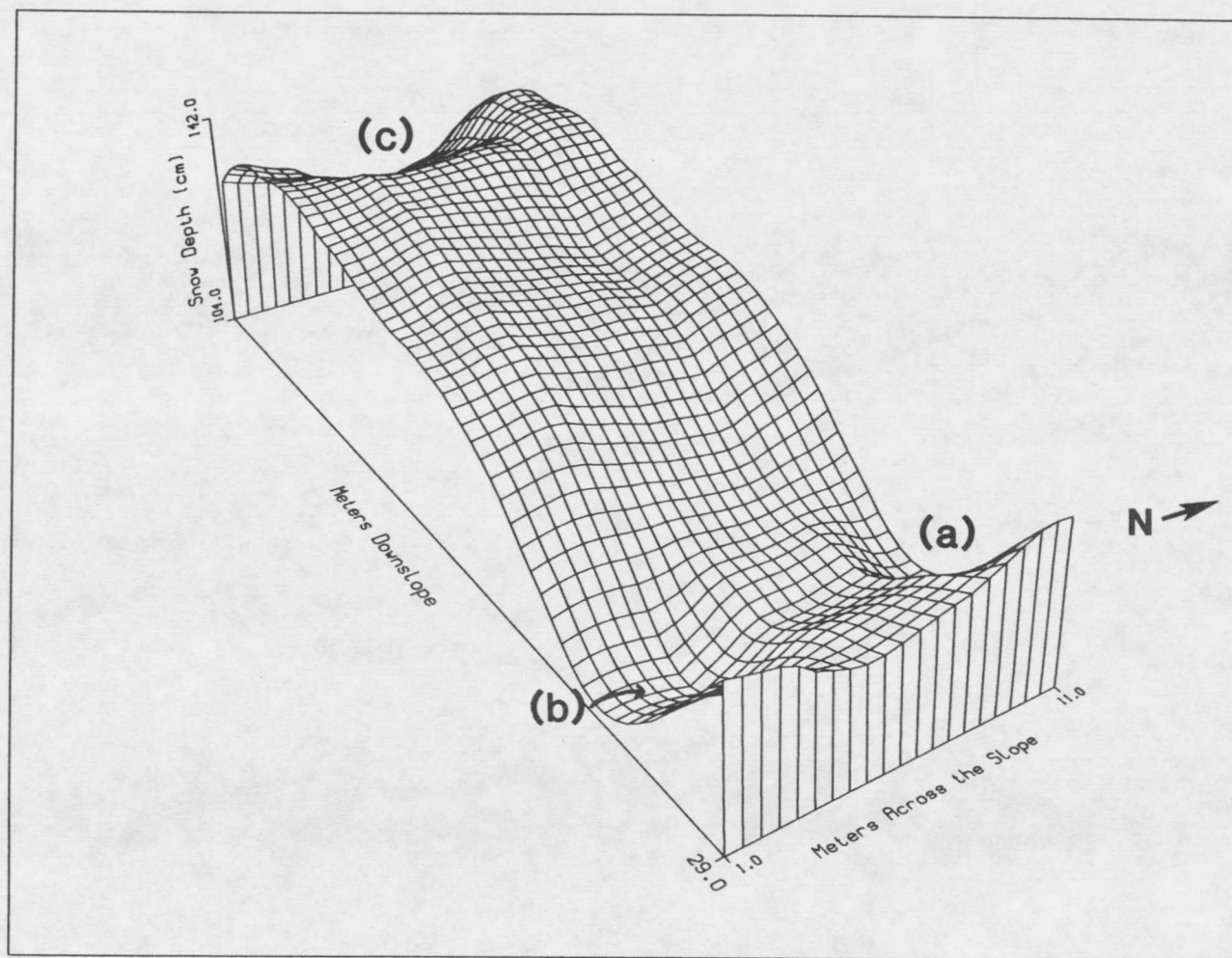


FIGURE 20: A three-dimensional perspective plot of snow depth for the Bridger 1 site in 1990 shows depth variations over the site. Decreases in snow depth at points (a), (b) and (c) are attributed to the interception of snow by trees at these locations.

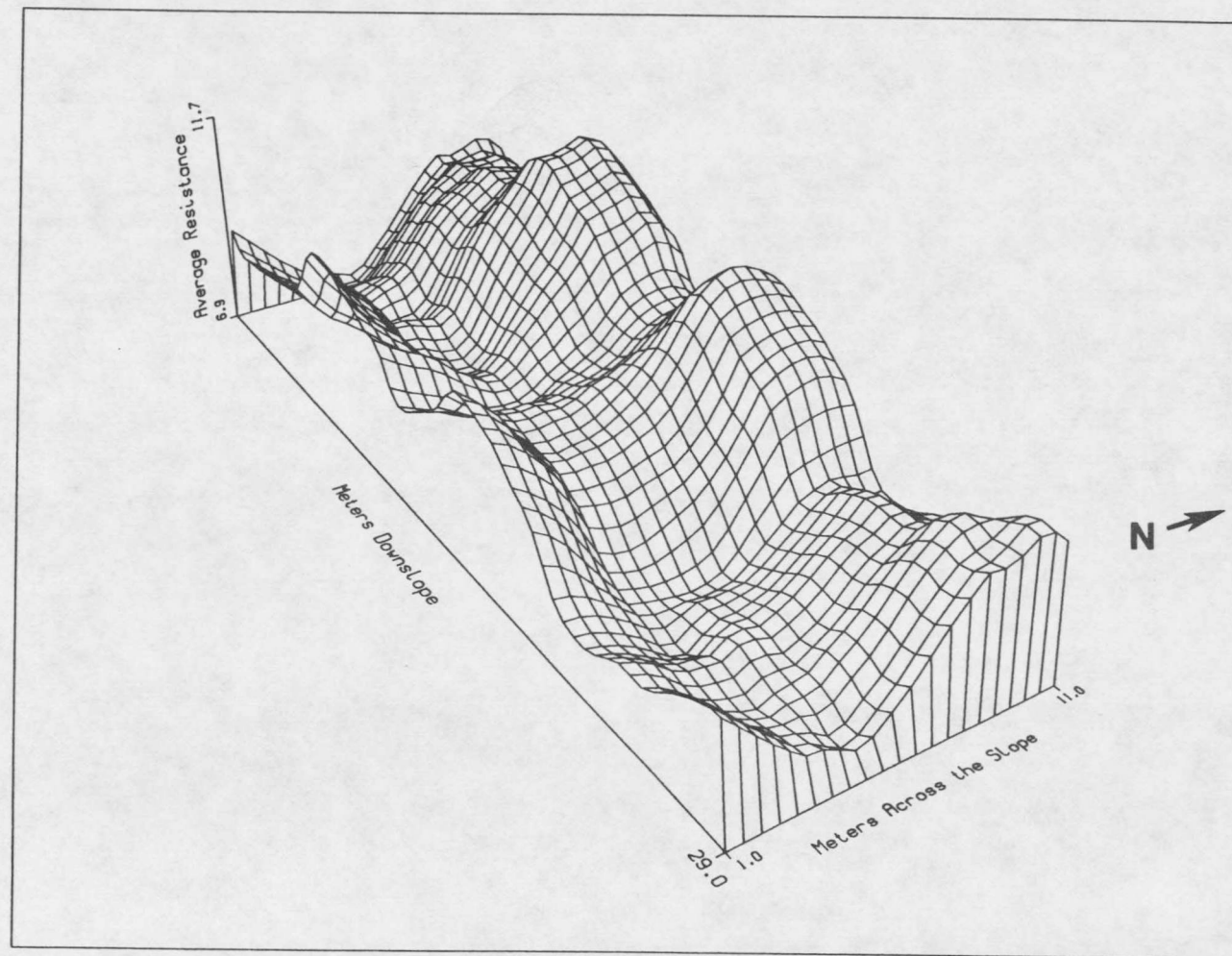


FIGURE 21: A three-dimensional perspective plot of average snow resistance for the Bridger 1 site in 1990 shows average resistance variations over the site.

Comparison of Geographic Features,
Depth, and Resistance, 1989-90

In contrast to the previous year, snow depth and geographic features could be correlated at this site in 1989-90. A comparison of depth and geographic features maps (Figures 16 and 20) shows local decreases in depth in the three regions where trees are located (points (a), (b) and (c) in Figure 16). One possible reason why such a correlation could be made this year and not the previous one may be related to the total snow depth. Since there was less snow in 1989-90 at the site at sampling time (Table 5), it was easier to sample under trees because there was more space underneath the branches in which to stand and properly use the instrument. In 1988-89 there was much more snow and this led to some measurements around the trees being missed because there were too many branches in the way. Values for these missed areas were averaged from the snow depth of the points around them and were input into matrices for the creation of 1988-89 maps.

Patterns of average resistance observed at this site did not relate to the geographic features (Figures 16 and 21). While the region in the vicinity of one group of trees (point (b)) was locally weaker than areas around it, the areas in the vicinity of the two other groups of trees (points (a) and (c)) were locally stronger. No change in resistance was noted for the area around the fallen log (point (d)). Further, multiple regression analysis, using an indicator variable to code whether or not the sample point was within 1 m of a tree, demonstrated an insignificant ($p\text{-value} = 0.441$) relationship when the presence of trees and depth were regressed on resistance.

No similarities between snow depth and average resistance maps were evident for the site (Figures 20 and 21). It was surprising, therefore, that the simple linear regression between depth and average resistance showed a fairly strong relationship (p -

value = 0.07) (Figure 22). Though this p-value was close to being significant at the 0.05 level, it was found that when a smaller data set was chosen (reduced from $n = 319$ to $n = 32$) the p-value rose to 0.22 and the slope of the linear regression line changed from positive to negative (Figure 23). Presumably the near-significant p-value was in response to: 1) the spatial relationship of the data, and 2) the one low depth/low resistance point which was well separated from the main part of the data (which were clustered in the region from 105 to 145 cm in depth) and thus would have an undue effect on the regression.

Though patterns of snow depth and average resistance varied between years, results for the two seasons were similar. For both years it was not possible to correlate snow depth to average resistance, nor was it possible to find areas of locally low resistance around geographic features. However, it was possible to show that the trees within the site affected the snow depth in 1989-90, something that was not observed in 1988-89. This is likely due to the decreased snow depth observed at the site in 1989-90 (Table 5) which facilitated sampling under the trees.

Bridger 2

Geographic Features

Even though Bridger 1 and Bridger 2 are adjacent to each other, the nature of the geographic features differ considerably between the sites. The geographic features within Bridger 2 consist primarily of rocks within the site (Figure 24), the most prominent of which are located in the southwestern corner of the site where a 64 m² rock outcrop exists (point (a)). There are many other loose boulders on the site, the largest one measuring 2.8 m by 3 m (point (b)). There are trees both around the perimeter of the site

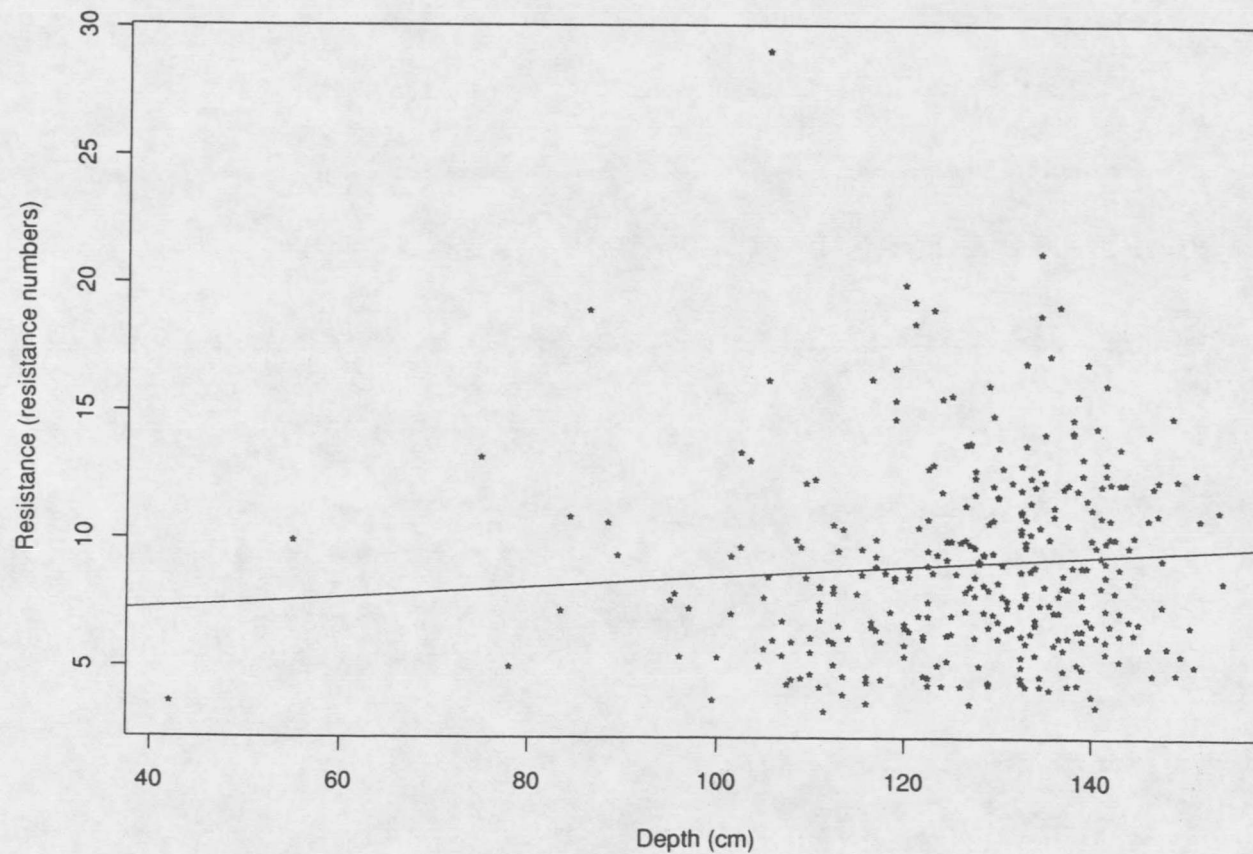


FIGURE 22: A simple linear regression between snow depth and average resistance at the Bridger 1 site in 1990 was nearly significant ($p\text{-value} = 7 \times 10^{-2}$), but this significance is in large part due to the low depth/low resistance value which has undue "pull" on the regression line.

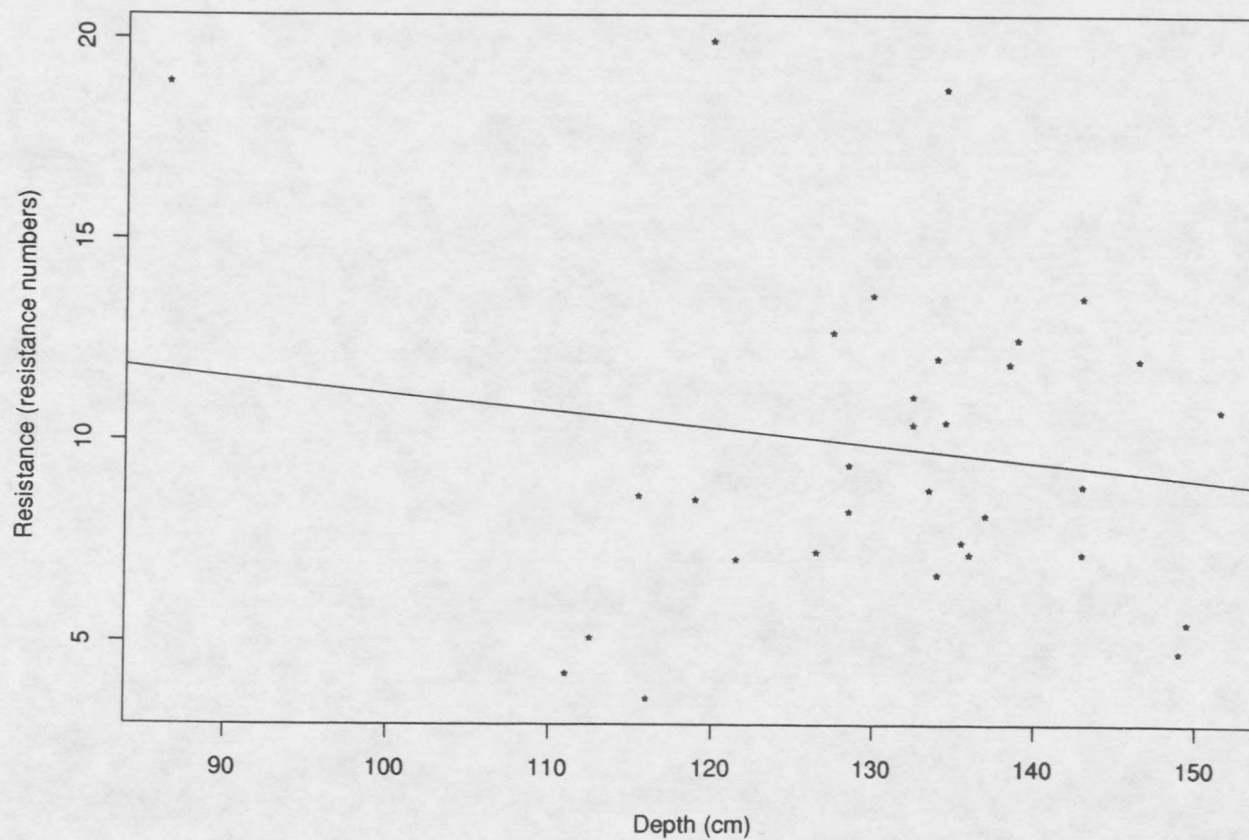


FIGURE 23: A linear regression with a reduced data set (reduced from $n = 319$ to $n = 32$) shows an insignificant relationship between snow depth and average resistance at Bridger 1 in 1990 ($p\text{-value} = 0.22$).

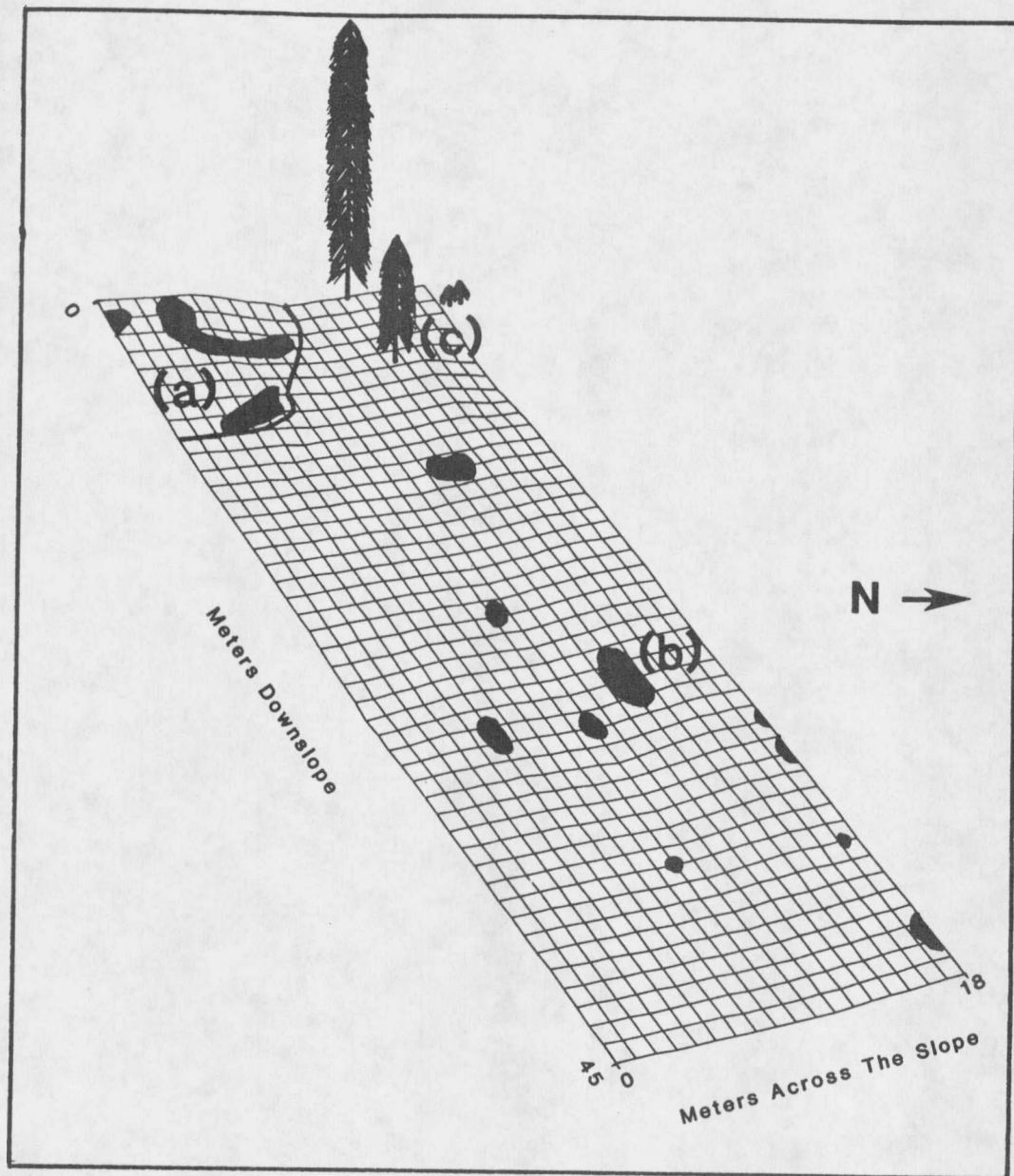


FIGURE 24: The geographic variability within the Bridger 2 site includes a rock outcrop (a), some large, loose rocks (the largest of which is at point (b)), and trees (point (c)). The grid represents the site, and was generated with topographic data. Shaded areas represent rocks.

and within the site. Those within the site are located near the top northern part, and are as tall as 14 m (point (c)).

Snow Depth and Average Snow Resistance, 1989-90

The minimum snow depth was measured at a spot where one of the largest rocks was shallowly buried (point (b) in Figures 24 and 25). Starting at the top of the slope, snow depth generally decreased going downhill, with one increase near the bottom of the site. Changes in depth across the slope appeared to be more subtle, increasing, gently decreasing, and then increasing again from south to north.

Average resistance data (Table 6 and Figure 26) show an extremely variable pattern with no clear trends for the site in 1988-89. Instead, localized zones of decreased and increased resistance were scattered around the slope.

Comparison of Geographic Features, Depth, and Resistance, 1988-89

Comparison of the geographic features (Figure 24) and snow depth (Figure 25) for 1988-89 do not show any clear visual correlations. Although areas under trees were observed to be generally shallower, and measurements on top of some large rocks indicated shallow depths, such effects were too localized to result in any visually-detectable patterns.

The seemingly haphazard pattern of average resistance also shows little correlation with snow depth (Figures 25 and 26). There appears to be some correlation at the toe of the slope, little elsewhere, and even some negative correlation. These observations are strengthened by the insignificant simple linear regression ($p\text{-value} = 0.4505$) (Figure 27). Again, these data are spatially related so even this large $p\text{-value}$ is

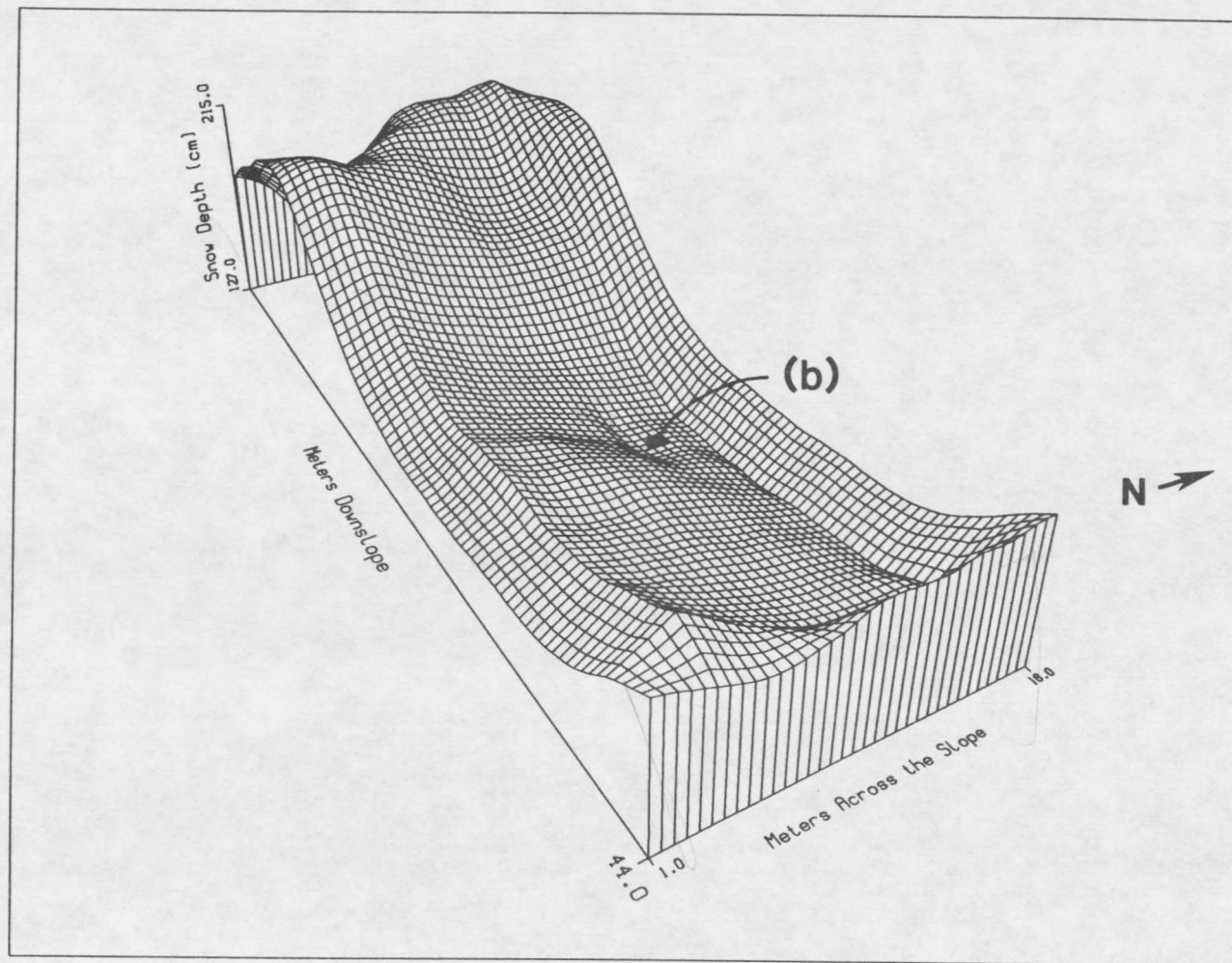


FIGURE 25: A three-dimensional perspective plot of snow depth for the Bridger 2 site in 1989 shows depth variations over the site. Note the wave-like pattern of snow deposition both across and down the slope.

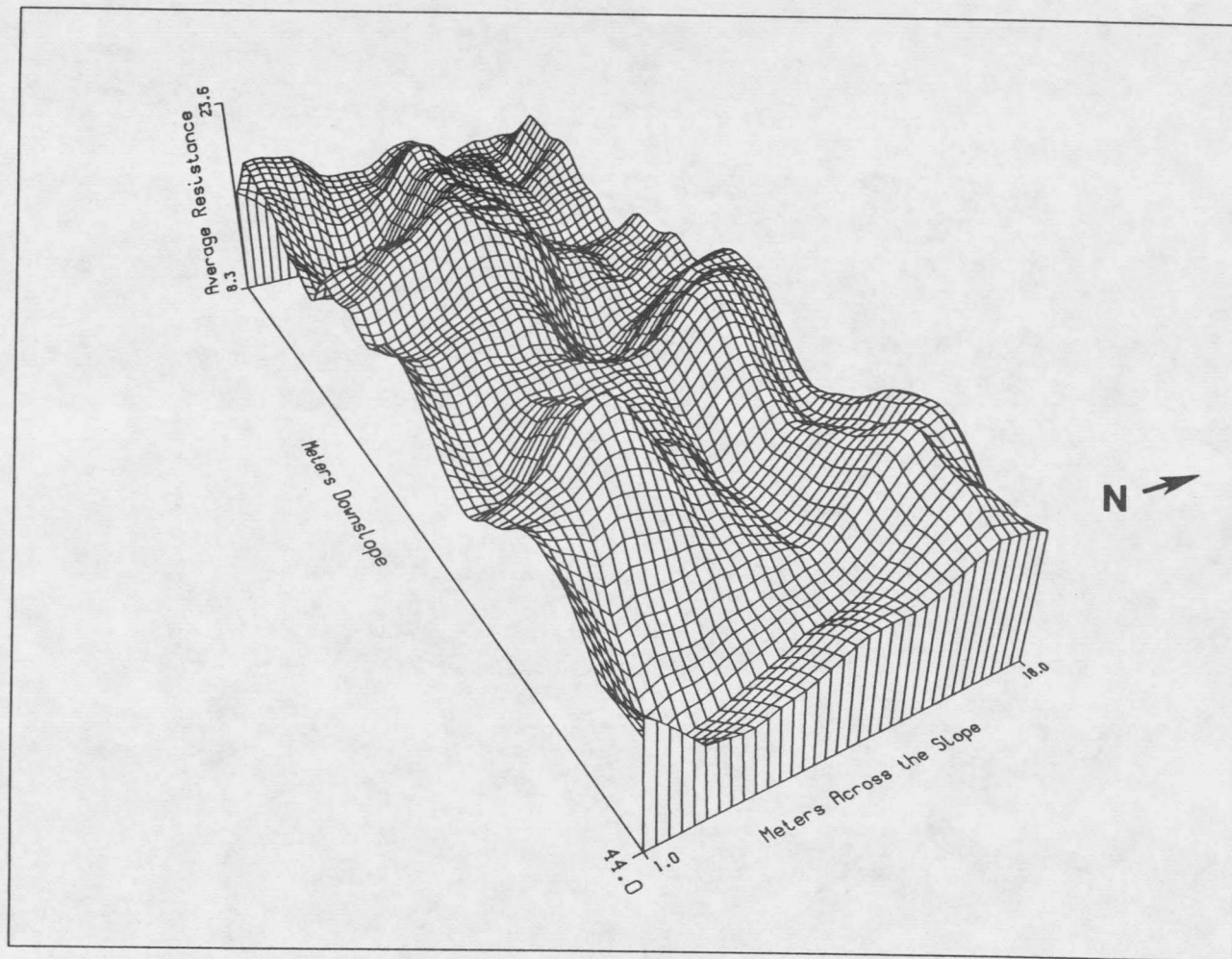


FIGURE 26: A three-dimensional perspective plot of average snow resistance for the Bridger 2 site in 1989 shows average resistance variations over the site.

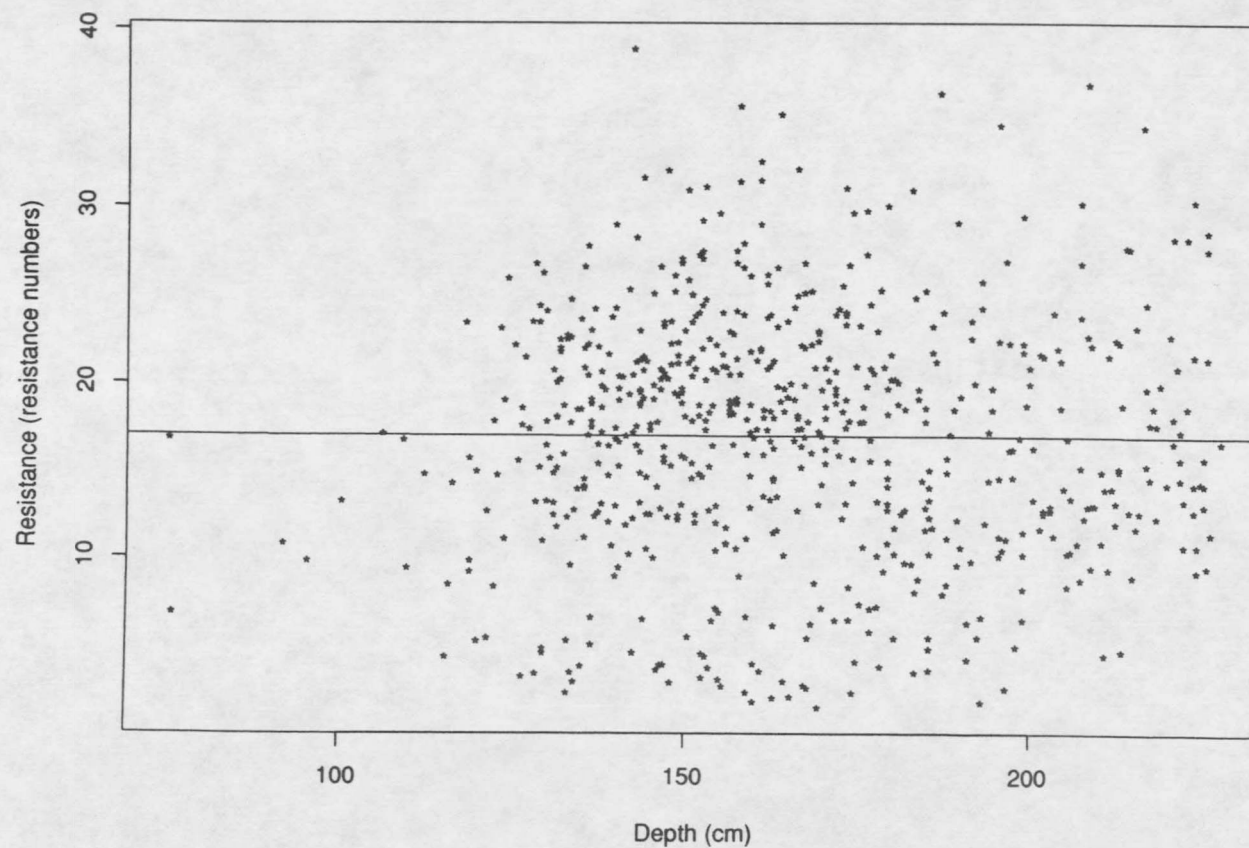


FIGURE 27: A simple linear regression between snow depth and average resistance at the Bridger 2 site in 1989 was insignificant ($p\text{-value} = 0.4505$).

likely to be underestimated. This site is complicated by variation in trees, rocks, and possibly even solar radiation (not measured), which may have affected resistance. These factors would tend to mute any relationship that might have been observed between depth and average resistance.

Resistance measurements at Bridger 2 cannot be easily related to geographic features. Field observations indicated a weaker snowpack around some of the rocks, evident because while sampling we fell through the snow in the vicinity of some of the larger rocks. These weaker areas were localized to only the area immediately above rocks (not to the larger areas around them). This might explain why they do not show up clearly on the map. In any event, a comparison of the average resistance (Figure 26) and geographic features (Figure 24) maps for the site shows that in some cases rocks are located in weaker areas, but in other cases there are weak areas without rocks or strong areas with rocks. No multiple regression was used this year to try to discern the relationship of rocks to resistance because the large number of "bad" data points, attributable to clogging of the probe, made such an analysis difficult.

Snow Depth and Average Snow Resistance, 1989-90

Although the snow depth was fairly uniform during 1989-90, there were greater variations in depth observed at the top (west) part of the site than over the rest of the site (Figure 28). Additionally, areas of decreased snow depth were observed in the southwest and southeast corners of the site. Snow depth was shallower and varied less than the previous season (Table 5). The minimum depth recorded was over the same rock as the previous season's minimum depth (point (b) in Figure 24). Comparison of snow depth maps for the two field seasons showed some similarities (Figures 25 and 28), most

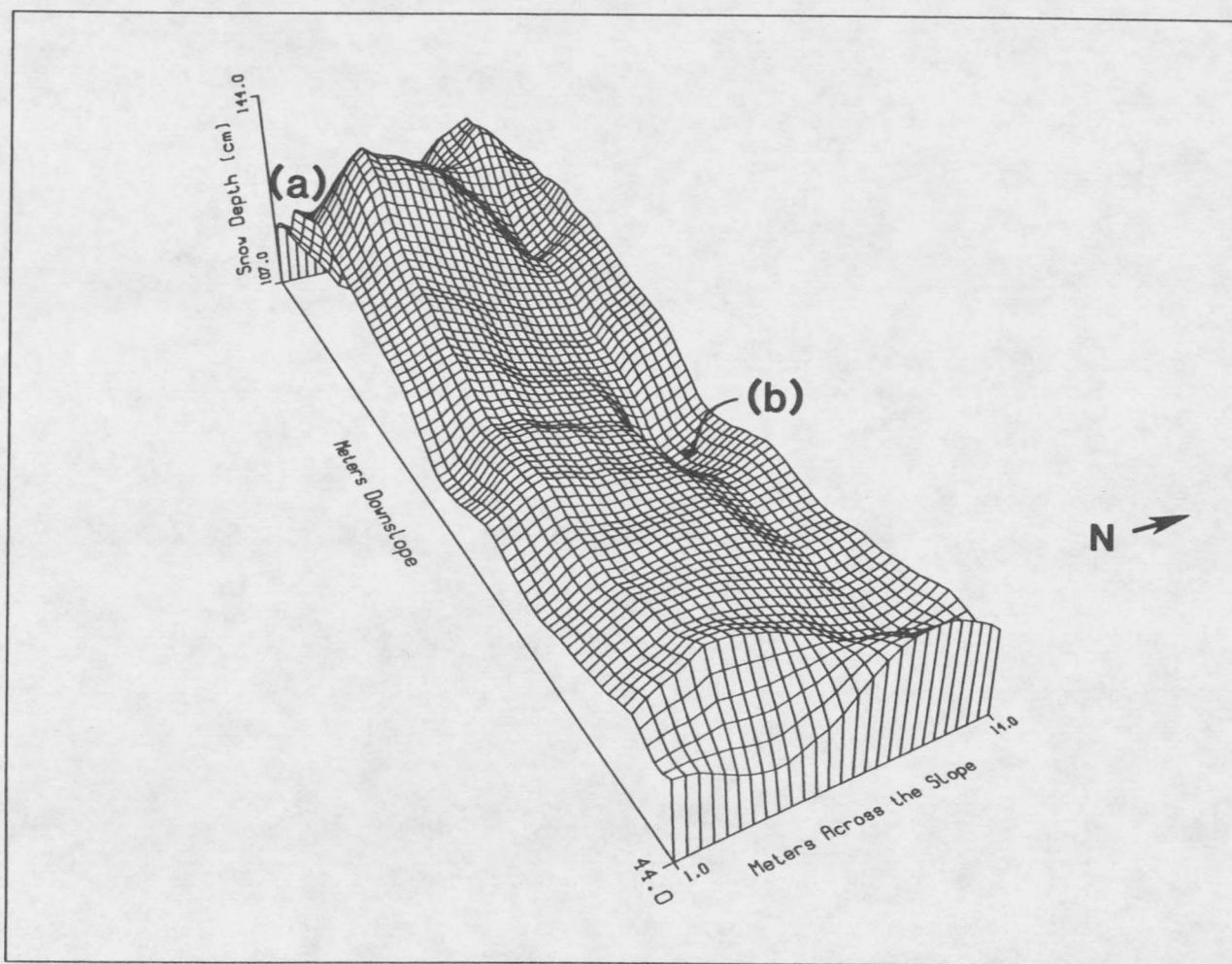


FIGURE 28: A three-dimensional perspective plot of snow depth for the Bridger 2 site in 1990 shows depth variations over the site. Decreases in snow depth are attributable the influence of a steep rock outcrop that allows the snow to sluff off (point (a)), and a large loose boulder that is shallowly buried (point (b)).

notably the subtle increase in depth observed going from the southern edge of the site towards the north and the small change in depth measured when continuing across the slope. Differences measured included the snow in 1989-90 having a much more obvious decrease in depth in the southwest corner of the site, while the snow in 1988-89 had a more noticeable "bulge" of increased depth in the area near the bottom of the site.

The average snow resistance map showed a ridge of increased resistance down the middle of the site from top to bottom (Figure 29). No other clear patterns in average resistance were observed. This pattern of resistance does not show any similarities to the patterns of resistance observed in 1988-89, which were much more variable. Again, the decreased variability observed in 1989-90 (Table 6) can be at least partially attributed to the more careful data collection techniques during the second year.

Comparison of Geographic Features, Depth, and Resistance, 1989-90

Some snow depth patterns can be related to the geographic features at the site (Figures 24 and 28). Decreased depth was observable at the rock outcrop in the southeast corner of the site, under the tree at point (c) and over the rock at point (b). The decreased depth under the tree and over the large buried rock was expected. The distinctive region of decreased depth in the area of the rock outcrop (point (a) in Figures 24 and 28) might be related to the relatively steeper slope (44°) at the location. Snow would be more likely to sluff off of a steep slope, decreasing depth. This possibility is strengthened by the increased snow depth observed immediately downslope of the outcrop, where the sluffing snow would be deposited. No characteristic pattern of snow depth created by drifting around trees was observed.

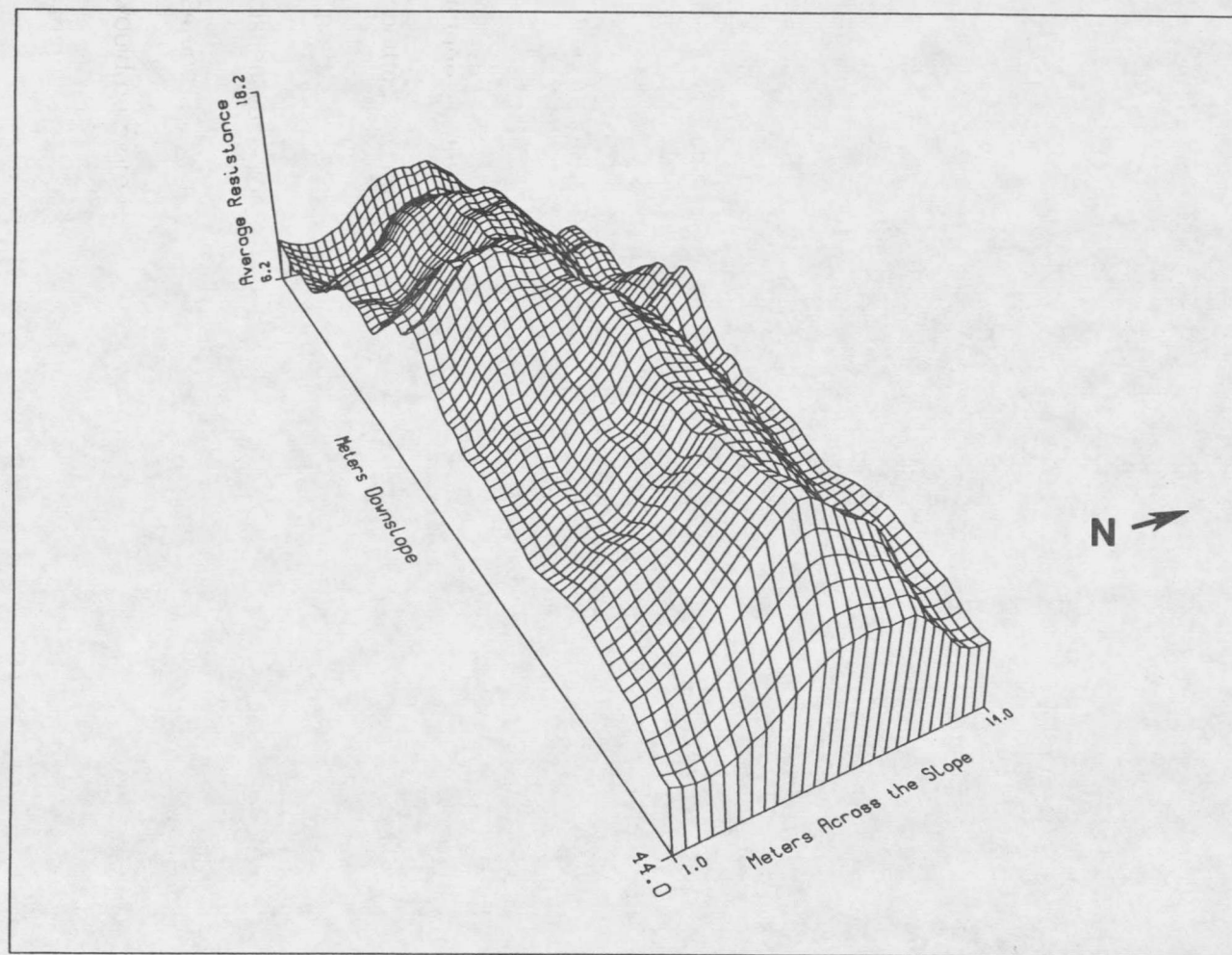


FIGURE 29: A three-dimensional perspective plot of average snow resistance for the Bridger 2 site in 1990 shows average resistance variations over the site.

Patterns of average resistance were generally not visually related to the geographic features of the site (Figures 24 and 29). There was a zone of somewhat lower resistance in the region of the rock outcrop, but the two do not appear to be clearly related. Since the absence of a visual relationship might be due to the smoothing functions used for the graphics, multiple regression using an indicator variable (whether the point was over a rock or not) was used to further test for a relationship. This analysis was used instead of a simple linear regression so that depth, which was known to have some relationship to resistance because of results from Bradley Meadows, could be controlled. Regressing the presence of rocks and snow depth on resistance indicated a highly significant relationship between the presence of rocks and a weaker resistance ($p\text{-value} < 10^{-6}$).

Field observations indicated that snow around rocks, in addition to the snow over the rocks, appeared to be weaker. To test whether rocks had such a "zone of influence", multiple regressions using measurements within a certain distance of the rocks were coded as the indicator variable. Such tests indicated that there was some evidence ($p\text{-value} = 0.091$) that snow within two meters of rocks had weaker resistance than did the snow on the other parts of the slope.

Comparisons of snow depth and average resistance maps do not visually show obvious similarities (Figures 28 and 29). Surprisingly, a linear regression run between depth and average resistance at the site was significant ($p\text{-value} = 7 \times 10^{-5}$) (Figure 30). As with the regression run on the 1989-90 data for Bridger 1, some low depth/low resistance points may have had an undue influence on the regression. When a smaller data set (reduced from $n = 616$ to $n = 48$) was selected from points at farther distances

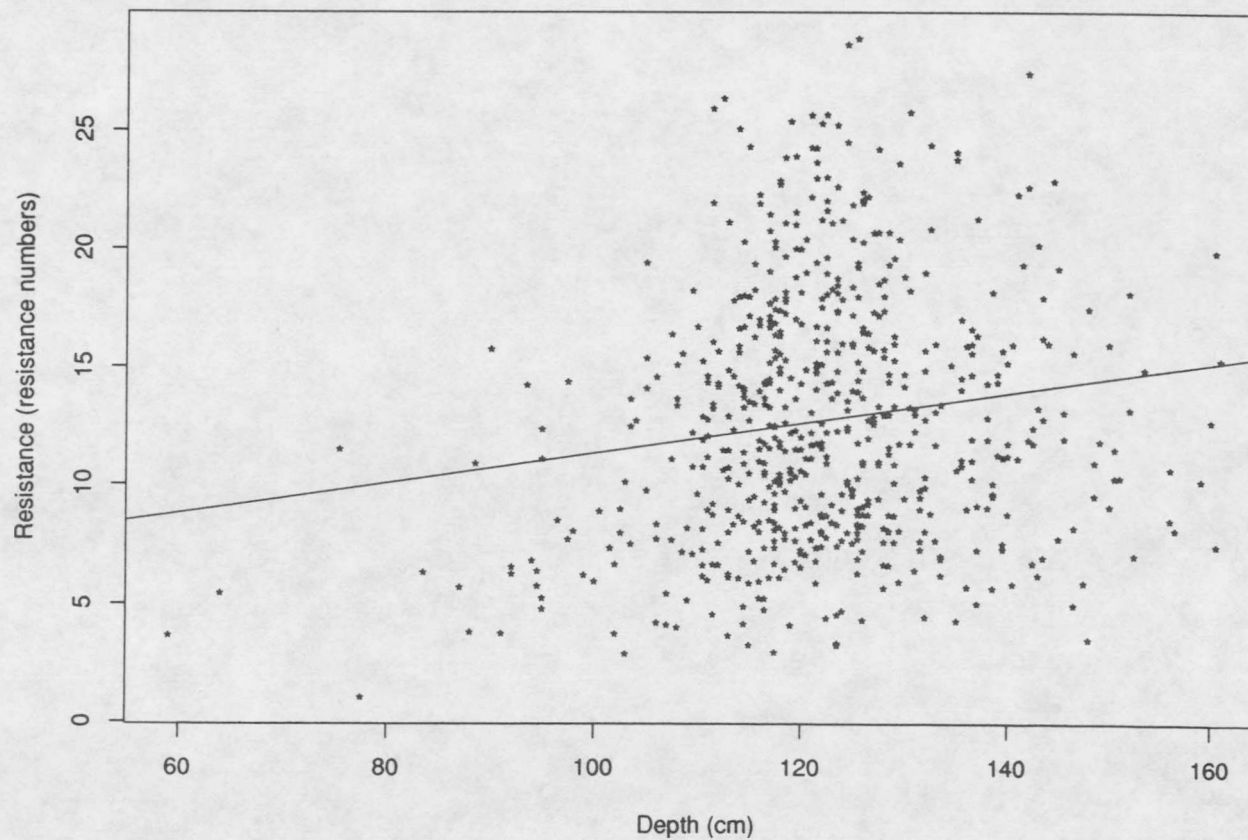


FIGURE 30: A simple linear regression between snow depth and average resistance at the Bridger 2 site in 1990 was significant ($p\text{-value} = 7 \times 10^{-3}$), but, like the previous year, this significance is in large part due to the low depth/low resistance values which have undue "pull" on the regression line.

apart the regression was insignificant ($p\text{-value} = 0.30$) (Figure 31). The significant $p\text{-value}$ was probably in response to both the low depth/low resistance points and the autocorrelation (due to the spatial relationship) of the data.

Results of comparisons of snow depth and geographic features varied between the two years. In 1988-89 there were no similarities between snow depth and the location of geographic features, while in 1989-90 similarities were observed. It is not clear why this is the case. Results of comparisons between depth and average resistance produced no visual similarities and insignificant $p\text{-values}$ for both years. A significant relationship between weak resistance and the presence of rocks was found the second year, and there was evidence that the rocks may have influenced average snow resistance within 2 m. Difficulties with the data precluded analysis of this relationship with the first year's data, but the result that rocks are related to resistance is what would have been expected given field observations at the site during both years.

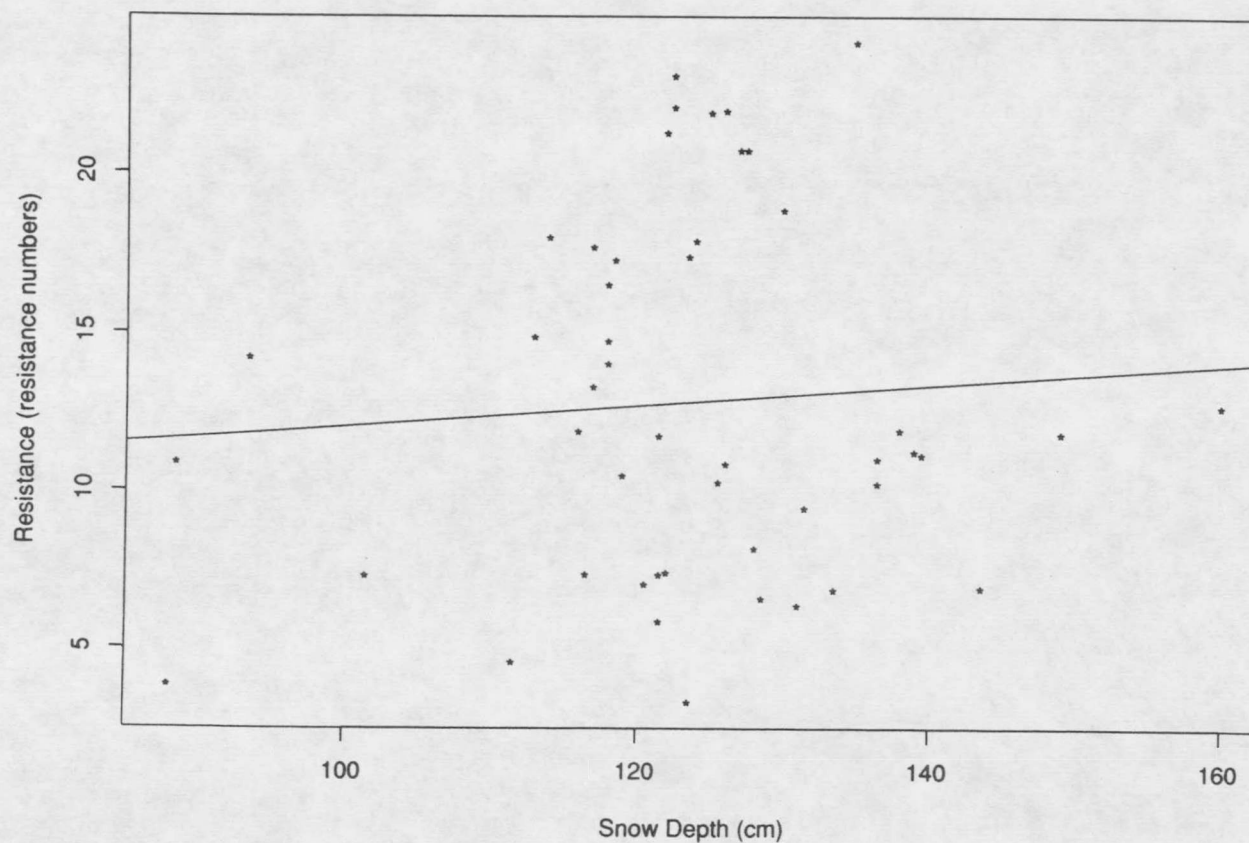


FIGURE 31: Like the previous season, a linear regression with a reduced data set (reduced from $n = 616$ to $n = 48$) shows an insignificant relationship between snow depth and average resistance at Bridger 2 in 1990 ($p\text{-value} = 0.30$).

CHAPTER 5

CONCLUSIONS

Relationship of Snow Depth to Geographic Features

The relationship of snow depth to geographic features varied between the Bradley Meadows and Bridger Bowl sites, and between the two field seasons. At the Bradley Meadows site, snow depth patterns were related to drift patterns around trees upwind of the study site during both years (Figures 5, 6, and 10). Such drift patterns might be the result of a horse-shoe shaped vortex which is created around three-dimensional surface features (Kind, 1981). Conversely, at both Bridger Bowl sites there were no similarities between geographic features (specifically the rocks and trees within and around the site) and snow depth in 1988-89 (Figures 16 and 17; Figures 24 and 25), and only minimal similarities were observed in 1989-90 (Figures 16 and 20; Figures 24 and 28). This is probably due to contrasts in site location. The Bradley Meadows site is on the edge of an exposed meadow, while the Bridger Bowl site has enough large trees around it to be protected from wind-induced drifting and scouring at the snow surface (Figure 3). Thus, at the Bridger Bowl sites the individual groups of trees do not collect snow on their lee sides like the trees at the Bradley Meadows site. The protected nature of the Bridger Bowl sites does not allow the same marked pattern of drift and wind eroded areas that can be observed at the exposed Bradley Meadows site.

[Trees also affect snow depth by intercepting falling snow, decreasing the amount that accumulates beneath them. An increased canopy cover causes a decrease in snow

accumulation in forested areas (Hardy and Hansen-Bristow, 1990). Decreased snow depth was observed around the small groups of trees inside the Bridger Bowl sites in 1989-90 (Figures 16 and 20; Figures 24 and 28), but this decreased depth was so localized that it was not easily detectable in the mapped data in 1988-89 (Figures 16 and 17; Figures 24 and 25). This lack of easy detection is due to the process utilized in creating the three-dimensional plots. In the data there is a certain amount of scatter due to actual snow depth variability and variability due to the operation of the instrument. To decrease that scatter, smoothing functions were used on the data. While such functions allow patterns in the data to be observed more easily, they also tend to wash out some small scale variability that might have otherwise been observed.

Relationship of Snow Depth to Average Resistance

The relationship between depth and average resistance varied. The insignificant relationship between depth and average resistance at both Bridger Bowl sites (Figures 19, 22, 27, and 31) contrasts sharply with the highly significant relationship observed at the Bradley Meadows site (Figures 9 and 13). Similar to the relationship between snow depth and geographic features, site differences help to explain why this relationship is so different. The Bradley Meadows site is relatively homogenous with a consistent slope and uniform substrate, with the only major variability being snow depth (which appears to be controlled largely by drifting around trees adjacent to the site). On the other hand, the Bridger Bowl sites are more complex due to the many trees and rocks located both within and around the sites. The trees and rocks within these sites locally affected resistance. Further, at the Bridger Bowl sites there were no definite snow drifts adjacent to trees (in contrast to the Bradley Meadows site), apparently because this area is relatively protected

from surface winds which would cause local drifting (Figure 3). Thus, the relationship between depth and average resistance at the Bridger Bowl sites was muted by other variables.

A relationship does, however, appear to exist between depth and average resistance data collected at the Bradley Meadows site both years (Figures 8 and 13). Snow depth is an important factor in snowpack genesis; snow insulates the relatively warmer ground (which stays close to 0°C (Perla and Martinelli, 1975)) from the cold air above. Thus, the snow depth in a localized area determines the local temperature gradient relative to adjacent snowpacks. Areas with shallow depths will have greater temperature gradients than nearby deeper areas. Larger temperature gradients facilitate the growth of weak, faceted snow crystals, which have low resistance. Snow depth, therefore, appears to be an important factor for spatial variability of average snow resistance at the Bradley Meadows site, and may also be important in other locations where wind deposition causes small scale variations in snow depth.

Temperature gradients for the areas of maximum and minimum depth at the Bradley Meadows site in 1988-89 can be calculated as examples of spatial variations in localized temperature gradients. At the time of sampling the maximum snow depth at the Bradley Meadows site was 198 cm and the minimum was 102 cm (Table 5). Using -12.4°C as an example ambient air temperature (this was the average temperature for February, 1989, which was a month dominated by a cold arctic system (Table 1)), and assuming a ground temperature of 0°C (Perla and Martinelli, 1975), the temperature gradient at the place of maximum depth was 0.063°C/cm , while the temperature gradient through the snowpack where the depth was at a minimum was 0.12°C/cm . Faceted crystal growth is dependent on vapor pressure gradients, which in turn depend largely on temperature

gradients. The temperature gradient of 0.1°C/cm is commonly cited as the level at which faceted crystal growth dominates over other processes (Perla and Martinelli, 1975). Thus, in this relatively small site there can be areas that are well within the realm of faceted crystal growth (0.12°C/cm) while nearby areas do not have temperature gradients necessary for faceted crystal growth (0.063°C/cm).

Relationship of Geographic Features to Average Resistance

Certain geographic features may locally affect average resistance. Smoothing functions applied to the data washed out small-scale differences and made visual comparisons difficult, but a multiple regression analysis indicated a significant relationship ($p\text{-value} < 10^{-6}$) existed between snow overlying rocks and lower resistance at Bridger 2. Further, snow within 2 m of rocks continued to show some evidence ($p\text{-value} = 0.091$) of weakened resistance, demonstrating the possibility of a "zone of influence" surrounding the rocks. Several mechanisms for this relationship between rocks and decreased resistance can be hypothesized. Many of the rocks at Bridger 2 are large, and observations at the site indicated those rocks became completely buried by snow later in the season than adjacent non-rock areas, and were associated with a thinner snowpack. This would increase the local temperature gradient, facilitating faceted crystal growth, and decreasing the resistance over rocks. Additionally, air pockets exist around the base of some rocks. Extra space would increase the area available for water vapor transport and allow room for faceted crystals to grow. It is also possible that rocks are simply more efficient at adding heat to the snow above than soil. Further studies on the effect of rocks on resistance, possibly taking into account the differing heat fluxes due to rock and soil substrates, would be valuable.

Snow Depth Patterns Observed and Their Significance

At all sites a noticeable wave-like pattern in snow depth was observed (Figures 6, 10, 17, 20, 25, and 28). Such patterns were more pronounced at some sites than others, but were observed both down and across the study sites. Wind deposition of snow in wave-like patterns has been observed in previous studies (Conway and Abrahamson, 1984a; Föhn and Meister, 1983). Föhn and Meister (1983) observed such patterns forming on the lee sides of ridges in exposed areas. They combined a potential flow model with a plume model to explain their observations of two snow depth maxima on either side of a localized minima on lee slopes of ridges.

Such depth patterns are conceivably being created at both sites by wind. The exposed nature of the Bradley Meadows site is a good location to observe such wind related features in snowpack. The patterns at the Bridger Bowl sites are more difficult to explain. Although these sites are protected from strong ground level winds (and thus there are no observable patterns of snow depth around trees within the site), winds do blow at tree top level. There are open areas to the south and west of the site, so upper level transport of snow into the area during high wind events is feasible, and such transport may be the cause for the subtle wave-like patterns of snow depth observed.

As discussed in the introduction, drift patterns might be important in explaining snowpack variability. Conway and Abrahamson (1984a) hypothesized that variations in depth due to patterns of wind deposition may be a primary factor in shear strength variability along the crown of recently avalanched slopes. They further discussed how such variations might change weak layer thicknesses across a slope, and hypothesized that the distribution of weak layers might be similar to drifting snow. Thus, areas with

deeper snow might have thicker weak layers and weaker shear strengths because there would be less tendency for contact (which would cause increased friction) between the stronger snow layers above the weak layer and the bed surface below that weak layer. Conway and Abrahamson (1984a) did not attempt to confirm these speculations. Conversely, Föhn (1988) found that areas characterized by low shear strength values had 30 to 40% lower slab depths, supporting the idea that areas of low snow or slab depth are areas of low shear strength. I would speculate that this might be due to the relationship of the weak layer to the gravitational forces acting upon it. The distribution of weak layer thicknesses on slopes is not known, but it is plausible that such a distribution for many types of weak layers might be fairly uniform. An example of this would be surface hoar, which, on a consistent slope unimpacted by wind or back radiation from trees, would be deposited fairly uniformly. Another example might be near-surface faceted crystals (classification 4b in the recent International Snow Crystal Classification (Colbeck, *et al.*, 1990)) which could also conceivably have a fairly uniform slope distribution. When buried by a storm with associated winds and variations in snow depths, areas with greater snow depth would have greater gravitational forces acting on them. Such forces may partially compact the weak layer through settling so that the stronger snow above and below that layer would come into contact with each other, thus strengthening that particular area. In contrast, areas that had less snow depth would have less gravitational forces acting upon them, and the weak layer in such areas might be more likely to remain unimpacted and subject to easier shear failure.

Such ideas may be important for the practical control of avalanches. For many years explosives have been typically placed in locations with the greatest snow depth, commonly found at the top of potential avalanche starting zones. My own experience,

and the experience of others (Dixon, pers. comm., 1990; Tremper, pers. comm., 1990), have demonstrated that placing explosives lower on the slope than these upper areas of maximum depth can often be more effective in releasing avalanches. Such lower placements may more commonly be in weaker regions of the snowpack. It is suggested that the best possible location for explosive placement may be in the snow depth minima between the two depth maxima. A thorough study of this suggestion would have to be pursued before concrete conclusions could be drawn.

Variabilities in Snow Properties Due to Depositional Differences

The variability in how snow was deposited may also be important in snow resistance variability at the Bradley Meadows site. Wind-deposited snow is generally smaller grained (because it has been broken during wind transport) and becomes more tightly packed (more dense) than snow that has not been wind transported and deposited (Prowse and Owens, 1984). Observations of snow drifts behind snow fences show an increased snow density in the drifts (Tabler, 1980). These increased densities are due not only to the mechanical breaking of snow into smaller pieces by the wind, but are also due to gravitational forces causing the compaction of the lower snowpack by the snow above it (Elder, pers. comm., 1990). If a large percentage of a deep snowpack has been wind deposited, then that snow will have a higher average density than a snowpack that has not been wind-deposited. A higher density snowpack has fewer pore spaces to facilitate the transfer of water vapor, thereby inhibiting or restricting faceted snow crystal growth and, therefore, preventing a weakening of the snowpack. Further, because denser snowpacks have higher conductivities they conduct heat at lower temperature gradients, thus reducing the potential for temperature gradient metamorphism. Ultimately, wind-

deposited snowpacks should be stronger and have a greater resistance. Snowpacks where accumulation is due primarily to snowfall without wind should have more loosely packed snow, more pore space, and be more susceptible to weak, faceted snow crystal growth, and consequently lower resistance levels. Thus, the drifted snow around the trees at the Bradley Meadows during both winters may have helped to restrict faceted crystal growth, thus creating a stronger resistance, due to three factors: 1) increased depth, which decreased the temperature gradient, thereby restricting faceted crystal growth, 2) increased density during wind deposition, which limited the pore space available for the growth of faceted crystals, and 3) increased conductivity (due to increased density), which allowed the snow to conduct heat at a lower temperature gradient, thereby restricting faceted crystal growth.

Wind deposition can also cause a great deal of localized variability in snow. Conway and Abrahamson (1984b) measured variations of up to 300% in air permeability (the ability of air to penetrate through snow) in newly wind deposited snow. Such variability might well have an effect on snow metamorphism, since a high permeability would better allow the transport of water vapor. Consequently, patterns of air permeability caused by wind may also have an effect on observable patterns of snow resistance at wind exposed sites.

Summary

The refined DR allowed the resistance of a slope to be characterized by many measurements in a relatively short time period. Results at one site suggested a relationship between tree locations, wind patterns and snow depth. This site also showed a significant relationship between snow depth and average snow resistance, though low

r^2 values indicate several compounding factors may be important. The conclusion that there are many factors affecting resistance was reinforced by results at a second site, which showed no relationship between depth and average resistance. This site has a greater complexity of geographic features. The geographic features at the second site which may have affected resistance included many rocks, which were significantly related to areas of weaker resistance.

This work suggests additional avenues for future research. First, and perhaps most importantly, an in-depth analysis of resistance profile data (Figure 4), which would take into account the different layers within the snowpack instead of just a gross measure of average resistance, needs to be undertaken. Analysis of profile information would be the most relevant information for predicting whether a slope might avalanche or not. Second, the relationship between geographic features and snow resistance should be studied further. Additional data collection on a variety of slopes might help clarify this relationship. Third, it would be useful to further study the relationship between snow depth and average resistance. If depth and resistance are strongly related under certain weather conditions, then estimation of resistance might be possible by measuring depth and monitoring the specific weather conditions. Fourth, the relationship between shear strength and resistance warrants further study. If such a relationship can be established, the time consuming shear frame could be replaced with the DR for studying weak layers on slopes. Since shear strength and weak zone location are critical for avalanche initiation, other studies could then be designed to correlate snowpack stability to different resistance patterns of potential avalanche slopes, leading to a prediction of optimum location for applying explosive avalanche control measures or for digging forecasting snowpits. Ultimately, resistance data of a slope might someday be one input to a

computer model which would take into account weather, snowpack, and other factors to accurately assess slope stability.

LITERATURE CITED

- Akima, H. 1978. A method of bivariate interpolation and smooth surface fitting for irregularly distributed data points. ACM Transactions on Mathematical Software, 4(2): 148-164.
- Balling, R. 1990. Personal communication. Department of Geography, Arizona State University, Tempe, Arizona.
- Becker, R.A., J.M. Chambers, and A.R. Wilks. 1988. The New S Language: A programming environment for data analysis and graphics. Wadsworth & Brooks/Cole Advanced Books & Software, Pacific Grove, CA, 702 pp.
- Bradley, C.C. 1966. The snow resistograph and slab avalanche investigations. Publication No. 69 De L'Association Internationale D'Hydrologie Scientifique. International Symposium on Scientific Aspects of Snow and Ice Avalanches, Davos, Switzerland, April 5th-10th, 1965, p. 251-260.
- Bradley, C.C. 1988. Personal communication. Systemic strength-weakness cycle in the snowpack and its relationship to deep slab avalanche location. Manuscript.
- Brown, R.L. 1977. A fracture criterion for snow. Journal of Glaciology, 19(81): 111-121.
- Brown, R.L. 1990. Personal communication. Department of Civil and Agricultural Engineering, Montana State University, Bozeman, Montana.
- Brown, R.L. and K.W. Birkeland. In preparation. A comparison of the digital resistograph with the rammsonde and shear frame. To be published in the Proceedings of the 1990 International Snow Science Workshop, Bigfork, Montana, October, 1990.
- Brown, R.L. and A. Hansen. 1985. Field studies on stress waves in natural snowcover. In P.R. Kry, ed., Snow Measurement Workshop, National Research Council of Canada Technical Memorandum 140: 89-110.
- Cliff, A.D. and J.K. Ord. 1981. Spatial Processes: Models and Applications. Pion Limited, London. 266 p.
- Colbeck, S., E. Akitaya, H. Gubler, D. McClung, R. Armstrong, J. Lafeuille, K. Lied, and E. Morris. 1990. The international classification for seasonal snow on the ground. The Avalanche Review, 8(3): 1-6.
- Compton, R.R. 1962. Manual of Field Geology. John Wiley and Sons, New York, 378 pp.
- Conway, H. and J. Abrahamson. 1984a. Snow stability index. Journal of Glaciology, 30(106): 321-327.

- Conway, H. and J. Abrahamson. 1984b. Air permeability as a textural indicator of snow. Journal of Glaciology, 30(106): 328-33.
- Conway, H. and J. Abrahamson. 1988. Snow-slope stability - a probabilistic approach. Journal of Glaciology, 34(117): 170-177.
- Custer, S.G. 1990. Personal communication. Department of Earth Sciences, Montana State University, Bozeman, Montana.
- Dent, J.D. and T.E. Lang. 1979. Modelling of snow flow. Journal of Glaciology, 26(94): 131-140.
- Dixon, R. 1990. Personal communication. Assistant Ski Patrol Director, Big Sky Ski Area.
- Dowd, T. 1984. A new instrument for determining strength and temperature profiles in snowpack. M.S. Thesis, Department of Engineering Mechanics, Montana State University, 42 pp.
- Dowd, T. and R.L. Brown. 1986. A new instrument for determining strength profiles in snowcover. Journal of Glaciology, 32(111): 299-301.
- Elder, K. 1990. Personal communication. Department of Geography, University of California at Santa Barbara, Santa Barbara, California.
- Elliot, R. 1990. Personal communication. Ski Patrol Director, Bridger Bowl Ski Area, Bozeman, Montana.
- Föhn, P.M.B. 1987. The "Rutschblock" as a practical tool for slope stability evaluation. *Avalanche Formation, Movement and Effects (Proceedings of the Davos Symposium, September 1986)*. IAHS Publication no. 162, p. 223-228.
- Föhn, P.M.B. 1988. Snowcover stability tests and the areal variability of snow strength. *Proceedings of the 1988 International Snow Science Workshop, Whistler, British Columbia, Canada*, p. 262-273.
- Föhn, P.M.B. and R. Meister. 1983. Distribution of snow drifts on ridge slopes: measurements and theoretical approximations. Annals of Glaciology, 4: 52-57.
- Grady, T.R. 1982. The effects of snow compaction on water release and sediment yield. M.S. Thesis, Department of Earth Sciences, Montana State University. 67 pp.
- Grady, T.R., S.G. Custer, and J. Montagne. 1982. The effects of snow compaction on water release and sediment yield, Bridger Bowl Ski Area, Gallatin County, Montana. Montana Resources Research Center Report No. 124, Montana State University, Bozeman, Montana.

- Gubler, H. 1977. Artificial release of avalanches by explosives. Journal of Glaciology, 19(81): 419-429.
- Gubler, H. (author) and R.L. Armstrong (translator). 1983. Artificial release of avalanches by explosives: An introduction for the field person. Unpublished and incomplete manuscript, 31 pp.
- Gubler, H. and H.P. Bader. 1989. A model of initial failure in slab avalanche release. Annals of Glaciology, 13: 90-95.
- Haas, J.E. and G.F. White. 1975. Snow Avalanche Hazard in the United States: A research assessment. Prepared by Members of the Staff, Assessment of Research on Natural Hazards. Monograph #NSF-RA-E-75-017. Institute of Behavioral Science, University of Colorado, 86 pp.
- Hardy, J.P. and K.J. Hansen-Bristow. 1990. Temporal accumulation and ablation patterns of the seasonal snowpack in forests representing varying stages of growth. In the Proceedings of the Western Snow Conference, Sacramento, California, in press.
- Jamieson, J.B. and C.D. Johnson. 1988. In-situ tensile strength measurements of alpine snow. Proceedings of the 1988 Snow Science Workshop, Whistler, British Columbia, Canada, p. 103-112.
- Juergens, J. 1984. Practical experience with aerial detonation of explosives for avalanche control. Proceedings of the 1984 International Snow Science Workshop, Aspen, Colorado, p. 67-69.
- Kind, R.J. 1981. Snow drifting. In Gray, D.M. and D.H. Male (eds.), Handbook of Snow: Principles, processes, management, and use. Pergamon Press, Toronto, p. 338-359.
- Lang, T.E. and J.D. Dent. 1979. Scale modelling of snow impact on structures. Journal of Glaciology, 26(94): 189-196.
- Lawrence, D.M. 1987. MicroEMACS Version 3.9e Full Screen Text Editor Reference Manual. Preliminary draft manuscript.
- McClung, D.M. 1979. In-situ estimates of the tensile strength of snow utilizing large sample sizes. Journal of Glaciology, 22(87): 321-329.
- Narita, H. 1980. Mechanical behavior and structure of snow under uniaxial tensile stress. Journal of Glaciology, 26(94): 275-282.
- Perla, R.I. 1969. Strength tests on newly fallen snow. USDA Forest Service Research Note RM-150, 12 pp.

- Perla, R.I. and T.M.H. Beck. 1983. Experience with shear frames. Journal of Glaciology, 29(103): 485-491.
- Perla, R.I. and M. Martinelli, Jr. 1975. The Avalanche Handbook. U.S. Department of Agriculture Handbook 489, 254 pp.
- Prowse, T.D. and I.F. Owens. 1984. Characteristics of snowfalls, snow metamorphism, and snowpack structure with implications for avalanching, Craigieburn Range, New Zealand. Arctic and Alpine Research, 16(1): 485-491.
- Quimby, W. 1990. Personal communication. Department of Mathematics and Statistics, Montana State University.
- Rosso, R.S. 1986. In-situ strength measurements of the snowpack. Proceedings of the 1986 International Snow Science Workshop, Lake Tahoe, California, p. 210-215.
- Schaerer, P.A. 1981. Avalanches. In Gray, D.M. and D.H. Male (eds.), Handbook of Snow: Principles, processes, management, and use. Pergamon Press, Toronto, p. 475-518.
- Smith, F.W. and R.A. Sommerfeld. 1985. The simulation of the statistical failure of snow slopes. Simulation Series, 15(1): 29-33.
- Sommerfeld, R.A. 1969. The role of stress concentration in slab avalanche release. Journal of Glaciology, 8(54): 451-462.
- Sommerfeld, R.A. and H. Gubler. 1983. Snow avalanches and acoustic emissions. Annals of Glaciology, 4: 271-276.
- Tabler, R.D. 1980. Geometry and density of drifts formed by snow fences. Journal of Glaciology, 26(94): 405-419.
- Tremper, B. 1990. Personal communication. Head Forecaster, Utah Avalanche Forecast Center, Salt Lake City, Utah.
- U.S. Forest Service Westwide Avalanche Network. 1989. Avalanche Notes. Rocky Mountain Forest and Range Experiment Station, April, 1989, 6 pp.
- Williams, K. 1978. Post-control avalanche releases. In the Deuxieme Rencontre Internationale sur la Nieve et les Avalanches, 12,13 et 14 de Avril, 1978, Grenoble, France. Association Nationale pour L'Etude de la Nieve et des Avalanches, p. 251-261.

APPENDIX

"S" FUNCTIONS

```

snow15_scan("m1.5",what=integer(0))

index_find.na(snow15)

n_length(index)

snow15matrix_matrix(0,50,2)
row_1
col_1

for (i in 1:(n-1)){
  j_i+1
  start_index[i] + 1
  end_index[j] - 1
  snow15matrix_matrix[row,col]_list(snow15[start:end])
  row_row+1
  if (row == 51) {row <- 1
                  col <- col + 1}
}

```

FIGURE 32: "S" function designed to put data into a matrix for further analyses.

```

function(data)
{
  dimensions <- dim(data)
  n <- dimensions[1]
  m <- dimensions[2]
  for(i in 1:n) {
    for(j in 1:m) {
      probe <- data[i, j][[1]]
      data[i, j] <- list(probe - min(probe))
    }
  }
  return(data)
}

```

FIGURE 33: "S" function designed to standardize all profiles by setting the smallest resistance value equal to zero, and adjusting the other values accordingly.

```

function(n, m)
{
  x <- c(0, 250)
  y <- c(0, 250)
  s1 <- d1[n, m]
  s1 <- s1[[1]]
  n <- length(s1)
  depth <- n:1
  depth <- depth/2
  plot(x, y, xaxis = "Resistance Index", main = "Snow Resistance Plot",
        type = "n")
  lines(s1, depth)
  abline(h = c(20, 40, 60, 80, 100, 120, 140, 160, 180), lty = 2)
}

```

FIGURE 34: "S" function designed to create a resistance profile.

```

function(data)
{
  dimensions <- dim(data)
  n <- dimensions[1]
  m <- dimensions[2]
  strength <- matrix(0, n, m)
  for(i in 1:n) {
    for(j in 1:m) {
      probe <- data[i, j][[1]]
      strength[i, j] <- mean(probe)
    }
  }
  return(strength)
}

```

FIGURE 35: "S" function designed to compute the average snow resistance for a sample point from the list of resistance numbers for that point.

```

function(data)
{
  dimensions <- dim(data)
  n <- dimensions[1]
  m <- dimensions[2]
  depth <- matrix(0, n, m)
  for(i in 1:n) {
    for(j in 1:m) {
      probe <- data[i, j][[1]]
      depth[i, j] <- length(probe)/2
    }
  }
  return(depth)
}

```

FIGURE 36: "S" function designed to compute snow depth for a sample point from the list of resistance numbers for that point.

