DEVELOPMENT OF METHODOLOGY FOR EVALUATION AND PREDICTION OF AVALANCHE HAZARD IN THE SAN JUAN MOUNTAIN AREA OF SOUTHWESTERN COLORADO

Richard L. Armstrong, Edward R. LaChapelle, Michael J. Bovis, Jack D. Ives

December 1974

Final Report April 1971 to September 1974

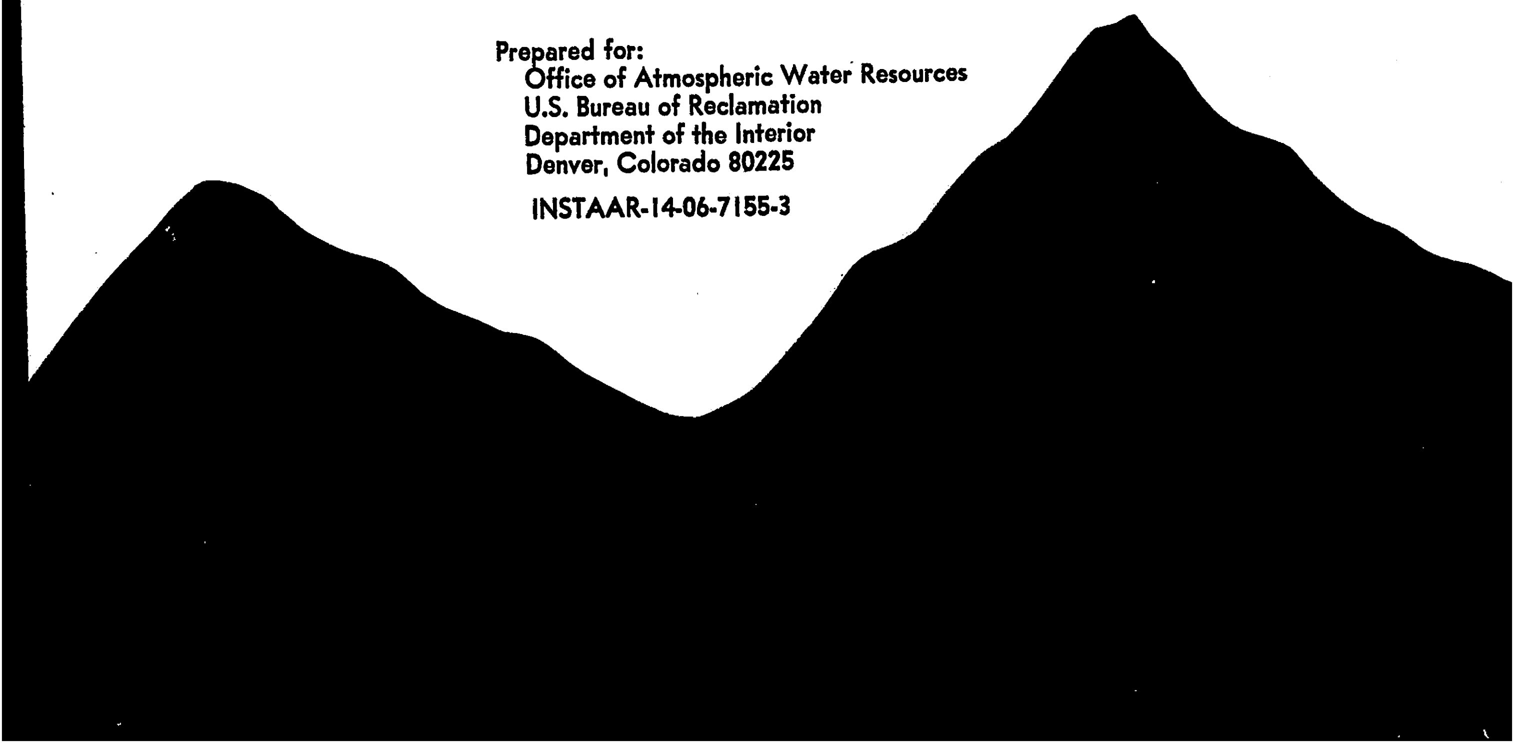
OCCASIONAL PAPER NO. 13

INSTITUTE OF ARCTIC AND ALPINE RESEARCH . UNIVERSITY OF COLORADO

BOULDER, COLORADO 80302

Prepared for:
Office of Atmospheric Water Resources
U.S. Bureau of Reclamation
Department of the Interior
Denver, Colorado 80225

INSTAAR-14-06-7155-3



1. Report No. INSTAAR-14-06-7155-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DEVELOPMENT OF METHODOLOGY FOR EVALUATION AND PREDICTION OF AVALANCHE HAZARD IN THE SAN JUAN MOUNTAIN AREA OF SOUTHWESTERN COLORADO		5. Report Date December 1974
		6. Performing Organization Code
7. Author(s) R.L. Armstrong, E.R. LaChapelle, M.J. Bovis, J.D. Ives		8. Performing Organization Report No. INSTAAR-14-06-7155-3
9. Performing Organization Name and Address Institute of Arctic and Alpine Research University of Colorado Boulder, Colorado 80302		10. Work Unit No.
		11. Contract or Grant No. 14-06-D-7155
12. Sponsoring Agency Name and Address Department of Atmospheric Water Resources Bureau of Reclamation Denver Federal Center Denver, Colorado 80225		13. Type of Report and Period Covered Comprehensive Final Data Report - April 1971 - Sept. 1974
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The project is studying the problem of avalanche initiation by analyzing the complex relationships among terrain, climate, and snow stratigraphy. Air and snowpack temperatures, wind speed and direction, precipitation rate and amount, snow settlement rate, net all-wave radiation at the snow surface, and snow density and water equivalent values are measured at the prime study site at Red Mountain Pass (3400 m). Climatological data are also collected routinely in Silverton (2830 m) and at the Rainbow site (3490 m) adjacent to the starting zones of the Brooklyns avalanche paths. Avalanche events are monitored by direct observation and by trip wires on selected paths. During the third winter, emphasis was placed on the development of the snow stratigraphy; abundant snow pit data were acquired from standard level snow study sites, from test slopes similar to avalanche release zones, and from avalanche fracture lines. Avalanche hazard forecasts based on weather and snowpack conditions were made daily. In addition, work began on a statistical model to forecast avalanche occurrence.

17. Key Words Avalanche, Colorado, snow, weather modification		18. Distribution Statement No limitations	
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 141	22. Price

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The East Guadalupe avalanche track (152-060) is located 8 kilometers north of Red Mountain Pass on the west-facing slope of Abrams Mountain. Its vertical drop is 800 meters. Avalanches release in the upper catchment basin each year but run across the alluvial fan to the road in the foreground only during very large events. A natural size 3 wet slab avalanche ran to within 100 meters of the road on April 17, 1973. The Slippery Jim avalanche track (152-061) initiates on the irregular slopes to the left of the Guadalupe gully and cuts the road several times, descending across the hairpin bends. West Guadalupe impinges on the road in the immediate foreground.

Photograph by Len Miller

ABSTRACT

This report covers research conducted by the San Juan Avalanche Project, Institute of Arctic and Alpine Research, University of Colorado for the period August 1973 to August 1974. The research is supported by a contract with the Bureau of Reclamation, U.S. Department of Interior, and has as its purpose the study of the nature and causes of snow avalanches in the San Juan Mountains of southwestern Colorado, and specifically within the area of Red Mountain Pass, Molas Divide and Coal Bank Hill. The ultimate objective of the project is to develop a methodology to evaluate and predict avalanche hazard within the study area in order to be able to accurately forecast avalanche occurrences. The project has undertaken the study of the problem of avalanche initiation by analysis of the complex relationship which exists among terrain, climate and snow stratigraphy. When the project was initiated, only a limited amount of climatological data was available for the study area. It was recognized that an avalanche prediction model relies heavily upon data gathered from highly accurate, reliable instruments installed on carefully selected sites. Therefore, a network of fixed instrumentation is utilized to measure meteorological parameters, determine certain physical properties within the snowpack, and detect avalanche events. Data regarding certain meteorological and snowpack parameters, as well as that related to the accurate accounting of avalanche events, including the numerous descriptive parameters which catagorize each event are dependent on highly skilled and well trained field observers.

The primary snow study site is located at Red Mountain Pass (3400 m) and includes instrumentation providing such basic information as air temperature, temperatures within the snowpack, wind speed and direction, precipitation rate and amount, snow settlement rate, and net all-wave radiation at the snow surface. In addition, an isotopic profiling snow gauge provides snow density and water equivalent values throughout the snowpack at 1.0 cm intervals. Trip wires have been installed in the paths of frequently occurring avalanches in order to acquire accurate event times.

The initial objective of establishing a research procedure capable of adequately observing and recording the various phenomena associated with avalanche initiation was accomplished during the first winter's research. The next step was to attempt to determine the relative contribution of each factor and to isolate those processes which contribute most directly to avalanche formation. During the next two winters' research, considerable emphasis was given to the study of snow stratigraphy.

Detailed investigations into the physical properties of the snow within the study area were prompted by the fact that the San Juan Mountains exhibit climatic extremes not found in more northerly latitudes where most practical and scientific knowledge of snow avalanche formation has been accumulated. The combination of high altitude, low latitude and predominately continental climate produces a specific <u>radiation snow climate</u>.

Generally, this condition is the result of two factors. First, the extreme nocturnal radiational cooling occurring on all exposures produces snowpack temperature gradients of a magnitude sufficient to cause significant recrystallization or temperature-gradient metamorphism. The second factor is the substantial amount of solar energy available to south- and west-facing slopes. This daytime condition causes melt just below the surface and subsequent freeze-thaw crusts. These two situations continue to influence the snowcover throughout the winter and the resulting stratigraphy is highly complex.

Therefore, during the second winter's research considerable emphasis was directed towards a better understanding of the snow stratigraphy within the study area through the acquisition of abundant snow pit data. These snow pits are of three types. One type is located at standard level snow study sites, a second type is located on a test slope or avalanche release zone and the third is associated with the actual fracture line of an avalanche. During the third winter, this emphasis was sustained with particular attention directed towards the temperature-gradient process. Snow temperatures were measured throughout the depth of the snowcover on a daily basis at sites at three different elevations. Periodic snow pits at these sites provided data showing the relationship between the magnitude of the temperature gradient and type of subsequent metamorphism determining crystal morphology.

As part of the daily operational procedure, this project produces an "in-house" stability evaluation and avalanche hazard forecast for the study area. Such forecasts are made for each 24 hour period and at more frequent intervals during storms. Each avalanche occurrence forecast is evaluated the following day in terms of actual conditions and events subsequent to the initial forecast. During the third winter the avalanche forecast procedure was further refined and the trend towards forecasts for specific groups of paths, as well as a general area forecast continued. Methods employed by the field observers to evaluate numerous meteorological and snowcover parameters in order to produce an avalanche forecast were isolated and described. On the completion of the third winter's data collection, work began on the development of a statistical model for the purpose of avalanche prediction.

Finally, the overall objective of the San Juan Avalanche Project continues to be to identify and analyse those processes which contribute most directly to the initiation of avalanches within the study area, to establish empirical relationships among these processes, and to expose these relationships to a detailed statistical analysis.

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PREFACE

In May 1971, the Office of Atmospheric Water Resources of the Bureau of Reclamation signed a three-year contract with INSTAAR for development of a methodology for evaluation and prediction of avalanche hazard in the San Juan Mountain area of southwestern Colorado. Jack D. Ives, Director of INSTAAR, and J. Christopher Harrison, INSTAAR Research Associate and member of the University of Colorado Cooperative Institute for Research in the Environmental Sciences (CIRES), were designated as principal investigators. It must be stressed, however, that right from the outset, the project was organized through a field base in the mountain town of Silverton on the assumption that most of the scientific initiative would evolve from a collaboration of the field team and three senior avalanche research consultants, Edward LaChapelle, Malcolm Mellor and Wilford Weeks. This, in fact occurred, and an important share of the success of the project results from the enthusiasm and resourcefulness of the field crew, and particularly Richard L. Armstrong, the Silverton Field Director. Drs. Mellor and Weeks have continued to provide valuable guidance and criticism, but the role of Dr. LaChapelle has grown to the extent that he carries a major share of the actual development, operation and analysis of the project, such that his role, and that of Richard Armstrong, is more the part of principal investigator.

In the early days of the project, when comparatively little was known about the snow climate of the San Juans, when virtually no weather and climatic data were available for the area above treeline, and when data on snow mechanics, snow stratigraphy and avalanche release were largely lacking, it was assumed that avalanches in this area were primarily direct action releases, because with the exception of the cycle of wet spring release, most occurrences coincided with precipitation of new snow. Another factor affecting the shape of the project for its first two years was the hope that experimentation with geophysical means of detection and recording might provide an important breakthrough in an extremely complex research area. Hence, the involvement of Dr. Harrison of CIRES.

Completion of three years of observation, data analysis, and regular brainstorming, in conjunction with rapidly increasing contact with internationally famous avalanche research centers, and particularly the Swiss Federal Institute for Snow and Avalanche Research, and the U. S. Forest Service Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, has led to some important gains in knowledge and some significant changes in approach.

1. The extensive testing of infrasonic and microseismic instrumentation revealed that no immediate breakthrough could be anticipated in this area. Thus, this section of our program was completed with the close of the second year.

2. Under Dr. LaChapelle's guidance, the large amount of data on snow mechanics, collected through fracture line profiles and other methods, has revealed that the great majority of the San Juan avalanches are of the climax type, since it has been shown that (a) snow conditions indicate prevelance of conditional instability throughout most of the winter and (b) while many avalanches do indeed occur during storm periods, not only the new snow, but in many instances, the entire snow pack releases, the new precipitation, therefore, serving as a triggering event. This, and associated work, led to the designation of the San Juan winter climate as a radiation snow climate with further realization that relatively low southerly latitude, and hence high angle sun coupled with moderate total snowfall, render simple comparisons with the pre-existing major avalanche research areas rather dangerous and unreliable.

3. A third important departure, reported in full in Chapter IV, was last winter's development of highly specific forecasts for certain groups of avalanche paths which constitute the major hazard to U.S. Highway 550 in the research area. Furthermore, probable avalanche occurrences, both natural and those likely to be released by artillery fire, were specified according to whether they would run in the upper track only, to mid-track, or for full track length. This degree of specificity introduces a new dimension to avalanche forecasting in the United States. To our knowledge, no such forecasting precision has previously been formally and systematically attempted for an entire winter on so many diverse avalanche paths. And the relatively high degree of actual forecasting accuracy is extremely gratifying.

From the foregoing, it is readily apparent that the end of the three-year contract period was rapidly approaching and, while a major advance can be claimed, more new questions had been raised than old ones answered. Perhaps this should not be surprising when dealing with field research of such a complex nature. Thus, in recognition of the importance of proceeding further, the Bureau of Reclamation added a fourth year to the contract (the current year, 1974-75). Furthermore, the Silverton objectives were significantly enlarged, both in the direction of expanding basic research in snow mechanics, and in the applied area of experimenting with field methods, old and new, for artificial release of avalanches. These developments have been made possible by a grant from the United States Army Research Office (Durham) for the basic snow mechanics research (Grant number RD-GS-11866 to LaChapelle and Ives) and by important financial commitments by the Federal Department of Transportation and the Colorado Department of Highways.

Finally, an additional dimension should be stressed. For the last three years INSTAAR has been pushing further and further into what may be described best as applied mountain geoecology. Specifically, this policy has assumed that growing competence, and a rapidly enlarging data bank from mountain research in several of the natural sciences should be applied to help solve problems of mountain development and land management for the general good of the state of Colorado. This progress received an important boost by a grant from NASA Office of University Affairs for application of space technology for solution of real world problems in mountain environments. One of the main thrusts of this grant has been the identification of areas subject to avalanche run-out (and other geologic hazards). Such work so far has been concentrated in the vicinity of Vail, Crested Butte, Telluride and Ophir, and in San Juan County.

Obviously, assessment of the cause of avalanche release and avalanche forecasting, and interpretation of historical extent of avalanche run-out and recurrence interval of the major destructive events are complementary pieces of the same overall applied research task. It is our intention to progressively fuse the objectives, personnel and experience of these two complementary pieces. An important administrative step has been the appointment of Dr. Michael Bovis as project coordinator of the NASA-PY operation. These activities are especially timely in view of the rapid growth in avalanche hazard in the Colorado Rocky Mountains through runaway land speculation and ski resort and tourism development. And in the broader international setting these objectives have been emphasized as a major segment of the new Unesco Man and the Biosphere Program (MAB), Project 6 - Impact of human activities on mountain and tundra environments.

Jack D. Ives

December 22, 1974

CHAPTER 1: INTRODUCTION

Richard L. Armstrong

Research relating to the nature and causes of snow avalanches in the San Juan Mountains of Southwestern Colorado is being conducted by the Institute of Arctic and Alpine Research, University of Colorado under contract to the Bureau of Reclamation, U.S. Department of the Interior (Contract No. 14-06-D-7155). This report contains the results of the San Juan Avalanche Project's third winter of research. The research objectives of the project remain the same as stated in the initial work plan for May, 1971 through September, 1972 and the Interim Report for the period August 1971 - July 1972 (Ives, et al., 1972). These goals are to develop a methodology which will seek to determine the causes of avalanches in the San Juan Mountains, and to begin to develop a forecast model for the prediction of avalanche occurrence. Research efforts continue to be concentrated within that area immediately adjacent to the 58 km of U.S. Highway 550 between Coal Bank Hill to the South and Bear Creek Falls to the north of Silverton, Colorado.

1973-1974 Instrumentation Network

In order to understand better the empirical correlations between avalanche occurrence and specific influential weather parameters, a network of meteorological instrumentation continues to be maintained. A detailed technical description of each type of instrument is included in the 1972 Interim Report (Ives, et al., 1972). Included in the 1973 Interim Report (Ives, et al., 1973) is a tabulation of instrument type as utilized by this project, the specific data made available by the instrument, and frequency and type of data reduction. The basic instrumentation network described in the 1973 Interim Report remains unchanged with the exception of the seismic and infrasonic equipment which was discontinued (see Chapter 6, 1973 Interim Report). In addition, the snow study site at Molas Divide was discontinued in order that studies of snow structure might be concentrated in the Red Mountain Pass area. Precipitation, as well as wind speed and direction data are made available for this site from instrumentation maintained by Western Scientific Services, Inc. Techniques employed in the collection, reduction and analysis of snow structure data are described in Chapter 3 of the 1973 Interim Report and pp. 21-30 of the 1972 Interim Report. In addition to the snow temperature data which had been acquired during the previous two winters, in situ thermocouple arrays were utilized at three sites: Silverton (2830 m), Chattanooga (3162 m) and Red Mountain Pass (3400 m). Snow temperature data were obtained on a daily basis, at 20.0-cm intervals, as well as at 5.0-cm increments within the top 20.0 cm of the snowcover at the Red Mountain Pass site. In addition, an RSG-1 Isotopic Snow Density Guage, manufactured by Idaho Industrial Instruments, Inc., was utilized at the Red Mountain Pass study site. This instrument provides total snowcover water content data and operates on the principle of attenuated electromagnetic energy as measured by a fixed source-detector arrangement. The total water content of the snowcover with respect to time as measured by the RSG-1 is presented in Figure 1, as well as water content data acquired by four other means.

The Aerojet Nuclear Isotopic Profiling Snow Guage continued to provide daily (Monday through Friday) snow density values at intervals of 1.25 cm within the snowcover at the Red Mountain Pass study site. A complete description of this particular instrument, as well as its capabilities in regard to avalanche research is included in Chapter 5 of the 1973 Interim Report. During the past winter, the profiling gauge continued to be dependent on a Dataphone link with the computer facility at the National Reactor Testing Station, Idaho Falls, Idaho. Consequently, data can only be obtained during those times of the day and week when this facility is available. It is anticipated that prior to the 1974-1975 winter, necessary modifications of this instrument required for an on-site readout will be completed. This capacity will enable the instrument to be utilized in an optimum manner as a tool in avalanche research. During the past winter, the profiling gauge was operated from November 19 to May 28. Of a total of 133 days during which the gauge could have operated, data was not available on 43 days. Problems causing these interruptions included poor quality or interrupted telephone transmission, malfunctions within the electronic components at the Red Mountain Pass site, as well as two periods when moisture, resulting from either condensation or a leak in the seal at the base of the access tubes, froze in the tubes and prevented the vertical travel of the detector unit.

Data Reduction and Analysis

All data provided by the various instrumentation installed and maintained by the San Juan Avalanche Project are reduced immediately after they are available at the Silverton project office. The time intervals for reduction vary according to the type of instrument and accessibility of the instrument site. Analysis of data regarding certain critical parameters is maintained on a current basis. The remaining data are analyzed whenever time and available personnel allow. An example of simultaneous data collection, reduction and analysis is a continuing chronology of the stratigraphic properties of the snowcover within the research area which is maintained throughout the winter. In addition, all data utilized in the formulation of the daily snowcover stability and avalanche occurrence forecasts receive whatever analysis the particular observer deems necessary. This method is highly subjective in nature and does not easily lend itself to quantitative analysis or evaluation. As an alternate approach to this empirical methodology, a statistical evaluation of a major portion of the weather, snowcover and avalanche data collected during the past three winters has been undertaken. This effort to establish numerical relationships between avalanche occurrence and pertinent snow and weather parameters by discriminant analysis is contained in Chapter 6 of this report.

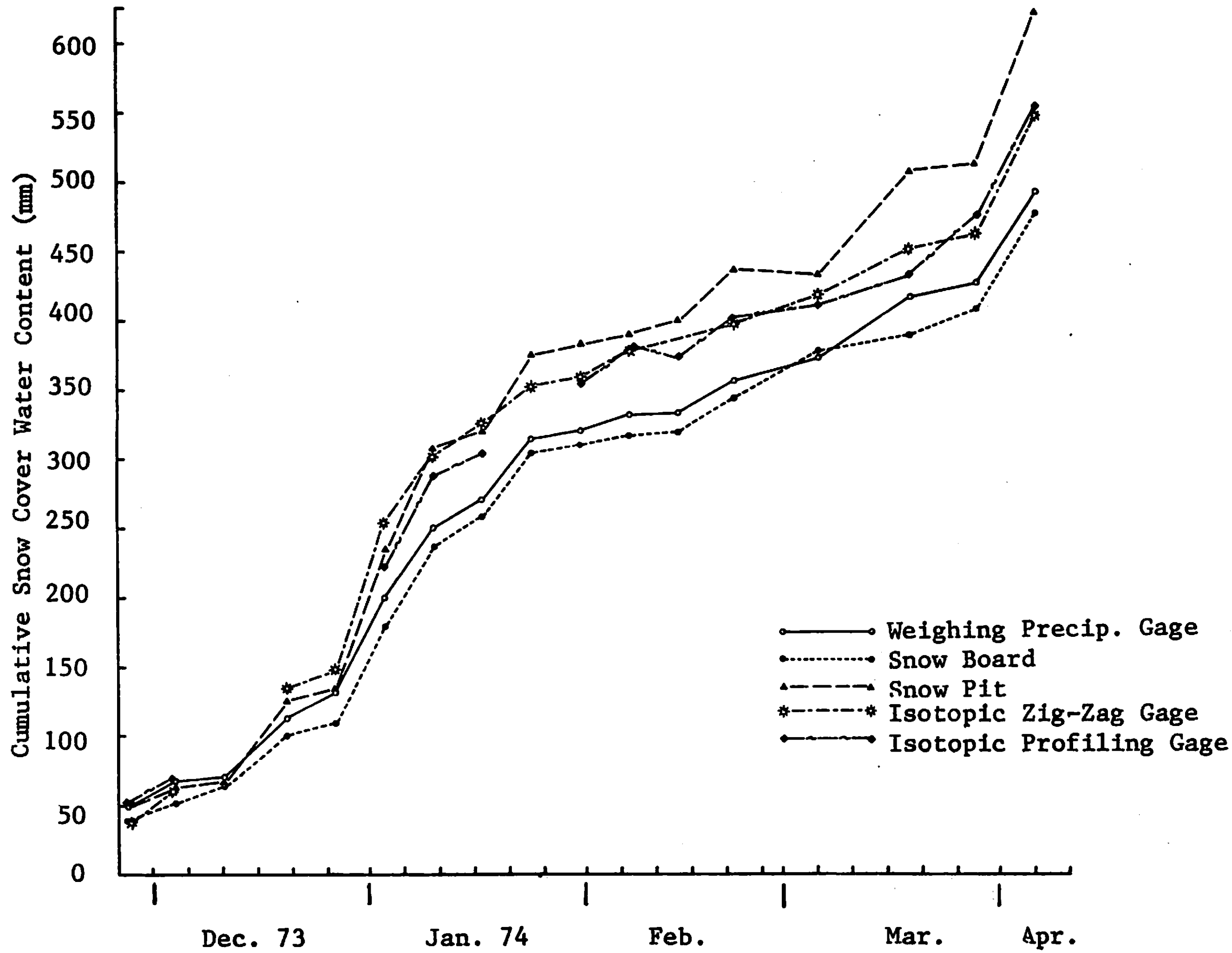


Figure 1. Cumulative snow cover water content as measured by five methods at the Red Mountain Pass snow study site for the period November 25, 1973 through April 5, 1974.

Physical Properties of the Snowcover

It was the initial intent of this project to acquire a significant amount of information regarding the stratigraphic properties of the snowcover within the study area and thus not to rely primarily on meteorological data for avalanche hazard evaluation. The need to emphasize snow structure data became even more apparent as research progressed. During the three winters of observation, a generally consistent pattern of snowcover stratigraphy has been established. Details regarding the evolution and influence on avalanche release of this type of snowcover are contained in Chapter 3 of the 1973 Interim Report and Chapter 3 of this report. In general, for an avalanche to release, the strength-stress relationship within the snowcover must provide for some type of mechanical failure. While factors leading to this critical condition vary from one climatic zone to another, it appears that the situation in the San Juan Mountains may be somewhat unique. Due to the complex snow stratigraphy created by the climate of this high-altitude and relatively low-latitude (37°54') site, numerous structurally weak layers exist within the snowcover. The moderate snowfalls and radiation snow climate of the San Juan Mountains combine to produce a snowcover which in most avalanche release zones can be described as conditionally unstable for most of the winter. While there is no evidence that these weak layers alone, due to their inadequate strength, contribute to spontaneous avalanche release, they remain constantly susceptable to either load-induced or thaw-induced avalanche release. No consistent relationship between precipitation amounts and rates (loading stress) and avalanche occurrence has been established thus far within the study area. However, data obtained from fracture line studies indicate that 89% of the avalanches investigated were the climax type, that is, the slab which released incorporated one or more layers of old snow not directly associated with the precipitation event causing the release. The amount of additional load required to initiate avalanche release may vary greatly, dependent upon the strength of the various weak layers and layer bonds. Therefore, this type of conditionally unstable snowcover can set the stage for load-induced avalanches which would not otherwise occur if the load had been deposited on stable snow.

During the past three winters, over 30% of the avalanches which affected U.S. Highway 550 were wet, or thaw-induced avalanches. Therefore, it is appropriate that specific attention be given to the genesis of this type of event as well as those methods available to forecast their occurrence. An analysis of data relating to spring avalanches is contained in Chapter 5 of this report.

Avalanche Forecasting

The formulation of a daily "in-house" avalanche forecast continued during the 1973-1974 winter. The same basic technique initiated during the 1972-1973 season was utilized. Each morning, the Red Mountain Pass observer is responsible for a snowcover stability evaluation and 24 hour avalanche occurrence forecast based on his knowledge of meteorological, snowcover and avalanche occurrence data. During storm periods, an observer is on duty at the Red Mountain Pass station 24 hours per day and avalanche forecasts are produced at more frequent intervals, depending on the intensity of the storm.

An avalanche forecast is a snowcover stability evaluation extended to some point in the future. The ability to make such a prediction depends heavily on the availability of accurate and timely mountain weather forecasts. This information was again provided by the staff meteorologists of E.G. and G., Inc., in Durango, Colorado. Each day a second observer evaluates the previous day's avalanche forecast based on actual observations of snowcover stability, avalanche occurrence and the accuracy of the meteorological forecast. An example of the actual format used by the daily forecaster is presented on page 55. Chapter 4 of this report contains a detailed analysis of methods employed by four observers in developing avalanche forecasts. The high degree of subjectivity inherent within this type of forecasting procedure, as it relates to the individual observer's biases and overall experience in the field, is described. Finally, an analysis of the level of success of this empirical approach is presented along with a discussion of how such a method can be combined with a statistical technique now being developed for the study area.

CHAPTER 2: 1973-1974 WINTER SUMMARY

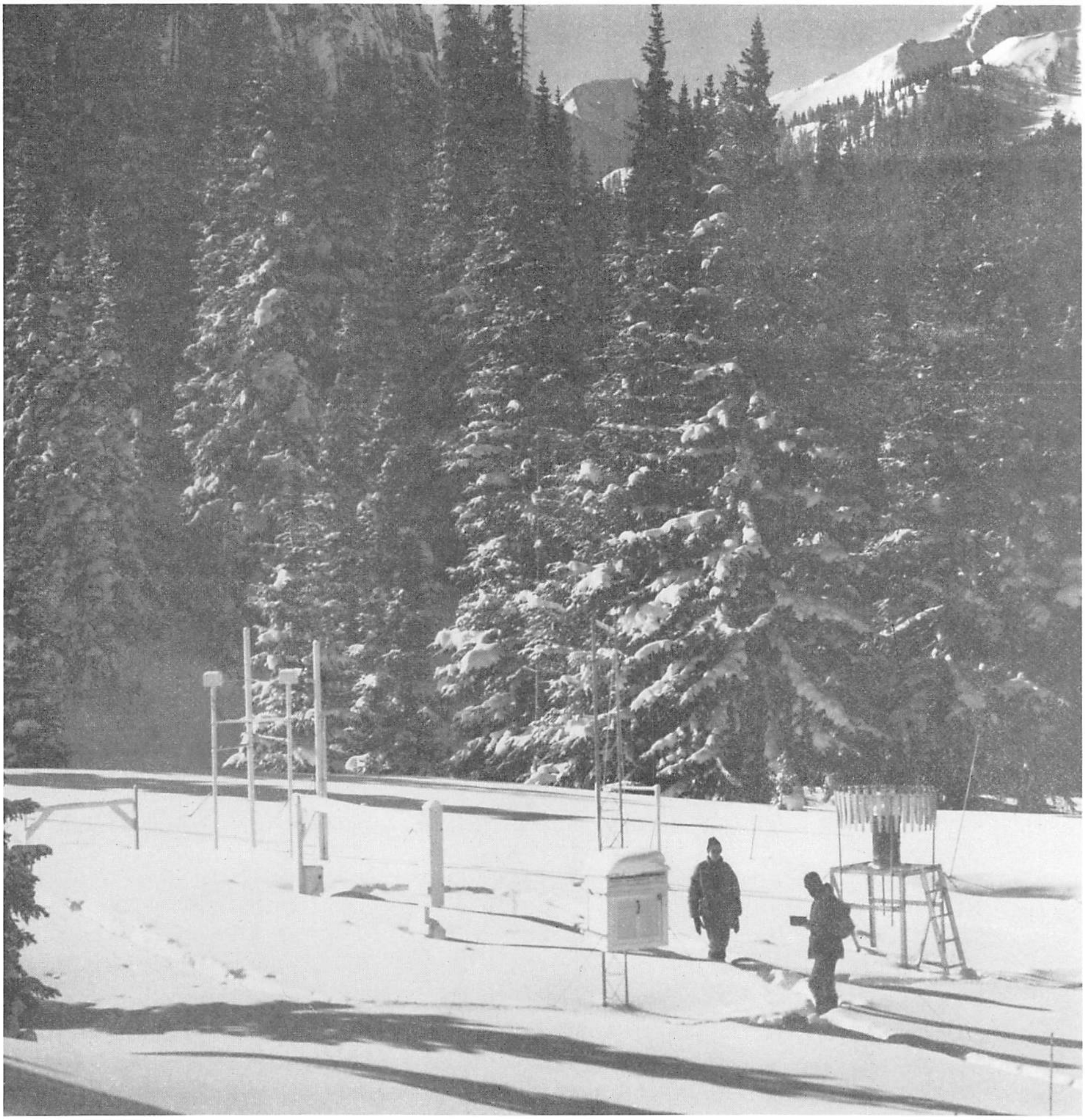
Richard L. Armstrong

During the period November 1 to April 30, precipitation occurred in the form of snow on 81 days at the Red Mountain Pass study site. On April 30, the snowpack contained 722 mm of water, 92% of the 1972-1973 amount on this date. At the Soil Conservation Service study site on Red Mountain Pass, 777 mm of water existed in the snowpack on this date, representing 94% of the 15 year average. Total snowfall measured at daily intervals was 789 cm at the INSTAAR study site. Maximum snowdepth at this location was 209 cm on 21 April. The average new snow density was .076 Mg/m^3. While the snowcover water equivalent on April 30 of both 1973 and 1974 was comparable, precipitation in the form of snow continued to occur during May of 1973 resulting in a total for that winter of 961 mm. In general, the precipitation regimes of the two winters differed greatly in two other areas. During 1972-1973, precipitation occurred on a continuous scale, with the snowpack depth steadily increasing throughout the winter. However, from January 10, 1974 to March 7, 1974, the snowdepth at the Red Mountain Pass study site fluctuated within the narrow range of 130 to 160 cm and a total of only 66 mm of precipitation occurred during this period. This pattern is clearly evident in that portion of Figure 7 showing the variation in snowdepth with time. A second major difference between the two precipitation patterns was the fact that while the 1972-1973 winter experienced 14 storm periods involving more than 20 mm of precipitation in 24 hours, only five such events occurred during the 1973-1974 winter.

The mean air temperature at the Red Mountain Pass study site for the period November through April was -7.9°C. The lowest recorded temperature was -24.5°C and occurred on January 3. During this period, the mean wind speed at Point 12,325 was 6.7 m/sec, with the highest one-hour average being 35 m/sec recorded on December 28 and the peak of 53 m/sec occurring on the same day. Northwest and south were the most frequently occurring wind directions, as demonstrated by the wind rose in Figure 2. Figures 3 and 4 contain wind direction for the period November 1971 to April 1974.

Within the boundaries of the study area and along the 58 km of U.S. Highway 550 between Coal Bank Hill and Bear Creek Falls in the Uncompaghre Gorge, 260 avalanches were observed during the 1973-1974 winter season. Sixty-four avalanches came in contact with the highway and of these, 46 had a depth of 1.0 m or more at the centerline. Of all avalanches observed, soft slab avalanches amounted to 59%; hard slab, 2%; dry loose, 13%; wet slab, 2%; and wet loose, 24%. Forty-seven avalanches were released artificially during the 1973-1974 winter.

A graphical presentation of precipitation, air temperature, wind speed and avalanche occurrence for the winter period is found in Figure 5. Figure 6 is a time plot of avalanche occurrence and total storm precipitation amounts measured at Molas Divide, Red Mountain Pass and Ironton Park.



Part of the snow study plot at Red Mountain Pass. From right to left instrumentation includes: recording precipitation guage with Alter shield; standard meteorological screen; "zig-zag" isotopic snow profiler (immediately behind screen); snow settlement guage; isotopic snow profiler (4 upright posts and connecting limbs); fixed thermocouple array. The three snow boards, master stake and data read-out shack are off the picture to right.

Photograph by Jack D. Ives

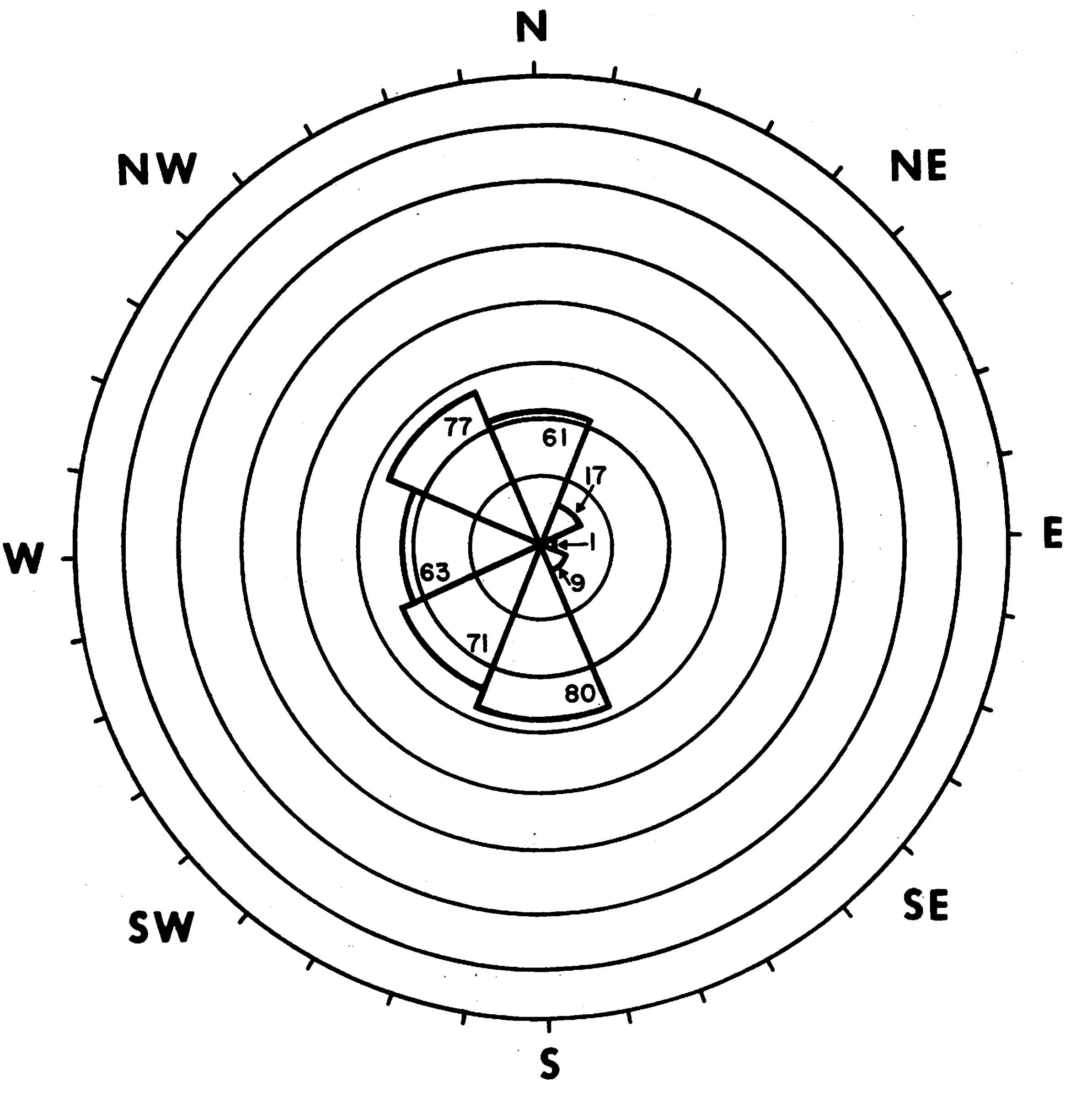


Figure 2. A directional wind rose constructed from 6-hour averages of wind direction when the wind speed was greater than 5.0 m/sec, Pt. 12,325, November 11, 1973 through April 3, 1974.

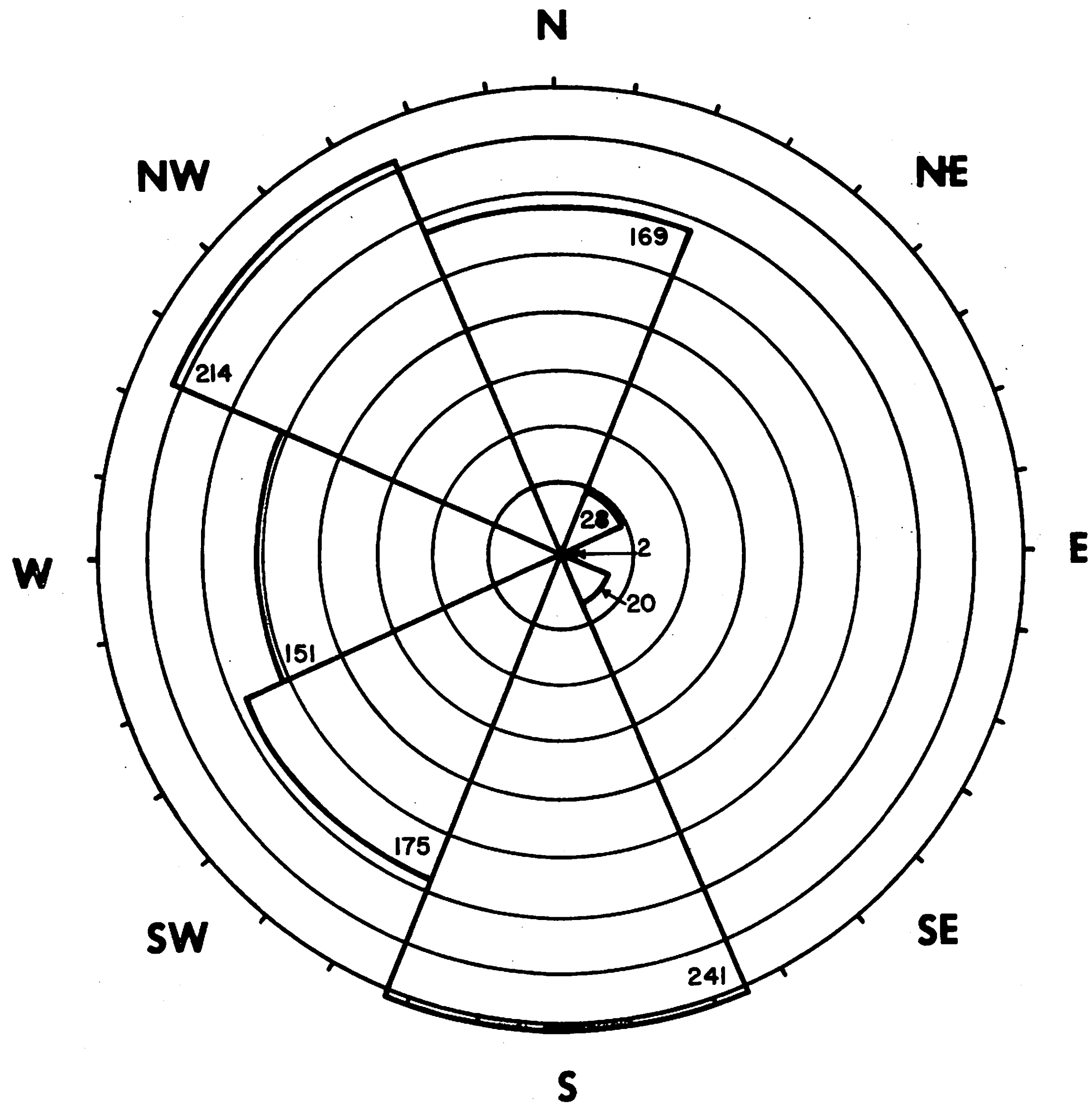


Figure 3. A directional wind rose constructed from 6-hour averages of wind direction when the wind speed was between 5 and 15 m/sec, Pt. 12,325, November 11, 1971 through April 18, 1974.

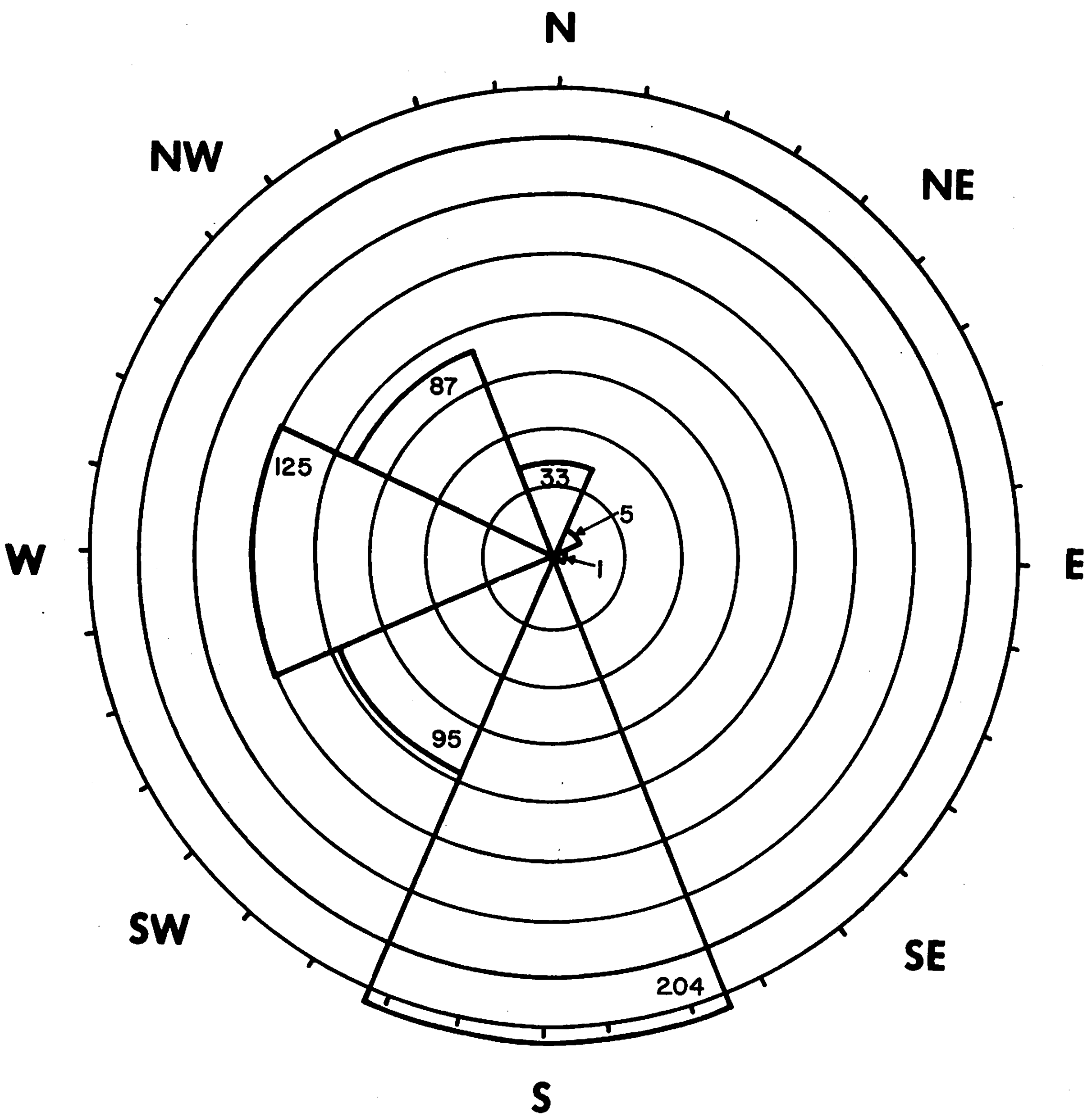


Figure 4. A directional wind rose constructed from one-hour averages of wind direction when the wind speed was greater than 15 m/sec, Pt. 12,325, November 11, 1971 through April 18, 1974.

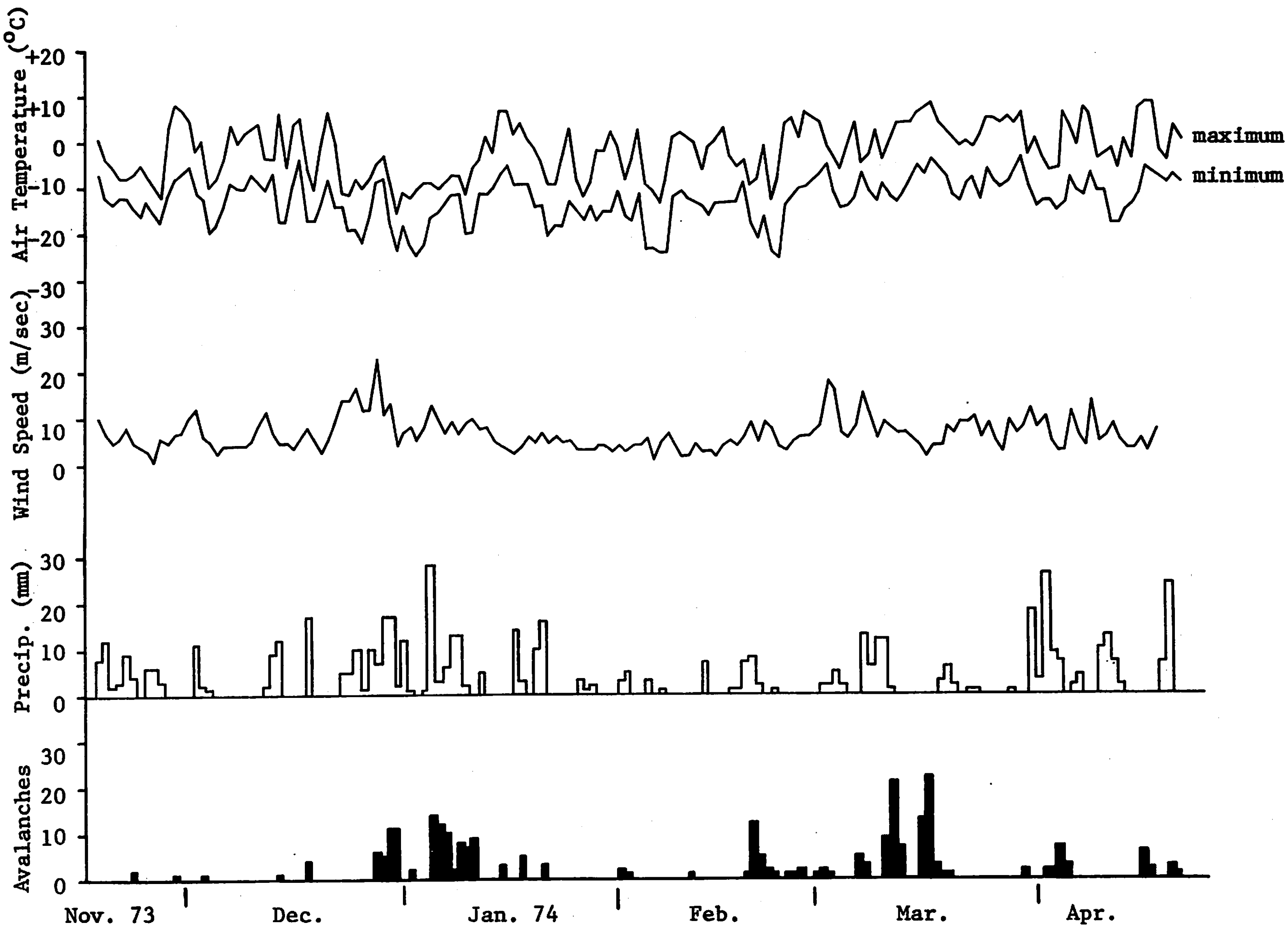


Figure 5. A diagram showing the variation in air temperature (°C) and precipitation (mm of water equivalent) measured at the Red Mountain Pass snow study site, wind speed (meters per second) measured at Pt. 12,325, and the daily totals of observed avalanches within the period November 18, 1973 through April 22, 1974.

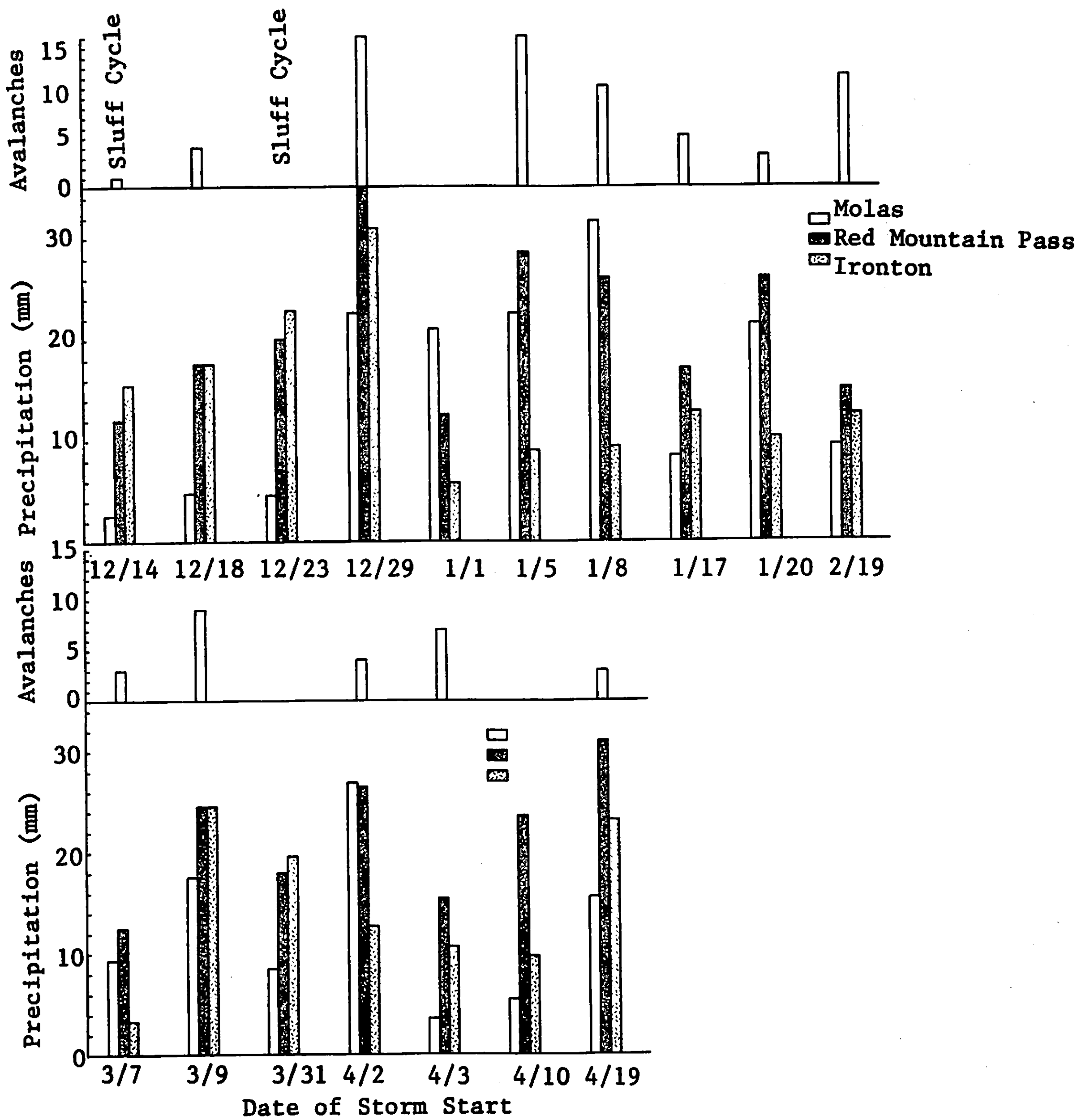


Figure 6. A diagram comparing precipitation amounts (mm of water equivalent) for storms with precipitation greater than 10 mm at Red Mountain Pass, for Molas Divide (12 km south of Silverton), Red Mountain Pass (16 km north of Silverton), and Ironton Park (25 km north of Silverton) and observed natural avalanche occurrences greater than size 1 along U.S. Highway 550. (Molas Divide and Ironton Park precipitation data were provided by Western Scientific Services, Inc.)

The variation in the density of the snowcover at the Red Mountain Pass study site with time is presented in Table 1 and Figure 7. Two factors caused deviations from a general pattern of increase in density with time. Figure 7 shows how the continued development of temperature-gradient snow, or "depth hoar", within a layer between the ground surface and a height of 30 cm causes a split in the zone 0.250-0.300 Mg/m^3. The upper portion of this zone is made up of fine-grained, equi-temperature snow which continues to increase in density while the lower portion is comprised of coarse-grained, temperature-gradient snow which increases only slightly in density throughout the remainder of the winter. This retarded densification rate is also evident in Figure 8 where data from platter one corresponds to the layer between the ground surface and a height of 30.0 cm. The second exception to the pattern of increase in density at a relatively constant rate with time, which was the general case at this location during the 1973-1974 winter, can be seen in the decrease in slope of the isolines in Figure 1 during the month of February. This period is within that portion of the winter which experienced minimal precipitation. It can be seen that the rate of densification of a sub-freezing natural snowcover is a function of precipitation, or stress application, as well as time.

A time plot of temperature variations (°C) within the snowpack at the Red Mountain Pass study site appears in Figure 9. The isotherms represent that temperature regime which exists far enough below the snow-air interface (25-35 cm) so as to be appreciably insulated from the short-term or diurnal temperature regime. Temperatures within this lower portion of the snowpack respond to the longer term variations in mean daily temperature, with the response-time lag being a function of depth. This relationship is apparent in Figure 9. As the snowpack continues to increase in depth, the general tendency is for the isotherms to slowly migrate upward seeking to maintain the same distance from the snow surface. This was the general pattern during the 1972-1973 winter and a similar situation can be seen in Figure 9 between January 4 and 22, 1974. However, given that no major variations occur in the mean daily air temperature regime, isotherms may maintain a horizontal configuration whenever the depth of the snowpack remains relatively constant. As previously described, this situation existed between late January and early March. On March 10, mean daily air temperatures at the study site began to rise at a significant rate reaching a maximum of +2.5°C on March 17. The zero degree isotherm responded to this warming trend and migrated upwards to the depth of 105 cm on 19 March. After March 17, however, air temperatures began to decrease and the zero degree isotherm dropped back down to the 25 cm level in the snowcover. On March 21, a gradual warming trend began and by April 1, the entire snowpack was isothermal at 0.0°C.

Temperature measurements which comprise the data in Figure 9 are made daily just prior to sunrise at the study site. Near-surface temperatures at this time often reflect those very low values (-15.0 - -25.0°C) caused by intense radiation cooling associated with the local climate. By mid-afternoon, these same layers may well be at or within a few degrees of freezing.

TABLE 1. 1973-1974 SNOWPACK DENSITY AND WATER EQUIVALENT VALUES AT THE RED MOUNTAIN PASS SNOW STUDY SITE

date	mean snowpack density (Mg/m^3)	total water equivalent (mm)
Nov. 26	.164	50.1
Dec. 3	.161	65.2
Dec. 10	.158	64.0
Dec. 19	.176	125.1
Dec. 26	.176	133.8
Jan. 2	.221	235.6
Jan. 9	.203	308.9
Jan. 16	.252	320.5
Jan. 23	.239	376.5
Jan. 30	.270	383.3
Feb. 6	.285	390.1
Feb. 13	.292	400.1
Feb. 21	.278	438.0
Mar. 5	.305	433.1
Mar. 18	.333	507.5
Mar. 27	.327	513.6
Apr. 5	.299	623.7

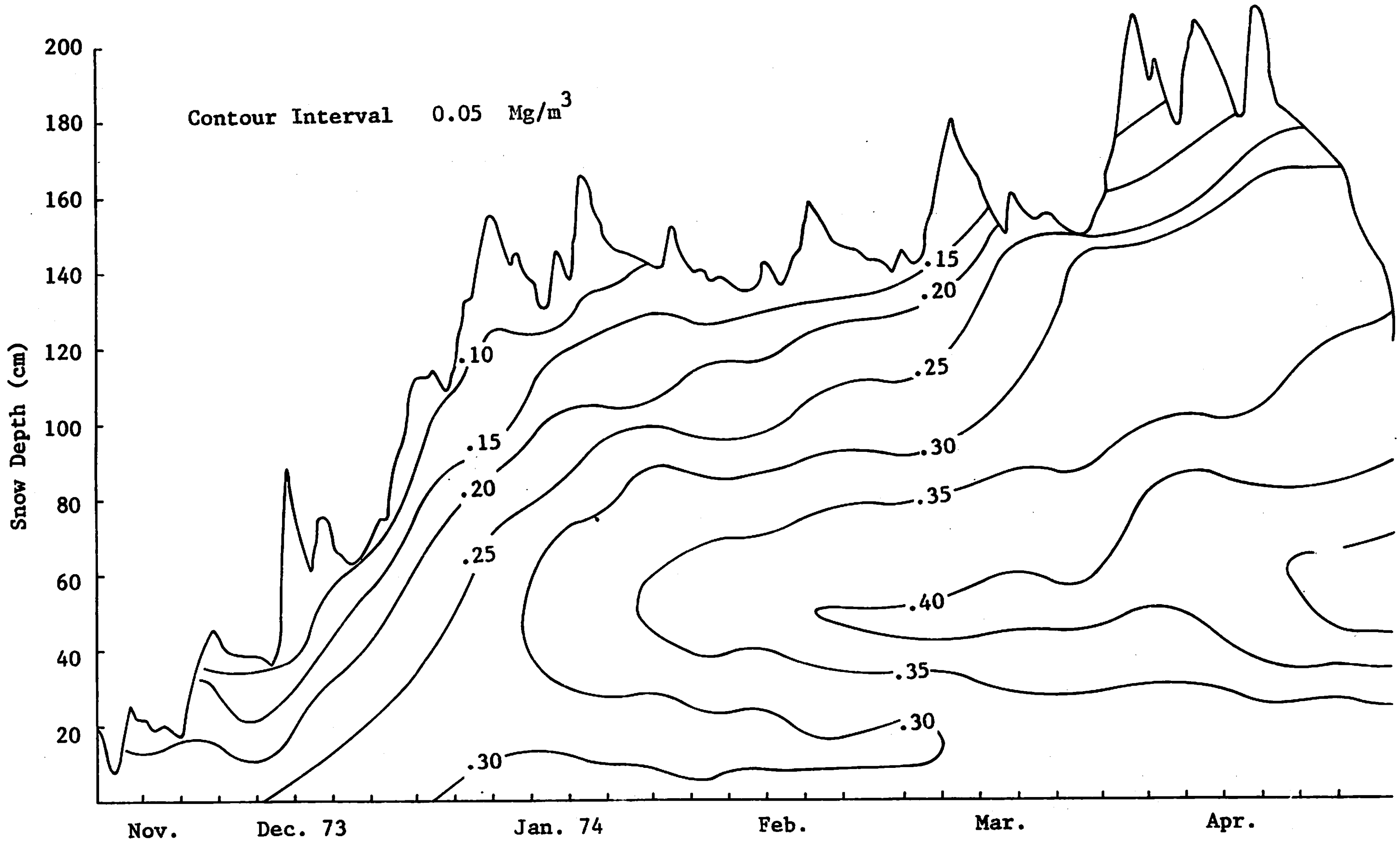


Figure 7. A time-stratigraphic plot of density variations (Mg/m^3) at the Red Mountain Pass snow study site for the period November 19, 1973 through April 30, 1974.

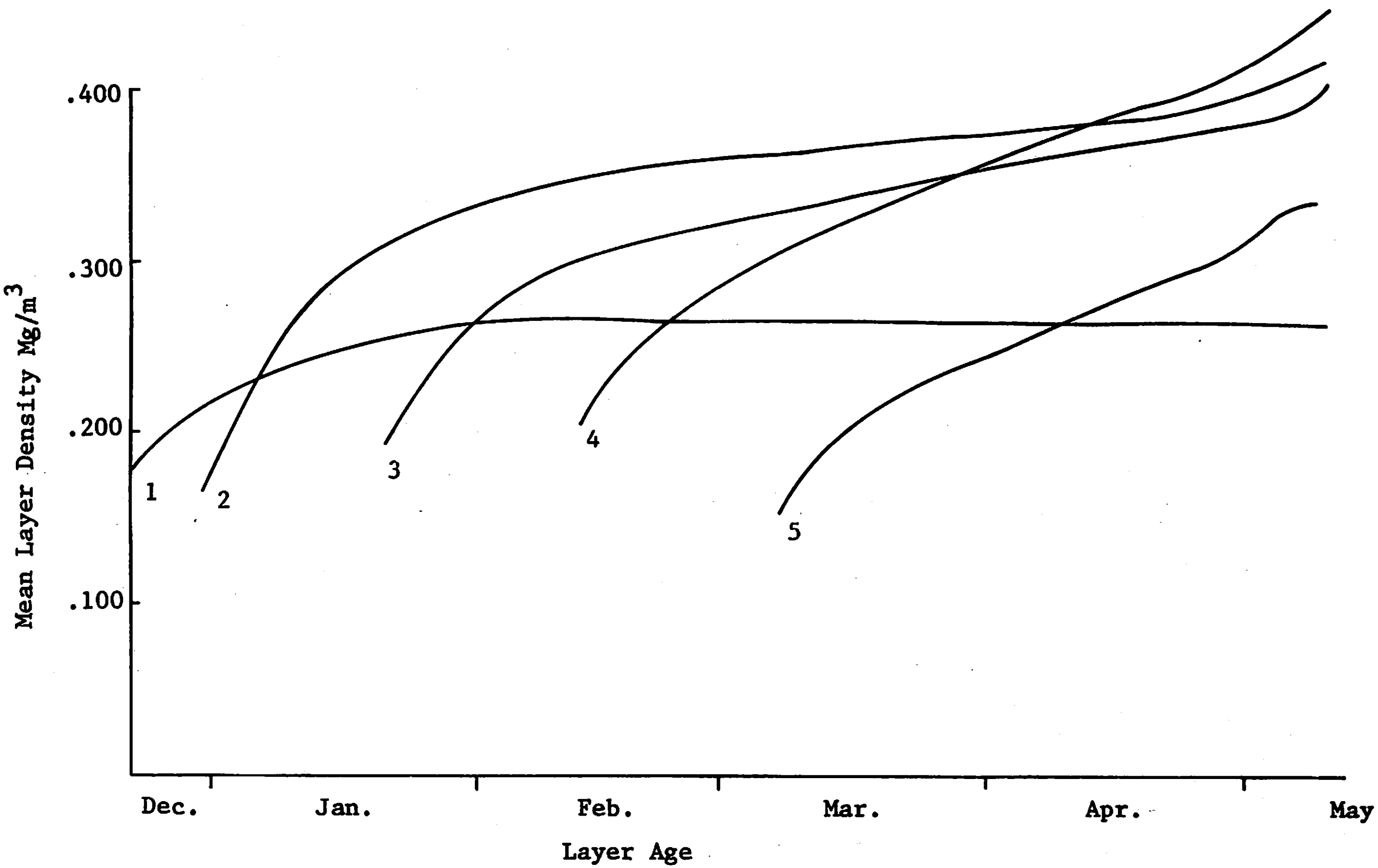


Figure 8. Snow layer densification rates at the Red Mountain Pass snow study site, 1973-1974.

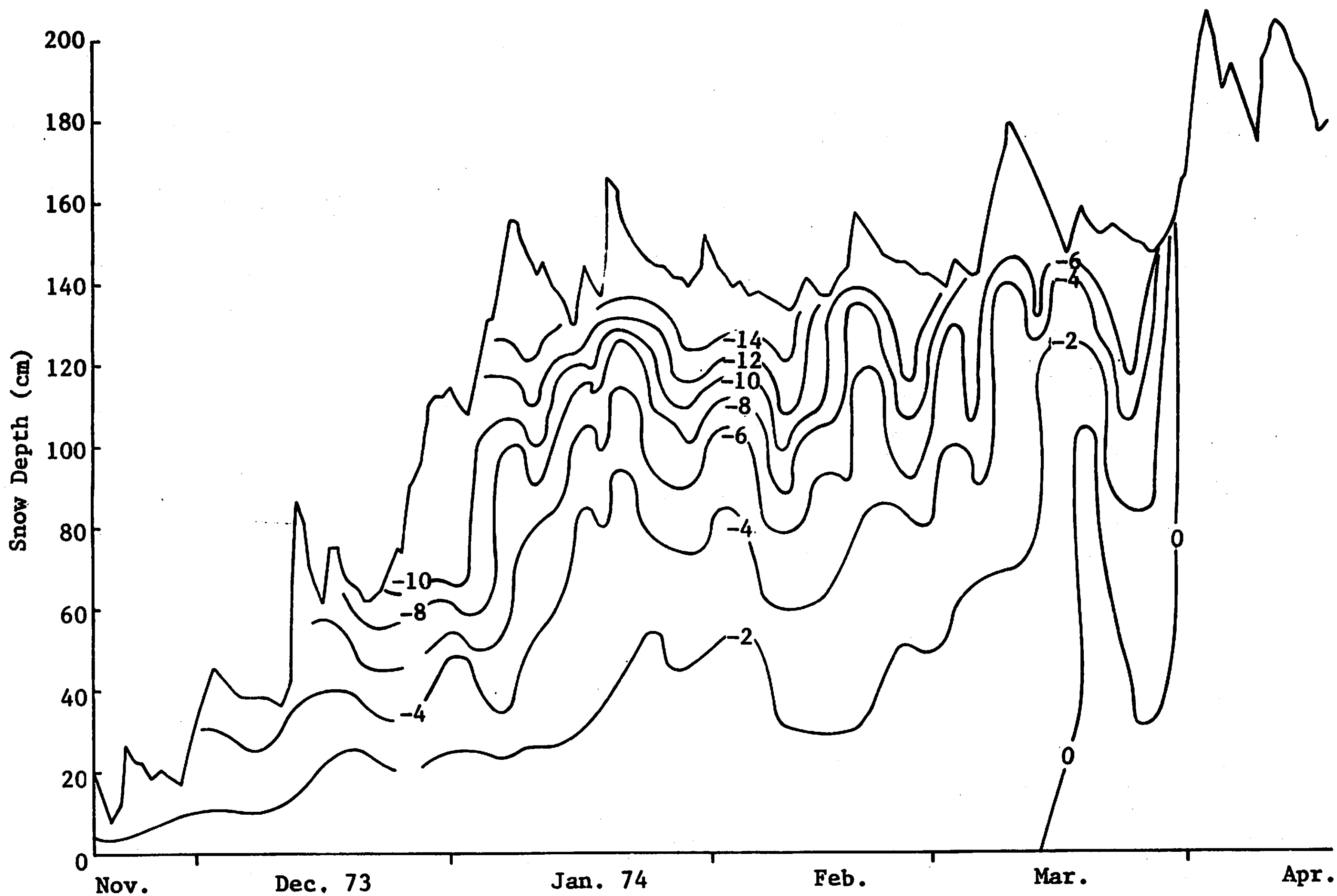


Figure 9. A time-plot of temperature variations (°C) within the snowpack at the Red Mountain Pass snow study site from November 15, 1973 through March 30, 1974.

Snow strength or hardness data as obtained by the rammsonde penetrometer at the Red Mountain site are presented in Figure 10. These data are composed of integrated rammsonde values to given depths (z) below the snow surface and in this case the ground is the base reference. Such a total integrated rammsonde profile is equal to the area (in kg-cm) under the resistance curve to that depth, i.e.

$$R_i = \sum_{z=0}^{z} R\Delta z$$

where R is the rammsonde resistance in kg, Δz is the depth increment in cm and R_i is the integrated rammsonde resistance in kg-cm. The dates corresponding to each data sample were selected to show the progressive increase in strength with time. However, during the period February 6 to March 5, the integrated rammsonde values very closely approximate the example presented for February 21. This period, during which rammsonde values increased only slightly with time, corresponds to that time interval when little mass was added to the total snowcover. After March 5, the rammsonde values rapidly increased as a response to both an increase in snowpack loading resulting from a new series of precipitation events, as well as a gain in strength associated with increasing snow temperature.

The preceeding summaries of snow density, temperature, and rammsonde values throughout the 1973-1974 winter pertain solely to the study site located on Red Mountain Pass. While this site is employed as the basic snowcover and climatic reference for the study area, other locations of snowcover investigation may or may not reflect the general pattern of development at the Red Mountain site. This lack of correlation is frequently the case at slope study sites as can be seen in the stratigraphic data contained in the fracture line studies presented in Appendix 1. Generally, the snowcover at other sites possesses a weaker structure with more frequent examples of poor layer bonding and more evidence of stratigraphic conditions produced by temperature-gradient processes. While average density values in the snowcover at the Red Mountain site are greater than the majority of the slope sites, the range of density values at the slope sites exceeds that which occurs at the primary study site. A more detailed description of the slope study sites, as well as the variations in snow structure among the sites, is presented in Chapter 3.

Unless otherwise stated, all air temperature and snowcover data contained in the following monthly summaries were recorded at the Red Mountain Pass snow study site. Wind speed and direction data were recorded at Point 12,325.

Monthly Summary

November: Snowfall first occurred at Red Mountain Pass on October 9, 1973. This 15 cm accumulation, however, melted within a few days and the study site was without snowcover until November 18. Slopes with

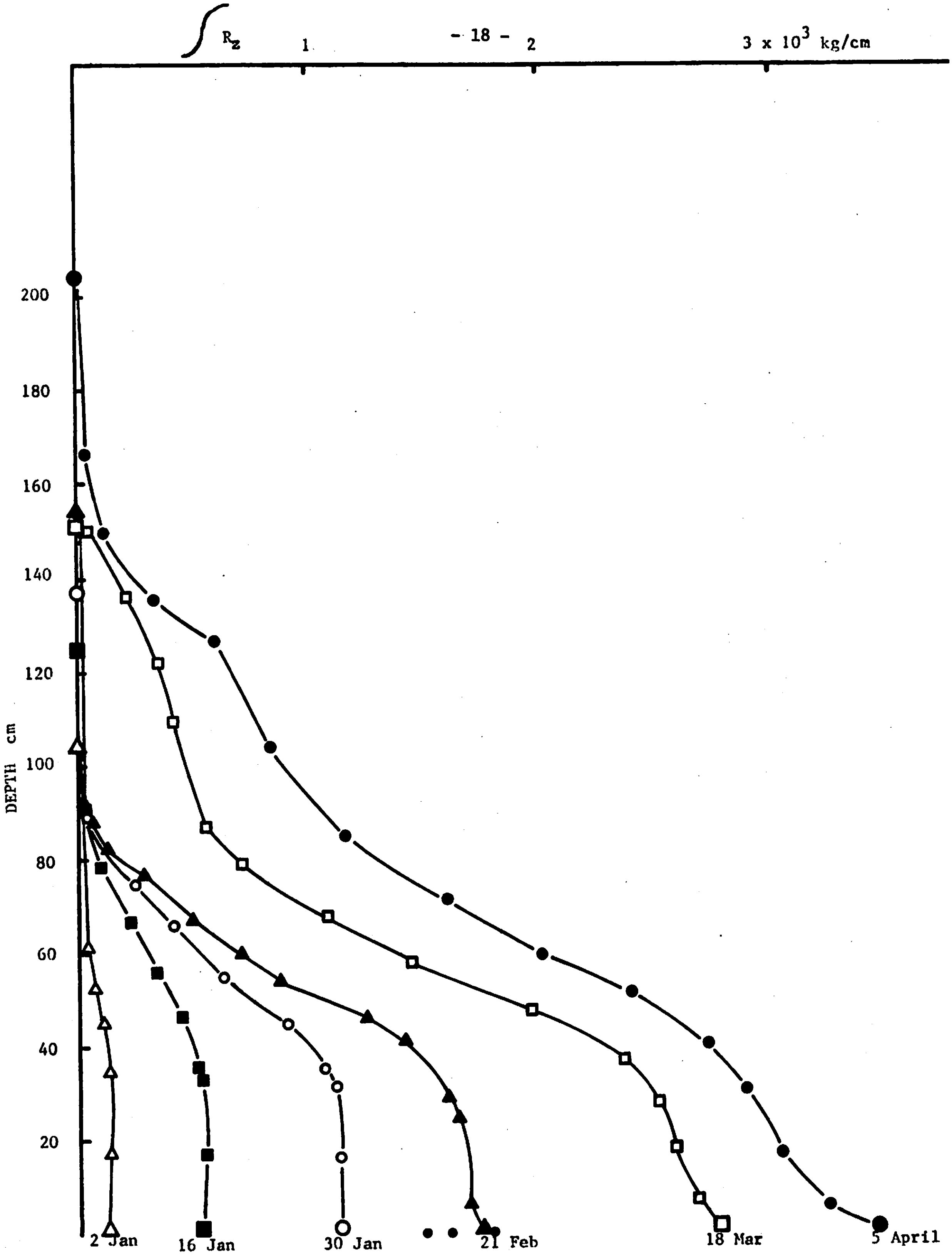


Figure 10. Integrated rammsonde resistance curves for six selected dates at the Red Mountain Pass snow study site during the 1973-1974 winter season.

northerly exposures, however, did maintain a minimal snowcover (5-20 cm) during this period, which due to its shallow depth developed into a layer of advanced temperature-gradient snow by the time the November 18 precipitation occurred. Total precipitation for November amounted to 57 mm and while precipitation was recorded on each day from November 18 to November 27, amounts were small and on the 30th, only 32 cm of snow-depth existed at the Red Mountain site. Thus, snowcover was insufficient to allow significant avalanche activity with only four small (size two) avalanches being observed during the last ten days of the month. As a point of comparison, 88 avalanches were observed during November of 1972, ten of which crossed the highway.

The minimal snowcover which accumulated during November continued to be a conspicuous component of the total snowcover throughout the winter. On north-facing slopes, especially those receiving no direct solar radiation during late November, the entire snowcover was composed of advanced temperature-gradient crystals. The influence of this weak basal layer on avalanche release was to become significant as the winter progressed. On south-facing slopes the thin snowcover was frequently warmed to the freezing point and then refrozen to form basal crust layers 15.0 to 25.0 cm in thickness. This occurred primarily during a warm period during the last few days of November when maximum temperatures reached +7.0°C.

December: During December, precipitation occurred on 15 days with total snowfall amounting to 174 cm with a water content of 131 mm. New snow density varied from an average value of 0.53 during the storm periods early in the month to a relatively high average value of 0.94 for the precipitation period which occurred during the last eight days of the month. Wind direction was predominately north and west. Between December 23 and 30, continuous high winds prevailed with 22 six-hour averages of greater than 10 m/sec and four, six-hour averages greater than 20 m/sec. The highest one-hour average, 35 m/sec, occurred on the 28th with a peak gust of 53 m/sec during this time period. Mean daily temperatures dropped from a maximum of 0.0°C on the 1st to a minimum of -19.0°C on the 31st. Additional meteorological data for the winter are presented in Table 2. The combination of steadily decreasing air temperatures and a shallow snowpack (average depth of 60 cm for the month) provided conditions necessary to produce the resulting structurally weak snowcover. Average rammsonde values remained below 2.0 kg at the Red Mountain study site and below 5.0 kg at representative slope sites, excluding the higher values of the basal crust layers associated with conditions described above in the November summary. Average density of the snowcover at the Red Mountain study site was .168 Mg/m^3, with the average value for slope study site and fracture line profiles being .192 Mg/m^3. Average temperature gradient at all points of investigation exceeded 0.15°C/cm.

In general, the relatively shallow snowpack of December possessed structural instability sufficient to produce numerous small and occasional medium sized avalanches. The first storm period of the month occurred between the 3rd and the 5th and contained 15 mm of precipitation.

TABLE 2

1973 - 1974 MONTHLY MET. SUMMARY

	Nov. (18-30 only)	Dec.	Jan.	Feb.	Mar.	Apr. (1-22 only)
Snowcover W.E. (mm) 1st day of Mo.	0	53	184	318	360	445
Number of days with Precipitation	12	15	17	12	15	14
Total Snowfall (cm)	76	174	178	63	87	199
Total Water (mm) Equivalent	53	131	134	37	85	162
New Snow (Mg/m^3) Density Range	.050-.087	.053-.094	.050-.120	.030-.090	.063-.103	.053-.100
Mean °C Monthly Temperature	-7.7	-8.7	-10.0	-10.0	-4.3	-5.3
Mean Daily °C Max Temperature	-6.3	-3.6	-5.0	-2.4	+2.1	+1.4
Mean Daily °C Min Temperature	-12.4	-13.7	-15.0	-15.9	-9.4	-12.2
Max Temperature °C	+7.5	+5.0	+8.5	+6.5	+9.0	+9.0
Min Temperature °C	-17.5	-23.0	-24.5	-24.5	-15.0	-18.0
Number of days with Temp > 0.0°C	4	9	9	11	22	11
Mean Monthly (m/sec) Wind Speed	6.7	8.3	6.2	4.5	8.4	6.1
Number of 6-hr averages > 10 m/sec	6	22	10	2	21	7
Number of 6-hr averages > 20 m/sec	0	4	0	0	4	0
Max One-(m/sec) hour average	19	35	22	15	26	23
Max. Gust (m/sec)	29	53	41	28	46	43

During this period, only one avalanche was recorded but this event is worthy of comment. The Cement Fill avalanche (010) is developing a record of releases apparently independent of other avalanche paths. The event on December 3 was an example of this pattern. By 1900 MST on the 2nd, 9 mm of the eventual total 15 mm of precipitation had occurred. At that time, wind direction changed from south to north and although the amount of new snow accumulated was small, the combination of the north wind, an optimum loading direction for the catchment basin of the Cement Fill Path, the additional precipitation, and winds averaging 8.5 m/sec were sufficient conditions to produce a size two hard slab avalanche which ran to mid-track and removed the fragile snowcover to the ground in some locations. Between the 5th and 12th, air temperatures increased with the average of the mean daily temperatures for the period being $-5.5^{o}C$, and avalanche hazard was determined minimal. Between the 12th and the 14th, 50.5 cm of snow fell with a water content of 22 mm. More than half of the total precipitation occurred during a 12-hour period between midnight and noon on the 14th. The accumulation of low density (0.030 - 0.050 Mg/m^3) snow accompanied by northwest winds averaging 5.0 m/sec produced extensive soft slab events on virtually every slope greater than 30° located above 3300 m in the immediate area of Red Mountain Pass. All events recorded occurred between midnight and noon on the 14th, incorporated only the new snow and were small in size (size one and two). Both loose and soft slab events were recorded, with the latter being associated with fracture lines of only 15 - 20 cm. The frequency of these events was greatest in the Red Mountain Pass area and diminished with increasing distance to the south with little or no activity south of the Brooklyns group. Only one event came in contact with the highway, the Blue Point avalanche path (097)* with a length of 6 m and a depth of 0.7 m. As is primarily the case with storms approaching from the north, Ironton Park received the greatest amount of precipitation, with less at Red Mountain Pass and continually decreasing amounts at sites farther south. A comparison of precipitation at Molas Divide, Red Mountain Pass and Ironton Park with avalanche events is presented in Figure 6.

On the 18th, 25 cm of snow containing 17.5 mm of water content was deposited with 13.5 mm of this total occurring within the ten-hour period between 0200 and 1200 MST. During this period, wind direction shifted from west, through northwest to north, producing a precipitation deposition pattern comparable to the previous storm. Again, maximum precipitation amounts were concentrated on Red Mountain Pass and those areas to the north, with the pass site receiving 21.8 mm, Ironton Park 17.5 mm, and Molas Divide to the south only 4.8 mm. During this storm period, however, a slightly different avalanche occurrence pattern developed. Activity was concentrated in the Uncompaghre Gorge, where 15 bank slides crossed the road. Two slides caught vehicles, one highway department snowplow and one private car, but no injuries or damages resulted. The physical characteristics of the new snow were similar to the previous storm

* Avalanche path number within Station 152: U.S. Highway 550, Coal Bank Hill to Ouray.

with low density (0.050 Mg/m^3) unrimed stellar crystals accumulating at moderate precipitation rates (1.0 - 1.7 mm/hr). When this type of new snow released as small soft slab avalanches, the necessary internal cohesion was apparently supplied by the simple mechanical interlocking of the arms and branches of the unrimed stellar crystals. Some unknown and perhaps subtle wind pattern characteristic, however, caused a maximum precipitation to occur at lower elevations, in this case within the Uncompaghre Gorge, while no avalanche activity was observed in the higher catchment basins.

Precipitation was recorded on each day during the period December 23 to January 2. Total snowfall was 92.0 cm with a water content of 89.0 mm. This period was made up of three separate storm episodes. The first, from the 23rd to the 26th, was of light intensity (average of daily maximum two-hour precipitation rates + 1.7 mm) with occasional breaks, and produced 25 cm of snow with 21.0 mm of water content. New snow density varied greatly from 0.030 Mg/m^3 at the storm start, to a maximum of 0.130 Mg/m^3. Winds were northerly (310 - 30°) with the mean speed of the six hour average periods being 15.5 m/sec and frequent one hour averages exceeding 20 m/sec. Initial crystal type was stellar with various states of modification resulting from both riming and wind effect, which caused the wide range of density values. As had been the pattern for the north storms occurring earlier in the month, precipitation was concentrated north of Red Mountain Pass with Ironton Park exceeding Red Mountain by 2.2 mm with 23.2 mm, and Silverton and Molas Divide recording 2.0 and 4.9 mm, respectively. New snow depths increased rapidly from the town of Ouray south into the Uncompaghre Gorge and at 0800 MST on the 24th, the NOAA weather station at Ouray had measured 58.0 cm of new snow with Red Mountain Pass having only received 3.0 cm at that time. Between 2400 MST on the 23rd and 0800 MST on the 24th, every well-defined bank slide within the Uncompaghre Gorge crossed the highway with depth at the centerline as great as 2.0 m. The length of road covered by these events was greatest where several bank slides released in close proximity, with the greatest length of 130 m accumulating in the region of the Mother Cline avalanche path (069). Investigations indicated that layers of higher density, heavily rimed and wind-drifted snow had released on weaker, low density layers of unrimed stellar crystals. No avalanche events were recorded outside the immediate area of the Uncompaghre Gorge during this period.

An additional 52.5 mm of water was measured in the 54.5 cm of snow which fell between the 27th and the 30th. Density values averaged 0.099 Mg/m^3 within the moderate to heavily rimed stellar crystals. Winds were from the west with six hour average speeds varying from 8.0 to 31.5 m.sec. Avalanche activity began at approximately 1000 MST on the 28th with Brooklyns I (023) and E (019) releasing as soft slabs and running to within 15 m of the highway. Another period of activity occurred between 1300 and 1500 MST with Brooklyns H (022) coming to within 6 m of the highway and with Blue Point (097), Blue Willow (096) and Willow Swamp Shoulder (095) reaching the highway.

Between 2030 and 2230 MST on the 29th, Brooklyns F (020), E (019) and B (016) reached the highway. These events occurred at a time when

32.0 mm of precipitation had accumulated at the Rainbow meteorological site, adjacent to the Brooklyns avalanche paths, and following six hours of wind speeds averaging 22.0 m/sec. Precipitation rate between 2200 and 2400 MST was 2.5 mm/hour. During the morning of the 30th, extensive soft slab activity occurred in the vicinity of Silverton. These releases were primarily small bank slides on north and east slopes and ran on or near the ground surface. They resulted from the loading of a snowcover underlain by mature temperature-gradient snow. The temperature gradients which generated this weak layer were the result of the shallow snowcover (approximately 50% of the 1972-1973 snowcover depth on this date) and the extreme temperature inversion condition common to the valley bottoms (2830 m) near Silverton. The same type of cycle was observed on the north side of Red Mountain Pass from below the Idarado Mine to the north end of Ironton Park (3200 - 2800 m). In addition, during the morning of the 30th between 0200 and 1200 MST, eight avalanches were recorded between Silverton and Red Mountain Pass with three events crossing the road. At 1330 MST, with visibility obscured by continuing precipitation, artillery control was directed towards the East Riverside avalanche path (064). Five rounds were fired; four produced no results at the highway level although avalanches may have been released which did not run full track and could not be observed due to very poor visibility. A fifth shot caused an avalanche to cross the highway with a depth of 2.0 m and a length of 60.0 m. The weather cleared on the 31st and continued control efforts produced six avalanches within the Muleshoe-Brooklyns groups, four of which reached the highway. These events generally incorporated low density soft slab snow (see Fracture Line Profile No 2) moving at high velocities, resulting in maximum run-out distances. In total, December produced 39 avalanches within the study area, 14 of which affected the highway.

<u>January</u>: During January, measurable precipitation occurred on 17 days and totaled 177.5 cm, containing 133.5 mm of water. The mean monthly wind speed was 6.2 m.sec with the most frequently recorded directions being south and west. No periods of prolonged high winds were recorded. The mean temperature for the month was -10.0°C with the mean daily maximum being -5.0°C and the mean daily minimum -15.0°C. The depth of the snowcover at Red Mountain Pass had increased to 139.0 cm on January 31st, with the maximum depth for the month of 166.0 cm being measured on the 21st. Snow strength as measured by the rammsonde increased slightly during the month from an average value on the 2nd of 1.9 kg to 8.2 kg on the 30th. Investigations of the shallow and structurally weak December snowcover indicated strength as an approximate function of depth. Beginning on January 2nd, however, a slightly more complex structure began to develop which was to be the dominant pattern for the remainder of the winter. On January 30th, this configuration was clearly evident: a stronger, mid-pack layer (average rammsonde value = 20.0 kg) between the depths of 30.0 cm and 90.0 cm, and bounded above by weaker, less dense new snow and below by a layer of fragile, coarse-grained temperature-gradient snow. Temperature-gradient crystals were first observed in a 10.0 cm layer at the ground surface on December 3rd. The density of this layer was 0.250 Mg/m^3.

By January 30th, this layer had expanded to a thickness of 30.0 cm and the density had increased to only 0.300 Mg/m^3, while layers above had already achieved densities as high as 0.362 Mg/m^3. This retarded rate of densification associated with the layer of temperature-gradient snow is apparent in Figures 7 and 8. Average temperature-gradient at the Red Mountain Pass site was 0.09°C/cm. Average density had increased to 0.237 Mg/m^3.

In general, snow structure on north-facing slopes began to develop in a manner similar to the pattern described above for the Red Mountain Pass study site, while south-facing slopes began to take on the characteristic structure observed during the previous winters: alternating layers of freeze-thaw crusts and fragile radiation-recrystallized snow. A more detailed description of the physical processes involved in the evolution of this type of snow structure is contained in Chapter 3 of the 1973 Interim Report and Chapter 3 of this report. The average density of the snowcover at slope sites was 0.232 Mg/m^3 and the mean temperature-gradient had been reduced to 0.070°C/cm.

The period of stormy weather which had begun on December 23 continued until January 12, with only two days, the 3rd and the 11th, not receiving measurable precipitation. Between the 1st and the 4th, 19.5 cm of snow containing 14.5 mm of water were recorded. While only one natural avalanche was observed during this period, this lack of activity was due only to insufficient loading of what was a highly unstable snowpack. This condition was better revealed when explosives were used to test the slope on which the north-facing study site is located. Initial use of explosives produced no results but when travel farther onto the slope produced pronounced settling beneath the observers' skis, two more charges were detonated, the third causing a size three soft slab to release. The slab was 100.0 cm thick and initially ran on a freeze-thaw crust lying above a 20.0 cm thick layer of depth hoar, but after running a short distance, incorporated the depth hoar layer and ran to the ground.

The storm period between the 5th and the 10th produced 84.0 cm of snow containing 50.0 mm of water. The most intense period of the storm occurred during the first day. On the 5th, between 1000 and 1400 MST, wind speeds averaged 20.0 m/sec from the south and between 0800 and 1400 MST, the precipitation rate averaged 2.2 mm/hour. The density of the new snow during this period averaged 0.085 Mg/m^3. Twelve avalanches were recorded during the afternoon of the 5th, with eight being size three or larger and with three crossing the highway. One of these events which occurred in the Brooklyns G (021) path at 1300 MST, blocked the road just prior to the arrival of a Colorado Highway Department snowplow traveling from Red Mountain Pass to Silverton. While the driver of the plow was in the process of removing the debris from the highway, the same avalanche ran again partially burying the plow. At this point, the snowplow could not move under its own power and while the driver was waiting in the cab for assistance, the vehicle was hit a third time. Throughout the incident, the driver remained uninjured and the snowplow incurred only moderate damage.

Only 3.0 mm of precipitation fell on the 6th and occasional periods of clear skies allowed the Colorado Highway Department to undertake control efforts. Seven avalanches were released with three crossing the highway. Control continued on the 7th and 8th producing six avalanches, three of which crossed the road. Precipitation increased again during the 8th and 9th, with 26.0 mm of precipitation occurring during the two days. Ten soft slab, size two and three avalanches were recorded for the period, with three events crossing the highway. Two of these occurrences were large bank slides at the East (149) and West (150) Lime Creek sites. The combined debris averaged 2.0 m in depth at the centerline of the highway and totaled 240.0 m in length. One private vehicle was buried with no injuries to the occupant. As the storm period was ending, control was again initiated on the 10th and 11th producing nine avalanches, five of which crossed the highway. A majority of the avalanches occurring during this six day period incorporated large amounts of snow, releasing the full snowcover when the basal depth hoar layer became incorporated in the moving avalanche. The result was large amounts of snow in the highway with closures totaling approximately 12 hours for this period. The period between the 3rd and the 11th produced 85% of the avalanches occurring during the month.

On January 15, the mean daily temperature was -2.0°C with a maximum for the day of +8.5°C. Three size two, wet loose avalanches occurred along with numerous wet sluffs as the surface layers of the recent accumulation of new snow were warmed to the freezing point.

Between the 17th and the 21st, 43.0 mm of precipitation were recorded. During the 17th and 18th, 18.0 cm of snow accumulated having an average density of 0.100 Mg/m^3. Five size two avalanches were observed on the 18th. These events appeared to include the new snow only and none came in contact with the highway.

Forty-two cm of new snow fell during the 20th and 21st with an average density of 0.067 Mg/m^3. Wind speeds during these two precipitation episodes averaged less than 5.0 m/sec. Avalanche activity primarily amounted to extensive sluffing over a broad area, both above and below timberline. Only the short, steeper paths such as Blue Point (097) and Rockwall (101) reached the highway. This was the last period of avalanche activity during the month, with generally fair weather and only 6.0 mm of precipitation occurring during the remaining ten days. In total, 96 avalanches were observed during the month, with 23 affecting the highway.

February: During February, total snowfall amounted to only 63.0 cm containing 42.0 mm of water. New snow density averaged 0.050 Mg/m^3. Wind speeds were minimal with only two periods with six-hour averages exceeding 10.0 m/sec. These conditions were not conducive to avalanche formation, with only 29 events being observed. Six avalanches affected the highway and an additional 14 small bank slides reached the highway in the Uncompaghre Gorge. The stratigraphic pattern of the snowcover at the Red Mountain Pass site remained the same as that described in the January summary. No significant changes occurred in terms of strength, structure or density during the month, partially as a result of the minimal new snow accumulation. This same condition prevailed on the release zone test slopes. Three precipitation periods occurred during the month, with only the last one being significant. On the first and second of the month, 18.5 cm of snow fell containing 8.0 mm of water. Low density (0.040 Mg/m^3), unrimed stellar crystals made up the new snow and only infrequent small surface sluffs occurred within this new snow layer. On the 13th, 9.5 cm of snow fell containing 7.0 mm of water and produced no observed avalanche activity. The only significant storm period occurred between the 17th and the 21st, with the majority of the precipitation occurring on the 19th and 20th. Total snowfall for the period was 32.5 cm with 20.1 mm of water.

Winds were from the north with speeds averaging from 5.0 to 10.0 m/sec. New-snow crystal type varied widely during the storm but was dominated by unrimed to lightly rimed stellars with an average density of 0.050 Mg/m^3. These conditions provided for widespread soft slab releases, the majority of which were size two. As had frequently been the case during the winter, precipitation under the influence of the prevailing north wind was concentrated in the area north of Red Mountain Pass. While occasional soft slab activity was recorded south of the pass, it was only on the north side that avalanches as well as bank slides reached the highway.

Twenty-one events reached or crossed the highway during this period, with the East Riverside (064) crossing the road twice, once as a natural event during the morning of the 20th and once as an artificial at 1300 MST on the same day. On the 22nd, control efforts were directed towards the East and West Riverside (064,074) but apparently all unstable new snow on the East Riverside had released previously and the older snow layers were stable in both avalanche tracks as no releases resulted.

March: New snow depth during the month of March did not increase significantly over February. The 87.5 cm of new snow which did fall, however, possessed an average density of 0.098 Mg/m^3, nearly twice that of February, and contained 85.0 mm of water. It was the temperature regime, however, which exerted the greatest influence on the snowcover during the month, as air temperatures began to increase on the 14th and reached a positive mean daily value of +2.5°C on the 17th. Snow temperatures responded accordingly with the zero degree centigrade isotherm moving to a height of 105.0 cm above the ground during this period (Figure 11).

During the first half of the month, midwinter conditions prevailed. Between the first and the 4th, 11.0 mm of precipitation were recorded. During this period, wind speeds averaged greater than 10.0 m/sec and between 1200 MST on the 2nd and 0600 MST on the 3rd, the average wind speed consistantly exceeded 20.0 m/sec. In apparent response to slope-loading caused by the significant snow transport of the south-southwest wind, the East Riverside (064) released at 0800 MST (time determined by trip-wire mechanism). This avalanche ran as a HS-N-3-0 and covered the highway to a maximum depth of 4.0 m for a distance of 20.0 m. The nearby Slippery Jim avalanche (061) released at approximately the same time, also as a HS-N-3-0, but did not reach the road. Fracture line

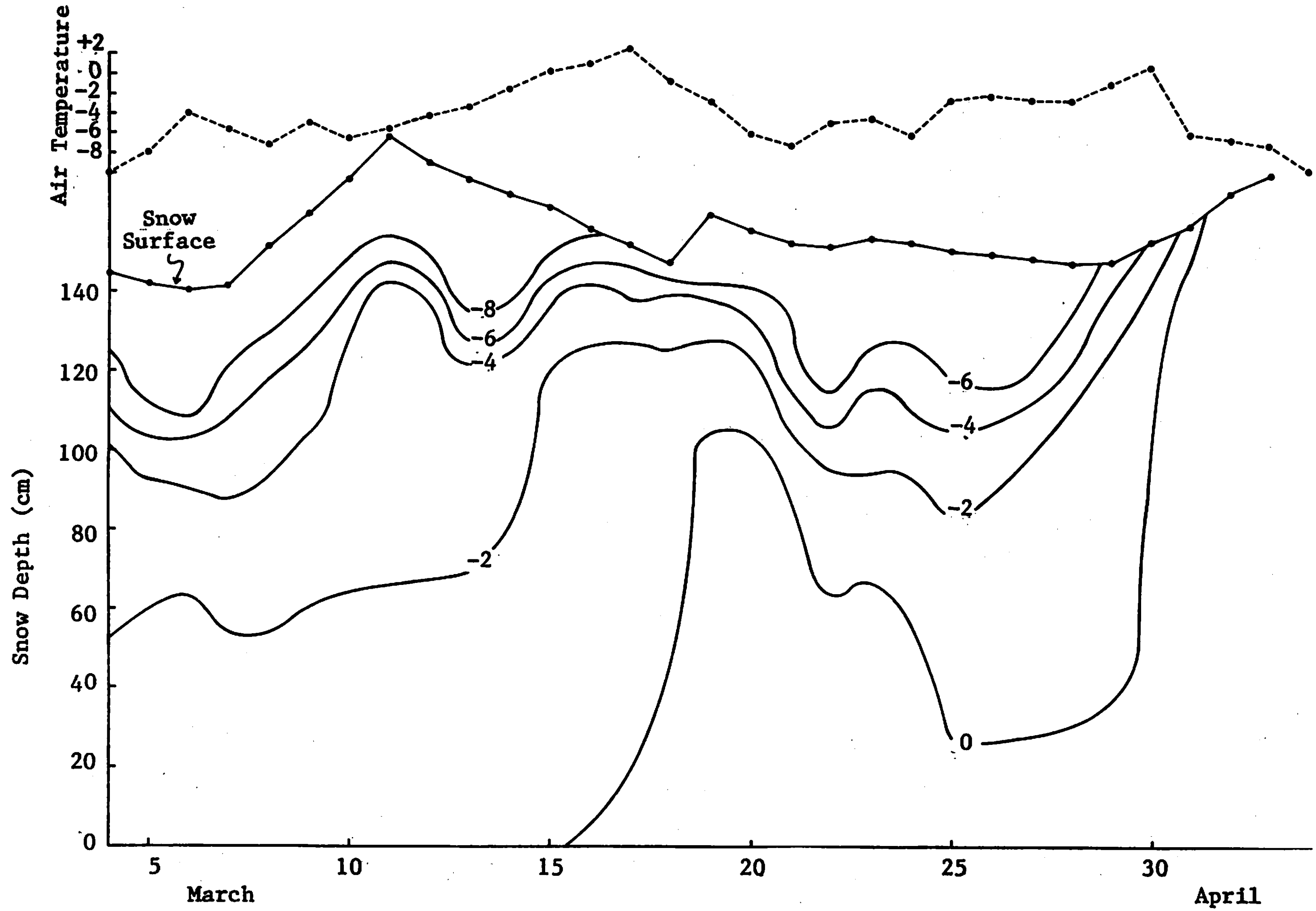


Figure 11. A comparison of snowpack temperatures (°C) and mean daily air temperatures (°C) at the Red Mountain Pass snow study site during March, 1974.

data available from both of these events indicate that both were climax type, incorporating numerous layers of older snow, and that the new snow which had been deposited on these slopes during the storm period prior to release comprised less than five percent of the slab. Shear strength within the subsurface layers was apparently insufficient to support even this small amount of additional load. In the case of the Slippery Jim, snow strength as measured by the rammsonde varied from an average of 50.0 kg within the slab to 4.0 kg at the plane of shear failure. This layer of weak temperature-gradient snow was located just above a layer of stronger (by a factor of ten), more consolidated snow which had been the surface snow layer during a period of unseasonably warm weather (maximum temperatures exceeding +6.0°C) in mid-January. Subsequent precipitation and lower temperatures were apparently responsible for the eventual formation of the weaker, temperature-gradient layer within which these avalanches released. As this period of high wind speeds continued into the 3rd of March, it was observed at Red Mountain Pass that advanced temperature-gradient snow had become incorporated into the blowing snow, indicating apparent wind scouring of the south-facing snowpack to significant depths. During the afternoon of the 3rd, the north-facing slope of Snowslide Gulch (132) ran as a SS-N-2-0. This event was also an apparent result of wind loading as precipitation at this time was insignificant (4.0 mm in the previous 48 hours).

The most significant precipitation period of the month began during the early morning hours of the 7th and continued through the 10th. Total precipitation for the period amounted to 43.5 mm of water, with 55.0 cm of snow with an average density of 0.092 Mg/m^3. At 1300 MST on the 7th, the Blue Point (097) released as a SS-N-3-0 and crossed the highway with a maximum depth of 1.5 m over a distance of 30.0 m. Up to this time, only 10.0 mm of precipitation had been recorded at a rate of 1.2 mm/hour. Later the same afternoon, two avalanches of the Brooklyns group released as soft slabs and ran to within 30 m of the highway. Precipitation continued to be light and intermittant until 1400 MST on the 9th, at which time a precipitation rate of 3.2 mm/hour was recorded for two hours. Avalanche activity during this period was restricted to small sluffs within the new snow. During the 10th, nine soft slab releases were recorded, one of which, the Willow Swamp Shoulder (095), covered the highway for a distance of 25.0 m with a maximum depth of 1.3 m. Five additional natural releases, size two and smaller, were observed on the 11th. Control efforts on the 11th and 12th were directed towards 16 paths, 14 of which released. The majority of these artificial releases were small (size two or smaller), primarily soft slabs incorporating only the surface layers of new snow. Of these, only the Blue Point (097) crossed the road. The exception to this pattern was the East Riverside (064). A total of 13 rounds were fired with both the 8th and 9th shot producing SS-AA-3-0 avalanches which ran full track and covered the highway for a distance of 30.0 m with a maximum depth of 4.0 m. Also on the 12th, the wet avalanche cycle began on the southeast-facing slopes of Engineer Mountain (elevation 3300 m). Engineer A (159) released as a WL-N-2-0 and Engineer B (160) as a WS-N-3-G. Two small, loose events occurred in the Brooklyns group which presumably incorporated wet surface snow as the maximum temperature for the day reached +5.5°C. In addition, the north-facing portion of the catchment basin of Champion (144) responded to control as a loose, size three avalanche which crossed the highway for a distance of 10.0 m with a maximum depth of 1.0 m. Control of the adjacent Jeanie Parker (140 and 141) and Peacock (142) produced no releases. Mean daily temperatures increased from -4.3°C on the 12th to +2.5°C on the 17th. On the 15th, a mean daily temperature of above freezing (+0.5°C) was recorded for the first time and 13 size two and three, wet loose avalanches were observed. Ten of these events ran only to mid-track. Of the remaining three, the East Riverside (064) and Brooklyn D (018) ran to within 5.0 m of the highway and the Champion (144) crossed the highway.

On the 16th, 30 wet avalanches were observed, three of which were slab type. The majority were size two events which frequently removed the entire snowcover and ran on the ground surface. Seven events reached the highway. Both the Champion (144) and the Blue Willow (096) released twice between 1200 MST and 1330 MST, crossing the road each time. From the 17th to the 19th, six more wet loose events were recorded, three of which crossed the highway. Beginning on the 19th, mean daily temperatures decreased and the cycle of wet avalanches ended. The mean daily temperature did not again rise above freezing until the 30th, at which time, two size two, wet loose avalanches were observed on north-facing slopes. Eighteen mm of precipitation were recorded on the 31st but no avalanches were observed. On March 31, the entire snowpack at the Red Mountain Pass study site became isothermal. As the snowcover slowly warmed during the month, the internal structure became more consolidated and the weak layers of temperature-gradient snow so frequently associated with mid-winter avalanche release conditions began to diminish. Releases incorporating old snow layers were generally associated with the cohesionless structure of the isothermal snow.

<u>April</u>: During April, 199.0 cm of new snow were measured having a water content of 161.8 mm. This was the greatest amount of precipitation to occur during any month of the winter. Although total precipitation was significant, three storms with greater than 30.0 mm of precipitation occurred, and precipitation rates were frequently high (2.2 - 3.0 mm/hour), few avalanches were observed. This condition was primarily due to the fact that the new snow was accumulating on an old snow base which possessed a relatively strong and homogeneous structure. By the first of April, the snowcover throughout the study area, except perhaps for some portions of the highest, north-facing catchment basins, had become isothermal. However, temperatures decreased during the first two weeks of April, with the average of mean daily temperatures being -6.5°C. The average mean daily temperature for the last two weeks of March had been -2.3°C. This drop in temperature provided increased strength within the snowcover through the refreezing of a significant portion of the liquid water produced during the warmer periods in mid-March. Since adequate bonding was accomplished between new and old-snow layers and no critical weak layers existed within the old snow, nearly all of the avalanches occurring in April released as loose or soft slab events within the structure of the new snow.

During the period April 1, through 4, 46.0 mm of precipitation occurred with over half of this amount occurring on the 2nd. During the morning of the 2nd, a general sluff cycle was observed in the Red Mountain Pass area. Beginning at 1000 MST and for a period continuing until mid-day on April 4, nine soft slab and two loose avalanches were observed, of which ten were size two, and one a size three event. Most of the releases ran only to mid-track. The Eagle (104) ran to within 40.0 m of the highway and the East Riverside Left (065) and East Riverside Right (063) reached the highway. The Blue Point (097) reached the highway twice during this period. Clear skies and increasing temperatures (maximum +6.5°C) on the 5th produced several small (size two) wet loose releases within the new snow. Between April 10 and 12, 33.0 mm of additional precipitation were recorded. This new snow accumulated on an old snow surface composed of a freeze-thaw crust with a thickness of 4.0 cm. This condition was the product of the high temperatures of the 9th when a maximum temperature of +7.5°C was recorded. The strength of this freeze-thaw crust, combined with an apparent absence of weak layers within the new snow, resulted in the fact that no avalanche events were observed during this period. Skies cleared on the 15th and by the 16th the maximum temperature reached +7.5°C, causing eight, wet loose, size two events to run to mid-track. Thirty-one millimeters of precipitation were recorded on the 19th and 20th. With old snow conditions comparable to those described in the previous storm, avalanche activity was restricted to a general sluff cycle releasing within the new snow layer. Those avalanches which did reach the highway were associated with short, steep paths such as the Blue Point (097), the Mother Cline (069) and bank slides in the vicinity of the East Riverside (064).

At 1200 MST on the 21st, the air temperature exceeded 0.0°C and a general cycle of wet loose, size one and two releases occurred on all but north-facing slopes. These events were restricted to the new snow and in their farthest extent reached mid-track. The only exception to this was the Eagle (104) which released as a size three, wet loose avalanche and crossed the highway over a distance of 10 m with a maximum depth of 2 m. No additional significant avalanche events occurred following this date within the study area.

CHAPTER 3: PHYSICAL CAUSES OF AVALANCHES IN THE SAN JUAN MOUNTAINS

Edward R. LaChapelle

In the Second Annual Report of the San Juan Avalanche Project (Ives, Harrison and Armstrong, 1973), Chapter Three: Physical Causes of Avalanches in the San Juan Mountains (LaChapelle) summarized the findings to date concerning the physical causes of avalanching in the research area.* Briefly, a predominantly radiation snow climate was identified which led to widespread temperature-gradient metamorphism of the snow cover. This metamorphism in turn was responsible for a predominantly low mechanical strength and strong stratigraphic differentiation of the snow on all exposures. The consequent pattern of avalanche formation largely favored soft slab, climax avalanches which for the most part were load-induced by precipitation events. A rapid rise of air and snow temperatures in the spring led to a pronounced wet snow avalanche cycle.

Data acquired during the third winter of the Project confirm and amplify these findings. No significant change is made in the basic conclusions and the reader is referred to detailed development of these conclusions in the Second Annual Report. The present summary will review the processes in the snowcover observed during 1973/74 and relate these to the previously identified physical causes of avalanches.

The character of the snow and avalanches in 1973/74 are compared with those for the previous winter in Table 3. In Table 4, a more detailed analysis is tabulated for the snow layer types found in the avalanche release zones during the third winter (compare with Table 3 in the Second Annual Report).

Table 3 shows that the basic avalanche pattern was very similar for the two winters: soft slab, climax avalanches were very much in the majority both years. The winter of 1973/74 experienced a different pattern of snow accumulation than the previous one, leading to snow of greater mechanical strength, a greater average slab avalanche thickness, and a moderate reduction of the total percentage of snow layers in which temperature-gradient metamorphism appears during the latter part of the winter. In 1972/73, the percentage of layers in which this phenomenon prevailed declines after the 1st of March. In 1973/74 the reverse was true, presumably reflecting effects of a prolonged period of clear weather and highly intermittent light snowfalls from early January until early March. (See Chapter 2 of the present report for details of winter weather and snow conditions.) Snowfalls of late December consolidated into a relatively strong mid-pack snow layer which generally improved the load-bearing capacity of the snowcover over the very weak capacity of the previous winter and which in some instances became involved as slab avalanches later in the season (Appendix 1, Fracture Line Profiles 7, 8, 11.)

Sixteen fracture line profiles were collected during winter of 1973/74 (Appendix 1), continuing the examination of snow structure at the point

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* This Chapter has been reproduced for the current report and is found in Appendix 4.

TABLE 3

COMPARISON OF SNOW AND AVALANCHE CHARACTERISTICS FOR WINTERS OF 1972/73 AND 1973/74

	1972/73	1973/74
Percent of fracture line profiles exhibiting soft or wet slabs	94%	81
Percent of fracture line profiles exhibiting climax characteristics	82%	88
Percent of snow layers in all release zone profiles to 1 March exhibiting TG metamorphism	71%	48
Percent of snow layers in all release zone profiles after 1 March exhibiting TG metamorphism	55%	60
Range of fracture line profile slab thickness, centimeters	19-122	32-155
Mean fracture line profile slab thickness, centimeters	60	98
Mean fracture line profile slab ram resistance, kilograms	3.3	8.7

TABLE 4. DISTRIBUTION OF SNOW TYPES BY LAYER THICKNESS
IN RELEASE ZONE PITS FOR WINTER OF 1973-1974

Total Layer Thickness (cm)	Λ	□	•○	+λ⬖	Complete Pit
To end Feb.	577	852	714	710	2853
March	370	442	304	181	1297
Winter	947	1294	1018	891	4150
Percent					
to end Feb.	20	30	25	25	100 (23 pits)
March	29	34	23	14	100 (7 pits)
Winter	23	31	25	21	100 (30 pits)

Temperature-Gradient Snow		Advanced Equi-Temperature	New and Partially
Advanced	Partial	Metamorphism	Metamorphosed Snow
Λ	□	• ○	+ λ ⬖

of avalanche release in the same fashion as in the previous winters. When measurements are made in the field, particular attention is paid to the character of the slab sliding surface, for these factors are critical to avalanche release, particularly in the case of climax avalanches. The pattern of sliding surfaces exhibited by the 1973/74 profiles continues that noted in the previous years: snow crusts, often very thin and fragile, are the principal sliding surface. Such crusts were clearly identified in 10 of the 16 profiles. Although old sun crusts are common, others of more obscure origin are also found. Only one sliding surface (Profile 14) is identified as a wind crust. In some cases, these sliding surfaces are very fragile, especially those occurring at the top of a depth hoar layer. Some crusts obviously originate from transient periods of melt (e.g., sun crusts), but others on north exposures appear to stem from more complex processes of metamorphism and mass transfer within a snow layer. On all exposures, persistent steep temperature-gradients characteristic of the San Juan snow climate tend to disintegrate crusts with time. This can lead to part or all of the crust serving eventually as a lubricating layer for slab release. An example of partial disintegration where an old crust contributes both the sliding surface and the lubrication is found in Profile 8.

Clearly-defined lubricating layers are less common in the profiles. In many cases poor adhesion between the slab layer and the sliding surface appears to be the cause of avalanching, rather than the presence of a separate layer of snow crystals with low shear strength. Local temperature-gradient weathering of the exposed sliding surface prior to the next snowfall which begins to build the slab is the most likely cause of this poor adhesion.

Avalanche studies throughout the world have identified the most favored angles of slope for slab release (U.S. Forest Service Avalanche Handbook, revised edition -- in press). Although large slab avalanches may fall from slopes ranging from 25° to 55° at the fracture line, there is a very pronounced peak of avalanche occurrence between 35° and 40°. The San Juan avalanche record conforms to this pattern. Of the 30 fracture line profiles recorded for the two winters 1972/73 and 1973/74 for which slope angles are known, 20 fell between 36° and 42°. Slope angles ranged from 25° to 48°, with 3 profiles on slopes 25-30°, 3 for 31-35° and 4 for 43-48°. The distribution of slab avalanche frequency with slope angle appears to be independent of climate or avalanche type. It is probably determined by the basic mechanical stress relations leading to slab avalanche formation.

The densification of snow with time is a basic characteristic of the snowcover which bears directly on avalanche formation through effects on both snow strength and slab weight. This characteristic is notably dependent on climate and on the type of metamorphism which takes place (LaChapelle, 1961). It is useful to examine the place of densification of San Juan snow in the framework of this climate dependence. Figure 12 compares snow layer densification derived from the settlement guage data at Red Mountain Pass study plot with densification curves from other climate zones. As with Berthoud Pass farther to the north in

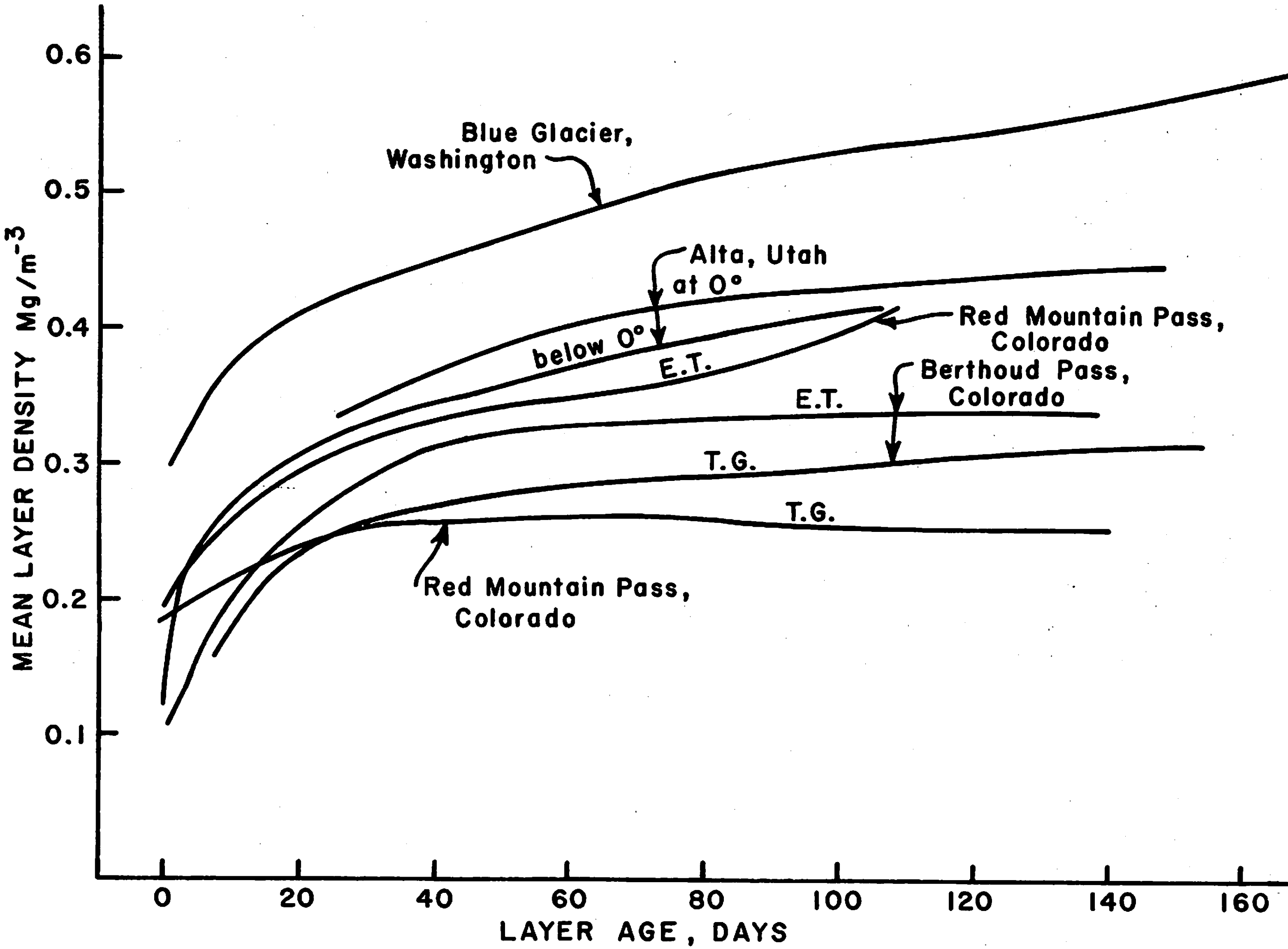


Figure 12. A comparison of snow densification in different climates. Length of records: Blue Glacier - 1 year, Alta - 5 years, Berthoud Pass - 3 years, Red Mountain Pass - 1 year. Curves are average value of several to many snow layers.

the Colorado Rockies, there are two distinct modes of densification depending on whether equi-temperature or temperature-gradient metamorphism predominates in a given snow layer. TG metamorphism tends to inhibit severely the densification process once the initial changes from new snow have taken place; this effect is obvious in both the San Juan Mountains and the Colorado Front Range. Notably different, however, are the paths of ET metamorphism at these same two sites. That for Red Mountain Pass is very similar to the densification process at Alta, Utah, where a substantially heavier snowfall regime prevails. (The upward swing of the ET densification curve for Red Mountain Pass after 70 days reflects the onset of spring melt. Data for dry and wet snow conditions are not separated as they are for Alta.) The densification patterns for ET snow at Alta and Red Mountain Pass appear to be more comparable in terms of new snow type, amounts of snowfall and prevailing mid-pack snow temperatures than are either of these patterns with that of the Colorado Front Range. Total water content of the snowcover also plays a role (see discussion below regarding effects of loading on snow strength). The shape of the Berthoud Pass ET curve in Figure 12 also suggests that a significant amount of TG metamorphism may in fact also have been at work in these observed layers.

Snowcover data from the first two years of the San Juan Project revealed a persistent pattern of lower average mechanical strength of the snowcover in avalanche release zones than in the level study plots. Systematic data analysis suggested that this difference was in large part due to variations in compressive metamorphism of each snow layer under superimposed snow loads between level ground and the inclined avalanche slopes. The component of body force acting perpendicular to the ground - and this component is the one which provides the compressive loading - declines with the cosine of slope angle for a given snow layer thickness. Comparison of mean snowcover ram resistance with total loading perpendicular to the ground for the 1972/73 data showed a consistent correlation between these two parameters. This comparison was plotted in Figure 15 of the Second Annual Report, showing remarkably small scatter and a consistent relationship for both study plot and release zone data. The same comparison is made for 1973/74 data in Figure 13. Again, a consistent relationship is obvious, although in this latter case a somewhat larger degree of scatter is observed. Figure 14 combines these data for the two winters. The overall results confirm the previous conclusion, which is sufficiently important to be restated here: the distribution of snow depths commonly found in the San Juan research area is such that compressive load values associated with higher snow strengths appear early in the winter on level ground but do not appear until much later in the winter on slopes above 30 degrees which are characteristic of avalanche release zones.

The regular sequence of snow profiles from release zone sites on Carbon Mountain near Red Mountain Pass provide the basis for plotting time profiles of snow cover evolution on slopes of different compass orientations. That for 1973/74 from the South Carbon site, displayed

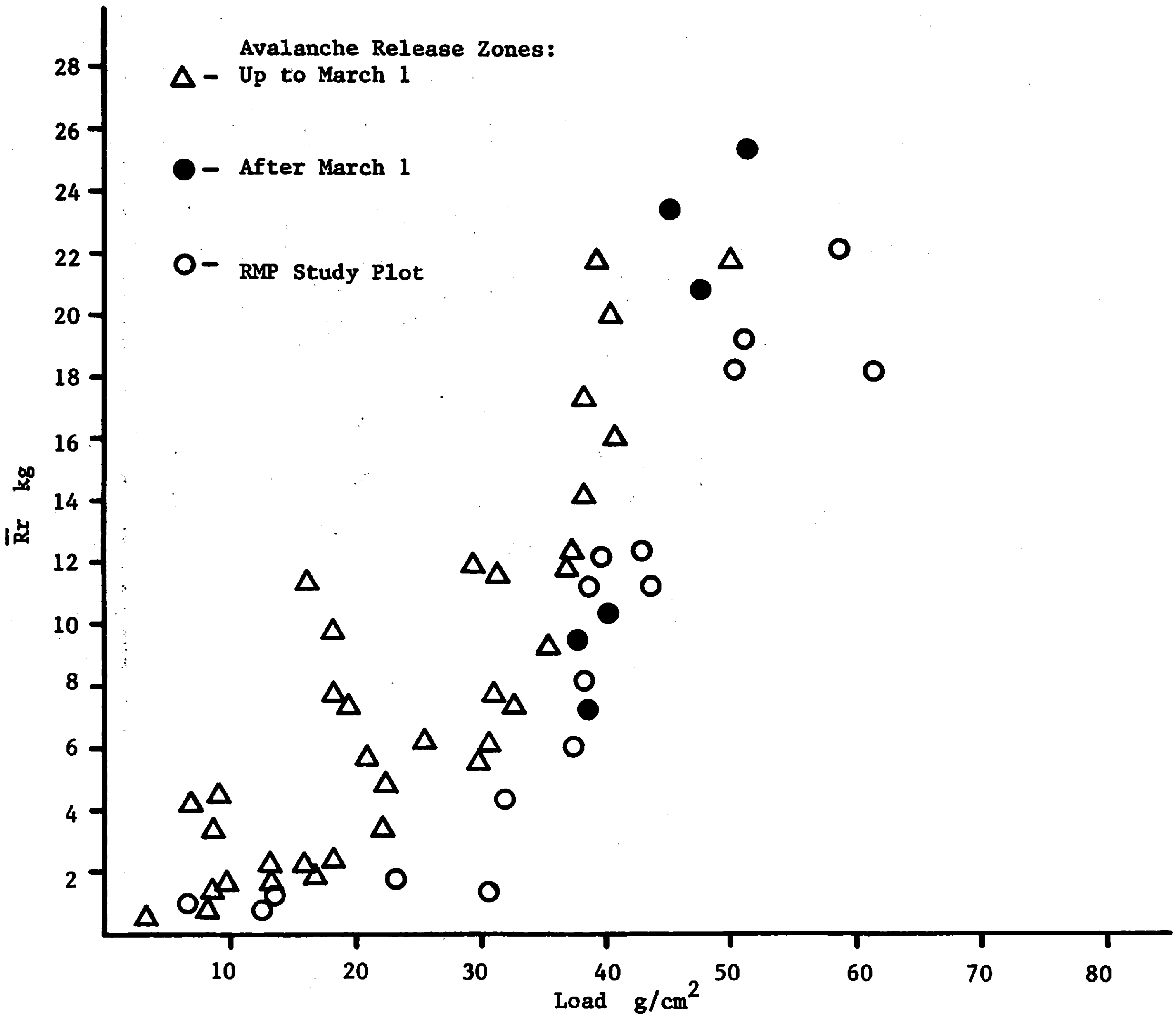


Figure 13. A plot of mean snow cover ram resistance as a function of total compressive loading perpendicular to the ground surface at the base of the snowcover for 41 release zone profiles and 16 profiles from the Red Mountain Pass snow study site for the winter of 1973-1974.

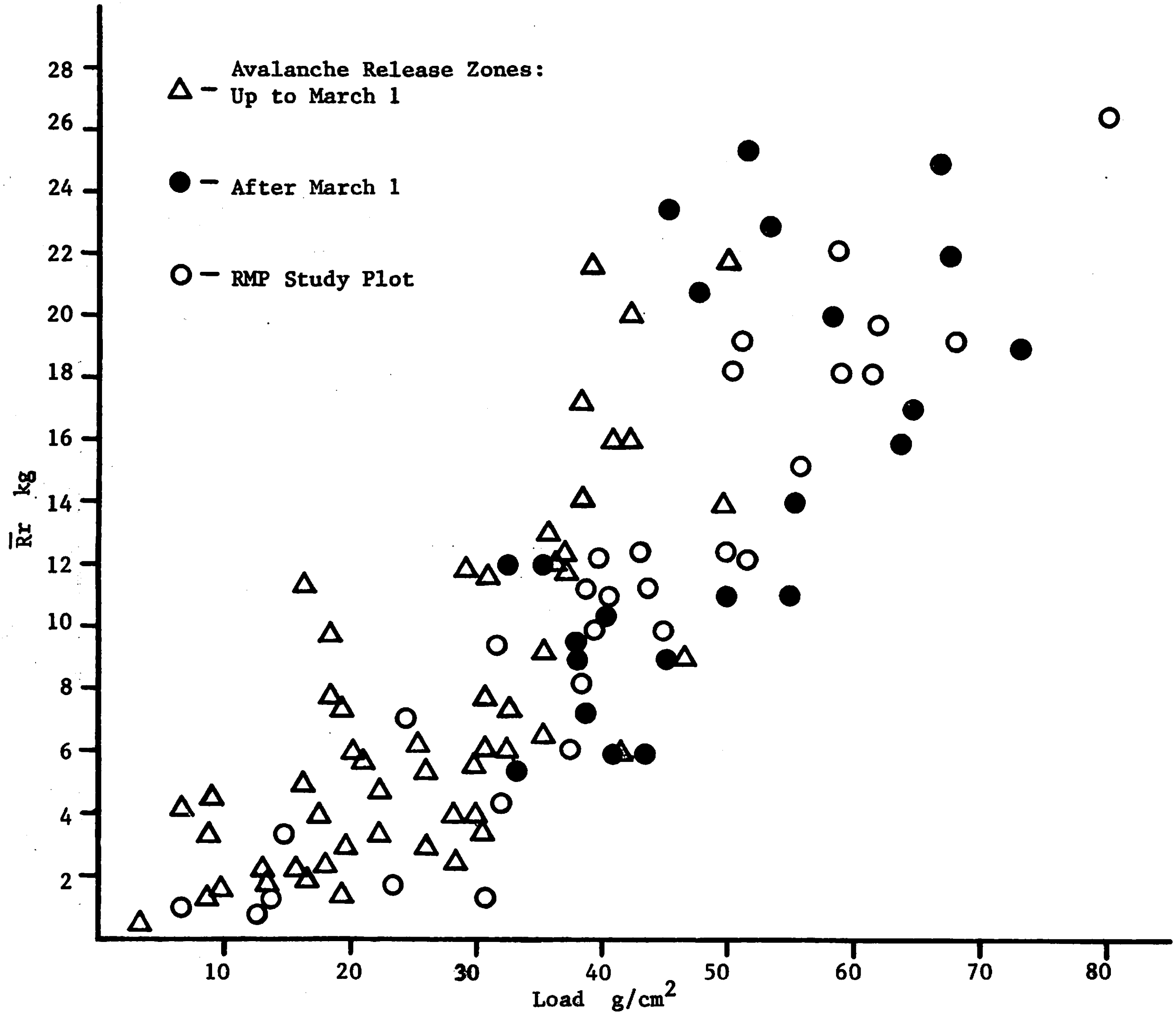


Figure 14. Mean snowcover ram resistance as a function of total compressive load perpendicular to the ground surface. The data from Figure 14 are combined with those from 1972-1973 for a total of 106 data points.

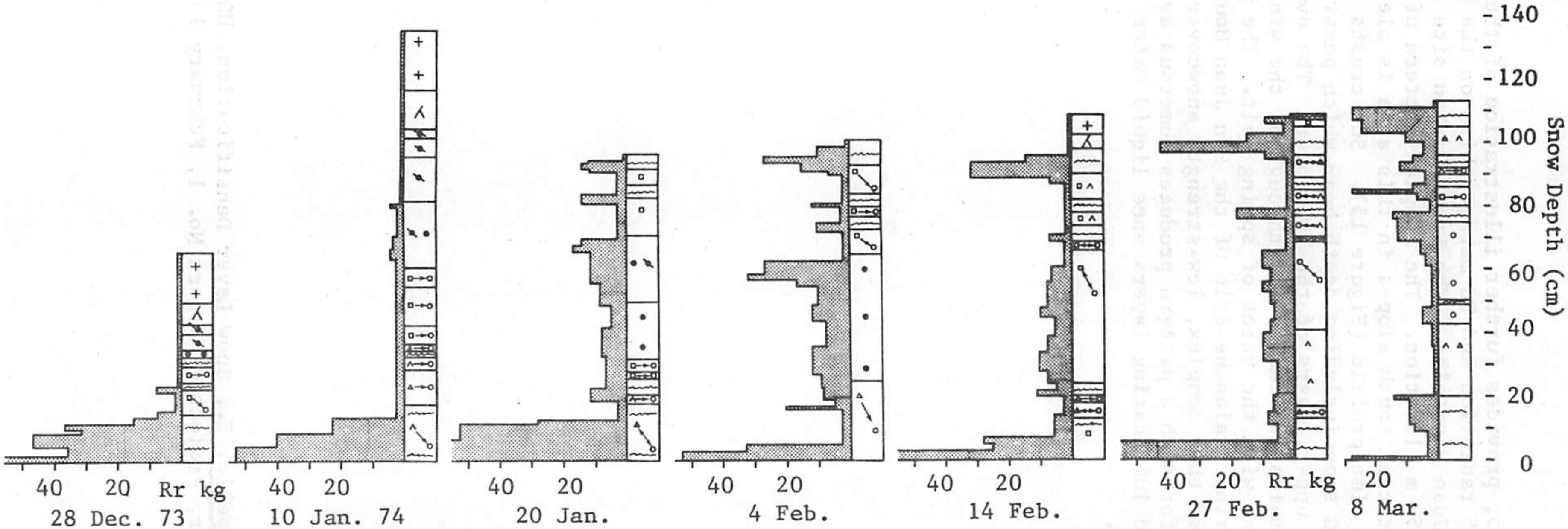


Figure 15. Time profile of winter snowcover evolution at the South Carbon avalanche release zone site showing snow crystal metamorphism and variations in ram resistance. This is a south-facing slope. A key describing snow crystal symbols is found in Appendix 1.

in Figure 15, provides further illustration of the previously-discussed influence of radiation and TG metamorphism on the basic snow climate of the San Juan Mountains. The South Carbon site is a south-facing slope at 3450 m elevation. The complex pattern of snow stratigraphy characteristic of south slopes in this area is clearly exhibited by the 1973/74 time profile (Figure 15). Sun crusts alternate with layers of TG snow including depth hoar which persists between crusts even in the upper layers of the snowcover. The overall snowcover strength remains remarkably low throughout the winter and suffers a sharp decline with the onset of spring melt. The well-developed and vigorous spring avalanche cyle of the San Juan Mountains stems directly from this complex, low-strength snowcover pattern on south exposures, for such a pattern produces numerous avalanche sliding surfaces and lubricating layers once liquid water is introduced by spring melt.

Ref: LaChapelle, E., Snow Layer Densification, USFS Alta Avalanche Study Center, Project F, Report No. 1, February 1961.

CHAPTER 4: AVALANCHE FORECASTING

Edward R. LaChapelle

The original proposal for the San Juan Avalanche Project envisioned two parallel lines of attack on developing a methodology for forecasting avalanches in the San Juan Mountains. One of these was an operational forecasting program initially based on established forecasting methods to be upgraded continually on the basis of experience. The other was acquisition of sufficient snow, weather and avalanche data to allow a statistical analysis of relations between avalanche occurrence and contributing snow and weather events. Supporting these two approaches would be an investigation of snowcover structure and the physical causes of avalanches as determined by after-the-fact investigation.

For the past three years the research program has been carried out essentially as it was designed. The statistical analysis has reached fruition at the end of the third year and is reported separately in Chapter 6. This present Chapter summarizes the results of the operational forecasting experience.

During the first winter of the Project, practical experience with the area was being developed by the Project staff. Forecasting and evaluation of avalanche hazard were limited to an informal basis. During the second and third winters, a formal forecasting program was established. Daily evaluations and forecasts were prepared and then were evaluated 24 hours later for accuracy. The method of compiling forecasts and the summary of their evaluations for the second winter have been discussed briefly in the Second Interim Report (September, 1973), Chapter 4, pp. 32-35. The same method of compiling forecasts was continued the third winter. Results from the third winter will now be given and the significance analyzed in more detail.

Briefly recapitulating, the avalanche forecast each day for the coming 24 hours was assigned an index number from I to V according to the anticipated degree of snow instability. The degree of instability characterized by each index number is given in Table 5. At the end of each 24-hour period (nominally from 0900 to 0900 each day) the actual degree of instability which was observed during the peiod was described by the same index numbers. This constituted the evaluation. Because the forecasting duty was rotated each day among the Project staff (three forecasters the second winter, four the third), the evaluation of the previous day's forecast was done by a different person than the forecaster and a degree of objectivity was preserved. This indexing method described here is a simple formalization for the results of conventional avalanche forecasting procedures which combine empirical experience with an analysis of contributory snow and weather factors. Other observers in other areas might well choose a different scale of index numbers or define them differently, but the basic methodology would be essentially the same. To this extent, the San Juan Avalanche Project has simple applied standard, developed practice in avalanche forecasting to a specific mountain area, then sought to maximize its accuracy on the basis of informed experience.

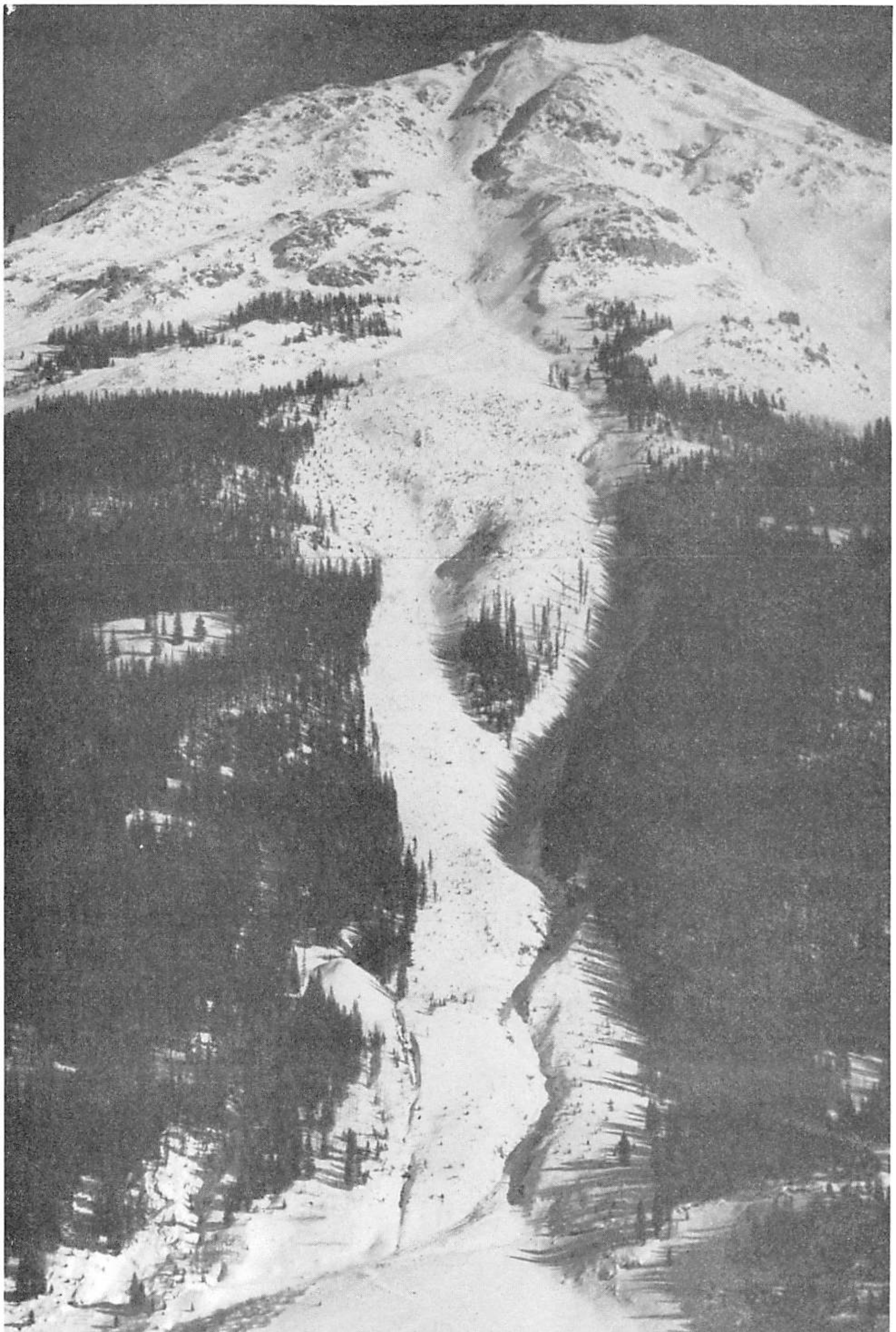
TABLE 5. NUMERICAL STABILITY INDEX

I.	Highly unstable:	More than 50% of slides that frequently run full track may be expected to run naturally. The remainder of all slides would react to control or run partially.
II.	Unstable:	Ten percent of slides that frequently run full track would run naturally. Most of the remainder would react to control or run partially.
III.	Transitional A:	Rare natural occurrence. Some slides would react to control depending on history or location. Index useful after a period of instability or during storm genesis.
IV.	Transitional B:	Some pockets of instability remaining or building in the absence of, or during insignificant precipitation.
V.	Stable:	Natural occurrence absent. Release only under extreme artificial conditions.

TABLE 6. AVALANCHE PATHS CONSTITUTING MAJOR

HAZARD TO U.S. HIGHWAY 550 BY GROUP

Ledge:	3 indistinct small paths
Muleshoe:	5 large paths
Brooklyns:	19 medium size paths
Champions:	4 medium size paths
Cement Fill:	1 path; complex starting zones
East Riverside:	1 path; complex starting zones



Idaho Gulch avalanche track (153-004), located on the northwest-facing slope of Kendall Mountain, has a vertical fall of 1050 meters and its runout extends into the town limits of Silverton. On December 27, 1971, a natural hard slab size 5 avalanche ran to the bottom of the track and crossed the Animas River. This avalanche is historically known to run several hundred meters beyond the confines of the gulch onto the flat land in the foreground. Just before the photograph was taken an avalanche had run down the lower half of the track to deposit the small triangle of snow debris at the apex of the alluvial fan.

Photograph by Jack D. Ives

Additionally, beginning in mid-winter of 1972/73 and for the full winter of 1973/74, an attempt has been made to prepare highly specific forecasts for certain groups of avalanche paths which constitute the major hazard to U.S. Highway 550 in the research area. Each of these groups is geographically limited in extent and consists of paths with similar characteristics and behavior. These paths are listed in Table 6. Each day a short-term (3-hour forecast--essentially a current evaluation) plus a 24-hour forecast was prepared for each of these groups. These forecasts specified whether a natural release was likely and whether release by artificial triggering was possible. Furthermore, probable avalanches, both natural and artificial, were specified according to whether they would run in the upper track, to mid-track or for full length of the path for each group.

This degree of specificity introduces a new advance in avalanche forecasting in the United States. To our knowledge, no such forecasting precision has heretofore been formally and systematically attempted for an entire winter on so many diverse avalanche paths. The results discussed below demonstrate that forecasting of this type is operationally feasible in the hands of trained and experienced observers. Following the format in the Second Interim Report (Table 4, p. 35), the summary of forecast evaluations for the general forecasts (index numbers) is presented in Table 7. The final (end-of-season) evaluation is ommited, for improved rigor of the 24-hour evaluation was obtained during the third winter. Days for which either a forecast or an evaluation are missing are omitted from this summary.

Discussion and analysis are essential to understanding the bare information presented in Table 7. First, the index numbers form an ordinal scale divided on an arbitrary and not necessarily uniform basis. A substantial amount of subjective judgment is involved in assigning the index to any given forecast, no matter what degree of objectivity may have gone into the forecast itself. This is less true of the evaluation, which can be based in most cases on actual observation of avalanche occurrences, but even here the distinction between Index Conditions IV and V is not easy to determine. Consequently, the evaluation of forecast accuracy in Table 7 can be regarded only as a general indicator rather than a highly specific assessment. In the winter of 1973/74 there were 26 forecasting errors (evaluation index differed from forecast index) out of 128 days examined, giving an overall accuracy rating of 80%. Out of these 26 errors, 12 involved an error between Index IV and V, a distinction determined by subjective assessment of rather stable conditions largely irrelevant to serious avalanche hazards. Eleven more of the errors involved Index III, a transitional state predicting rare natural avalanche releases. Thus there remained only three errors for the entire winter involving Index II; the other two were overestimates of hazard. While the overall accuracy declined slightly from the second to the third winter (80% vs. 82%), this, in part, was a consequence of many more Index IV days occurring the third winter, a condition difficult to evaluate accurately. The maintenance of nearly the same accuracy in spite of this fact speaks for an increase in forecasting skill which is further born out by the success

TABLE 7

EVALUATION OF AVALANCHE FORECAST METHOD, 1973/74

Month	Days Examined	% Accuracy 24 hr. eval.	Number of Index Days (evaluated) I	II	III	IV	V
Nov.	12	58				3	9
Dec.	29	76		2	5	12	10
Jan.	30	90		4	10	13	4
Feb.	27	78			5	8	14
Mar.	30	84		3	6	9	12
Totals	128	80		9	26	45	49

in forecasting for specific path groups (see below). With only one failure to foresee a serious instability (Index II) out of nine such days during the winter, the practically important forecasting accuracy is in fact 89%.

Of much greater importance to practical avalanche hazards in the San Juan Mountains is the specific and detailed forecasts for avalanche path groups which affect U.S. 550. In Table 8 these forecasts for the winter of 1973/74 are compared with the record of actual avalanche occurrences which deposited snow on the highway. This, like the Index II situation above, is the only real test of forecasting accuracy: were the forecast procedures actually able to predict the avalanches which did occur? Including all the forecasts of stable conditions in a forecasting accuracy assessment gives a distorted picture, for stable conditions prevail most of the time. (In fact, someone completely ignorant of avalanche forecasting and the target area could achieve a creditable paper score by simply forecasting no avalanches every day of the winter--but practically this would be useless.)

For the 26 days on which avalanches reached the highway, forecasting errors were made on 7 days, giving a formal accuracy rating of 73%. Of these 7 errors, 3 involved the failure to predict large natural avalanches and, hence, were the most serious failures. More significant than the errors, though, is the fact that avalanches, both natural and artificial, were predicted on numerous occasions with high precision. Considering the technical difficulties of making such specific forecasts and the fact that new ground was being broken in the application of conventional forecasting procedures, the overall accuracy depicted in Table 8 is remarkable. Trained and experienced observers, building on experience with a given area, can apply conventional avalanche forecasting techniques in a highly specific fashion with good success.

Closer examination of some of the errors in forecasting avalanches which reached the highway is instructive. One error, that of 2 March, occurred when high wind transport of snow, developing after the forecast had been prepared, led to natural releases. The area meteorological forecast failed to predict this high wind. Four of the 7 errors occurred during the first half of March, during a period of transition from winter cold snow to spring wet snow conditions. Two of the errors, 12 and 15 March, were made by an inexperienced observer who was not alert to the problems of this transition period, but this period may, in fact, be a difficult one to forecast even by an experienced hand.

The daily forecasts during 1973/74 were prepared on a rotating basis by four different observers except for November, when one man did most of both forecasting and evaluating. These four observers can be ranked in order of decreasing experience as follows:

Observer A - Many years of experience with avalanche forecasting and control at a major ski area. With San Juan Project all three years.

Observer B - Diverse but interrupted experience with avalanche forecasting and control in ski areas. With San Juan Project all three years.

Observer C - Experienced meteorological observer but no avalanche experience prior to San Juan Project. With Project all three years.

Observer D - Experienced meteorological observer but no avalanche experience prior to 1973/74.

Observer D was intentionally added to the staff the third winter in order to ascertain how much of the developed experience with forecasting in the San Juan Mountains could be communicated to a newcomer. The individual forecasting scores (as determined from the Index analysis) for these four observers are listed in Table 9. Obviously, the forecasters were conservative: overestimates of hazard predominated over underestimates, 18 to 8. The newcomer accumulated a substantial error score, as might be expected, but even maximum experience does not guarantee success, for Observer A made the only underestimate of an Index II condition for the entire winter. Observer B's high error score is perhaps unfair, for 5 of the 12 errors were recorded in November when he was the only observer preparing his own evaluations, which he did all too consciencously when dealing with the tricky problems of separating Index IV from Index V.

The record of operational avalanche forecasting by the San Juan Project has demonstrated to date that application of conventional methodology, informed by the accumulated data on conditions peculiar to the San Juan Mountains, can lead to a successful general forecasting scheme and can, furthermore, allow the state of the art to be carried to the point where highly specific and accurate forecasts can be generated for individual avalanche paths or path groups. Forecasting accuracy is by no means 100% overall, but critical errors involving the prediction of serious snow instability have been reduced to a remarkably low minimum. In spite of the complex character of the natural phenomena involved, plus the uncertainties of mountain weather forecasts, it can be safely stated that an operational avalanche forecasting scheme is possible for the San Juan Mountains based on conventional procedures alone. The remaining problem now is to place the developed methodology on a formal basis which can be communicated to subsequent users. As a first step to this end, the four forecasters working during winter of 1973/74 were asked to put down on paper their individual operating procedures, including a list of the contributory factors which they reviewed in preparing their daily forecasts. The results are illuminating, but difinitely leave some unsolved problems.

Table 10 summarizes the factors of terrain, weather, snow and avalanche occurrence that each observer/forecaster deemed to be significant in his own forecasting. The outstanding feature of Table 10 is the lack of agreement on what was significant. Each forecaster obviously had his own ideas about how to forecast avalanches, or at least said he did.

The latter seems to be the actual case, as will be developed in this discussion. There is only one unanimous factor--wind speed and direction. Several other factors, such as snow stratigraphy, precipitation intensity, old snow stability, and new snow density and crystal type, are uniformly recognized as important by the experienced men. Obviously, the newcomer had developed a much shorter list of factors during the short history of his experience. This is only to be expected. But some of the anomalies among the experienced observers are less expected and deserve comment. Two observers, A and C, gave strong emphasis in their written reports to test-skiing on test slopes near the Red Mountain Pass station during storms. This is the classic and effective method of identifying soft slab, direct-action avalanche conditions. It is addressed to instabilities in new-fallen snow but is notoriously unreliable for climax avalanche conditions. The three-year record of fracture line profiles accumulated by this Project have demonstrated that no less than 89% of all avalanche releases examined are climax in nature. Does this reliance on test skiing come from habit? Does it represent self-deception on the part of the observers, or is there a real link between new snow instability and climax avalanche release in the San Juan Mountains whose physical nature has yet to be established? Further examination of Table 10 reveals other peculiarities. For instance, only two observers reported that they considered topographic features and current winter avalanche history of individual paths in preparing a forecast. Consideration of these factors is essential to the success in specific path forecasting described above. In fact, such forecasting is impossible without regard to these factors. It seems obvious that the other forecasters indeed did take them into account, but failed to so report.

The general conclusion here must be that the forecasters' written reports about what they did diverge widely from what they actually did. These men have definite skills in recognizing unstable snow, sharpened these skills for a particular area, and were able to communicate some of them to a newcomer on a daily tutelage basis. But the systematic codification of these skills and their written transmission is yet an unsolved problem. This problem is not peculiar to this Project, for it has been reported many times over by other workers in the field. In fact it is not peculiar to avalanche forecasting. A speed skater can tell that one rink has a different "feel" from another but he cannot explain what the difference is. A master baker can judge unerringly the quality of bread dough, but he cannot explain in words how he does it. An Australian aborigine can predict the occurrence of rain many miles away while leaving a Western observer completely puzzled about how he does it. Such examples can be multiplied many times over whenever complex natural phenomena are involved in human perception. Solution to this problem of how to communicate ill-defined but real skills is a pressing goal in psychology which lies outside the scope of this present study. We must conclude that an accurate forecasting methodology for the San Juan Mountains can be developed and applied by using conventional forecasting methods, but that this in large measure must be done by on-the-job training and experience rather than by formal pedagogy.

Nevertheless, a reasonable synthesis can be made of the forecasters' experience in this research area by examining the composite forecasting methodology in the light of information developed by investigating the physical causes of avalanching in the San Juan Mountains (summarized in Chapter 3). The conclusions reached in this fashion constitute the essential finding of this Project for the application of conventional forecasting methodology to this area. The following specific factors will need to be considered by anyone producing operational avalanche forecasts for the San Juan Mountains:

1. Dry snow avalanches are very predominantly the climax soft slab type. This information tells the experienced forecaster that he is dealing with an unstable snowcover of low structural strength and with frequent weak interface bonding between snow layers. Most, but not necessarily all, significant precipitation events will load at least some slopes to the point of failure.

2. Major avalanches generated by fair-weather transport of snow by the wind are rare. Only one path, Cement Fill, consistently produces a threat to the highway from this source.

3. Wet snow avalanches are confined to a clearly-defined spring cycle associated with initial thaw of the snow cover. Onset of wet avalanching appears to be closely related to rise of the mean daily air temperature above $0^{o}C$ in the release zones.

4. There are large meso-scale variations in snowfall and avalanche activity within the study area. Snowfall distribution is strongly affected by meteorological character of individual storms and especially by prevailing direction of moisture-laden winds.

TABLE 8

FORECASTING RECORD FOR AVALANCHES REACHING U.S. 550
WINTER OF 1973/74

The specified forecast in each case is for the period of 24 hours or less during which the avalanche event took place. Numbers following avalanches give depth and width on highway in feet. "A" means artillery release, all other events are natural.

Occurrence Date	Forecast	Avalanche Event(s)	Remarks
Dec 14	Natural slides in upper parts of paths	Blue Point 2 20	FCST OK
Dec 18	Natural slides in upper parts of paths	ERS Left 4 20 Blue Point 3 50 Mother Cline 6 25 ERS South 3 30	FCST OK
Dec 28	Artificial release possible, no natural slides	Willow Swamp 2 75	Natural instability underestimated
Dec 29	Brooklyns will run naturally to full track	Blue Point 2 70 Brooklyns B 2 50	FCST right on
Dec 30	Eagle and Telescope to mid-track evening of 29th, full track AM on 30th. (Natural release)	Eagle 3 50 Eagle I 100 Telescope 6 350	FCST right on
Dec 31	Full-track artificial releases possible in Muleshoe Group	Eagle A 3 150 Telescope A 2 100	FCST right on
Jan 5	Natural releases to run full-track.	Brooklyns G 15 250 Eagle 3 50 Porcupine 3 50 Rockwall 8 100	FCST right on
Jan 6	Artificial releases possible, running full-track	Brooklyns C A 2 75 East Riverside A 5 70 15 80	FCST right on
Jan 7	Artificial releases possible, running full-track	Brooklyns C A 1 25 Silver Ledge A 4 75	FCST right on
Jan 8	No natural slides	Willow Swamp 11 200	FCST ERROR

TABLE 8 (continued)

Occurrence Date	Forecast	Avalanche Event(s)	Remarks
Jan 9	General Class II hazard	Lime Creek 8 700 3 50	FCST OK
Jan 10	Artificial releases possible, running to mid- or upper track.	Mother Cline A 1 20 Willow Swamp A 15 250	FCST right on
Jan 11	Artificial releases possible, running to mid- or upper track.	Champion A 14 250	FCST right on
Jan 21	Natural releases running mid- or full-track	Blue Point 4 100 Rockwall 2 100 1 150	FCST OK
Feb 20	General Class III hazard on 19th, artificial releases possible on 20th but not natural slides	East Riverside 4 50 East Riverside A 14 Mother Cline 10 300 Silver Point 6 20 Blue Willow 2 20 Blue Point A 4 25	FCST ERROR for natural slides FCST OK for artificial releases
Mar 1	Stable conditions, no avalanches	Dunsmore 1 30	FCST ERROR
Mar 2	Stable conditions, no avalanches (fcst made March 1)	East Riverside 12 70	FCST ERROR (Mar 1 & 2 slides caused by high winds missed by weather fcst)
Mar 7	General Class III hazard, no activity for specific slide groups	Blue Point 5 100	FCST Marginal
Mar 10	General Class II hazard	Willow Swamp 4 80	FCST OK
Mar 11	No natural or artificial releases	East Riverside A 13 100 A 13 100 Blue Point A 7 30	FCST ERROR
Mar 12	No natural slides on Champion, no forecast given for artificial releases	Champion A 3 30	FCST not verifiable

TABLE 8 (continued)

Occurrence Date	Forecast	Avalanche Event(s)	Remarks
Mar 15	Stable conditions, no avalanches	Champion 8 40	FCST ERROR
Mar 16	Wet loose snow instability, natural releases to mid- or full-track	Blue Willow 3 60 Champion 4 25 Blue Willow 4 25 Champion 5 50 Brooklyns I 5 55	FCST right on
Mar 18	Class III condition for wet loose slides, otherwise stable	Mother Cline 3 20	FCST OK
Mar 17	Class II condition for wet loose slides	Blue Point 2 6	FCST OK but overstated
Mar 19	General instability for wet loose slides	Jackpot 2 70 Mother Cline 3 60	FCST OK

TABLE 9

FORECASTING ERRORS BY OBSERVERS

+ = hazard overestimated - = hazard underestimated

Error by Index Number	Number of Events
A	
+1	2
-1	2 (one involved failure to predict II)
	4
B	
+1	6
+0.5	2 (one overestimated a II)
-1	3
-2	1
	12
C	
+1	1
-1	1
D	
+2	1
+1	6 (one overestimated a II)
-1	2
	9

Total of 26 errors in 128 evaluation days.

-11 involved III

- 3 involved II

TABLE 10

Factor	A	B	C	D
General Stratigraphy		X		X
Study Plot Stratigraphy	X	X	X	
Carbon Mtn. Stratigraphy	X		X	
Explosive Tests			X	
Ski Testing - Carbon Mtn.	X		X	
Weather Forecast			X	
Storm Precip. (Amount)	X		X	X
P.I. / S.I.	X	X	X	
Slope Loading (Precip. & Wind)			X	
Old Snow Stability	X	X	X	
Old Snow Sfc		X		X
Old Snow Depth			X	X
New Snow Properties (General)		X	X	
Specifically: Density	X	X	X	
Crystal Type	X	X	X	
Structure				
Depth	X			X
Old Snow - New Snow Bond			X	
Unstable Stratigraphy Patterns			X	
Wind Speed & Direction	X	X	X	X
New Snow Temperature		X	X	
Lt. Wt. Ram			X	
Tilt-board	X			
Current Avalanche Releases	X			
Air Temperature & Trend	X	X		X
Wind Drift in Clear Weather	X			
Snow Depth in Starting Zones		X		

TABLE 10 (continued)

Factor	A	B	C	D
Starting Zone Terrain		X	X	
Winter Meteorological History		X		
Avalanche Occur. History		X	X	
Meso-Scale Snowfall Distribution		X		

DAILY FORECAST AND EVALUATION RED MOUNTAIN PASS

X = natural
0 = artificial

date time observer

GROUPS	PRESENT FORECAST (3 hour)		24 HR FORECAST (based on E.G. & G.)		SLIDES WILL RUN TO:			HIGHWAY (yes/no)
	YES	NO	YES	NO	upper track	mid track	full track	
Riverside								
Ledge								
Mule Shoe								
Brooklyns								
Cement Fill								
Champion								
REVISED FORECAST	time			observer				
Riverside								
Ledge								
Mule Shoe								
Brooklyns								
Cement Fill								
Champion								

COMMENTS:

EVALUATION: date__________ evaluator__________

CHAPTER 5: WET SNOW AVALANCHES

Richard L. Armstrong

By definition, the potential for wet avalanches is absent as long as the entire snowcover is below 0.0°C. Water in the liquid phase and thus a snow temperature equal to 0.0°C is the required ingredient for the formation of wet avalanches. Because of this rather simple relationship, it is sometimes felt that the time and location of wet avalanche releases can be predicted with greater precision than dry snow avalanches. Whether or not this is true, the need to accurately forecast wet snow avalanche occurrence is acute. This is because unlike dry snow, a wet snowcover does not respond in the desired manner to control by explosives. The physical properties of the wet snow suppress the propagation of the shock wave essential to the release of a snow slab. This condition may be due to an accelerated rate of stress relaxation through creep, preventing the existence of a mechanical condition comparable to the unstable dry slab. Therefore, while an efficient mid-winter avalanche control program may be capable of eliminating major portions of a given hazard, a comparable opportunity is not available in the case of wet snow avalanches. Wet avalanches must be forecast as natural occurrences and appropriate precautions taken at the predicted time and location of the event.

The need to acquire specific information regarding wet snow avalanches in the Red Mountain Pass area is emphasized by the fact that more than 30% of the avalanches recorded during the 1972/73 and 1973/74 winters were within this category. Of the avalanches reaching the highway, again more than 30% were of the wet snow type. Perhaps the most readily available data which can be used in the forecasting of wet snow avalanches is air temperature. Figures 16 and 17 show the relationship between mean daily air temperature as measured in a standard weather shelter at the snow study site at Red Mountain Pass and the occurrence of wet snow avalanches for the two periods, April 25-29 and May 7-12, 1973. Figure 18 shows this same relationship for March 15-19, 1974. The fact that temperature values exceed the freezing point at the time when the avalanching begins is simply a coincidental index value. Air temperatures within the areas of some starting zones may well be lower than those recorded at the Red Mountain Pass study site and snow temperatures of certain south-facing release zones could be expected to be higher than snow temperatures within the study site. However, these index values, as observed for two spring avalanche cycles do provide substantial information regarding event forecasting.

The following is a discussion of some of the meteorological and snowcover data which influence the formation of wet snow avalanches. The value of each parameter is analyzed in terms of wet snow avalanche forecasting in the Red Mountain Pass area of the San Juan Mountains. While the San Juan Avalanche Project has been in operation for three winters, data regarding wet snow avalanches is available for only two of these. This is because the 1971/72 winter experienced a low total snowfall, 60% of the fifteen-year average according to the Soil Conservation Service. In addition, several storms during the late winter produced sustained periods of high winds resulting in the catchment

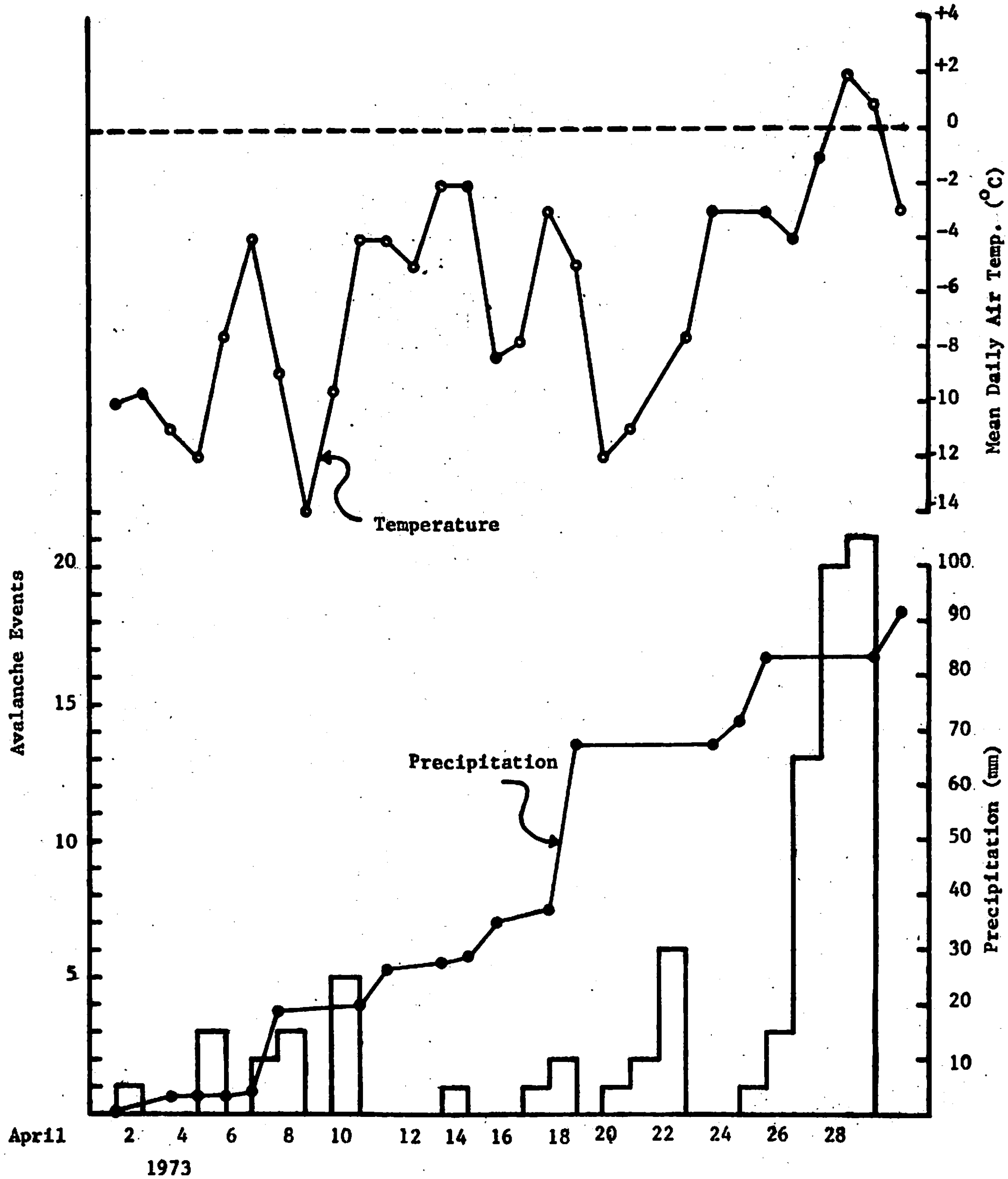


Figure 16. Wet snow avalanche events observed during April, 1973 compared to precipitation (mm) and mean daily air temperature (°C) recorded at Red Mountain Pass.

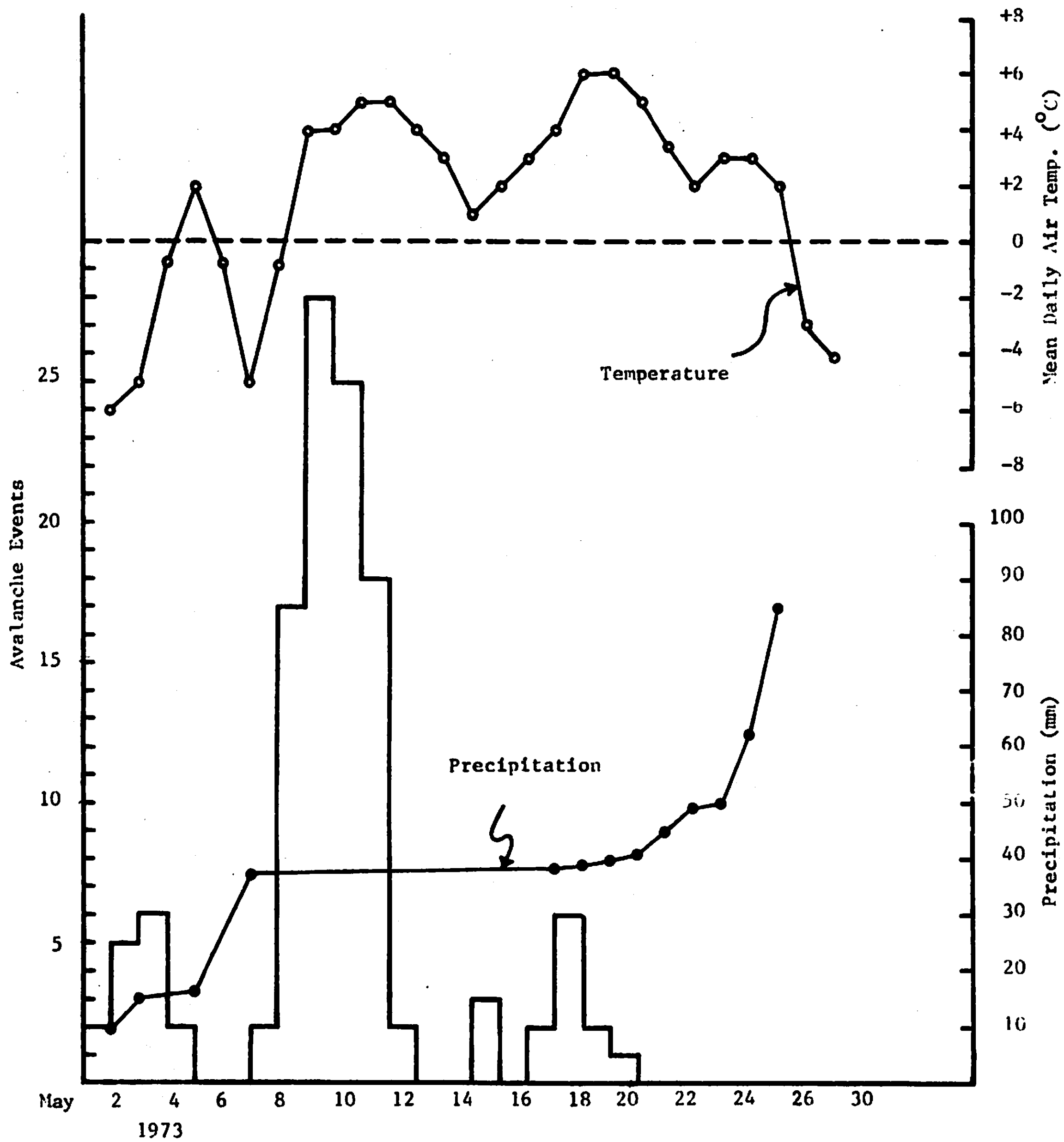


Figure 17. Wet snow avalanche events observed during May, 1973 compared to precipitation (mm) and mean daily air temperature (°C) recorded at Red Mountain Pass.

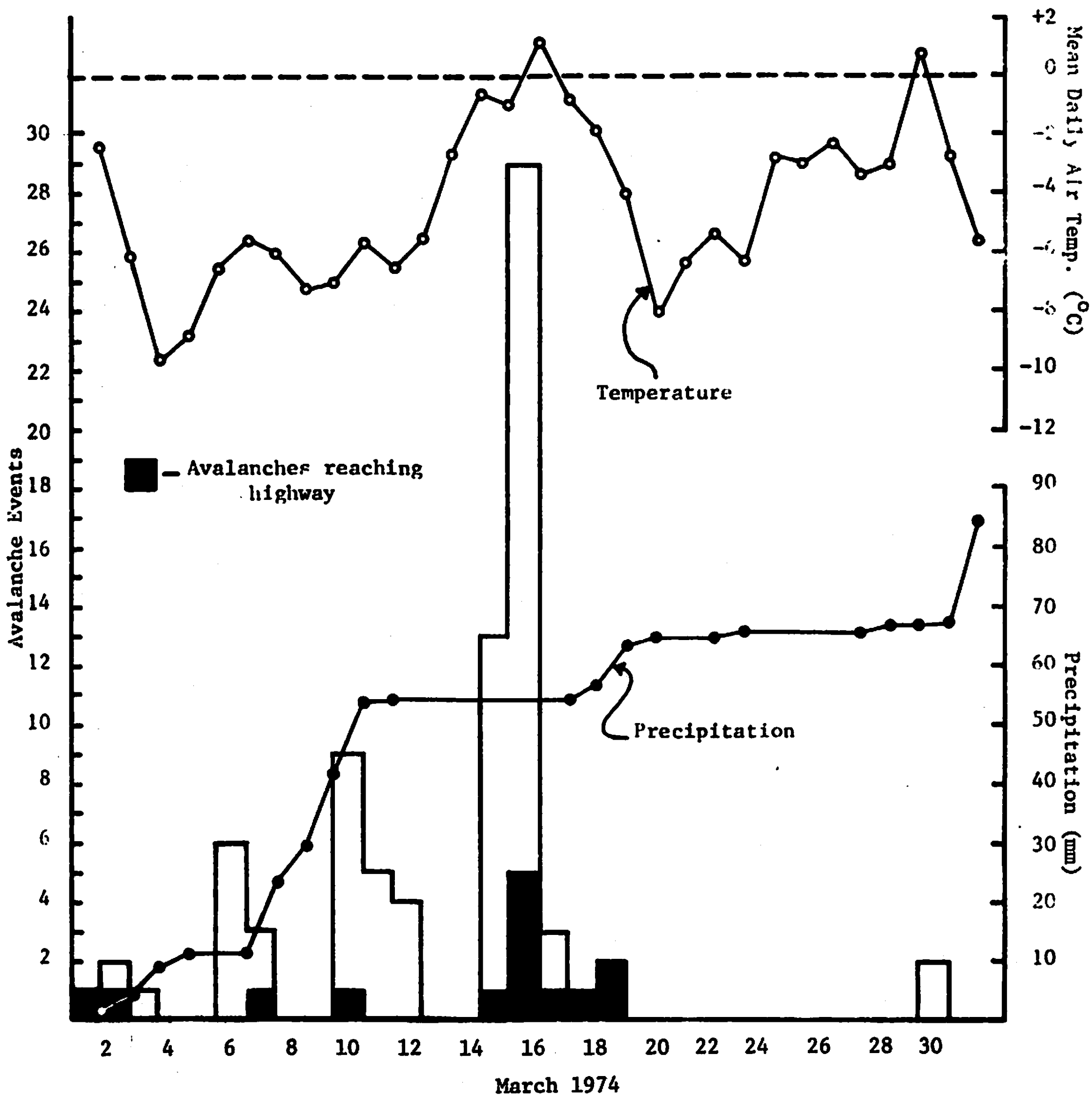


Figure 18. **Wet snow avalanche events observed during March, 1974 compared to precipitation (mm) and mean daily air temperature (°C) recorded at Red Mountain Pass.**

basins, which would have been the release zones for wet avalanches, being scoured free of snow. During late April and early May of 1973, a series of significant wet avalanches occurred. During March of 1974, numerous wet avalanches also occurred, and while they were smaller in magnitude and frequency than those of 1973, they did offer an additional opportunity to study this phenomenon.

A basic objective in the study of avalanches in cold (below 0.0°C) snow is to understand the relationship between changing strength and stress patterns. This changing stress pattern is the product of additional loading to the slope in the form of newly deposited snow with strength being a function of varying stratigraphic conditions. In the case of spring or temperature-induced avalanches, the primary emphasis is placed on changes in strength. Generally, this type of avalanche occurs without the additional loading of precipitation but with a condition of decreasing snow strength combined with a fixed stress pattern. It is possible that snowfall may occur at a time when such an additional load will contribute to wet avalanche release. However, the dominant pattern of decreasing snow strength had already provided the primary condition for release.

This decrease in the bulk strength of the snowcover is the result of a decrease in intergranular cohesion. Heat is available to melt these intergranular bonds from the increasing air temperatures (conductive or molecular component) and the greater amounts of solar energy (radiation component) available at the snow surface at the onset of spring conditions. The process of warming the snowcover is gradual and can take on the order of 15 to 30 days in the San Juan Mountains to change the snowcover from a mid-winter temperature regime to isothermal. When a given portion of the snowcover becomes isothermal, the bonds between the grains melt. Such bonds are the product of an earlier sintering process associated with equi-temperature metamorphism.

The effect of a warm rain falling on a sub-freezing snowpack must be considered within certain climatic zones, but such a condition is not known to occur in the San Juan Mountains. Rain falling on isothermal (0.0°C) snow provides negligible temperature gradients for conductive heat transfer and thus little energy for melting is introduced.

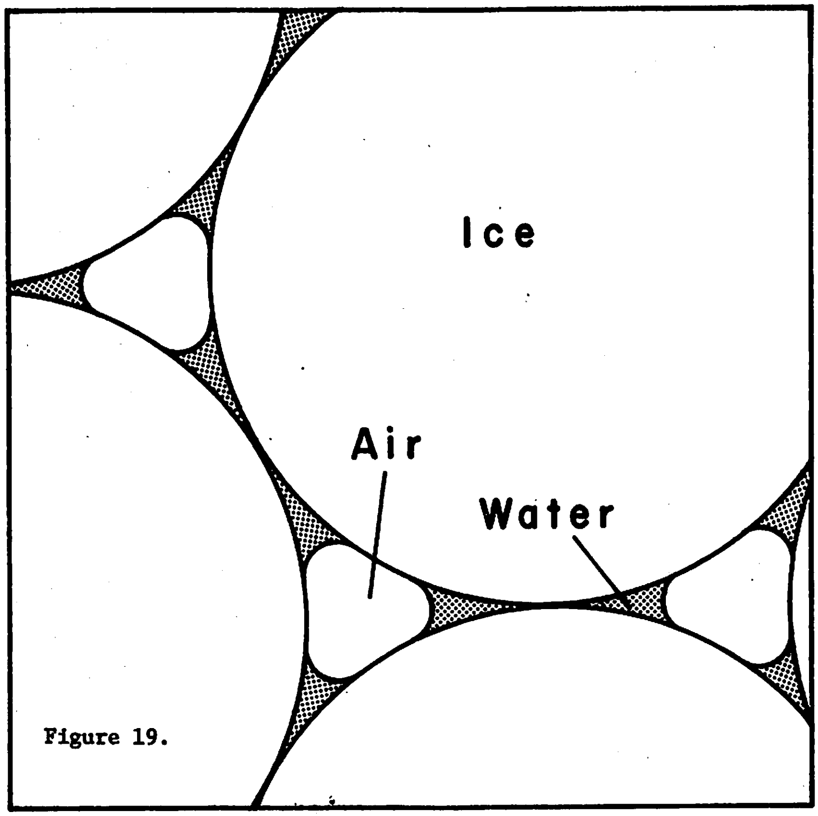
While increased solar energy is the cause of higher air temperatures, the effect of direct radiation is low on a snowcover with an albedo of 90 percent or greater. This value, however, drops to approximately 60 percent when the snow becomes wet. Also, some short-wave radiation penetrates 10-20 cm into the snowcover, causing near-surface melting. During midwinter, this has little effect on the temperature regime of the snowcover as a whole. As long as the major portion of the snowcover remains below 0.0°C, this warming of the surface layers to the freezing point may have no more effect than to release occasional small wet loose surface avalanches. The stronger midwinter temperature gradient slowly diminishes primarily as a long range function of heat conduction and insolation. This condition can be observed indirectly via mean daily temperature values (see Figure 11).

Once the potentially unstable snow layer has been warmed to 0.0°C throughout, the entire amount of solar energy is available for the melting process. As initial melt occurs, small amounts of free water cling to the grains due to surface tension. As melting accelerates, free water begins to flow down into the snowcover. The rate of flow depends on the temperature and structure of the snow as well as the actual amounts of free water. The water flows until it either freezes due to contact with a colder layer or is blocked by an impermeable layer. The water will spread out over such layers until additional percolation channels can be created. As increasing amounts of free water become available, percolation continues, ice layers deteriorate and heat is transferred further down into the snowcover.

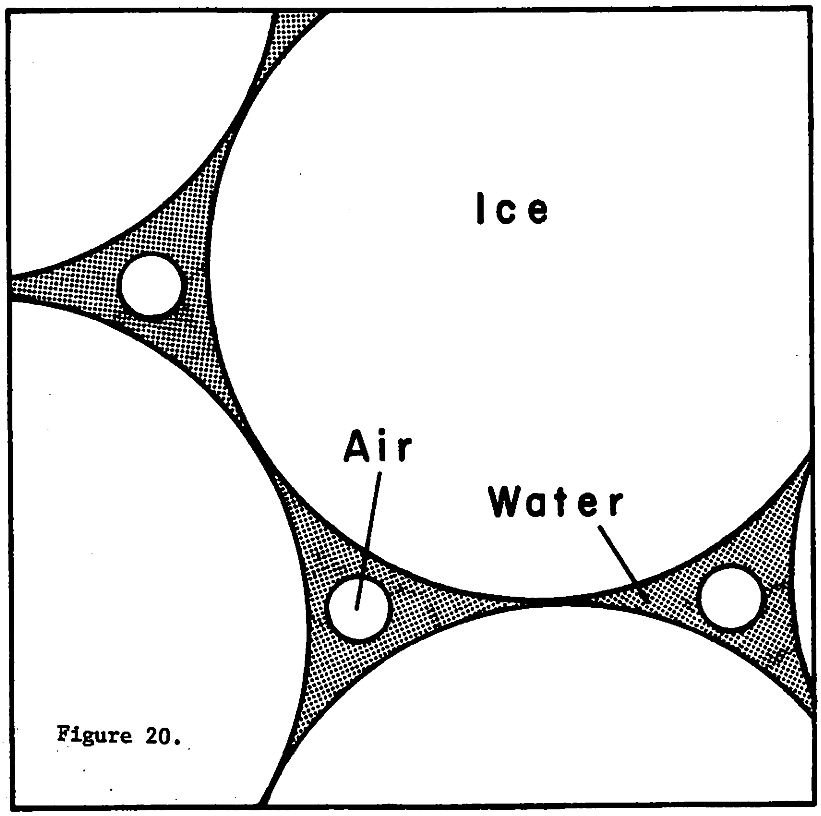
The metamorphism, strength, and desification of wet snow are controlled by the small temperature gradients between the grains. In order to describe these processes, Colbeck (1974) has catagorized the saturation regimes in wet snow as either pendular or funicular, i.e., low or high saturation respectively. At low values of saturation, the water volume is greater than the capillary requirement, but less than that necessary to cause adjacent water volumes, separated by air bubbles, to coalesce (Figure 19). In this regime, the water pressure is much less than atmospheric pressure and the air phase exists in more or less continuous paths throughout the snow matrix.

In the funicular regime saturations are greater than 14% of the pore volume and the air occurs in bubbles trapped between the ice particles (Figure 20). The equilibrium temperature of the snow matrix is controlled by the size of the air bubbles and the size of the ice particles and, for any given air content, the particle sizes dictate the distribution of temperature locally within the mixture of ice particles. The smaller particles exist at a lower equilibrium temperature, causing heat flow from the larger particles and rapid melting of the smaller particles. The result is the disappearance of the smaller particles and the subsequent growth of the intermediate and larger particles. The average particle size increases without a significant change of density in the snow matrix.

The thermodynamics of the pendular regime is significantly different because of the lesser cross-sectional areas of water available for heat flow and the existence of another interface, the gas-solid surface. The equilibrium temperature of the matrix is a decreasing function of both capillary pressure and particle size. At small water contents, the temperature differences between particles and the area of heat flow are both reduced and much lower rates of grain growth are observed. The large "tensional" forces developed in the water phase give strong intergranular attractions and the bonds assume a finite size which is determined by the relative effects of capillary pressure and particle size. The strength of snow at low water saturations should be high. Much of the grain-to-grain strength in the pendular regime is caused by the water "tension" drawing particles together. In spite of the large stresses induced by the attractive forces, no melting occurs at the grain contacts because the large values of capillary pressure reduce the temperature of the entire snow matrix.



Pendular Regime



Funicular Regime

In the funicular regime rings of water coalesce forming isolated bubbles of air trapped between the ice grains and the water phase exists in continuous paths completely surrounding the snow grains. The permeability to liquid water is greatly increased at larger saturations and the capillary pressure, or "tension", of the liquid water is reduced. In the funicular regime, the equilibrium temperature at a contact between grains is decreased by the compressive stress between the grains. The temperature depression is further increased by overburden pressure causing melting of the intergrain contacts and removing bond-to-bond strength.

Optimum conditions for the existence of the funicular regime would occur over impermeable boundaries, at stratigraphic interfaces, and within highly permeable zones capable of large flow rates. The type of snow structure common to the Red Mountain Pass area, consisting of alternating layers of coarse-grained, cohesionless temperature-gradient snow and stronger freeze-thaw crusts and wind slabs, would be highly conducive to the funicular regime. Melt associated with the equilibrium temperature depression occurring in the funicular regime would create extensive zones of minimal shear strength and provide those conditions contributing to the release of wet-slab avalanches.

Once the bulk of the snowcover has become isothermal, the immediate potential for wet avalanche release is greatly increased. The next period providing significantly warm air temperatures will be of much greater importance than an earlier period with comparable air temperatures but subfreezing snow temperatures. As noted above, wet snow has a lower albedo than dry snow. Therefore, as the surface layers begin to melt, the wet snow is capable of absorbing more solar radiation, which in turn causes more melt to occur. Once the deteriorating strength of the snowcover reaches the point where it can no longer resist gravitational stresses, it will release as either a loose or wet slab avalanche, depending on shear boundary conditions. These boundaries may be caused by stratigraphic irregularities within the snowcover or the snow-ground interface itself. While the slab type is often of greater magnitude, due to its release over a broader area, wet loose avalanches can also incorporate large amount of snow depending on how deep into the snowcover the percolation of meltwater has advanced prior to release, and how much additional snow may be released by the moving avalanche.

As mentioned above, the effect of rising air temperatures on avalanche occurrence is not independent of snow temperature. One would not expect significant wet snow avalanching if above freezing air temperatures occurred when the snowcover existed within a midwinter temperature regime. The first indicator of significant snow temperature increases occurs when the snowcover of the south-facing study area on Carbon Mountain becomes isothermal throughout. This has occurred approximately 10-15 days prior to significant spring avalanche cycles. In using the level study site as an index, the following observations were made. When the entire thickness of the snowcover has warmed to within 2.0°C or less of freezing, the possibility of thaw-induced avalanche events greatly increases. Once this criteria is met, the next requirement is for the mean daily air temperature to exceed the freezing level and at that point avalanches occur.

During both the late winter and early spring of 1973 and 1974, measurements of net all-wave radiation were made at the Red Mountain Pass study site. Daily net positive values did occur during these periods, but as with air temperature, such values were associated with significant wet snow avalanches only after the snowcover had warmed to the appropriate extent. Once this had been accomplished, daily net radiation values approaching zero (-5.0 to -15.0 cal/cm^2) occurred on those days just prior to the wet avalanche cycles. Because air temperature is partially a function of this radiation regime and since temperature data are both easier to record and reduce, greater emphasis is placed on the temperature parameter in the effort to forecast wet avalanche release.

As meteorological conditions begin to reflect a springtime regime, the responses within the snowcover are apparent at the study site. With the initial melting of intergranular bonds, rammsonde strength decreases. During both years when wet avalanches have been observed, this trend has been apparent prior to the beginning of the cycles. Snow settlement also appears to respond to the presence of free water within the snowcover. Accelerated settlement rates appear in late spring (see Figure 8, Chapter 2) but apparently occur only at that point when the snowcover is totally saturated with percolating free water, a condition which has occurred in the study site from two to six weeks following the wet avalanche cycle. Snow temperature is the critical parameter within the snowcover as values progress towards the freezing point. If the study site is to be used as an index, it would appear that when the entire snowcover has been warmed to a temperature between -2.0 and 0.0°C, conditions are adequate for wet snow avalanches given appropriate daytime air temperatures. These three parameters, air temperature, rammsonde resistance, and snow temperature, which do act as indicators before the fact, are shown for 1973 and 1974 in Figures 21 and 22 together with the avalanche event record. During both periods, snow temperature and rammsonde data have indicated that the stage was set, but in each case the avalanche cycle began only after the mean daily air temperature exceeded 0.0°C.

During both 1973 and 1974, an additional predictor has appeared in the form of wet snow avalanche events occurring on south and east facing slopes at elevations considerably lower than those of the release zones of the Red Mountain Pass area. On April 22, 1973, wet loose avalanches occurred on Engineer Mountain A (159); B (160); and C (161), five days prior to the major spring wet avalanche cycle. On April 25, 1973, a wet slab size three avalanche released to the ground on Engineer C, indicating the extent to which free water had penetrated the snowcover at that location. Again in 1974, a WS-N-3-G was recorded at Engineer B on March 12, three days prior to the major spring wet avalanche cycle. The elevation of the release area of the Engineer group is approximately 500 m lower than those with similar slope aspect in the Red Mountain Pass area. The value of wet snow

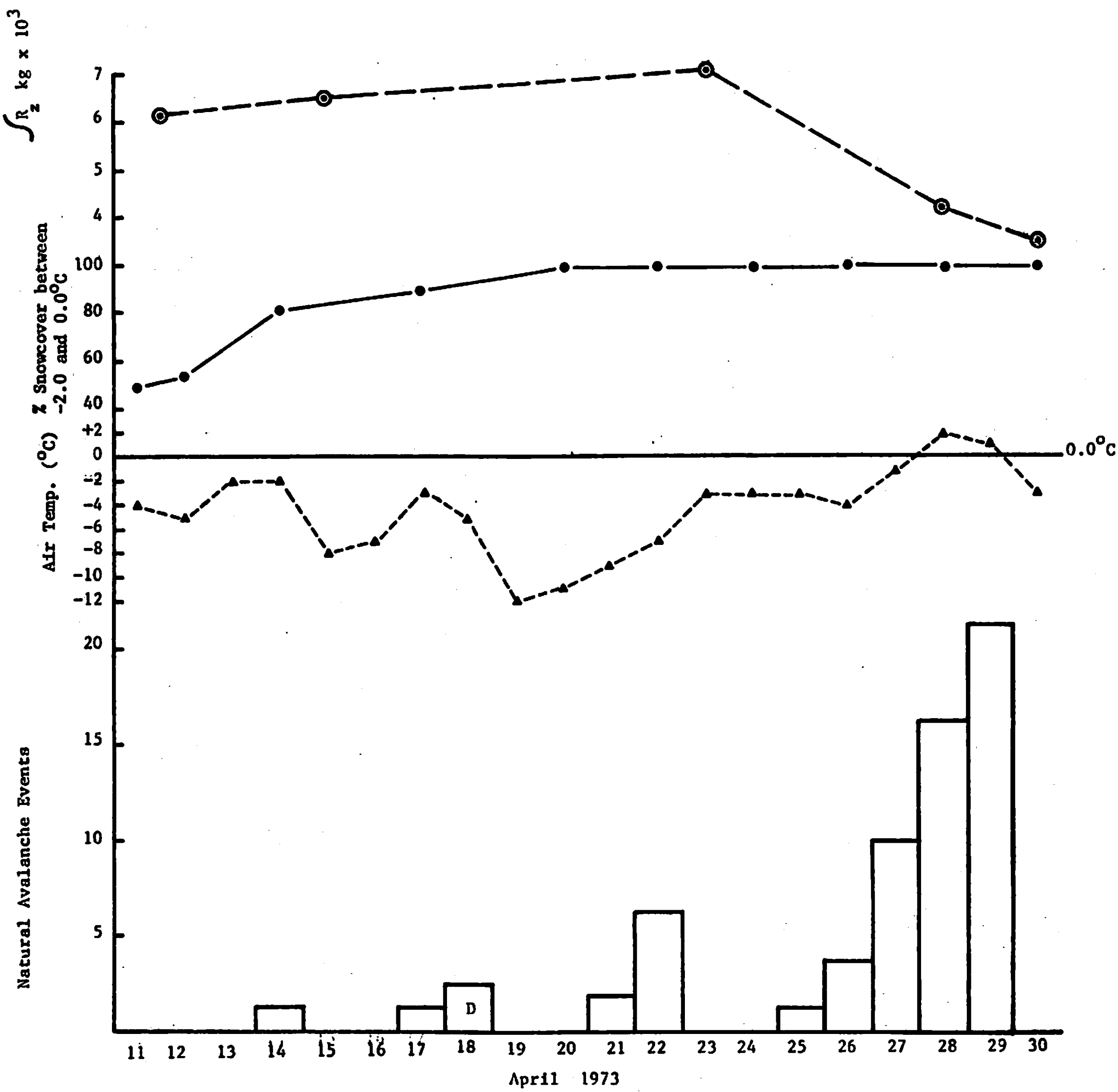


Figure 21. A comparison of integrated ram resistance, percent of snowcover between -2.0 and 0.0°C, and mean daily air temperature (°C) at Red Mountain Pass and observed natural wet snow avalanche events during April, 1973. (D = dry snow event)

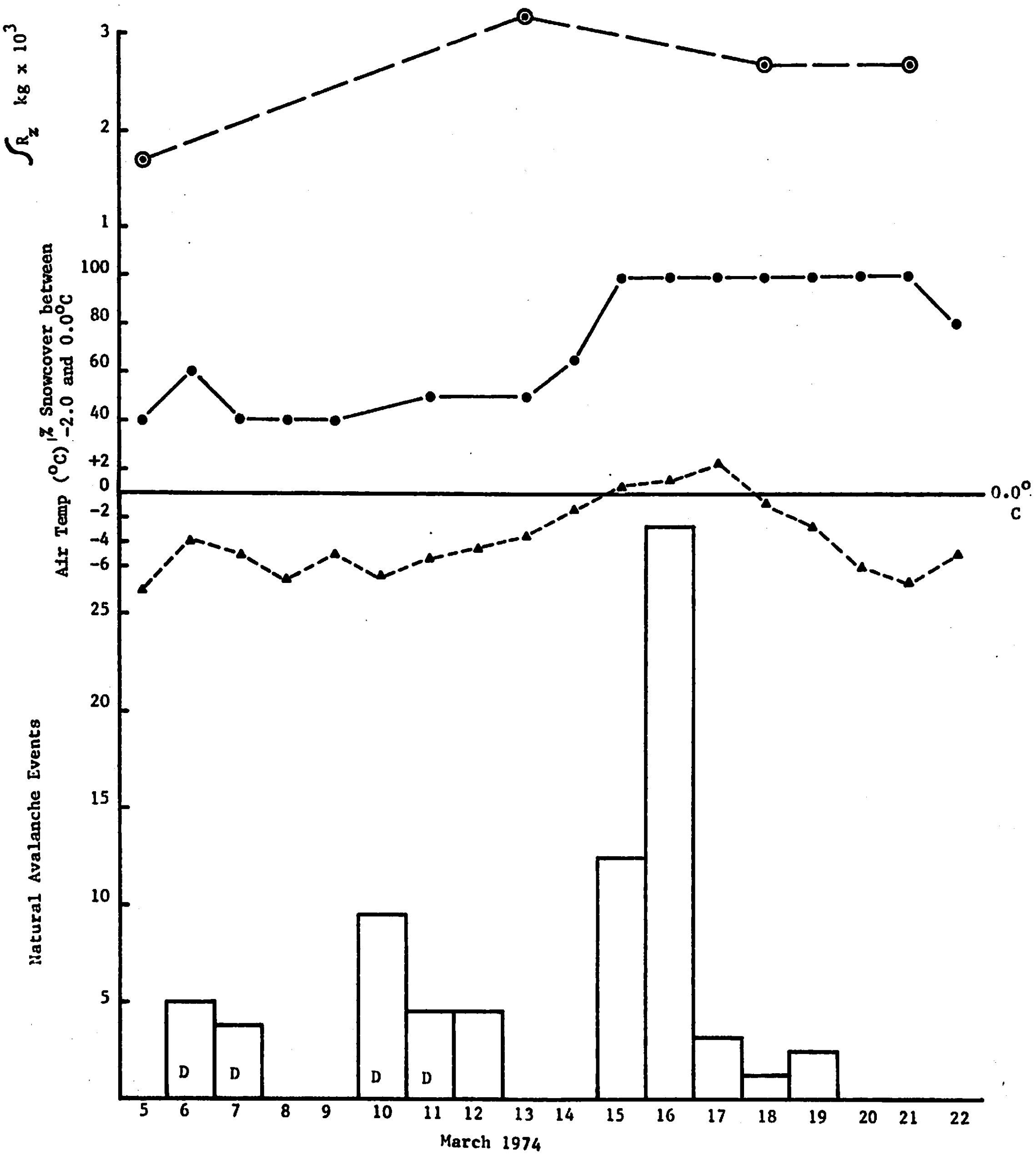


Figure 22. A comparison of integrated ram resistance, percent of snowcover between -2.0 and 0.0°C, and mean daily air temperature (°C) at Red Mountain Pass and observed natural wet snow avalanche events during March, 1974. (D = dry snow event)

avalanche activity on Engineer Mountain as a precurser to a major cycle in the Red Mountain Pass area is enhanced by the fact that these paths present little or no hazard to the highway.

During those days when wet avalanches occur, the time of an event is, to a considerable extent, a function of slope aspect. The possibility of a consistent relationship is complicated by several factors. If a release area is adjacent to exposed soil or rock surfaces, the snow-cover will be receiving increased amounts of heat due to long-wave radiation from the bare ground. Consequently, the snow may be warmed at a rate greater than another area with more favorable slope angle and aspect regarding direct solar radiation. If the release zone possesses the topography of a steep-sided gully, the sides of the gully may be receiving maximum solar radiation at some time prior to that which would be expected when considering the aspect of the over-all release zone. An avalanche releasing on such a sidewall could set the main track in motion. As described earlier, optimum conditions for release exist not necessarily at the time of maximum air temperature or solar radiation but somewhat later in the day when the wet snow surface is capable of absorbing increased amounts of solar radiation. Therefore, even though optimum sun angle for a south-facing slope might occur at noon, avalanching may not begin to occur until sometime later, perhaps coincidental with slopes possessing a more westerly orientation.

Figure 23 shows the extent to which the time of release is a function of the slope orientation within selected groups of avalanche tracks which frequently affect the highway during spring cycle conditions. A relationship between time of day and slope aspect is apparent, but an even more striking pattern appears within the clusters representing individual avalanche path groups. The large crosses indicate the time at which the appropriate slope angle and aspect of the given release zone would theoretically receive maximum direct, clear-sky solar radiation. The slope with the more easterly aspect shows a definite time lag between maximum energy received and the beginning of avalanche activity. This condition agrees with the concept of increased productivity of free water, and subsequent avalanche release at some point following that time when the surface snow first becomes wet. As the day progresses the lag diminishes because as time elapses, the snowcover is being gradually warmed by the increasing air temperatures so that when optimum solar angle occurs, a significant amount of melt has already taken place at the surface.

All of the preceeding information has related to the determination of the onset of the wet avalanche cycle. Once initiated, high hazard will continue until certain criteria are met. Avalanches will continue to release over a period of time depending upon slope angle, aspect and elevation of starting zones. Once north-facing slopes with relatively high elevations have released, such as East Riverside (064) and the Mill Creek Cirque Group (108-114) in the Red Mountain Pass area, general hazard could be considered diminished.

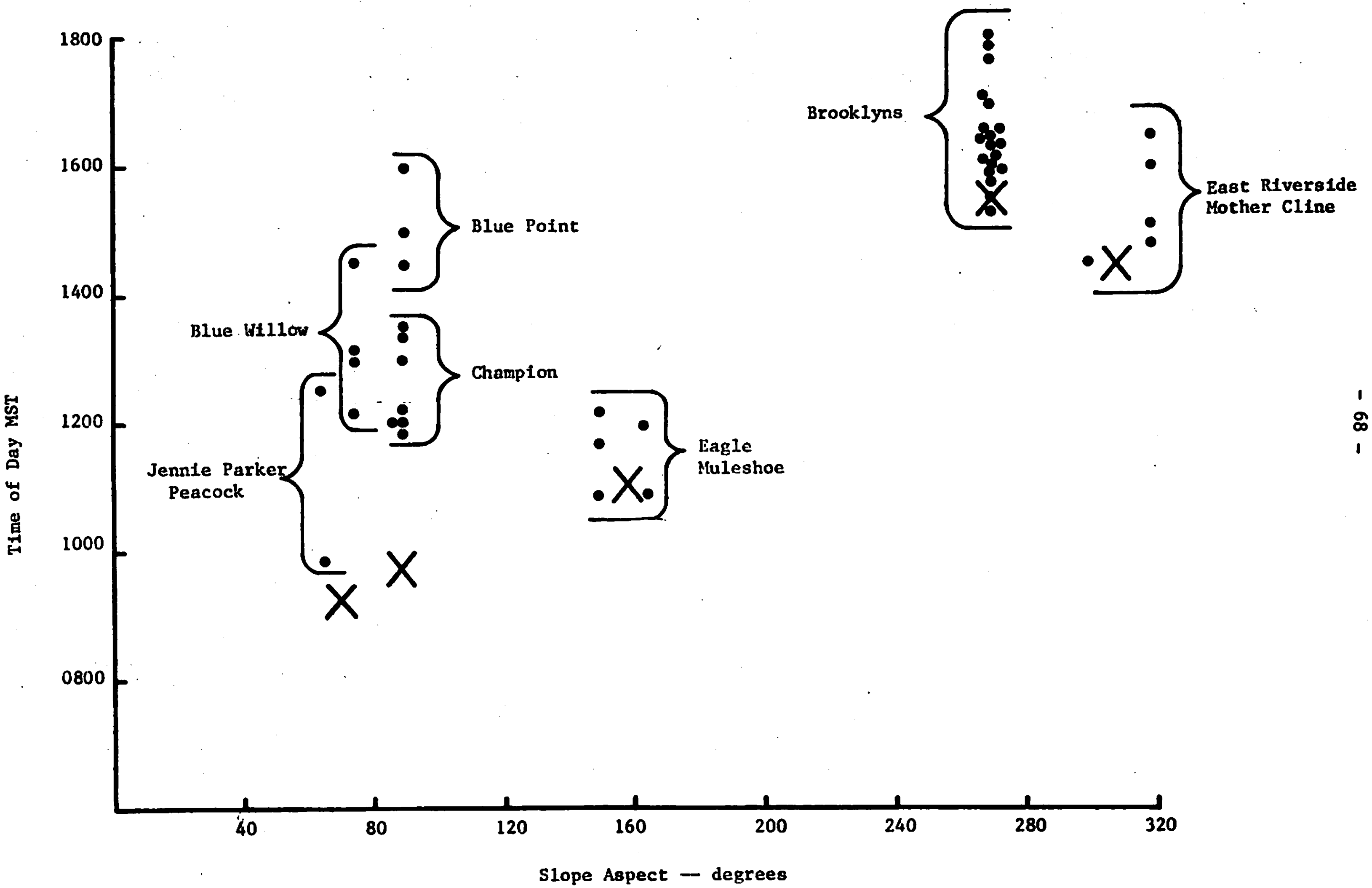


Figure 23. Wet snow avalanche events grouped by slide path as a function of slope aspect and time of day.

Finally, some discussion is necessary to explain those characteristics which caused the 1973 wet avalanche cycle to differ from that occurring in 1974. During late April and early May of 1973, the wet avalanche cycle produced 187 events, of which 60 crossed the highway. Thirty percent of the avalanches were slab type. During mid-March of 1974, a total of 68 wet snow avalanches were recorded, of which 13 crossed the highway. Only 4% of the avalanches were slab type. Not only did the frequency and type of wet avalanche differ from 1973 to 1974, but also the magnitude. In 1973, 24% of the events were size three or larger, while during 1974, avalanches of this magnitude accounted for only 13% of the total. Factors contributing to these differences are as follows. The total snowcover depth and water content at the time of the 1973 cycle exceeded that of 1974 by 60%. The spring cycle of 1973 occurred six weeks later in time, beginning on April 27 as opposed to March 15 of 1974. On the later date, 22% more solar energy is ideally available on a south-facing slope with an angle representative of actual release zones. The snowcover of 1973 was in, or very near to, an isothermal condition for at least eight days prior to the beginning of the April 27-29 cycle as can be seen in Figure 21. Each night during this period, air temperatures were 6.0 to 17.5° below freezing causing the surface snow layers to refreeze. This condition, however, would retard the melt process for only a short period. During the next cycle of May 8-12, air temperatures at an elevation of 3400 m remained above freezing throughout each night.

Nevertheless, it is likely that the snow surface within the avalanche release zones did reach sub-freezing temperatures due to radiation-cooling. However, the thickness of the crust and extent of sub-freezing temperatures within the surface layers must have produced minimal effect in terms of the energy required for melting the following day. This was the situation which preceeded the early morning release on the east-facing Peacock (142) at 0952 MST on May 11. This was a wet loose, size five avalanche which ran to the ground and crossed the highway for a distance of 50 m with a maximum depth of 2 m. In contrast, at the onset of the cycle of March 15, 1974, the snowcover had only begun to approach an isothermal condition (Figure 22). On the morning of the 15th, the temperature of the top 30 cm of the snowcover at Red Mountain Pass was between -10.0 and -2.0°C with the 90 cm layer beneath being -1.0 and -2.0°C, and only the lowermost 40 cm being at or near 0.0°C. The additional amount of solar energy available in late April and early May of 1973, combined with a snowcover temperature regime which caused only minimal amounts of heat to be consumed in raising the temperature of the snow to the freezing point created a condition where very rapid melt and subsequent percolation of free water prevailed. This rapid and deep percolation of melt water followed by an almost immediate loss of intergranular strength may have precluded any possible adjustment of stress conditions by slower creep deformation and caused instead the large volume releases associated with this particular period. The greater number of slab avalanches which occurred during the 1973 cycle may be explained by looking at the snow structure and avalanche occurrence record of the preceding winter period. Not only did precipitation during the 1972-1973 winter greatly exceed that of the following winter, but considerably more snow existed within the various release zones and avalanche paths for an additional reason. Numerous storms which produced moderate to heavy amounts of precipitation were associated with only small and infrequent avalanche events, causing significant amounts of snow to remain within the avalanche tracks. In such a snowcover, percolating free water came in contact with a complex stratigraphy which had been developing over the past four to six months. A snow structure, common to the Red Mountain Pass area, consisting of alternating layers of weak temperature-gradient snow and stronger freeze-thaw crusts and wind slabs, in combination with the melt water, created the inadequate strength conditions at the shear boundaries required to initiate slab-type avalanches.

The occurrence of wet snow avalanches depends largely upon air temperatures, heat flux and water content in the snow. The usual period for widespread release of wet snow avalanches is spring when snow temperatures rise and melting begins as a function of the seasonal trend of air temperature. Since the initial requirement for a wet snow avalanche is melting temperatures through the bulk of the snowpack, systematic snow temperature measurements are essential in order to forecast the onset of wet snow conditions. Once the snow is "warm," within 2.0°C of the melting temperature in the case of the Red Mountain data, the probability of release varies with the amount of free water held in the pore space of the snow and the effect of this free water on snow structure. Although it is possible to directly measure free water content as well as its subsequent effect on intergranular strength within the snowcover, emphasis here is given to indirect estimates of the generation of melt water. Air temperature is considered in conjunction with snow temperature data. In addition, consideration is given to slope exposure and radiation balance. Regarding the latter, it must be emphasized that the short-wave (solar) component of the radiation balance may not be a dominant factor for such a highly reflective material as snow. Long-wave radiation from warm clouds as well as warm winds are highly effective in melting snow.

Ref. Colbeck, S. C., Grain and Bond Growth in Wet Snow, Paper presented at the International Symposium on Snow Mechanics - Grindelwald, Switzerland, 1974. In Press.

CHAPTER 6: STATISTICAL ANALYSIS

Michael J. Bovis

Introduction

The purpose of this chapter is to outline the structure and operation of a statistical procedure for the real-time forecasting of avalanche occurrences in the San Juan study area. The analysis is restricted to the 1972-73 and 1973-74 seasons due to the anomalous pattern of occurrences during the 1971-72 season. To ensure an accurate timing of occurrences, the analysis is restricted further to events along Station 152 (Highway 550) where most of the observer effort has been concentrated to date. These decisions do not rule out the possibility of applying the forecast method to a wider area within the San Juan Mountains, since Station 152 comprises over 150 slide paths of greatly differing size and stability.

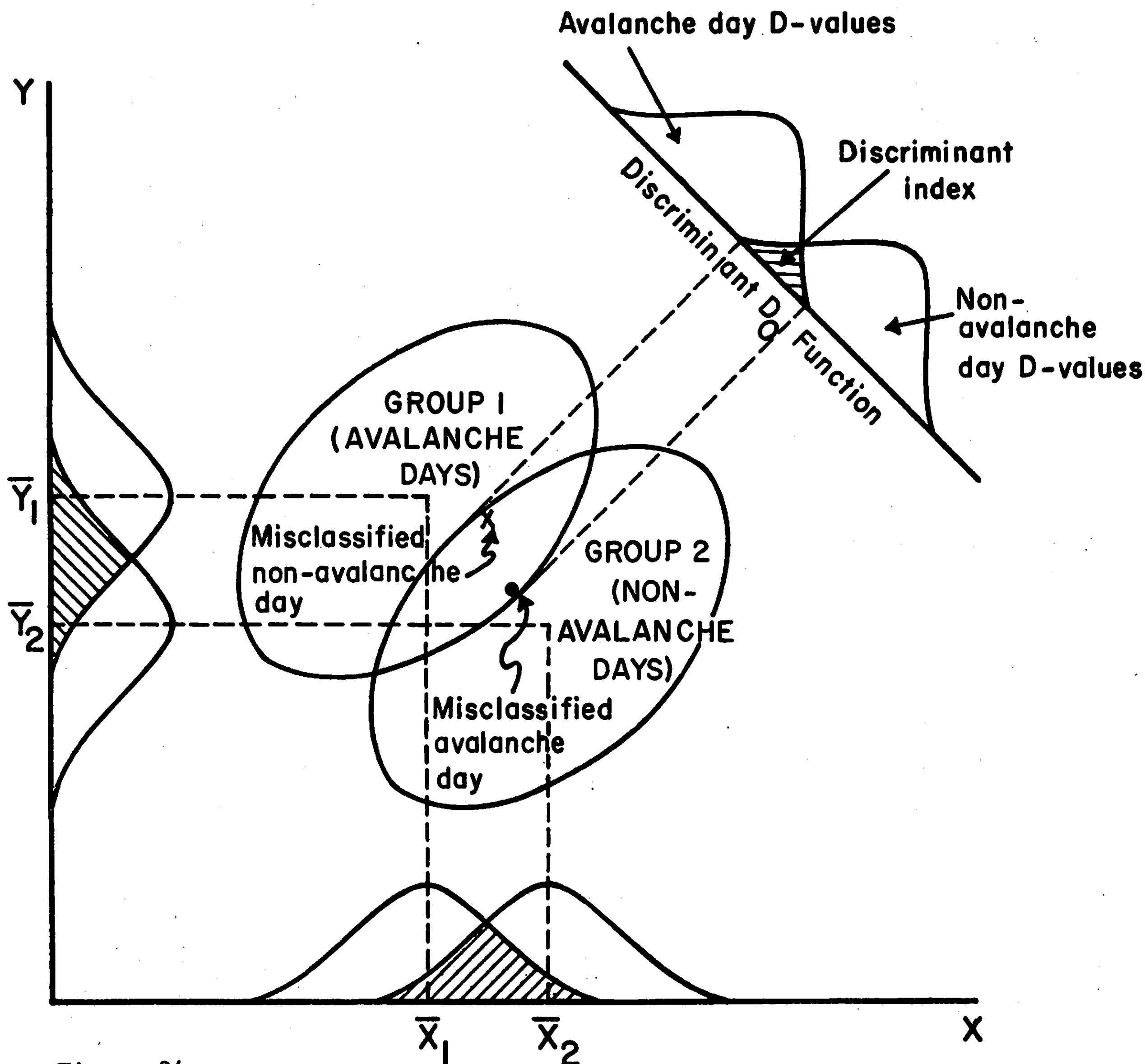
Method

In this chapter, the avalanche season is defined by the first and last recorded occurrences along Station 152. Both avalanche and non-avalanche days are operationally confined to this period. Within each of the two seasons considered, dry avalanche and wet avalanche periods are defined by the transition (usually abrupt in the San Juan Mountains) from dry to wet slides, based on the U.S. Forest Service slide classification. This partition of the avalanche season should be important in forecasting since the two types of slide appear to depend on different antecedent meteorological and snowpack conditions (see Results).

The forecast method discussed here is similar to those presented by Judson and Erikson (1973) and Bois, Obled and Good (1974) in that it is based on linear discriminant functions computed from several meteorological and snowpack variables, measured on sets of avalanche and non-avalanche days. By hypothesis, the sets are regarded as mutually exclusive and a prime purpose of the analysis is to select variables which provide an optimal separation of the two sets. The basic principle is illustrated in Figure 24 for a two-group, two-variable case.

The method presented here differs from those cited above in two important respects: (1) a stratification of events on the basis of magnitude is carried out in both the dry and wet seasons (Table 11); (2) meteorological and snowpack parameters are integrated over varying time periods prior to an event or non-event date (Table 12). The input variables listed in Table 12 are based on data from the Red Mountain Pass site (precipitation, air and snow temperatures) and the Point 12,325 site (wind speed). This choice reflects the need for real-time data summaries in a forecast situation.

Stratification on the basis of magnitude provides a variable operational definition of an avalanche day although it is constrained by considerations of sample size as Table 11 indicates. The integration of measured parameters



Avalanche day D-values
Discriminant index
Discriminant D₀ Function
Non-avalanche day D-values
Y
X
GROUP I (AVALANCHE DAYS)
GROUP 2 (NON-AVALANCHE DAYS)
Misclassified non-avalanche day
Misclassified avalanche day
$\overline{Y}_1$
$\overline{Y}_2$
$\overline{X}_1$
$\overline{X}_2$

Figure 24.

TABLE 11

Stratification of avalanche events.

Stratum	1972-73		1973-74	
Dry Avalanches	N*	No. of variables	N*	No. of variables
1. All dry slides (natural and artillery releases)	60	9	28	13
2. Natural dry slides ≥ magnit. 2	60	9	25	13
3. Natural dry slides, at least 3 ≥ magnit. 2	17	9	11	13
4. Natural dry slides ≥ magnit. 3	13	9	7	13
Wet Avalanches				
5. All wet slides (natural and artillery releases)	24	9	12	9
6. Natural wet slides ≥ magnit. 2	17	9	8	9
7. Natural wet slides, at least 3 events ≥ magnitude 2	12	9	5	9
8. Natural wet slides ≥ magnit. 3	15	9	7	9

* Number refers to maximum of the three integration periods (i.e. 5 days, 3 days and 2 days prior to event or non-event date).

TABLE 12

Input Variables

Variable Number	Description
1	Total precipitation over an N^* day period prior to event or non-event date (mm water equivalent).
2	Total precipitation in period 1200 hrs. on day prior to event to 1200 hrs. on event date (mm water equivalent).
3	Maximum 6hr. precipitation intensity in period 1200hrs. on day prior to event to 1200hrs. on event date (mm wat.equiv.).
4	Mean 2hr. air temperature over an N^* day period prior to event or non-event date (^{o}C).
5	Mean 2hr. air temperature during same period as (2) above (^{o}C).
6	Maximum 2hr. air temperature in same period as (2) above (^{o}C).
7	Mean 6hr. wind speed over an N^* day period prior to event or non-event date (m/sec).
8	Mean 6hr. wind speed during same period as (2) above (m/sec).
9	Maximum 6hr. wind speed during same period as (2) above (m/sec).
10	Mean temperature gradient in snowpack, 2.5 - 5.0cm depth below surface, over an N^* day period prior to event or non-event date (^{o}C/m).
11	Mean snowpack temperature at depth 2.5cm below surface over an N^* day period prior to event or non-event date (^{o}C).
12	Mean snowpack temperature at depth 5.0cm below surface over an N^* day period prior to event or non-event date (^{o}C).
13	Snowpack temperature at depth 2.5cm below surface on day prior to event or non-event date (^{o}C).

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* N = 2, 3 or 5 days.

over variable time periods enables the length of the forecast period to be varied recursively to obtain an optimal value. In this study, periods longer than five days have not produced an improved separation of avalanche and non-avalanche days. This occurs because an integration period of, say, ten days, is longer than the time interval between many avalanche days so that the values of variables 1, 4, 7, 10, 11, and 12 (Table 12) will be approximately the same for avalanche and non-avalanche days when this time step is used.

The integration of variables over different time steps is performed by a routine which requires that the raw input variables (e.g., the two-hour precipitation and air temperature data) reside temporarily on separate mass-storage files, within which calendar months are demarcated by logical records. For each of the three time steps (the 2, 3 or 5 days preceding the day in question), a set of variables is computed for each day in a chronologically ordered sequence of avalanche and non-avalanche days (Figure 25). The latter set is generally the longer one and is reduced to approximately the same length as the "avalanche set" by random sampling, as suggested by Bois, Obled and Good (1974). Cases with missing data are then eliminated from each set to create a single file suitable for input to a discriminant analysis program.

Stepwise discriminant analysis is performed first using program BMD 07M, from the BMD Series, University of California, Berkeley. The program is used to define a set of input variables, S, which make significant contributions to the discriminant process. Significance testing is based on the value of an F-statistic

$$F = \frac{(N - 2 - r + 1)n_1 n_2}{r(N - 2)(n_1 + n_2)} \cdot D^2 \qquad (1)$$

where N is the total number of cases (n_1 from Group 1, n_2 from Group 2), r is the number of variables and D^2 the square of the Mahalanobis distance between the two multivariate group means. Following this, a discriminant value (D-value) is assigned to each case in each group from a linear combination of the variables in S and a discriminant index, D_0 (Figure 24) is computed from:

$$D_0 = \frac{1}{2} \sum_{i=1}^{r} \lambda_i \, (\bar{A}_i + \bar{B}_i) \qquad (2)$$

where λ_i is the ith coefficient of the discriminant function and $\bar{A}_i$, $\bar{B}_i$ are the mean values of variable i over groups A and B. As Figure 24 indicates, D_0 may be used to classify a future date as either an avalanche or a non-avalanche day by computing a D-value from:

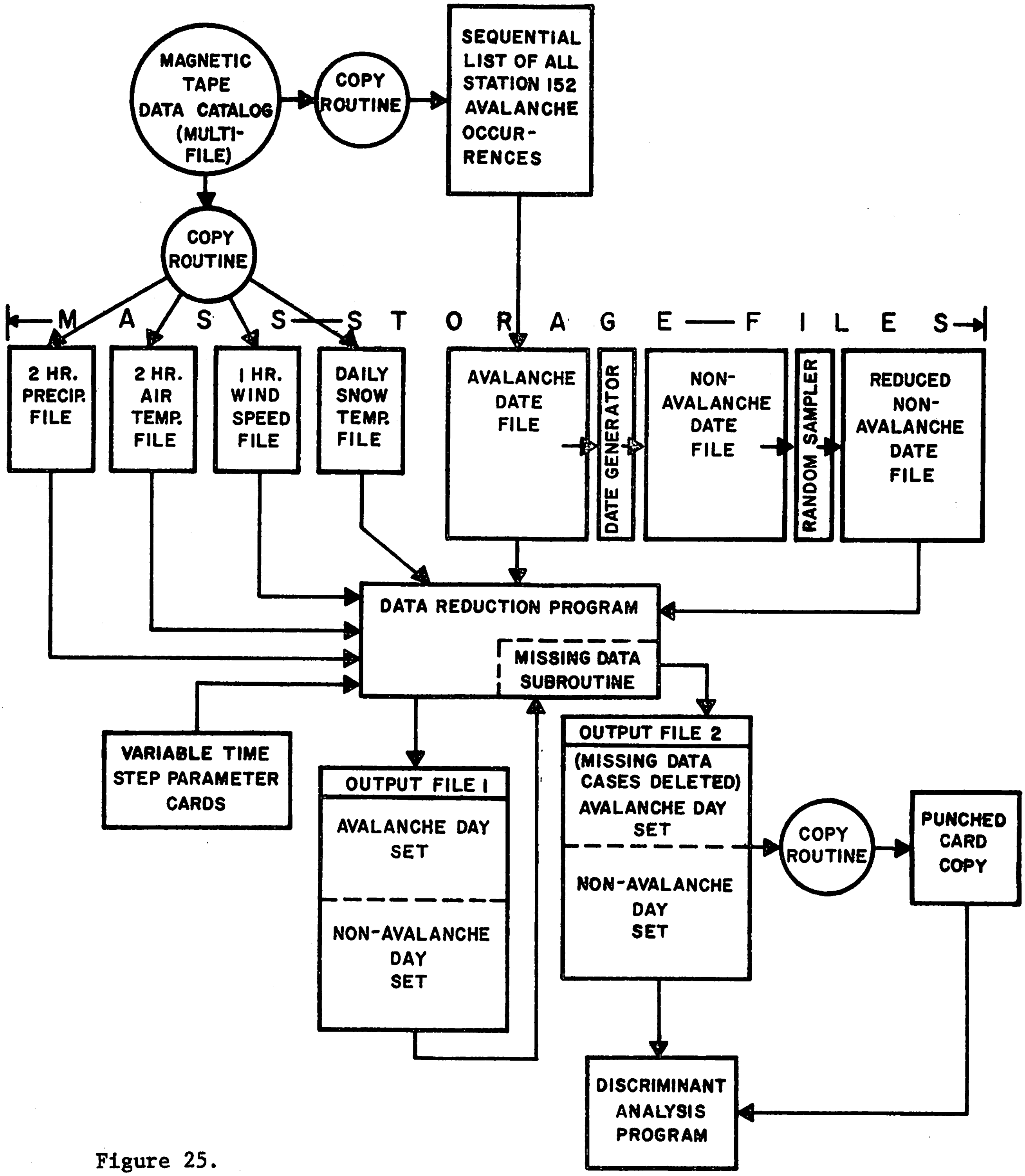

MAGNETIC TAPE DATA CATALOG (MULTI-FILE)
COPY ROUTINE
SEQUENTIAL LIST OF ALL STATION 152 AVALANCHE OCCURRENCES
COPY ROUTINE
MASS STORAGE FILES
2 HR. PRECIP. FILE
2 HR. AIR TEMP. FILE
1 HR. WIND SPEED FILE
DAILY SNOW TEMP. FILE
AVALANCHE DATE FILE
DATE GENERATOR
NON-AVALANCHE DATE FILE
RANDOM SAMPLER
REDUCED NON-AVALANCHE DATE FILE
DATA REDUCTION PROGRAM
MISSING DATA SUBROUTINE
VARIABLE TIME STEP PARAMETER CARDS
OUTPUT FILE 1
AVALANCHE DAY SET
NON-AVALANCHE DAY SET
OUTPUT FILE 2
(MISSING DATA CASES DELETED)
AVALANCHE DAY SET
NON-AVALANCHE DAY SET
COPY ROUTINE
PUNCHED CARD COPY
DISCRIMINANT ANALYSIS PROGRAM

Figure 25.

$$D = \lambda_1 X_1 + \lambda_2 X_2 + \ldots + \lambda_r X_r \tag{3}$$

where the λ terms are estimated from a previous set of avalanche and non-avalanche days and the X-values are input variables such as those listed in Table 12. In a forecast situation, the λ terms are treated as fixed constants and the X-values are measured on a real-time basis.

In this analysis the 1973-74 data have been used where possible, as an independent set to test the efficiency of the 1972-73 season discriminant functions computed from various sub-sets of events (see Efficiency of the Forecast Method). This type of test is sensitive to between-season differences in the frequency and types of avalanche occurrences, so that a model based on a 1972-73 type of season might not serve as an efficient forecast tool during a 1971-72 type of season. With the acquisition of more data in subsequent seasons, the reliability of the forecast method should improve, as a greater range of conditions is incorporated into the discriminant analysis.

Results

The results of the discriminant analysis for the 1972-73 and 1973-74 seasons are presented under separate sub-headings. This reflects the decision to make no a priori assumptions of similarity between the two seasons. An assessment of similarity is made in Section 4.

1972-73 season: Results for this season are summarized in Tables 13, 14 and 15. Variable numbers correspond to those in Table 12 and are listed in their order of entry into the discriminant function. Two criteria are used to terminate the list: (1) the F-value for the significance of group separation falls below the one-percent level; (2) the addition of significant variables does not improve group separation. In instances where no variable entered produces a significant group separation at the one-percent level, the first three that are significant at the five-percent level are shown. The percentages of misclassified days in columns five and six refer to the number of D-values from, say, Group 1, that lie on the Group 2 side of the discriminant index (Figure 24).

Comparisons based on the first four strata of Table 1 are summarized in Table 3. In each case, variables are integrated over five-, three- and two-day periods prior to each event or non-event date. In line 1 of Table 13, an avalanche day is defined very broadly by the occurrence of at least one slide of any magnitude on Station 152, irrespective of whether releases were natural or triggered by artillery. The high (≅ 50) percentage of avalanche days misclassified in the first three lines of Table 13 is probably due to assigning equal weights to all avalanche days. For example, many of the 60 avalanche days in line 1 involved only one event, whereas others had ten or more. The importance of maximum 6-hour precipitation

TABLE 13

Summary of discriminant analysis: dry slides, 1972-73.

Comparison	No. of days prior	Order of entry of variables	Percentage of days misclassified: Avalanche days	Non-events
1. All dry slides vs. non-events (N=60,57)	5	3, 4, 5, 6	53	19
2. Same (N=58,57)	3	3, 1, 5, 4, 6	45	30
3. Same (N=60,58)	2	3, 5, 6, 4, 1	48	28
4. Dry natural slides ≥ 2* vs non-events (N=60,57)	5	3, 4, 5, 6	53	19
5. Same (N=58,57)	3	3, 1, 5, 4, 6	45	30
6. Same (N=60,58)	2	3, 5, 6, 4, 1	48	28
7. Dry natural slides ≥ 3 events ≥ 2* (N=17,17)	5	2**, 9**, 7**	53	18
8. Same (N=17,17)	3	2**, 1**, 4**	38	13
9. Same (N=17,17)	2	2**, 9**, 7**	53	6
10. Dry natural slides ≥ 3* (N=13,13)	5	8, 1, 3, 9	23	8
11. Same (N=13,13)	3	8, 2, 5	38	8
12. Same (N=13,13)	2	8, 2, 5	31	8

* Refers to slide magnitudes on an ordinal scale of 5

** $F_{.95} < F < F_{.99}$ Absence of a double asterisk indicates $F > F_{.99}$

intensity (variable 3, Table 12) is indicated in each of the three time steps. The optimum separation of avalanche and non-avalanche days is achieved by a three-day integration of meteorological variables, with total water equivalent prior to the event date being of "secondary" importance. (A strict physical significance cannot be assigned to the ordinal position of a variable since its inclusion at a given step of the discriminant process is contingent upon the variables already included in the discriminant function.)

The sample of days with events of magnitude greater than or equal to two contains the same dates as lines 1-3; accordingly, the results are identical. The operational definition of avalanche days on the basis of at least three natural events of magnitude two or greater (lines 7-9, Table 13) reduces the bias caused by assigning an equal weight to days irrespective of the number of occurrences. Also artillery releases are excluded that might not be easily predicted from the same linear combination of antecedent weather conditions used to predict natural releases. None of the time steps produce significant separation of groups at the one-percent level but apart from the three-day integration, in which precipitation variables are again prominent, the degree of separation achieved is notably better than in the unstratified comparisons (lines 1-3).

In lines 10-12, stratification by days containing events greater than or equal to magnitude three gives an even better separation of the two groups although this is based on a reduced sample of only 17 avalanche days. Optimum separation is achieved at the five-day integration and suggests the wind re-distribution of snow in the 12-hour to 24-hour period preceding an event (variable 8) is an important physical cause of larger releases, particularly when combined with a high precipitation in the days prior to an avalanche day (variables 1, 2 and 3). Most of the snow falling during this period would be available for transportation since sintering and densification probably require a somewhat longer time.

The stratification of wet slides in Table 14 follows that in Table 13. Two significant differences between the two tables are evident: (1) sample sizes are generally smaller in Table 14 due to the shorter length of the wet slide season; (2) the degree of separation of event and non-event days is generally clearer in Table 14. In all but two of the comparisons in Table 14, antecedent air temperature (variables 5 and 6) is the first variable entered into the discriminant function (Table 12). As with dry avalanches, a stratification by magnitude improves group separation although at the expense of sample size. Under isothermal snowpack conditions, the mean and maximum 2-hour air temperature in the 12-hour to 24-hour period preceding an event appear to be the prime determinants of releases. These variables may provide an index of the quantity of free water in the snowpack and hence reduced cohesion. The secondary importance of precipitation over, in particular, the five and three-day integrations, suggests that releases are produced by a progressively increasing tangential shear stress applied to a

TABLE 14

Summary of discriminant analysis: wet slides, 1972-73.

Comparison	No. of days prior	Order of entry of variables	Percentage of days misclassified: Avalanche days	Percentage of days misclassified: Non-event days
1. All wet slides vs. non-events (N=22,10)	5	No significant F-values		
2. Same (N=24,10)	3	1,6	21	20
3. Same (N=24,11)	2	6, 1, 8, 9	21	18
4. Wet natural slides ≥ 2* vs non-events (N=17,10)	5	6**, 1**, 7**	18	25
5. Same (N=19,11)	3	6**, 1, 8	10	18
6. Same (N=19,11)	2	5**, 1, 4, 8	16	18
7. Wet natural slides ≥ 3 events ≥ 2* vs non-events (N=10,10)	5	5**, 9**, 8	10	20
8. Same (N=11,10)	3	5**, 1, 2	18	10
9. Same (N=11,11)	2	5**, 1, 8	0	0
10. Wet natural slides ≥ 3* vs non-events (n=13,10)	5	3, 8	8	30
11. Same (N=13,10)	3	6**, 1, 4	31	40
12. Same (N=14,11)	2	6**, 4**, 5**	14	18

*Refers to slide magnitudes on an ordinal scale of 5

** $F_{.95} < F < F_{.99}$ Absence of a double asterisk indicates $F > F_{.90}$

snowpack already weakened by the presence of interstitial meltwater.

The comparisons in Tables 13 and 14 are all based on avalanche versus non-avalanche days. As noted above, the dry and wet slide periods produce substantially different discriminant functions. This is re-inforced in Table 15, where the two groups are compared directly. In a real-time forecast situation, prediction could be seriously in error by applying the dry slide discriminant functions beyond the dry slide-wet slide transition date. Since this date appears to vary by as much as one month from year to year, both sets of discriminant functions should be applied from, say, March 1 until the onset of the wet slide cycle. The procedure is outlined in Figure 26, in which a non-avalanche forecast at step 3 implies either (1) wet slides are likely to occur; (2) neither dry nor wet slides are likely to occur. Alternatively, both the dry and wet slide functions could be used after March 1, irrespective of whether a non-avalanche forecast is made using the dry slide functions.

1973-74 season: The description of classification procedures, deletion of variables and the stratification of the avalanche season outlined in the 1972-73 sub-section apply also in this sub-section. The number of comparisons in Tables 16 and 17 are less than in the previous season due to a much smaller sample of avalanche days, particularly in the dry slide period (Table 11). The results of the unstratified comparison of dry slide and non-event days (lines 1-3, Table 16), are broadly similar to those in the previous season. Precipitation statistics in the 12-hour to 24-hour period preceding releases are again of prime importance in group separation. The percentage of misclassifications is notably lower in the 1973-74 season. These figures might have been higher had the sample of avalanche days been larger, since a wider range of conditions would have been encountered. The discriminant functions in Table 16 are based on thirteen variables compared to nine in the previous season (Table 12). The inclusion of snow temperature variables in the 1972-73 analysis would have caused many avalanche days to be deleted, due to the short snow temperature record in this season.

Unlike the 1972-73 season, the stratification of avalanche days on the basis of magnitude two (lines 4-6, Table 16) produces an improved separation of groups. Again, precipitation totals over the 12-hour to 24-hour period prior to an event are dominant and reflect the number of "direct-action" soft-slab releases within this season. Although the importance of variable 2 in the Table 16 comparisons can be related to slope loading, the interpretation of air temperature is less clear. Precipitation periods in this season are generally associated with a rise in air temperature due to synoptic factors and local latent heat releases. That the latter may be of lesser importance in determining air temperature changes is suggested by the low Pearsonian correlation between precipitation and air temperature variables. From a physical standpoint, a rise in air temperature concurrent with slope loading may increase the rate of secondary creep in new and old snow, providing that rapid densification and stabilisation have not already taken place.

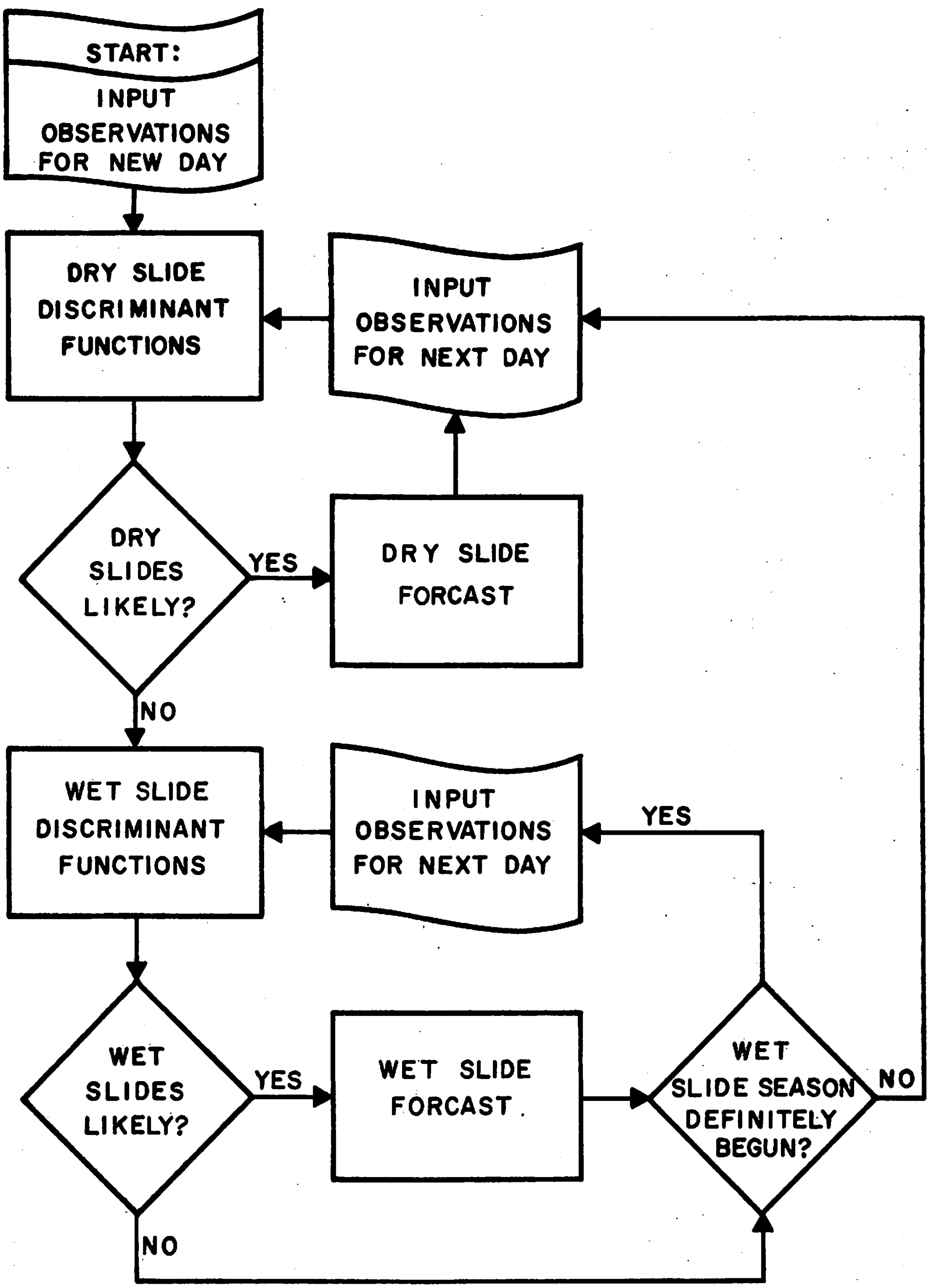

START:
INPUT
OBSERVATIONS
FOR NEW DAY
DRY SLIDE
DISCRIMINANT
FUNCTIONS
INPUT
OBSERVATIONS
FOR NEXT DAY
DRY
SLIDES
LIKELY?
YES
DRY SLIDE
FORCAST
NO
WET SLIDE
DISCRIMINANT
FUNCTIONS
INPUT
OBSERVATIONS
FOR NEXT DAY
YES
WET
SLIDES
LIKELY?
YES
WET SLIDE
FORCAST
WET
SLIDE SEASON
DEFINITELY
BEGUN?
NO
NO

Figure 26.

TABLE 15

Summary of discriminant analysis: dry and wet slides, 1972-73

Comparison	No. of days prior	Order of entry of variables	Percentage misclassified: Dry avalanche days	Percentage misclassified: Wet avalanche days
1. Dry slides vs. wet slides (N=30, 22)	5	4, 5	0	5
2. Same (N=30, 24)	3	5, 1	0	8
3. Same (N=30, 24)	2	5, 7	3	4

TABLE 16

Summary of discriminant analysis: dry slides, 1973-74

Comparison	No. of days prior	Order of entry of variables	Percentage of sample misclassified: Avalanche days	Percentage of sample misclassified: Non-event days
1. All dry slides vs. non-events (N=24, 30)	5	2, 4, 5, 12	37	17
2. Same (N=28, 32)	3	2, 4, 5	46	12
3. Same (N=28, 32)	2	2, 8, 4	39	10
4. Dry natural slides ≥ 2* vs. non-events (N=21, 30)	5	2, 4, 5, 12	28	13
5. Same (N=25, 32)	3	2, 4, 5, 13	36	13
6. Same (N=25, 32)	2	2, 8, 7, 4	32	9
7. Dry natural slides ≥ 3 events ≥ 2*		Insufficient sample size		
8. Dry natural slides ≥ 3*		Insufficient sample size		

* Refers to slide magnitudes on an ordinal scale of 5

This assertion is supported by the observed temperature dependence of the strain rate and elastic moduli of snow (Bader, 1962, p. 31; Mellor, 1968, p. 28).

Only one set of comparisons is possible for wet slides (Table 17) since in other stratifications of days, the number of cases is less than the number of variables (Table 11). No physical significance can be attached readily to variable 8 (mean wind speed during preceding 24 hours) in the three time integrations in Table 17 since its average value is lower over the avalanche day group, indicating a higher wind-loading potential for non-avalanche days in this instance. Although the separation of groups is clearer than in lines 1-3 in Table 14, the figures in column five might have been larger in a larger sample of events, since a greater range of conditions would exist, with a commensurate increase in the probability of misclassification on any given day.

The direct comparison of dry and wet slide days in Table 18 in large measure reproduces the results of the previous season and underlines the need to test both the dry and wet slide prediction equations near to the transition date.

Efficiency of the Forecast Method

The use of an empirically-derived forecast model assumes that a broad similarity in avalanche controls exists from year to year. The assumption is tested here by using the 1973-74 data as a test set for the 1972-73 discriminant functions. The test only partly simulates a real-time forecast situation since the status of days in the test season is known.

In most of the dry slide comparisons in Table 19, non-avalanche days are predicted more accurately than avalanche days. Although the test samples in lines 7-9 are small, the prediction of days with at least three slides of magnitude two or greater is seen to be much more accurate than the predictions in lines 1-3 and 4-6. Also indicated in Table 19 is the number of misclassified dry avalanche days on which either one or two events occurred along Station 152. This is expressed as a percentage of the total dry avalanche day sample. When allowance is made for misclassification of these avalanche days, the discriminant functions are seen to function satisfactorily on days containing several avalanche events. The 1972-73 dry slide discriminant functions are useful for evaluating avalanche hazard since major cycles which pose a threat to communications, are readily distinguished from non-avalanche days.

The prediction of wet slide days in the 1973-74 season is summarized in Table 20. The number of days misclassified is reduced sharply at the two-day integration. As noted in Table 19, a large percentage of the misclassifications occur on days having only one or two events. However, the number of non-avalanche days misclassified is large in both the three- and two-day integrations.

TABLE 17

Summary of discriminant analysis: wet slides, 1973-74

Comparison	No. of days prior	Order of entry of variables	Percent of sample misclassified: Avalanche days	Percent of sample misclassified: Non-avalanche days
1. All wet slides (N = 12,14)	5	8**, 2**, 5**	17	36
2. Same as above (N = 12,14)	3	8**, 2**, 5**	17	36
3. Same as above (N = 12,14)	2	8**, 2**, 5**	17	36
4. Wet natural slides $\geq$ 2*		Insufficient sample size		
5. Wet natural slides $\geq$ 3*		Insufficient sample size		

* Refers to slide magnitudes on an ordinal scale of 5

** $F_{.95} < F < F_{.99}$

TABLE 18

Summary of discriminant analysis: dry and wet slides, 1973-74

Comparison	No. of days prior	Order of entry of variables	Percentage of sample misclassified: Avalanche days	Non-avalanche days
1. Dry vs wet slides (N=15,12)	5	5, 2, 1, 5	0	0
2. Same (N = 15,12)	3	4, 9, 1	7	3
3. Same (N = 15,12)	2	4, 9, 1	13	8

TABLE 19

Prediction of 1973-74 dry avalanches

Comparison	No. of days prior	Percentage of days misclassified: Avalanche days	Avalanche days, ≤ 2 events	Non-events	Variables used
1. Dry slides non-events (N=24, 30)	5	37	25	27	3, 4, 5, 6
2. Same (N=28, 32)	3	36	21	22	1, 3, 4, 5, 6
3. Same (N=28, 32)	2	43	29	22	1, 3, 4, 5, 6
4. Dry slides, ≥ 2* vs. non-events (N=21, 30)	5	33	24	27	3, 4, 5, 6
5. Same (N=25, 32)	3	32	24	22	1, 3, 4, 5, 6
6. Same (N=25, 32)	2	40	28	22	1, 3, 4, 5, 6
7. Dry slides, ≥ 3 events ≥ 2* (N=11, 11)	5	0		27	2, 7, 9
8. Same (N=13, 13)	3	8		23	1, 2, 4
9. Same (N=13, 13)	2	8		15	2, 7, 9

TABLE 20

Prediction of 1973-74 wet avalanches

Comparison	prior	Percentage of days misclassified: Avalanche days	Avalanche days, ≤2 events	Non-events	Variables used
1. Wet slides vs. non-events (N=12, 14)	3	50	25	43	1, 6
2. Same (N=12, 14)	2	25	8	57	1, 6, 8, 9

*refers to slide magnitudes on an ordinal scale of 5

Conclusions

The results in the section on Efficiency of the Forecast Method show that a prediction of avalanche days in one season using functions derived from previous seasons requires a stratification of avalanche days by slide type and magnitude. The overall accuracy achieved in this prediction suggests that the forecast method is feasible in the San Juan area, and is most effective in forecasting days on which two or more occurrences are likely on Station 152. Also the results in the foregoing section indicate that the controls of avalanche release are similar from year to year. Although a strict physical interpretation cannot be placed on all the terms in the discriminant functions, they nevertheless serve as the basis for a real-time forecast using primarily meteorological variables.

Limitations of sample size have not allowed a stratification of events by individual slide paths as carried out by Judson and Erikson (1973), using a much larger sample of avalanche days. For the near future, the forecast will apply to the whole of Station 152. During the 1974-75 season, forecasting will probably be based on discriminant functions derived from the combined data of the 1972-73 and 1973-74 seasons. This should improve the forecast accuracy since such a prediction equation integrates conditions over two seasons instead of one, as in the foregoing section. An attempt will also be made to forecast occurrences on particular slide paths, on which instability presages a major avalanche cycle.

The coefficients of each discriminant function are listed in the Appendix together with the related discriminant index. A pocket calculator should suffice to calculate the values of variables selected from Table 12. The information in the Appendix is sufficient therefore, to allow a real-time avalanche forecast in the field, provided that real-time data summaries are available. A forecaster located at the Red Mountain Pass site would not possess real-time air temperature or precipitation data but could overcome this by taking frequent chart readings. Hopefully, future hardware modifications will permit real-time forecasts to be prepared for the San Juan area.

References

Bader, H., 1962. The physics and mechanics of snow as a material. U.S. Army CRREL Monograph II-B. 79 p.

Bois, Ph., Obled, Ch., and W. Good, 1974. Multivariate data analysis as a tool for day by day avalanche forecast. (Paper presented at the International Symposium on Snow Mechanics, Grindelwald, 1974. In press.)

Judson, A. and B. J. Erickson, 1973. Predicting avalanche intensity from weather data: a statistical analysis. USDA Forest Service Research Paper RM-112. 12 p.

Mellor, M., 1968. Avalanches. U.S. Army CRREL Monograph III-A3d. 213 p.

APPENDIX TO CHAPTER 6

Discriminant functions and discriminant indices based on combined 1972-73 and 1973-74 data.

The discriminant functions and indices for each stratification of events are listed separately under the headings Dry Slides and Wet Slides. A discriminant function is given for each stratum in the general form

$$D = C_1X_i + C_2X_j + C_3X_k$$

where D is the discriminant value of a particular day in the avalanche season, the C-terms are fixed coefficients and the X-terms are variables derived from real-time data summaries. The subscripts i, j, k, etc. refer to the variable numbers in Table 12. Note that these are always given in numerical order, but are not necessarily consecutive. The D-value is then compared with the discriminant index in the right-hand column, and a forecast is made from the relations:

$D > D_0$ implies a high probability of avalanche occurrence

$D < D_0$ implies a high probability of a non-event day

The discriminant functions are repeated for each of the three data integration periods discussed in Sections 2 and 3 of this chapter. All of the functions and indices are empirically derived and therefore, should not be applied outside of their particular stratum. Also, all coefficients and discriminant indices are based on the units of measurement in Table 12. No other units may be used with this set of equations and indices.

APPENDIX (cont.)

DRY SLIDES

Stratum	No. of days prior	Discriminant Function	Discriminant Index D_0
1. All dry slides vs. non-events (N=84, 87)	5	$D=.00166X_3-.00083X_4+.00055X_5$	.00642
2. Same (N=86, 89)	3	$D=.00024X_1+.00019X_2+.00111X_3-.00092X_4+.00096X_5$	.00550
3. Same (N=88, 90)	2	$D=.00149X_3+.00024X_8$	.00455
4. Dry natural slides ≥ mag.2 vs. non-events (N=82, 87)	5	$D=.00010X_1+.00159X_3-.00096X_4+.00078X_5$	.00713
5. Same (N=83, 89)	3	$D=.00020X_1+.00141X_3-.00094X_4+.00117X_5-.00022X_6$	.00356
6. Same (N-85, 90)	2	$D=.00157X_3+.00023X_8$	.00470
7. Dry natural slides, at least 3 events ≥ mag.2 vs. non-events (N=28, 28)	5	$D=.00091X_1+.00169X_2+.00518X_3-.00183X_4+.00158X_5$	.04155
8. Same (N=29, 31)	3	$D=.00153X_1+.00359X_2+.00202X_5$	.01740
9. Same (N=31, 34)	2	$D=.00131X_1+.00264X_2+.00192X_8$	.03338
10. Dry natural slides > mag.3 (N̄-18, 18)	5	$D=.00539X_2+.00583X_3+.00556X_5-.00385X_6$	.00582
11. Same (N=22, 22)	3	$D=.00491X_2+.00194X_5-.00410X_6+.00304X_8$	.03777
12. Same (N=22, 24)	2	$D=.00584X_2-.00583X_5+.01061X_8$	.14740

APPENDIX (cont.)

WET SLIDES*

Stratum	No. of days prior	Discriminant Function	Discriminant Index D_0
1. All wet slides vs. non-events (N=34, 24)	5	$D=.00081X_1+.01304X_2-.02036X_3+.00773X_5$	-.00257
2. Same (N=36, 24)	3	$D=.00332X_1+.00390X_2-.00573X_4+.01437X_5-.01058X_7$	-.04399
3. Same (N=36, 35)	2	$D=.00320X_1+.00280X_2-.00758X_4+.01599X_5$	.00578
4. Wet natural slides ≥ mag.2 vs. non-events (N=25, 24)	5	$D=.00065X_1+.00860X_6$	.04979
5. Same (N=27, 24)	3	$D=.00308X_1+.00809X_5+.00373X_6$	.02214
6. Same (N=27, 25)	2	$D=.00393X_1-.00738X_4+.01664X_5$	.00075
7. Natural wet slides ≥ mag.2 vs. non-events (N=17, 24)	5	$D=.00133X_4+.00864X_5+.00426X_6$	.01044
8. Same (N=17, 24)	3	$D=.00394X_1-.00486X_4+.01929X_5$	.00065
9. Same (N=18, 25)	2	$D=.00457X_1-.00663X_4+.02071X_5$	-.00419

*The strata for "at least 3 events ≥ magnitude 2" are missing due to insufficient sample sizes.

ACKNOWLEDGMENTS

We would first like to acknowledge the contribution of the field team to the overall research efforts of 1973-1974. Without the hard work and constant contributions of Rod Newcomb, Don Bachman, Betsy Vesselago and Imants Virsnieks this report could not have been produced. Rod Newcomb has provided most of the snow structure data collected over the three-year period. The acquisition of fracture line profiles requires considerable physical energy as well as skillful over-snow travel in hazardous areas. Rod is responsible for 80% of all the fracture line profiles collected. Phil Laird acted as Rod Newcomb's assistant for three months during the winter and made significant contributions to general data acquisition and reduction.

At INSTAAR on the Boulder campus, Claudia Van Wie provided valuable liaison between Silverton and the University and made significant contributions to the initial efforts regarding statistical analysis of snow structure and climatic data. John Clark provided continued advice as well as direct assistance in the installation, maintenance, and repair of various instrumentation systems. Marilyn Joel undertook all the drafting.

The assistance provided this project by Nel Caine, both through creative suggestions relating to field procedure as well as assistance in the review of manuscripts is greatly appreciated. In addition, Nel Caine made specific contributions towards establishing statistical methods for data analysis.

We would like to thank our consultants, Dr. Malcolm Mellor, for his continued advice and assistance in snow mechanics problems, and Dr. Wilford Weeks for his suggestions concerning the statistical analysis of project data.

Additional thanks go to personnel of the Colorado Department of Highways; specifically Tuffy Foster, Noel Peterson,and Ray Ledford, who provided valuable avalanche occurrence data and promoted cooperation and mutual data exchange during periods of artillery control.

We would also like to express our appreciation for the interest in avalanche safety demonstrated by San Juan County Sheriff Virgil Mason and his deputy, John "Scotty" Jackson through their continued efforts to organize and conduct annual avalanche training schools in Silverton.

We apologize for a belated thanks to Fred Johnson whom we neglected to acknowledge in the 1973 Interim Report, for providing avalanche occurrence data for the area between Silverton and Coal Bank Hill for a significant portion of that winter.

The cooperation which has evolved between the San Juan Avalanche Project and the U.S.F.S. West Wide Avalanche Data Network Project, and specifically Arthur Judson, is gratefully acknowledged.

Olin Foehner, Bureau of Reclamation project monitor, has provided constant support and administrative advice throughout the project.

APPENDIX 1

FRACTURE LINE PROFILES

The following crystal-type symbols are used:

Unmetamorphosed New Snow

+	No Wind Action
→	Wind Action
V	Surface Hoar

Equi-temperature Metamorphism

λ	Beginning	Decreasing Grain Size
⁄	Advanced	
•	Beginning	Increasing Grain Size
o	Advanced	

Temperature-gradient Metamorphism

□	Beginning
Λ	Partial
Δ	Advanced

Melt-Freeze Metamorphism

~	Sun Crust

Layer Hardness

VS	Very Soft
S	Soft
MH	Medium Hard
H	Hard
VH	Very Hard

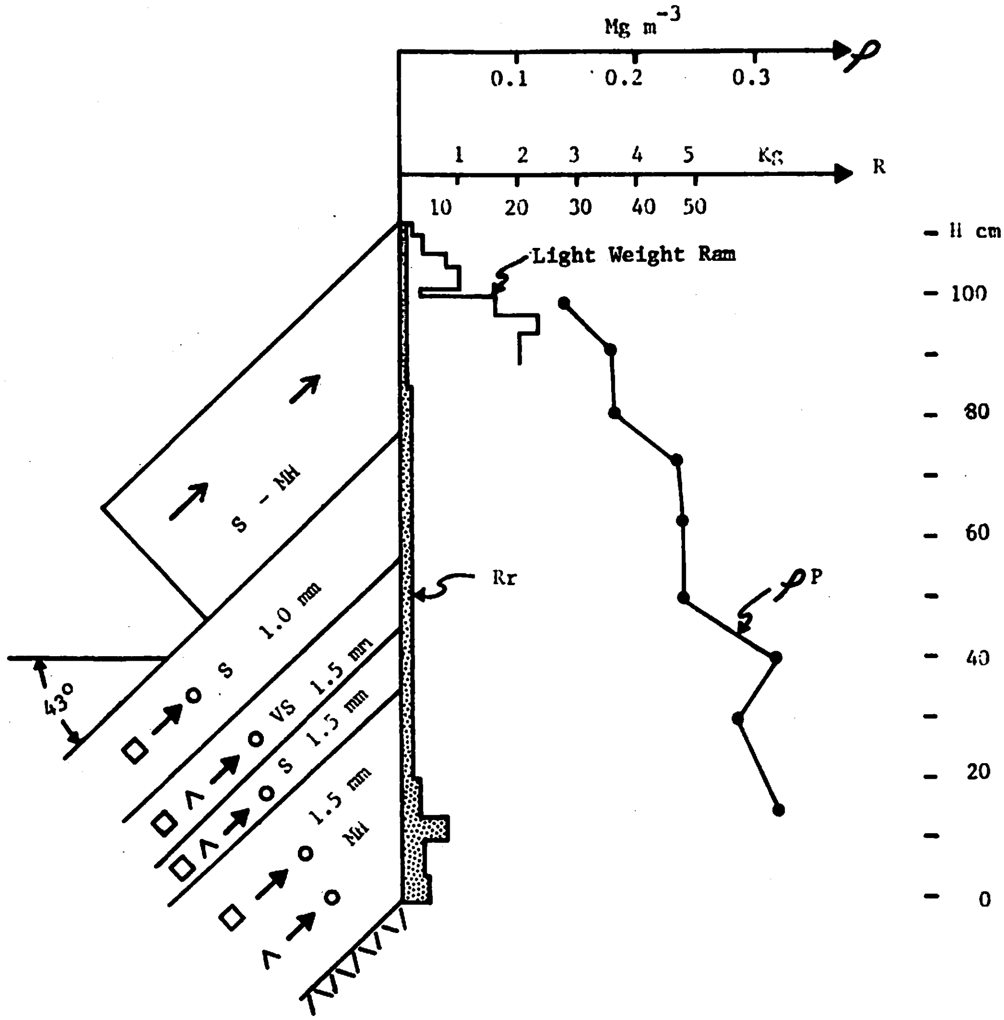
Crystal Size

Provided as diameter in mm; e.g. 1.0-1.5 mm

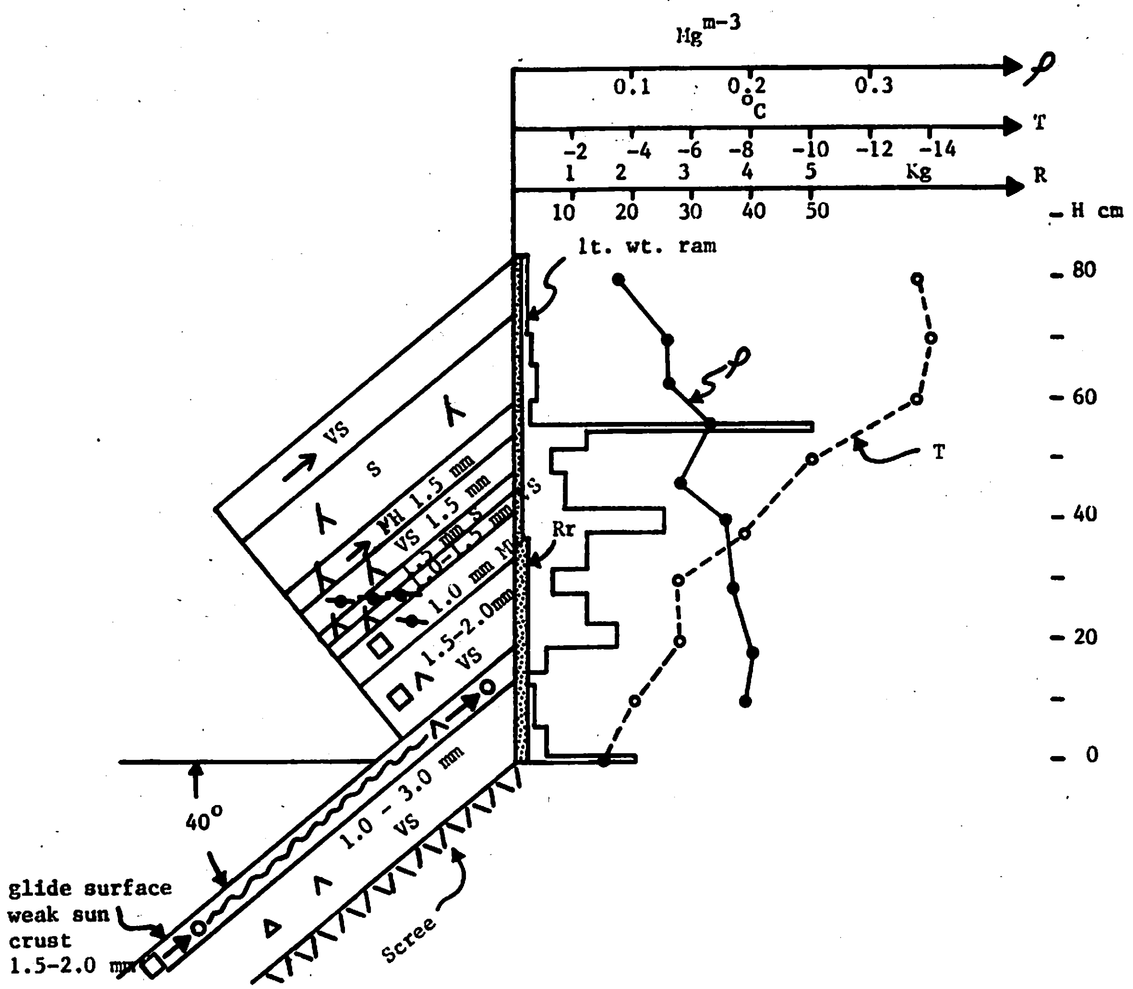
→ Indicates transition between two crystal types.

FRACTURE LINE PROFILE #1

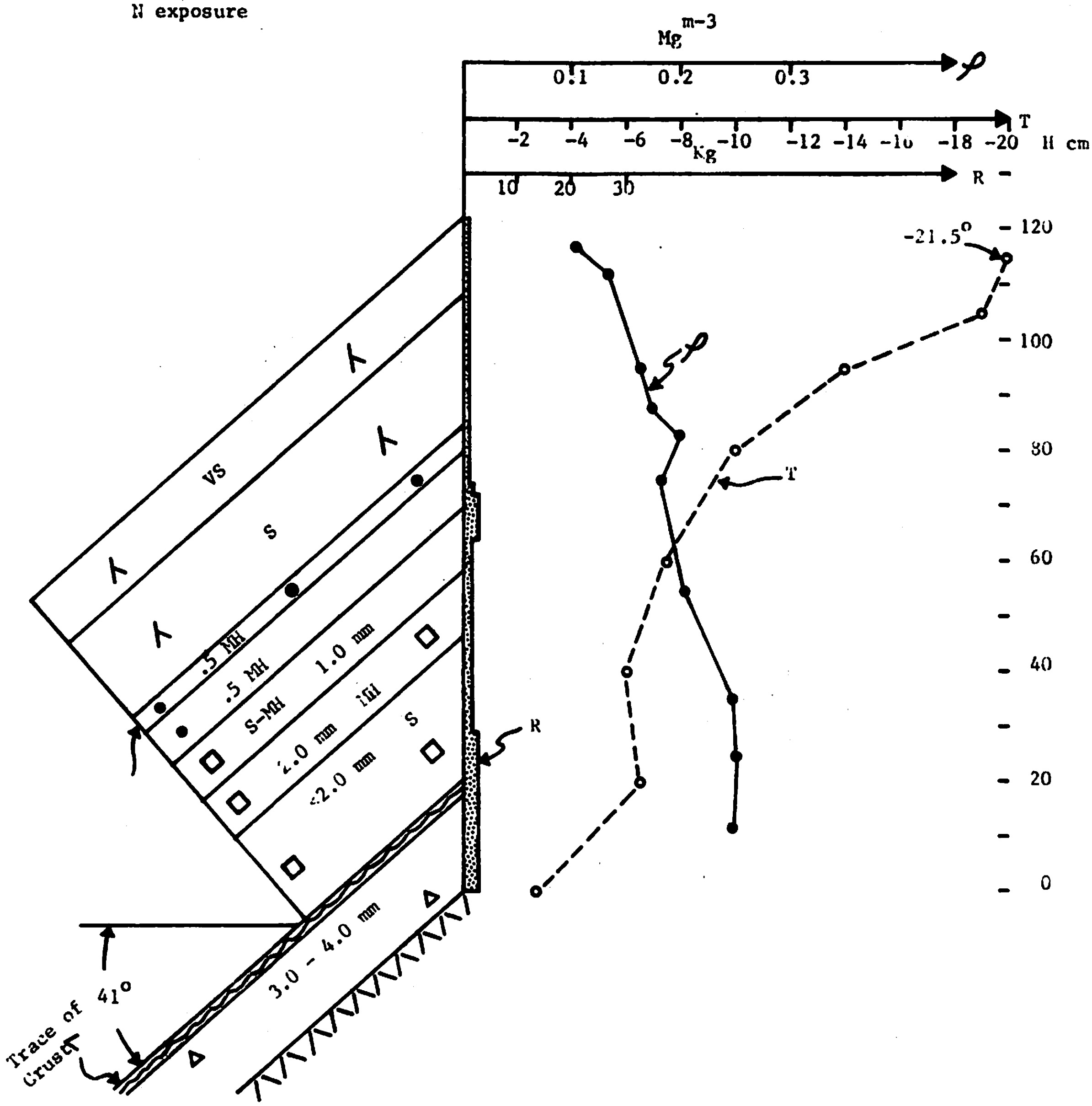
Willow Swamp Shoulder
December 28, 1973
SS-N-2-0 (Dec. 28, 1973)
3400 m elevation
E N E exposure



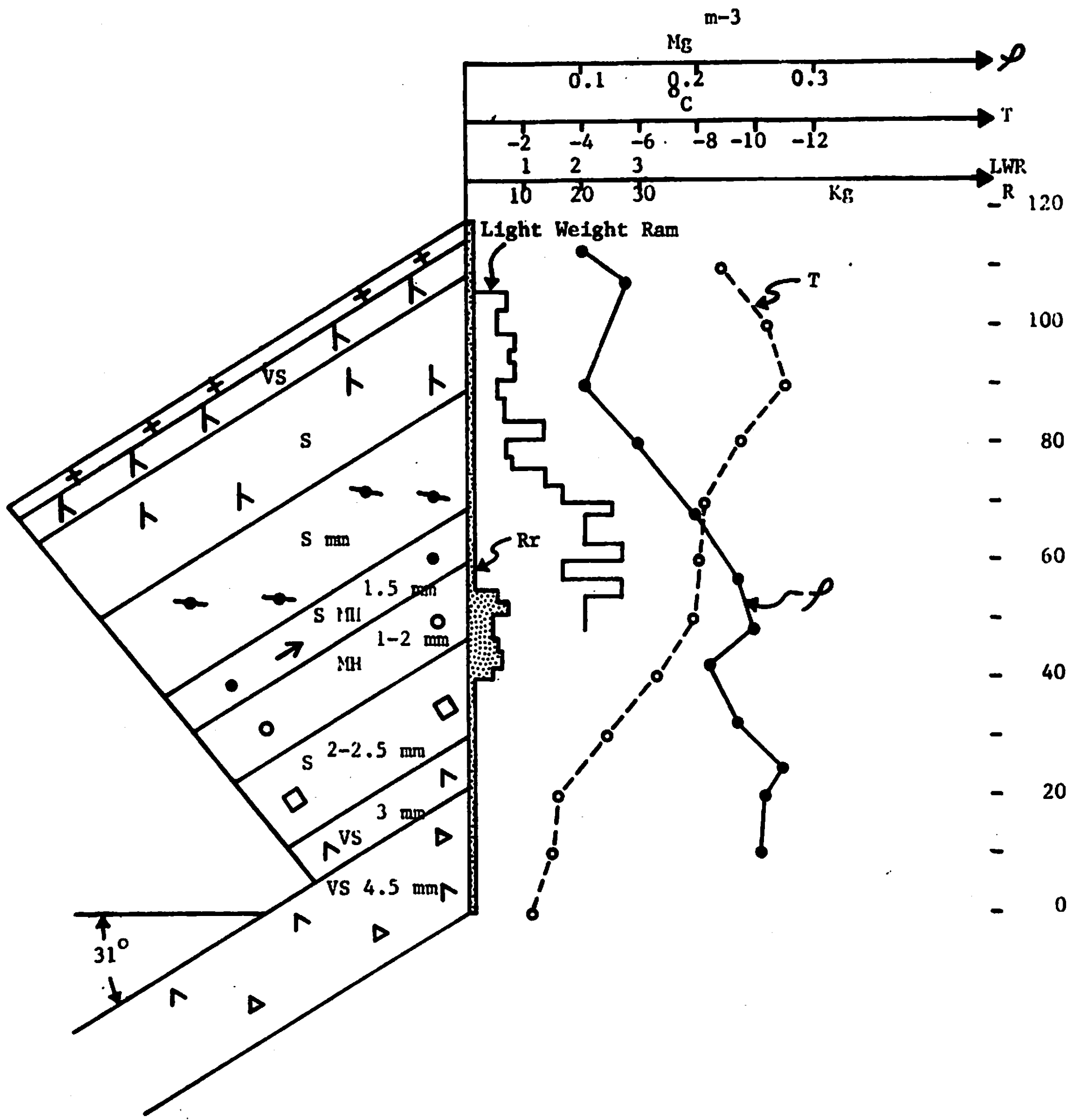
FRACTURE LINE PROFILE #2
Brooklyns E
December 31, 1973
SS-AA-2-OG (Dec. 31, 1973)
3400 m elevation
W exposure



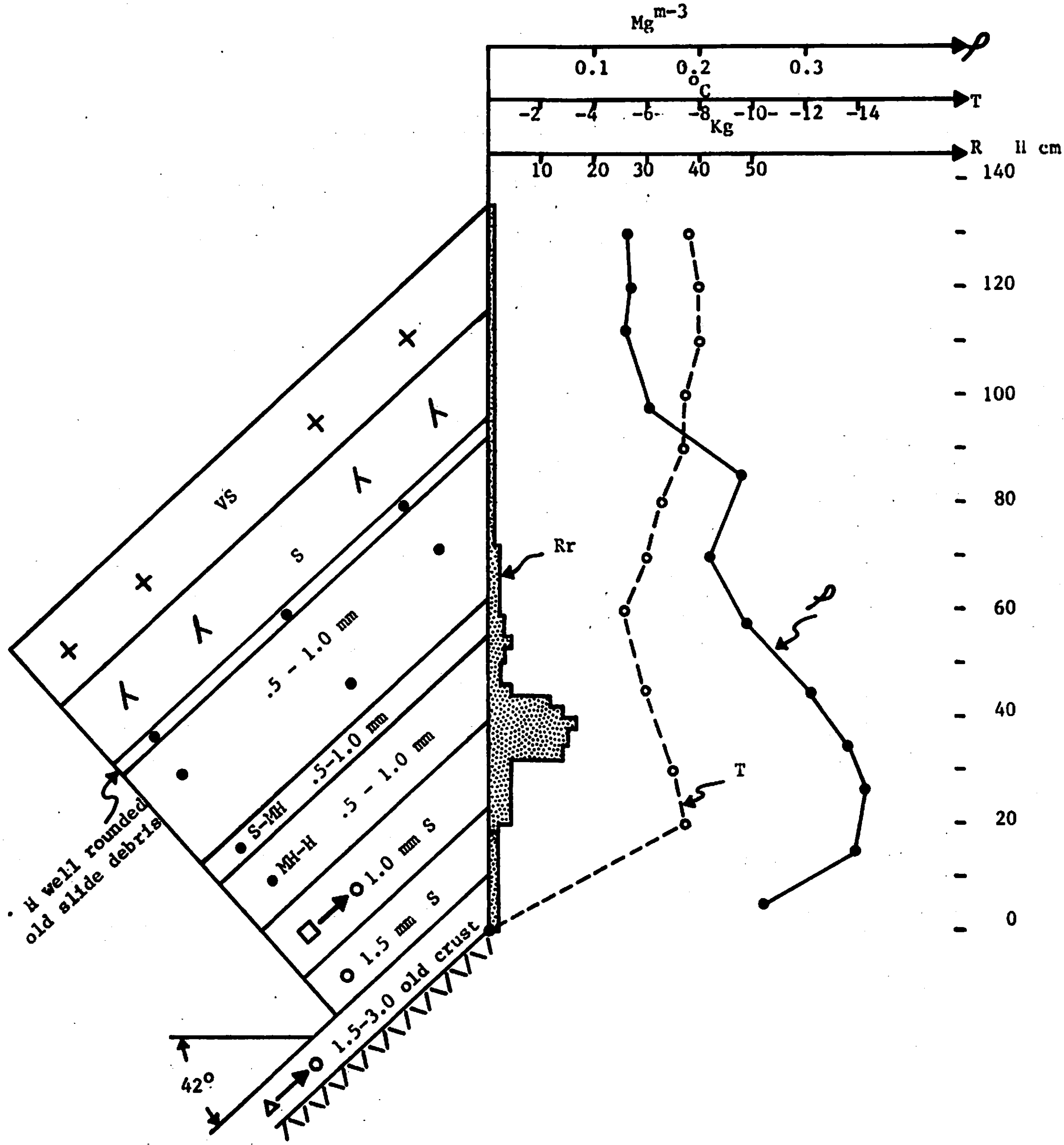
FRACTURE LINE PROFILE #3
North Carbon Test Slope
January 3, 1974
SS-AE-3-OG (Jan. 3, 1974)
3500 m elevation
N exposure



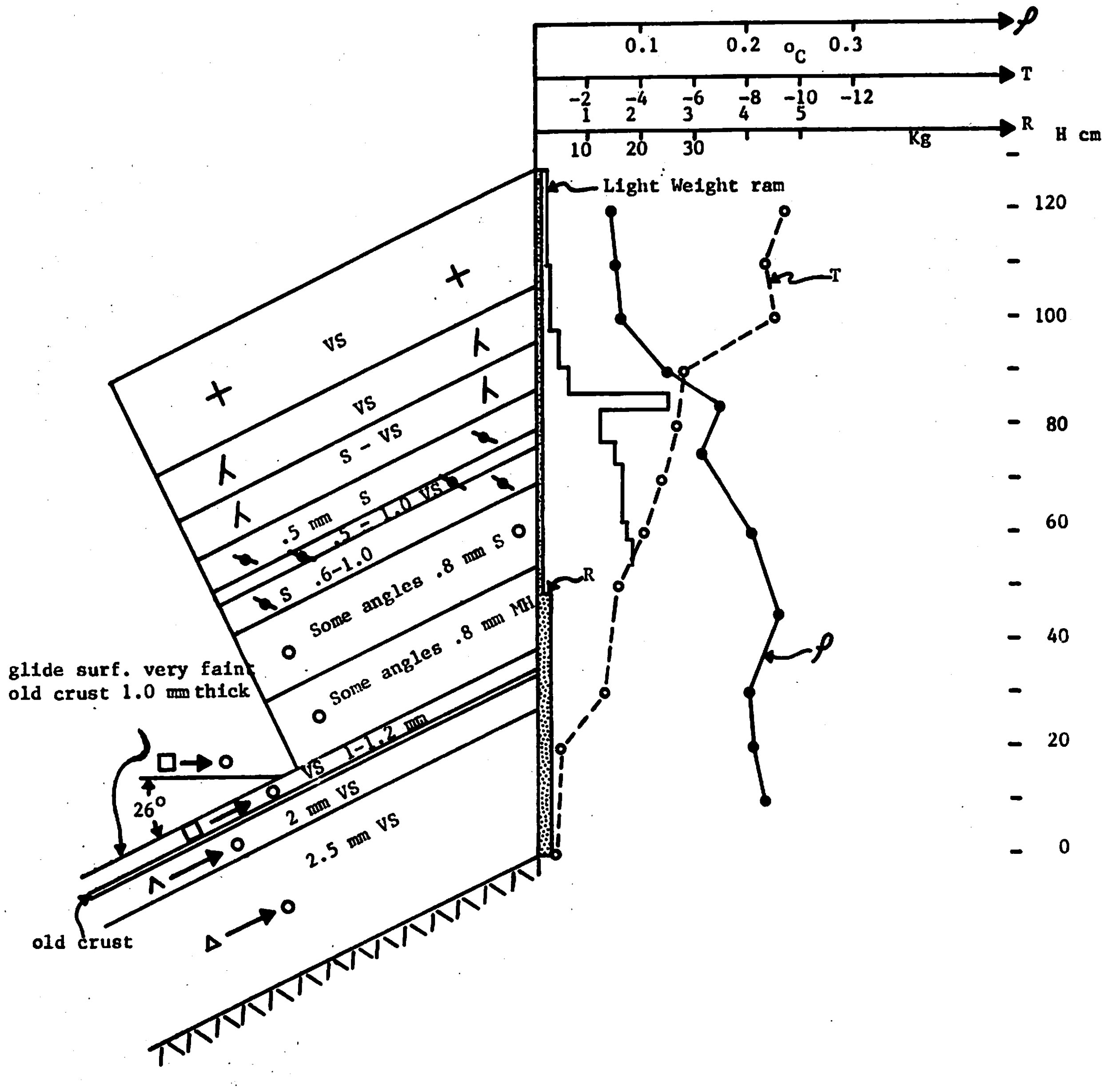
FRACTION LINE PROFILE #4
Silver Ledge Mine
January 7, 1974
SS-AA-3-OG (Jan. 7, 1974)
3350 m elevation
ENE exposure



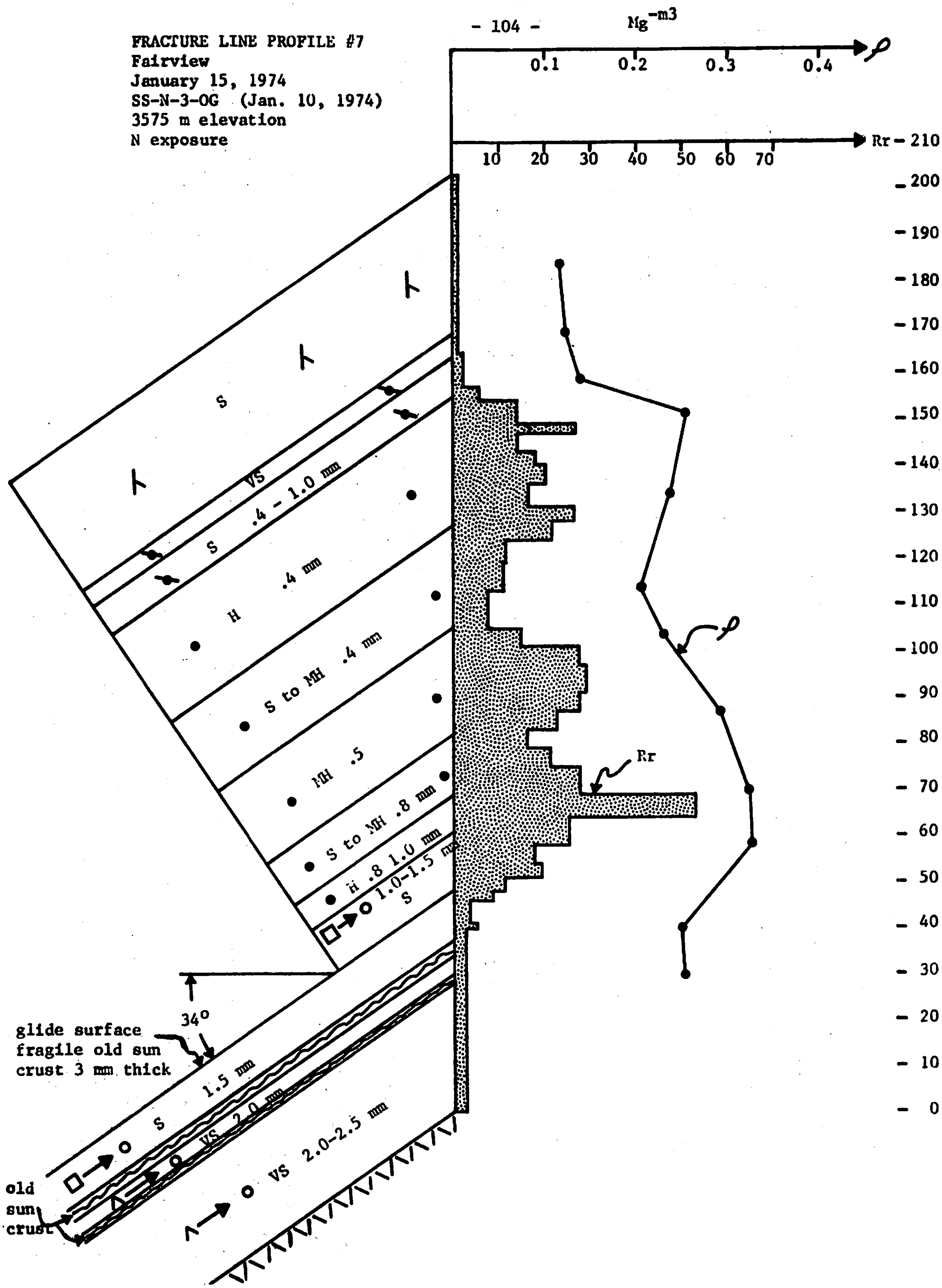
FRACTURE LINE PROFILE #5
Willow Swamp Shoulder
January 8, 1974
SS-N-3-OG (Jan. 8, 1974)
3400 m elevation
ENE exposure



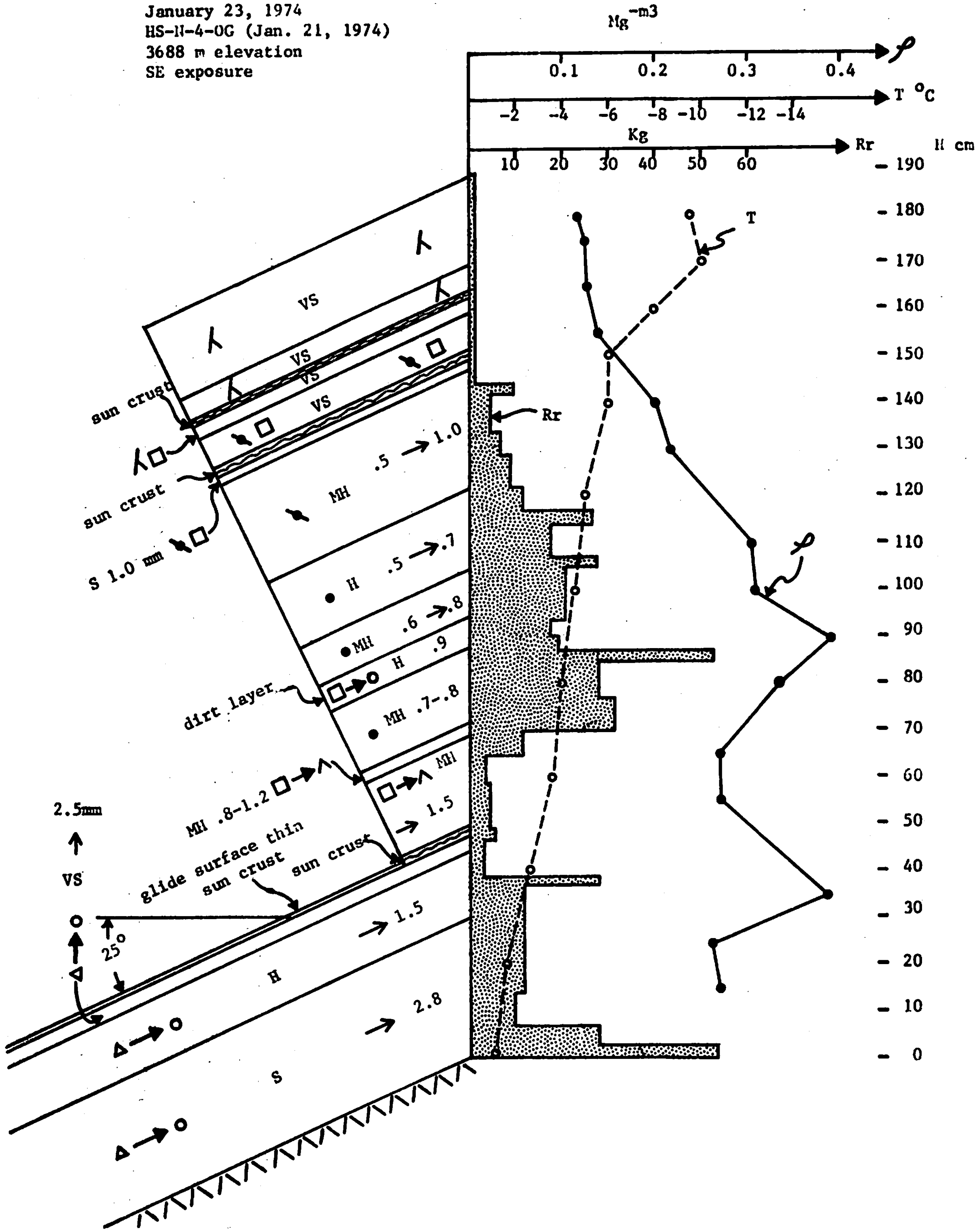
FRACTURE LINE PROFILE #6
Cement Creek - Bunker Hill
January 9, 1974
SS-N-2-OG (Jan. 9, 1974)
3000 m elevation
ESE exposure



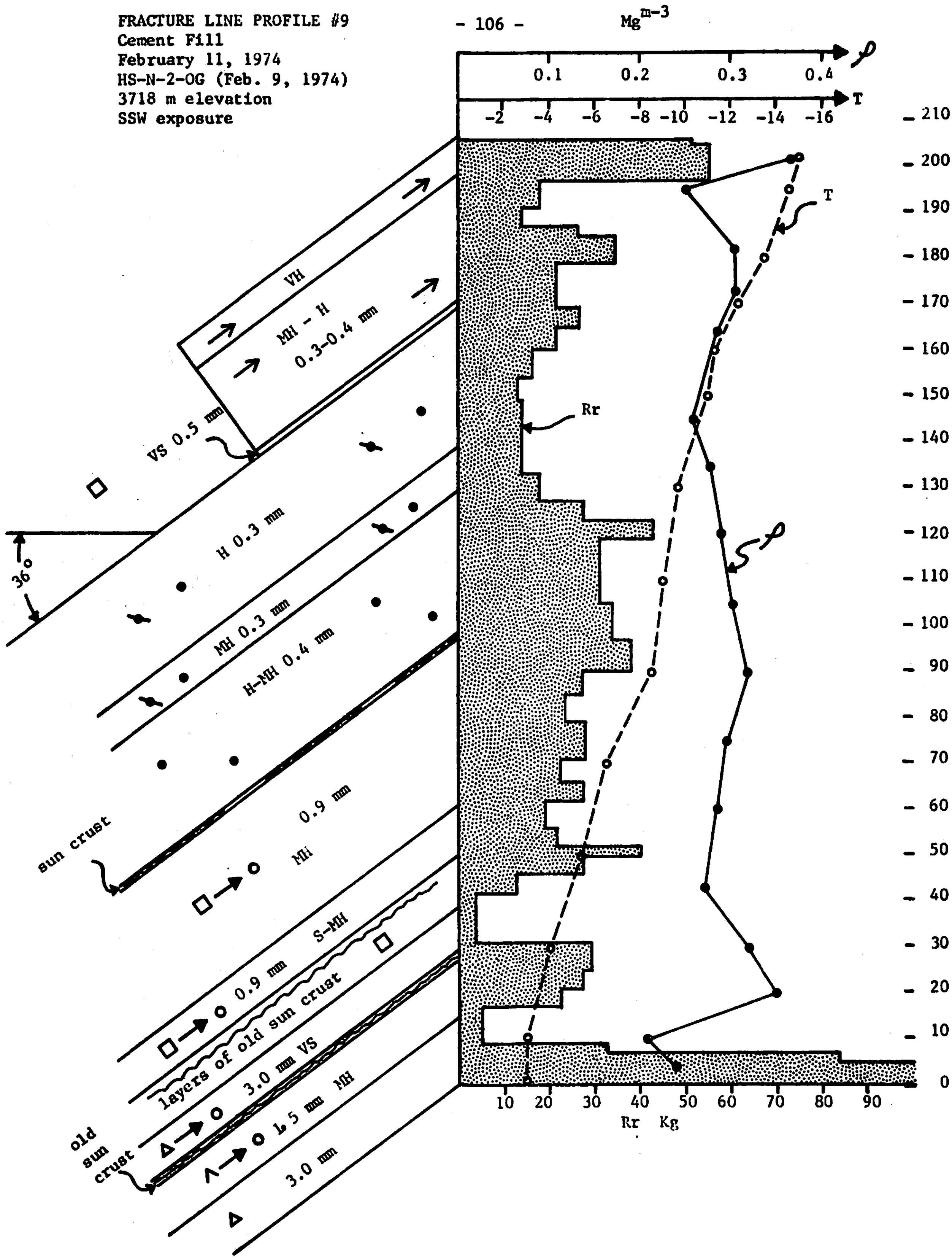
FRACTURE LINE PROFILE #7
Fairview
January 15, 1974
SS-N-3-OG (Jan. 10, 1974)
3575 m elevation
N exposure



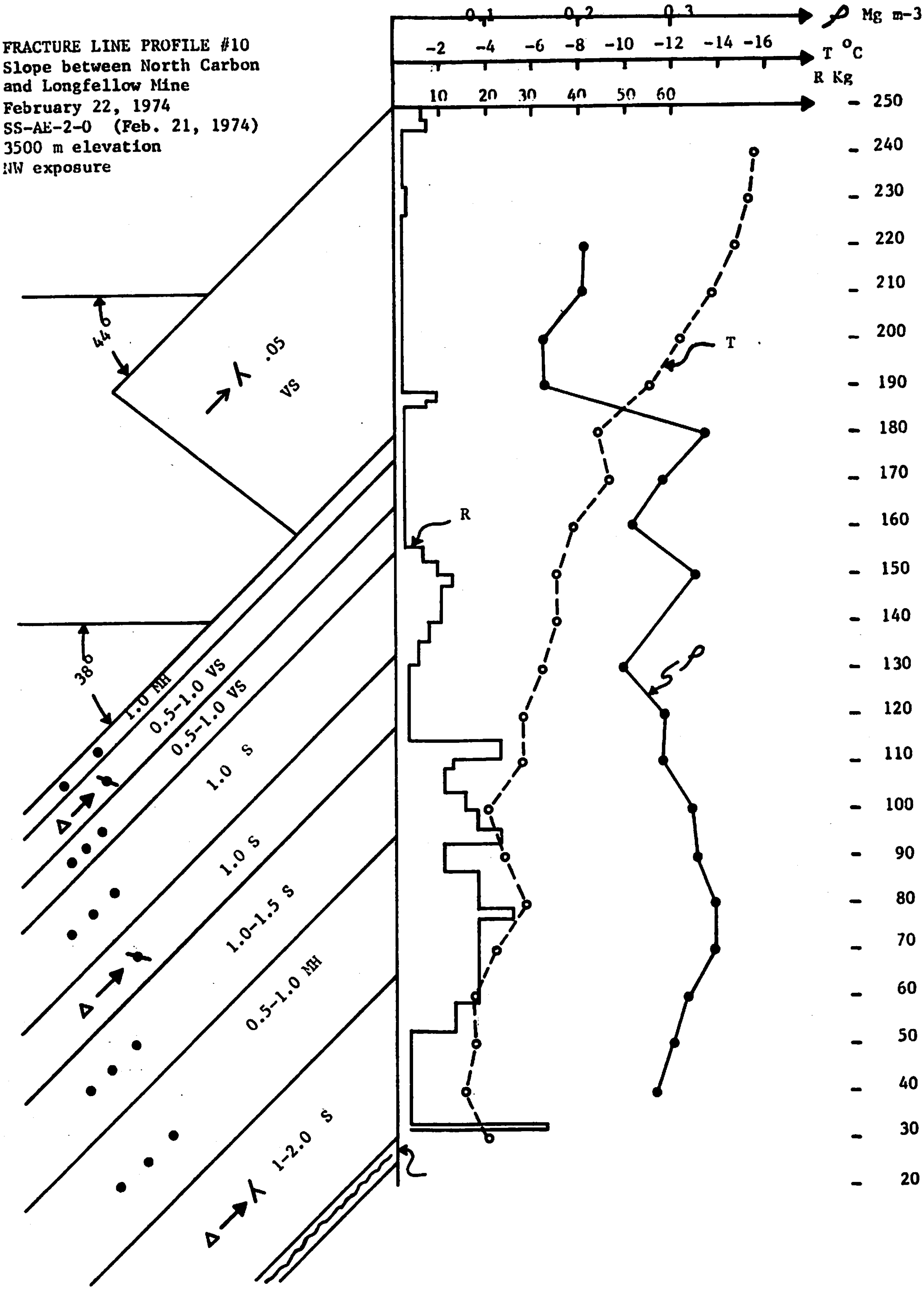
FRACTURE LINE PROFILE #8
NE Shoulder Pt. 12,325
January 23, 1974
HS-N-4-OG (Jan. 21, 1974)
3688 m elevation
SE exposure

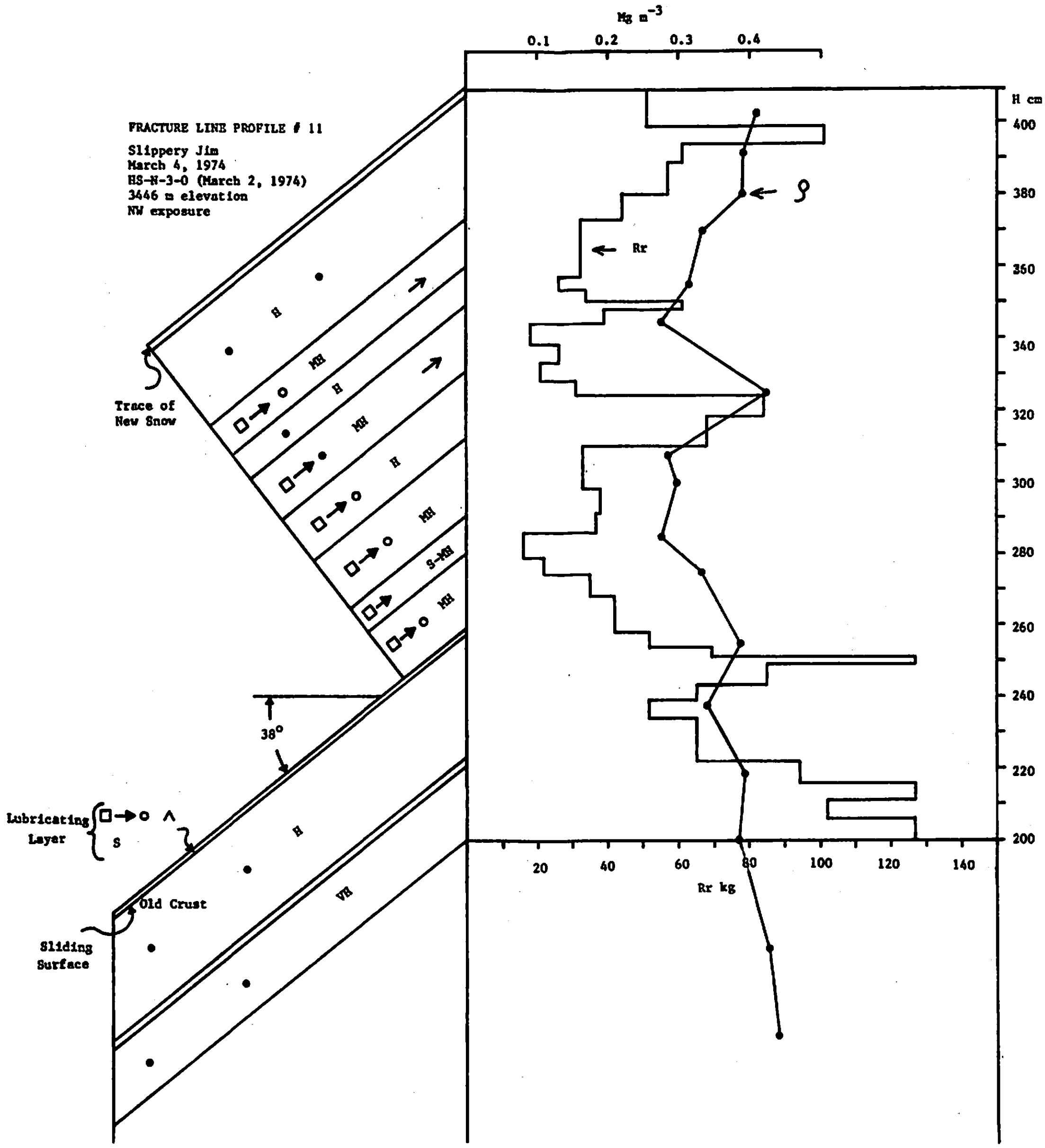


FRACTURE LINE PROFILE #9
Cement Fill
February 11, 1974
HS-N-2-OG (Feb. 9, 1974)
3718 m elevation
SSW exposure

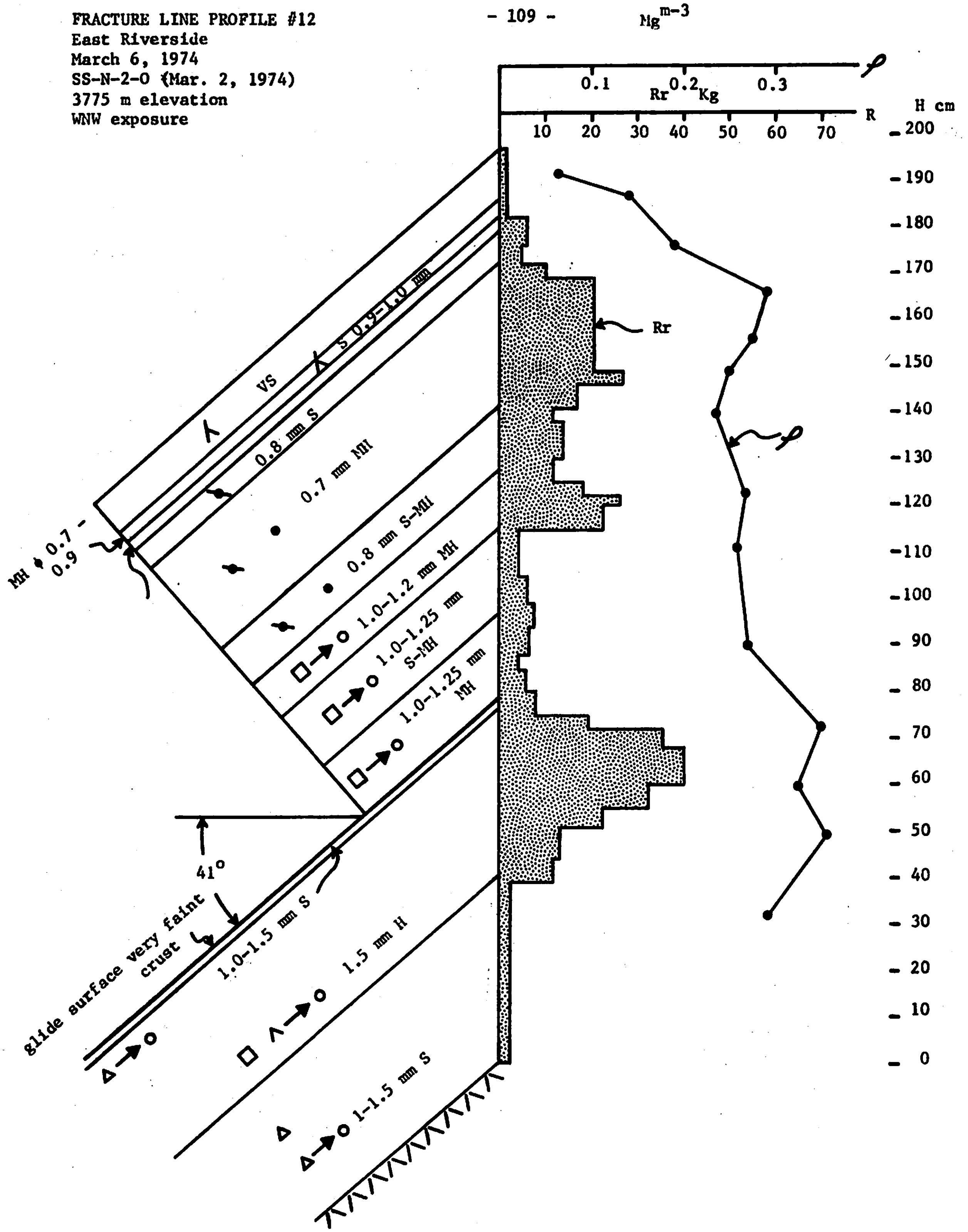


FRACTURE LINE PROFILE #10
Slope between North Carbon
and Longfellow Mine
February 22, 1974
SS-AE-2-0 (Feb. 21, 1974)
3500 m elevation
NW exposure

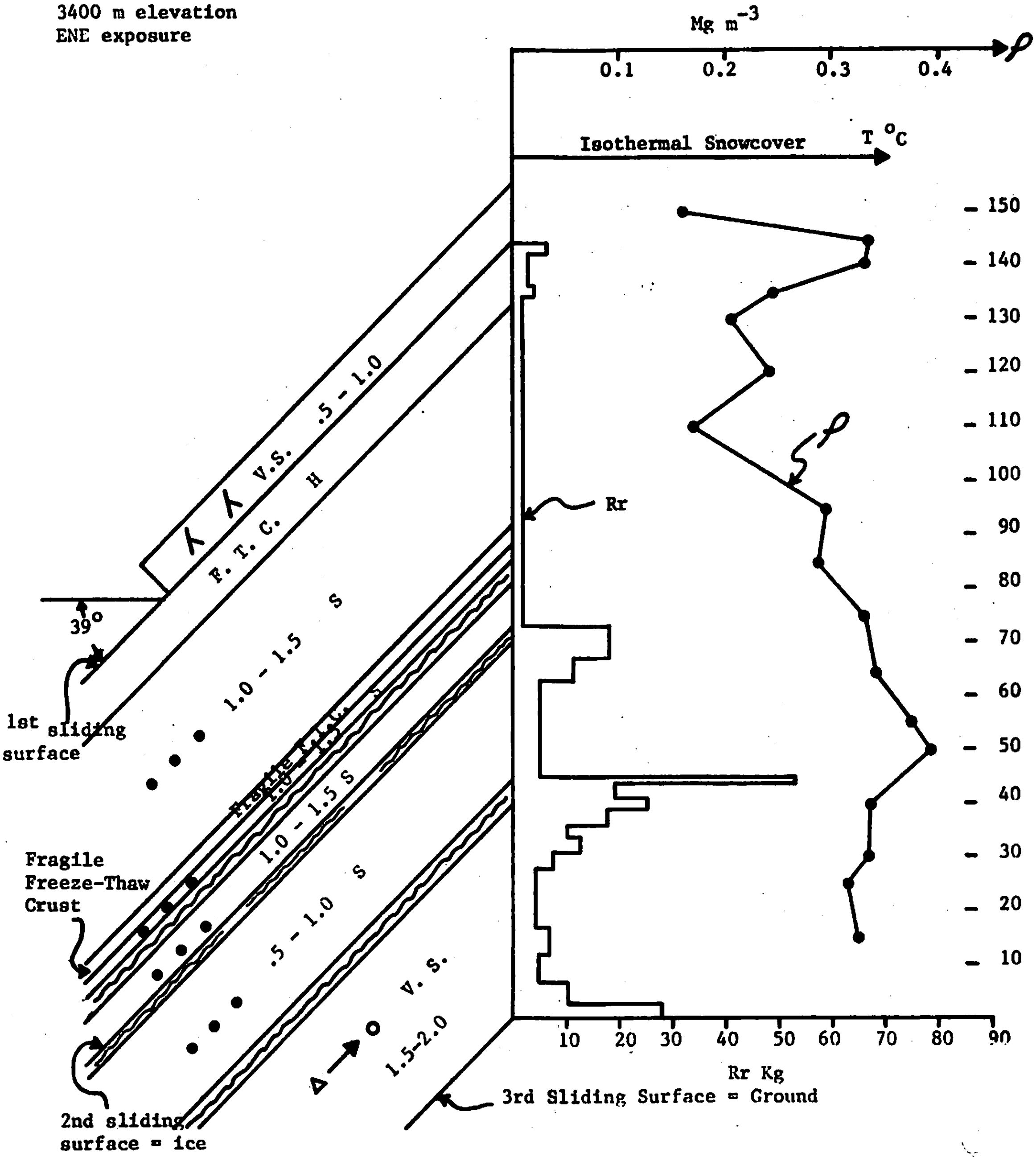



Mg m^{-3}
0.1 0.2 0.3 0.4
FRACTURE LINE PROFILE # 11
Slippery Jim
March 4, 1974
HS-N-3-0 (March 2, 1974)
3446 m elevation
NW exposure
Trace of
New Snow
H cm
400
380
360
340
320
300
280
260
240
220
200
ρ
Rr
H
MH
S-MH
38°
Lubricating
Layer
S
Old Crust
Sliding
Surface
VH
20 40 60 80 100 120 140
Rr kg

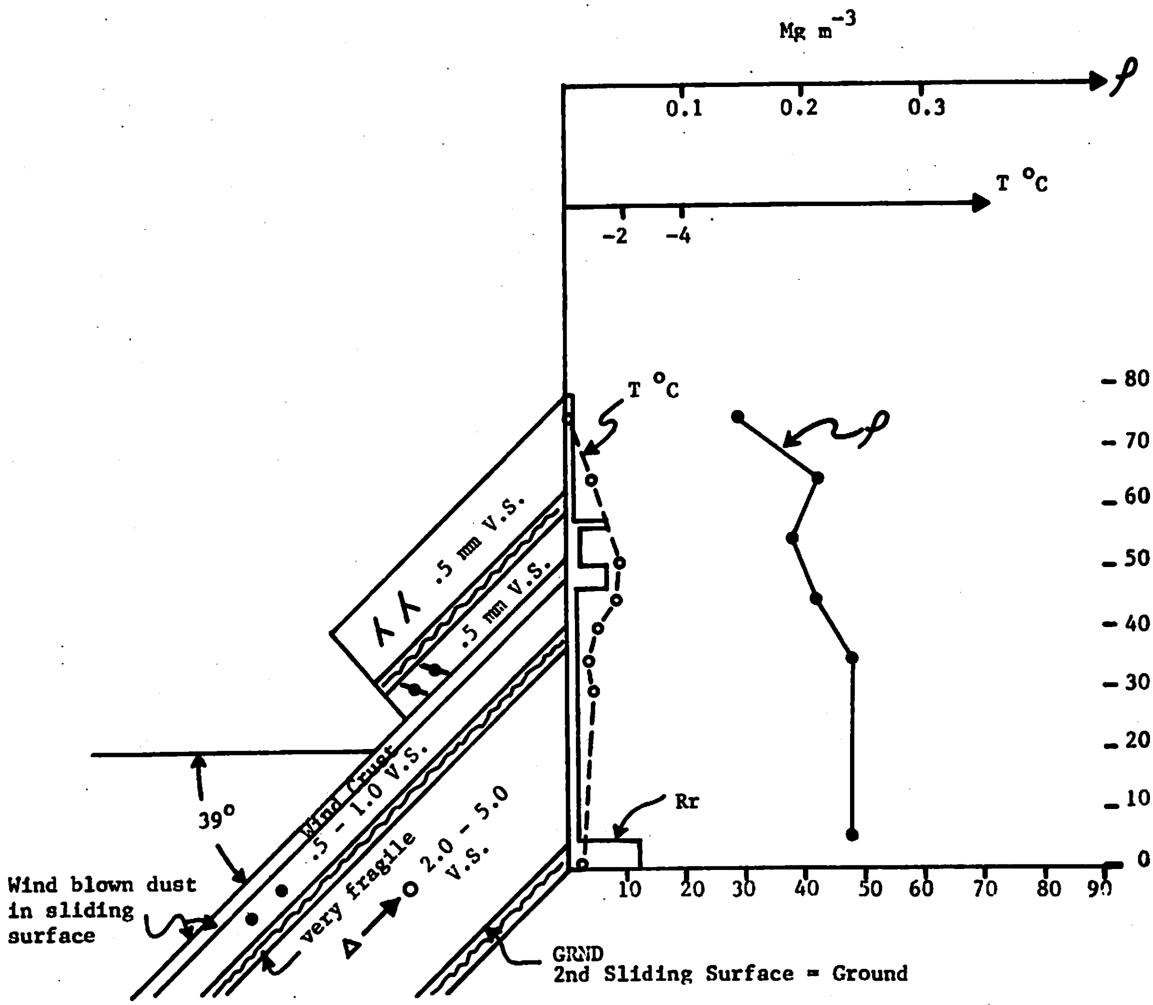
FRACTURE LINE PROFILE #12
East Riverside
March 6, 1974
SS-N-2-O (Mar. 2, 1974)
3775 m elevation
WNW exposure



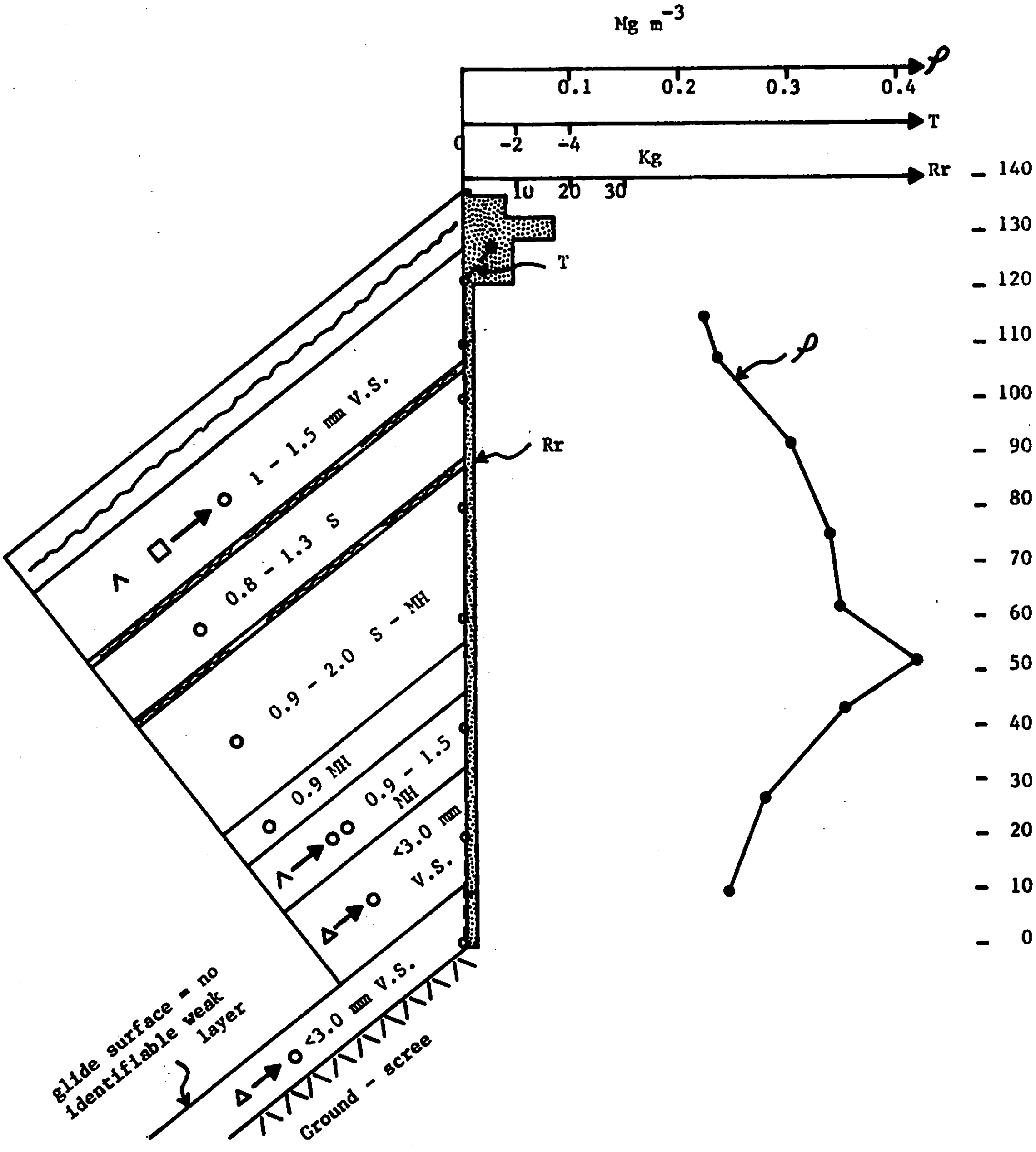
FRACTURE LINE PROFILE #13
Willow Swamp Shoulder
March 11, 1974
SS-N-2-G (Mar. 10, 1974)
3400 m elevation
ENE exposure



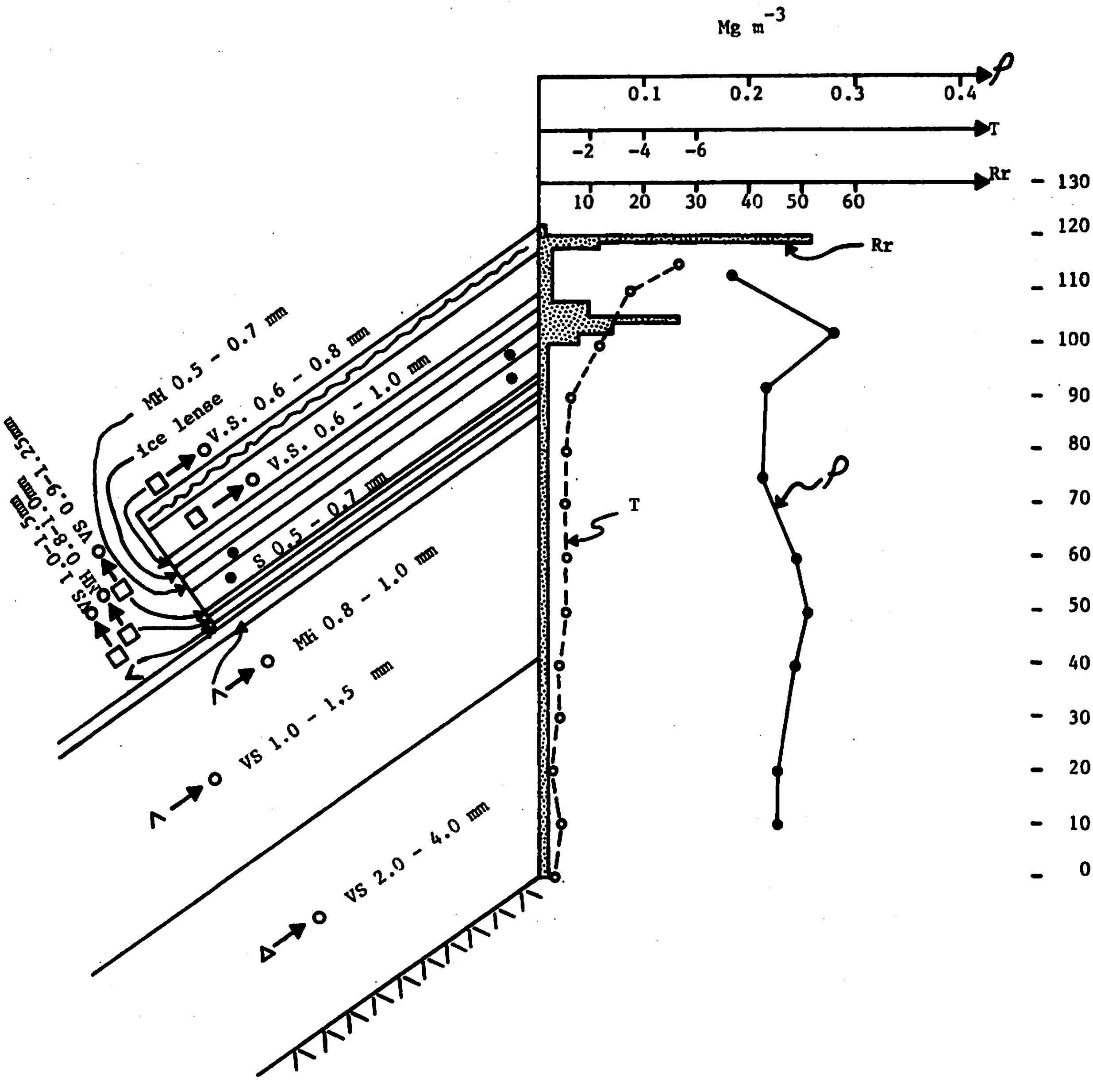
FRACTURE LINE PROFILE # 14
Ernest
March 12, 1974
SS-N-3-G (Mar. 10, 1974)
3350 m elevation
E exposure



FRACTURE LINE PROFILE #15
Second Twin Crossing
March 17, 1974
WS-N-3-O (Mar. 16, 1974)
3416 m elevation
WSW exposure



FRACTURE LINE PROFILE #16
Cemetery
March 18, 1974
SS-N-2-0 (Mar. 16, 1974)
3300 m elevation
NW exposure



APPENDIX 2

RECORD OF AVALANCHE OCCURRENCES IN THE STUDY AREA FOR THE 1973-1974 WINTER

The following is a key to the table:

Year:	
Month:	
Day:	
Time:	2405 = event thought to have occurred in the A.M.; exact time unknown
	2417 = event thought to have occurred in the P.M.; exact time unknown
Name:	Name of individual avalanche path
Station:	152 = U.S. Highway 550
	153 = Cement Creek
	157 = Silverton
Path Number:	Number for individual avalanche path
Control:	First digit (4) = 75 mm howitzer
	Second digit = number of shots fired
Type:	HS = Hard Slab
	SS = Soft Slab
	WS = Wet Slab
	L = Loose
	WL = Wet Loose
Trigger:	N = Natural
	AS = Artificial-Skier
	AE = " -Explosive
	AA = " -Artillery
	AL = " -Avalauncher
	AO = " -Other (snowmobile, snowcat, sonic boom, etc.)

Size:	1 = Sluff, any snowslide running less than 150 feet slope distance, regardless of other dimensions such as width, fracture line, etc. All other avalanches are classified by a number 2 - 5 that designates their sizes. This size classification is based on the concept that size should convey an estimate of the volume of snow that is transported down an avalanche path rather than a threat to life or property. In addition, sizes 2 to 5 are reported relative to the slide path, that is, a "small" avalanche is one that is small (moves a small volume of snow down the path) for the particular avalanche path.
	2 = Small, relative to the avalanche path
	3 = Medium
	4 = Large
	5 = Major or maximum
Running Surface:	O = Avalanche ran on an old snow surface in the starting zone
	G = Avalanche ran to the ground in the starting zone
Motion:	S = Sliding is when the snow breaks loose and moves downslope without rolling or tumbling
	F = Flowing or tumbling motion; the snow whether granular or in blocks moves along the snow or ground surface in a rolling, turbulent action
	P = Airborne powder refers to snow that billows up in a dust cloud; motion is turbulent and very fast
	M = Mixed air and ground motion
Slab Depth:	Estimation of thickness or depth of fracture line at right angles to the slope to the nearest foot
Layers:	A = Avalanche involves only new snow
	B = Avalanche penetrates deeper and includes old snow layer or layers
Percent:	Percent of total avalanche path affected
Starting Zone:	Starting area when avalanche is viewed from below
	T, M, B = Top, middle, bottom
	L, C, R = Left, center, right (of the midline of the path)

Vertical Fall:	Estimate in feet of the vertical fall distance of the avalanche, not slope distance
Debris Location:	Location of debris or where avalanche stopped A = Fracture or starting zone B = Transition or bench partway down track C = Bottom of track or runout zone
Center Line Depth:	Estimation in feet of the maximum depth of avalanche debris at the centerline of a road
Length of Center Line:	Estimate in feet of the maximum length of centerline covered by avalanche debris

year	month	day / time / avalanche path	station number / path number / control	type / trigger / size / running surface	motion	slab depth / layers	percent / starting zone / vertical fall	location of debris / center line depth	length of center line
73	11	232405BLUE POINT	152097	L N10			5 M 75C		
73	11	232415US BASIN	152035	SS N20			5 T B		
73	11	292405IMOGENE	152119	SS N2G		2	5 M B		
73	12	032405CEMENT FILL	152010	HS N20		2	5TC 500B		
73	12	140400BLUE POINT	152097	L N20		1	50TR 200C	2	20
73	12	182405BLUE POINT	152097	L N20			10T 150C	3	50
73	12	181530ERS SOUTH	152062	SS N20			25TC 150C	3	30
73	12	180830ERS LEFT	152065	SS N2G		2	25TC 150C	4	20
73	12	181530MOTHER CLINE	152069	SS N20		1	10TR 200C	6	25
73	12	281000BLUE POINT	152097	N20			10T 150C		
73	12	281430BLUE WILLOW	152096	SS N20		2	25TC 150C		
73	12	281000BROOKLYNS E	152019	SS N20			10TR 700C		
73	12	281300BROOKLYNS H	152023	SS N20			25TC1000C		
73	12	281000BROOKLYNS I	152024	SS N20			25TC 900C		
73	12	281445WILLOW SWAMP	152095	SS N20		2	10ML 200C	2	75
73	12	291400BLUE POINT	152097	SS N2			10TC 200C	2	70
73	12	292230BROOKLYNS B	152016	SS N20			50T 500C	2	50
73	12	292030BROOKLYNS E	152019	SS N20			25T 700C		
73	12	292030BROOKLYNS F	152020	SS N20			25T 900C		
73	12	292405SILVER GULCH	152073	SS N3			10T 2200C		
73	12	302405BATTLESHIP	152128	SS N20		4	10TC2500C		
73	12	301500BULLION KING	152107	SS N30			25T 2000C		
73	12	302405DESTROYER	152129	SS N30		4	75TC2200C		
73	12	301245EAGLE	152104	SS N30	J		10TC2200C	1	100
73	12	300200EAGLE	152104	SS N20		4	10ML1000C	3	50
73	12	301330ERS	15206441	SSAA30	JP	6	25TC3000C	6	200
73	12	302405PICKLE BARREL	152131	SS N20		2	50TC 450C		
73	12	302415RED MTN 2	152047	SS N20		4	25TR 800C		
73	12	302405SAN JUAN	152122	SS N20			10TC 250B		
73	12	302405SNOWSLIDE GULCH	152132	SS N20			25TC2000C		
73	12	300230TELESCOPE	152105	SS N30	J		25MC1000C	6	350
73	12	311110BROOKLYNS E	15201941	SSAA		2	50TR 900C	2	150
73	12	311105BROOKLYNS F	15202041						
73	12	311107BROOKLYNS J	15202541						
73	12	311110BROOKLYNS L	15202741	SSAA		2	50TR 900C		
73	12	311035BULLION KING	15210741	SSAA30	M	6	50TC2100C		
73	12	311120CEMETERY	15203042						
73	12	311025EAGLE	15210441	SSAA20	P	2	25TC1800C		
73	12	311020EAGLE	15210441	SSAA30	JP	4	25TR1800C	3	150
73	12	311030MULESHOE	15210641	SSAA30	M	2	25TC2100C		
73	12	311040PORCUPINE	152103411						
73	12	311020TELESCOPE	15210541	SSAA30	M	4	50TC1800C	2	100
74	01	031135N CARBON	152 2 3	SSRE30	F	4R	50TL 200C		
74	01	032405FULL MOON GULCH	152034 .	SS N40		4	75TC1800C		
74	01	052415BATTLESHIP	152128	SS N30		4	10TR2600C		
74	01	052415BISMARK	152127	SS N30		4	25TR1800C		
74	01	051300BROOKLYNS G	152022	SS N40			75TC 800C15		250
74	01	051400BROOKLYNS I	152024	SS N30			50TC1000C		
74	01	051404CEMENT FILL	152010	SS N30		4	25TR2500C		
74	01	052415CEMETARY	152031	SS N20			10TC 300B		
74	01	051500EAGLE	152104	SS N2			25T 1500C	3	50
74	01	051330IMOGENE	152119	SS N30			75TC1900C		
74	01	051500JULIO	152116	SS N20		2	50MC 300C		
74	01	051500OTAH	152118	SS N30		4	50MC 300C		
74	01	051500PORCUPINE	152103	SS N2			25T 1300C	3	50
74	01	051500ROCKWALL	152101	SS N30			50TC 400C	8	100
74	01	051500SAM	152117	SS N20		2	25MC 500C		
74	01	0515002ND TWIN CROSSNG	152032	SS N20		2	50MC 800C		
74	01	060930BROOKLYN C	15201741	SSAA20	P	B	50TC 800C	2	75
74	01	060930BROOKLYN G	15202241	SSAA20	P	A	25TC 300B		
~~74~~	~~01~~	~~060930BROOKLYN K~~	~~15202641~~	~~SSAA20~~	~~P~~	~~A~~	~~75TC 700C~~		
74	01	060930BROOKLYN L	15202741	SSAA20	P	A	25TC 350B		

~~74~~	~~01~~	~~060930BROOKLYNS-OTHERS~~	~~152~~						~~45~~
74	01	061000EAGLE	15210444						
74	01	061055E RIVERSIDE	15206441	SSAA2G	P	8	5MC1000C	5	70
74	01	061210E RIVERSIDE	15206443	SSAA2G	P	8	5MR1800C	15	80
74	01	061210E RIVERSIDE	15206448						
74	01	061100SLIPPERY JIM	15206142						
74	01	061500SLIPPERY JIM	152061	SS N2G		2	10MR 300C		
74	01	061000TELESCOPE	15210541						
74	01	071330BROOKLYNS B	15201641	SSAA2G			10TL 400B		
74	01	071330BROOKLYNS C	15201741	SSAA2G			25TC 650C	1	25
74	01	071330BROOKLYNS C	15201741	SSAA2G			10TR 200		
74	01	071330BROOKLYNS G	15202242						
74	01	071100CHAMPION	15214441						
74	01	071100JENNIE PARKER	15214143						
74	01	071100PEACOCK	15214241						
74	01	071400SILVER LDGE MINE	15210041	SSAA2G	M	4B	10TL 150B		
74	01	071400SILVER LDGE MINE	15210041	SSAA10		1A	5TL 50A		
74	01	071400SILVER LDGE MINE	15210041	SSAA3G	S	4B	10TR 200C	4	75
74	01	082415NATIONAL BELL N	152043	SS N30		6	10MR 500C		
74	01	081045WILLOW SWAMP SN	152095	SS N3G		4C	75TL 200C	11	200
74	01	091530BLUE POINT	152097	SS N20		1	10ML 150C		
74	01	092405ERNEST	152115	SS N20		2	50MC 450C		
74	01	092415FULL MOON GULCH	152084	SS N3G		6	25TL1500B		
74	01	092405JULIO	152116	SS N20		4	25MR 300C		
74	01	092000W LIME CREEK	152150	SS N3G		4	75TC 250C	8	700
74	01	092000E LIME CREEK	152149	SS N2G		4	5TL 250C	3	50
74	01	092405W GUADALUPE	152075	SS N2G		4B	25MC 800C		
74	01	092415SILVER GULCH	152073	SS N30		4	25TL2000C		
74	01	101345BATTLESHIP	152127	SS N4G		6	50TR2500C		
74	01	100930E RIVERSIDE	15206444						
74	01	100900MOTHER CLINE	15206943	SSAA20	M	1	5TL 400C	1	20
74	01	101400W RIVERSIDE	15207545						
74	01	101445WILLOW SWAMP	15209541	SSAA3G		5	25TL 300C	15	250
74	01	101445WILLOW SWAMP	15209542	SSAA3G		5	50TC 400C		
74	01	101445WILLOW SWAMP	15209541	SSAA2G		3	10TR 200C		
74	01	111005CHAMPION	15214441	SSAA2G		4	5TC 300B		
74	01	111005CHAMPION	15214441	SSAA4GJM		6B	80TL1800C	14	250
74	01	111030ENGINEER MTN C	15216141	SSAA20	F	1A	5TL 150B		
74	01	111030ENGINEER MTN C	15216141	SSAA20	F	1A	5TR 200B		
74	01	111200HENRY BROWN	15215543	SSAA20	F	1A	5TL 200C		
74	01	112405NATIONAL BELL N	152043	SS N30		4	25TC 700C		
74	01	112405RED MTN 3	152044	SS N20		4	10ML 700B		
74	01	111200SWAMP	15215441						
74	01	112405TAVERN	152123	SS N30		4	75TC 350C		
74	01	152415BROOKLYNS G	152022	WL N20			5TL 250B		
74	01	152415BROOKLYNS K	152026	WL N20			TC 250B		
74	01	152415EAGLE	152104	WL N20			5TC 400B		
74	01	182415BROOKLYNS G	152022	SS N20		1	5TC 300B		
74	01	182415EAGLE	152104	L N20			5MR 700B		
74	01	182415IST TWIN XING	152031	L N20			5TL 450B		
74	01	182415N MINERAL BRIDGE	152033	L N20			10TC 450B		
74	01	182415TELESCOPE	152105	L N20			5TL 750B		
74	01	210200BLUE POINT	152097	SS N30			75TC 200C	4	100
74	01	210845ROCKWALL	152101	SS N20				2	100
74	01	210845ROCKWALL	152101	SS N20				1	150
74	02	010900BLUE POINT	152097	L N20			150C		
74	02	010900BLUE WILLOW	152096	L N20			100C		
74	02	021000NO MINERAL BDGE	152033	L N20			5MC 300B		
74	02	112417WILLOW SWAMP	152095	L N20			10TL 180B		
74	02	190920NO CARBON	152	LAS20			TC 200C		
74	02	201100BLUE POINT	15209742	SSAA20		1	25TL 300C	4	25
74	02	201000BLUE WILLOW	152096	SS N20		1	25TC 200C	2	20
74	02	201030EAGLE	15210442						
74	02	202405E RIVERSIDE	152064	N				4	50
~~74~~	~~02~~	~~201300E RIVERSIDE~~	~~15206444~~	~~SSAA20~~		~~4~~	~~10MC2200C~~	~~14~~	~~70~~
74	02	201300E RIVERSIDE	15206442						

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74 02  202405MOTHER CLINE      152069   SS N20    1  75TC 250C10  300
74 02  200230SILVER POINT      152070    L N20       50T  800C 6   20
74 02  202415SWISS             152052   SS N30    4  75MC1500C
74 02  201030TELESCOPE         15210543
74 02  201100WILLOW SWAMP      15209541 SAA20         5TL 150B
74 02  201100WILLOW SWAMP      152095    L N20        5TC 200C
74 02  212405IMOGENE           152119   SS N20    1   5TR 300B
74 02  211500LONGFELLOW        152039   SS N20    1  25TC 200C
74 02  212405MILL CK A         152108   SS N20    1   5MC 200B
74 02  212405MILL CK C         152110   SS N20    1  10MC 300B
74 02  212405MILL CK D         152111   SS N20    1  25MC 500C
74 02  221245E RIVERSIDE       15206449
74 02  221300W RIVERSIDE       15207448
74 02  231500BULLION KING      152107   SS M20    1  10TL2000C
74 02  251030BROOKLYNS K       152026    L N20       10TC 600C
74 02  262417TELESCOPE         152105    L N20        5TR 350B
74 02  272405BROOKLYNS C       152017    L N20       10TC 400B
74 02  271100NO MINERAL BOGE   152033    L N20        5MC 350B
74 03  012417DUNSMORE          152068   WL N20       25TC 250C 1   30
74 03  020800E RIVERSIDE       152064   HS N30   7B  25TR2600C12   70
74 03  022405SLIPPERY JIM      152061   HS N30   4B  25TL1800B
74 03  031300SNOWSLIDE GL      152132   SS N20        5TL1000B
74 03  062405EAGLE             152104   SS N20    1  10ML 500B
74 03  062405BROOKLYNS B       152016    L N20            350
74 03  062405BROOKLYNS N       152029    L N20          M 300
74 03  062405BROOKLYNS H       152023    L N20            400
74 03  062405BROOKLYNS I       152024    L N20            400
74 03  072417BROOKLYNS M       152028   SS N20    1  25MC 450C
74 03  071330BLUE POINT        152097   SS N30    1  75TC 250C 5  100
74 03  072417BROOKLYNS I       152024   SS N30    2    MC 700C
74 03  102417BROOKLYNS D       152018   SS N20    2  50TC 450C
74 03  102417BROOKLYNS E       152019   SS N20    2  50TC 500C
74 03  102417BROOKLYNS F       152020   SS N20    1  50TC 900C
74 03  102417BROOKLYNS G       152022   SS N20    2  50TC 700C
74 03  102417BROOKLYNS K       152026   SS N20    1  50TC 600C
74 03  102405EAGLE             152104   SS N20    2   5BL 400C
74 03  102417ERNEST            152115   SS N3G    2  50TC 600C
74 03  102405MULESHOE          152106   SS N20
74 03  102417WILLOW SWAMP      152095   SS N2G    2  10ML 150C 4   80
74 03  110925BLUE POINT        15209741 SSAA30 M 2A  75TC 200C 7   30
74 03  112417BROOKLYNS G       152022    L N10
74 03  112417BROOKLYNS H       152023   SS N20       50
74 03  112417BROOKLYNS I       152024    L N20       50   800
74 03  110845BROOKLYNS J       15202541  LAA20       75TC 800
74 03  112417BROOKLYNS K       152026    L N20       25   300
74 03  110845BROOKLYNS L       15202741 SSAA20 M 2   75   800
74 03  110845BROOKLYNS M       15202841 SSAA20 M 1     TC 300B
74 03  110845BROOKLYNS N       15202941 SSAA2G 7 2   75   600C
74 03  110815EAGLE             15210441  LAA10          T  80A
74 03  111120E RIVERSIDE       15206447
74 03  111120E RIVERSIDE       15206441 SSAA30   2U     M 2700C13 100
74 03  111120E RIVERSIDE       15206441 SSAA30   2U     M 2700C13 100
74 03  111120E RIVERSIDE       15206443
74 03  111030E RIVERSIDE       15206441 SSAA2L   2      ML1100
74 03  110835MULESHOE          15210641 SSAA20   1          500B
74 03  112405NATIONAL BELL NO152043     HS N20   5   25MR 250B
74 03  110815PORCUPINE         15210344  LAA10
74 03  110835TELESCOPE         15210542 SSAA20             1100
74 03  111050W RIVERSIDE       15207442
74 03  110915WILLOW SWAMP      15209542 HSAA20 M 2   75TC 350C
74 03  122417BROOKLYN C        152017    L N20            450
74 03  122417BROOKLYN D        152018    L N20       50   500
74 03  121030CHAMPION          15214443  LAA30       25  1200C 3   30
74 03  121500ENGINEER MTN A    152159   WL N20       50TC 500B
74 03  121200ENGINEER MTN B    152160   WS N3G    1  75TL 700C
74 03  121015JENNIE PARKER     15214045
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74	03	121015PE'COCK	15214241							
74	03	151600BROOKLYNS C	152017	WL	N2G		25TC	300B		
74	03	151600BROOKLYNS C	152017	WL	N2G		25TC	300B		
74	03	151600BROOKLYNS D	152018	WL	N3G		75TC	650C		
74	03	151600BROOKLYNS G	152022	WL	N2G		25TC	500B		
74	03	151600BROOKLYNS H	152023	WL	N3G		75TR	800C		
74	03	151600BROOKLYNS K	152026	WL	N2G		50TC	400B		
74	03	151600BROOKLYNS L	152027	WL	N2G		75TC	400B		
74	03	151200CHAMPION	152144	WL	N3G		10MC	650B	8	40
74	03	152417E RIVERSIDE	152064	WL	N2G		5BL	500C		
74	03	152417DAISY HILL	152085	WL	N20		5TA	300B		
74	03	152417DAISY HILL	152085	WL	N20		5TC	300B		
74	03	151600N MINERAL BRIDGE	152033	WL	N2G		25MC	300B		
74	03	152417SLIPPERY JIM	152061	WL	N20		5BC	300		
74	03	161210BLUE POINT	152097	WL	N20		10TR	175C		
74	03	161210BLUE WILLOW	152096	WL	N10		75TC	75C	3	60
74	03	161300BLUE WILLOW	152096	WL	N2G		25TR	100C	4	25
74	03	161700BROOKLYNS F	152020	WL	N2G		10TL	600B		
74	03	161530BROOKLYNS G	152022	WL	N2G		10TC	500B		
74	03	161500BROOKLYNS H	152023	WL	N2G		25TC	350B		
74	03	161530BROOKLYNS I	152026	WL	N3G		75TC	900D	5	55
74	03	161300BROOKLYNS L	152026	WL	N20		10TR	400B		
74	03	161700CEMETARY	152030	WS	N20	1	5ML	300B		
74	03	161320CHAMPION	152144	WL	N2G		25TR	800B	5	50
74	03	161215CHAMPION	152144	WL	N2G		25TC	800B	4	25
74	03	161700EAGLE	152104	WL	N20		5TR	1500B		
74	03	161400JENNIE PARKER N	152140	WL	N20		5TC	250B		
74	03	161500N MINERAL BDGE	152033	WS	N3G	3	25TL	800B		
74	03	161030ROCKWALL	152101	WL	N1G		5BR	75C		
74	03	161600 2ND TWIN CROSSNG	152032	WS	N3G		25ML	600C		
74	03	161100SILVER GULCH	152073	WL	N20		5ML	600B		
74	03	161200ST GERMAIN	152059	WL	N20		25TL	150B		
74	03	161200TAVERN	152123	WL	M20		25TL	300C		
74	03	161100WATER GUAGE N	152076	WL	N20		50TC	300B		
74	03	161100W GUADALUPE	152075	WL	N20		5BL	300C		
74	03	161100WHITE FIR	152072	WL	N2G		10TL	600B		
74	03	171500BLUE POINT	152097	WL	N2G		25TR	150C	2	6
74	03	172417EARTH	152078	WL	N2G		75MC	250C		
74	03	172417WATER GUAGE N	152076	WL	N3G		75TC	400C		
74	03	181450MOTHER CLINE	152069	WL	N20		5TR	250C	3	20
74	03	191630MOTHER CLINE	152069	WL	N20		10MR	200C	3	60
74	03	191600JACKPOT	152071	WL	N30		50TC	350C	2	70
74	03	301500MILL CK A	152108	L	N20		5BC	175C		
74	03	301500MILL CK C	152110	L	N20		10MC	300B		
74	04	021000BLUE POINT	152097	SS	N20	1	50TC	200B		
74	04	021000BROOKLYNS K	152026	SS	N20	1	25TC	500M		
74	04	032145EAGLE	152104	SS	N30		25TR	1200B		
74	04	032417 1ST TWIM CROSSNG	152031	SS	N20		10TR	500M		
74	04	041000BLUE POINT	152097	SS	N20	1	50TC	200B		
74	04	042405BROOKLYN GULCH	152054	SS	N20	1	5ML	300M		
74	04	042485 GUADALUPE	152060	SS	N20	1	5ML	400M		
74	04	042405E RIVERSIDE R	152063	SS	N20	1	25TL	350B		
74	04	042405E RIVERSIDE L	152065	L	M20		TC	250B		
74	04	042405MOTHER CLINE	152069	SS	N20	1	10ML	250M		
74	04	040830MOTHER CLINE	152069	L	N20					
74	04	051600BROOKLYNS	152	WL	N2G		5T	350M		
74	04	051600 1ST TWIM CROSSNG	152031	WL	N2G		5ML	300M		
74	04	052417N MINERAL BDGE	152033	WL	N2G		5M	300M		
74	04	161600BROOKLYNS F	152020	WL	N20		5TC	300M		
74	04	161600BROOKLYNS G	152022	WL	N20		10TC	400M		
74	04	161600BROOKLYNS K	152026	WL	N20		5TL	200M		
74	04	161600N MINERAL BDGE	152033	WL	N2G		5MC	300M		
74	04	161600MULESHOE	152106	WL	N20		5TC	250M		
74	04	161600TELESCOPE	152105	WL	N20		5MC	350M		
74	04	171600EAGLE	152104	WL	N20		5TC	800M		
74	04	171600MULESHOE	152106	WL	N20		5TC	400M		
74	04	201300BLUE POINT	152097	SS	N20		75TC	200B		75
74	04	202405EAGLE	152104		N20			B		
74	04	201300WILLOW SWAMP	152095	SS	N20		25TL	200M		
74	04	211145EAGLE	152104	WL	N30		50T	1800B	6	30

TABLE 21

1973 - 1974 sluff (size 1) events

not included in Appendix II (Highway 550)

month	date	time (MST)	location and description
Dec	14	1400-1000	Red Mountain Pass north to Idarado mine, small soft slab events on steep rolls and banks Sluffs in all high catchment basins in vicinity of Red Mountain Pass
Dec	18	daylight	15 bank slides crossed road between State Bridge and south end of Uncompaghre Gorge
Dec	24		Approximately 15 bank slides in road in vicinity of Mother Cline (069) including these specific slide paths: East Riverside (064) East Riverside Left (065) South of Emergency Phone (066) Cliff (067) Dunsmore (068)
Dec	30		Extensive soft slab, size 1 and 2 events in Silverton area on steep banks and in areas of comparable elevation, i.e. Ironton Park
Jan	8		Loose events on Ledge (102) and the Brooklyns
Jan	9		Loose events on Blue Point (097) and other steep slopes near the highway at Red Mountain Pass
Jan	16		General wet loose cycle with most frequent occurrences in Uncompaghre Gorge
Jan	20-21		Extensive sluff cycle from Ouray to Silverton in high catchment basins and steep wooded slopes Small soft slab bank slides
Feb	20		General sluff cycle from Red Mountain Pass through Uncompaghre Gorge, all steep slopes running as sluffs or small soft slab events. Road in Gorge closed by slides 0230 MST as result of these events, including these numbered paths: North of Emergency Phone (066) Cliff (067) Dunsmore (068)
March	9		Minor sluff cycle in new snow, vicinity of Red Mountain Pass

TABLE 21 (continued)

month	date	time (MST)	location and description
April	2		General loose sluff cycle in vicinity of Red Mountain Pass, particularly in Brooklyns, North Mineral Bridge (033), and some high cirques
April	4		Five sluffs in road in vicinity of Mother Cline (069) and extensive sluffing and shallow soft slab activity in new snow.
April	20		General sluff cycle in Uncompaghre Gorge, slides in road from East Riverside (064) and Mother Cline (069) and Blue Point (097). Activity also on steep banks in the vicinity of Red Mountain Pass and Mill Creek Cirque and the Brooklyns.
April	21		General wet loose cycle in new snow on all but north-facing slopes.

TABLE 22

Avalanche Events along Highway 550 greater than
#1 in order of frequency, November 1971 - April 1974

avalanche path number	avalanche path name	number of events
104	Eagle	55
097	Blue Point	53
105	Telescope	27
095	Willow Swamp	27
033	North Mineral Bridge	25
106	Muleshoe	25
061	Slippery Jim	20
022	Brooklyn G	19
144	Champion	18
128	Battleship	16
023	Brooklyn H	15
020	Brooklyn F	14
027	Brooklyn L	14
065	East Riverside Left	14
110	Mill Creek C	14
160	Engineer Mountain B	13
069	Mother Cline	13
017	Brooklyn C	12
019	Brooklyn E	12
024	Brooklyn I	12
107	Bullion King	12
159	Engineer Mountain A	11
018	Brooklyn D	11
026	Brooklyn K	11

TABLE 22 (continued)

avalanche path number	avalanche path name	number of events
010	Cement Fill	10
016	Brooklyn B	10
044	Red Mountain 3	10
060	East Guadalupe	10
119	Imogene	10
161	Engineer Mountain C	10
032	2nd Twin Crossings	9
073	Silver Gulch	9
101	Rock Wall	9
113	Mill Creek F	9
114	Mill Creek G	8
151	Gobblers Knob	8
030	Cemetery	7
085	Daisy Hill	7
091	King	7
109	Mill Creek B	7
117	Sam	7
125	Ophir Road East	7
155	Henry Brown	7
043	National Bell North	6
047	Red Mountain 2	6
074	West Riverside	6
132	Snowslide Gulch	6
063	East Riverside Right	5
075	West Guadalupe	5
076	Water Gauge North	5
084	Full Moon Gulch	5
096	Blue Willow	5
108	Mill Creek A	5
140	Jennie Parker North	5
150	West Lime Creek	5

APPENDIX 3

BIBLIOGRAPHY OF AVALANCHE LITERATURE

Supplement No. 2, September, 1974

San Juan Avalanche Project

Institute of Arctic and Alpine Research

University of Colorado

A supplement to previous bibliographies contained in the 1972 and 1973 Interim Reports. References are to literature dealing with snow avalanche phenomena as well as information related to the physical and mechanical properties of snow.

Aburakawa, H. and others. 1972: Daisetsu-yama ni okeru kokasetsu no kenkyū. II. (Studies of hard snow in Mt. Daisetsu. II.) Teion-kagaku: Low Temperature Science, Ser. A (30): 129-143.

Akitaya, E. 1974: Studies on depth hoar. International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland (IUGG-IASH).

Ambach, W. and A. Denoth. 1974: On the dielectric constant of wet snow. International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland (IUGG-IASH).

Bois, P., Obled, C. and W. Good. 1974: Multivariate data analysis as a tool for day by day avalanche forecast. International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland IUGG-IASH).

Armstrong, R.L. 1974: Avalanche hazard evaluation and predication in the San Juan Mountains of Southwestern Colorado. Advanced Concepts and Techniques in the Study of Snow & Ice Resources, Proceedings of Interdisciplinary Symposium, Monterey, Calif., December 1973. National Academy of Sciences, pp. 339-346.

Armstrong, R.L. 1973: Avalanche studies in the San Juan Mountains of Southwestern Colorado. Proceedings of the Western Snow Conference, Grand Junction, Colorado, April 1973, Colorado State University Press, pp. 44-52.

Bradley, C.C. and W. St. Lawrence. 1974: Kaiser effect in snow. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Breu, K. 1970: Lawinenverbau im Kanton Schwyz. Praktische Fortswirt für die Schweiz, 106. Jahrg (6-7): 280-286.

Brown, C.B. and R.J. Evans. 1974: Effect of glide and creep on rigid obstacles. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Brown, R.L. and T.E. Lang. 1974: On the fracture properties of snow. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Brown, C.B., R.J. Evans and E.R. LaChapelle. 1972: Slab avalanching and the state of stress in fallen snow. J. of Geophysical Research 77(24): 4570-4580.

Colbeck, S.C. 1974: Grain and bond growth in wet snow. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Colbeck, S.C. and G. Davidson. 1972: Water percolation through homogeneous snow. The Role of Snow and Ice in Hydrology. Proceedings of the Banff Symposium, September 1972. IASH-AISH Publication No. 107, pp. 242-258.

Curtis, J.O. and F.W. Smith. 1974: Material property and boundary condition effects on stresses in avalanche snowpacks. J. Glaciology 13(67): 99-109.

deQuervain, M.R. 1972: Snow structure, heat, and mass flux through snow (theme paper). The Role of Snow and Ice in Hydrology. Proceedings of the Banff Symposium, September 1972. IASH-AISH Publication No. 107, pp. 203-227.

Diunin, A.K. 1974: The new results in mechanics of snow storms. IUGG-IASH International Symposium on Snow Mechanics, April 1974. Grindelwald, Switzerland.

Diunin, A.K., ed. 1970: Zheleznyye dorogi v slozhnykh fiziko-geografich eskikh uslociyakh (Railways in complicated physical and geographical conditions.) Trudy Novosibirskogo Instituta Inzhenerov Zheleznodorozhnogo Transporta, Vyp. 115, 161 p.

Dolov, M.A. and V.A. Khalkechev. 1972: Fizika Snega i dinamika snezhnykh lavin (The physics of snow and dynamics of snow avalanches). Vysokogornyy Geofizicheskiy Institut Trudy, Vyp. 23, 327 p.

Endo, Y. and others. 1972: Sapporo no heichi sekisetsu danmen sokutei shiryō hōkoku (Shōwa 44-45 nen, 45-46 nen oyobi 46-47 nen tōki). (Report of pit-wall observations of snow cover in Sapporo (1969-70, 1970-71, and 1971-72). Teion-kagaku: Low Temperature Science, Ser. A, Supplement to No. 30, Shiryō Shū: Data Report, p. 10-28.

Federer, B. 1971: Abschwachung von Schockwellen in der Schneedecke. Wissenschaftliche Verhandlungen der Schweizerischen Naturforschenden Gesellschaft, 151. Jahres-versammlung in Freiburg, p. 146-149.

Fritzsche, I.W. 1974: New electronic avalanche rescue devices. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Giorgi, M. and others. 1971: Misura della temperatura superficiale di un manto nevoso mediante radiometro all'infrarossa. Bollettino del Comitato Glaciologico Italiano, Ser. 2(19): 241-250.

Good, W. 1972: Optimaler Einsatz der Mittel zur Ortung Lawinenverschütteter. Winterbericht des Eidgenössischen Institutes für Schnee- und Lawinenforschung (35): 154-162.

Grigorian, S.S. 1974: Mechanics of snow avalanches. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Gubler, H.U. 1974: On the rammsonde hardness equation. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Hatano, T. and T. Imai. 1969: Itasaku no būsetsu-kinō ni tsiute (On the function of the slat snow fence). Seppyō 31(2): 37-43, English abstract, p. 43.

Herb, H. 1971: Lawinensicherung durch Schneefeld sprengungen im bayerischen Alpenraum. Annalen der Meteorologie, Neue Folge (5): 247-248.

Hoinkes, H.C. 1972: Zur Meteorologie der lawinen. Sicherheit in den Bergen, Jahrbuch (Österreichischer Kuratorium fur Sicherung vor Berggefahren, Wien), pub. 1973, p. 73-87.

Hotchkiss, W.R. 1972: Avalanche awareness and safety for snow scientists in the field. Proceedings of the Western Snow Conference, 40th annual meeting, pp. 75-80.

Hoyer, M.C. 1971: Puget Peak avalanche, Alaska. Geological Society of America Bulletin. 82(5): 1267-1284.

Huzioka, T. and others. 1972: Nadare kansoku jikkenshitsu jikken shamen no sekishitsu chōsa hōkoku. VI. (Snow cover observations at the avalanche research station, Toikenbetsu, northern Hokkaido, VI) Teion-kagaku: Low Temperature Science, Ser.A, Supplement to No. 30, Shiryō Shū: Data Report, p. 29-32.

Huzioka, T. and others. 1971: Seppō kansoku jikken shitsu jikken syamen no sesshitu chosa hokoku. V. (Shōwa 45-46 nen, fuya). (Report of investigations of snow character at the avalanche research station, Toikenbetsu, northern Hokkaido. V. (1970-71). Teion-kagaku: Low Temperature Science, Ser. A, Supplement to No. 29, Shiryō Shū: Data Report, pp. 21-27.

Huzioka, T. and others. 1971: Shamen sekisetsu no kyodō no kenkyō. I-sekisetsu-nai no yugami, wai sokudo (Studies of the behavior of snowcover on slopes. I-strains and strain-rates). Teion-kagaku: Low Temperature Science, Ser. A(29): 125-134, English summary, pp. 133-134.

Huzioka, T. and others. 1970: Nadare kansoku jikkenshitsu no setushitsii chōsa hōkoku. IV. (Report of investigation of snow conditions in avalanche research experimental cave and slope, Toikenbetsu, northern Hokkaido. IV (1969-70). Teion-kagaku: Low Temperature Science, Ser. A, Supplement to No. 28, Shiryō Shū: Data Report, pp. 37-42.

Isaenko, E.P. 1974: Snow avalanche impact pressure on an obstacle. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Ishida, T. and others. 1971: Teshio chihō sanchi no seppi chōsa. I. (Observations of cornices in Teshio mountainous district. I.) Teion-kagaku: Low Temperature Science, Ser. A(29): 93-101, English summary, pp. 100-101.

Ives, J.D. 1972: INSTAAR's avalanche research project in southwestern Colorado. Arctic and Alpine Research 4(4): 289-290.

Kawada, K. and T. Huzioka. 1972: Sanjiku asshuku ni yoru yuki no hakai (Fracture of snow under triaxial compression). Teion-kagaku: Low Temperature Science, Ser. A(30): 53-64, English summary, p. 64.

Knight, C.A. and N.C. Knight. 1973: Snow crystals. Scientific American 222(1): 100-107.

Kobayashi, D. 1972: Studies of snow transport in low-level drifting snow. Contributions from the Institute of Low Temperature Science, Ser. A(24): 58 p.

Kobayashi, D. and others. 1971: Teshio chihō sanchi no seppi chōsa. II. (Observations of cornices in Teshio mountainous district. II.) Teion-kagaku: Low Temperature Science, Ser. A(29): 103-114, English summary, pp. 113-114.

Kobayashi, F. and A. Fujino. 1970: Bakuha ni yoru jinkō-nadare hassei kōhō kara nadare hassei bōshi kōhō e no tenkai ni kansura jikken-kenkyū (Experimental study of the development from engineering methods using explosives for the production of man-made avalanches to engineering methods for the prevention of their production.) Seppyō 32 (3): 63-70, English abstract, p. 70.

Kobayashi, F. 1969: Jinkō-setsuhō no ichi-kōhō (Artificial release of avalanches). Seppyō 31(2): 44-49.

Kojima, K. 1974: A field experiment on the rate of densification of natural snow layers under low stresses. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Kolomyts, E.G. 1970: Rost kristallov pri konstruktivnom metamorfizme snezhnoy tolshchi (The growth of crystals under constructive metamorphism in snow pack). Materialy Glyatsiologicheskikh Issledovaniy. Khronika Obsuzhdeniya, Vyp. 17, pp. 117-124, English summary, p. 170.

Kuroiwa, D. 1974: Mechanics and structure of snow as a dispersed system. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Kuroiwa, D. 1974: Metamorphism of snow and ice sintering observed by time lapse cine-photomicrography. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Lang, T.E. and R.L. Brown. 1974: Stress concentration in sloping snow pack from geometric imperfections. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Lang, T.E. and others. 1973: Buckling characteristics of a sloping snow slab. J. Geophysical Research 78(2): 339-351.

Langham, E.J. 1974: The mechanism of rotting of ice layers with a structured snowpack. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Linlor, William I. and James L. Smith. 1974: Electronic measurements of snow sample wetness. Advanced Concepts and Techniques in the Study of Snow & Ice Resources, Proceedings of Interdisciplinary Symposium, Monterey, Calif., December 1973. National Academy of Sciences, pp. 720-729.

Linlor, W.I. M. F. Meier, and J.L. Smith. 1974: Microwave profiling of snowpack free-water content. Advanced Concepts and Techniques in the Study of Snow & Ice Resources, Proceedings of Interdisciplinary Symposium, Monterey, Calif., December 1973. National Academy of Sciences, pp. 729-737.

Lovie, C. 1971: Les avalanches de neige en Savoie durant l'hiver 1969-1970. Annalem der Meteorologie, Neue Folge (5): 235-239.

Makeyev, V.M. 1971: Snezhnaya lavina (Snow avalanche). Informatsionnyy Byulleten' Sovetskoy Antarkticheskoy Ekspeditsii (82): 91-92.

Martinelli, M., jr. 1972: Simulated sonic boom as an avalanche trigger. USDA Forest Service Research Note RM-224, 7 p.

Martinelli, M., jr. 1974: Snow avalanche sites: their identification and evaluation. USDA Forest Service Information Bulletin 360, 27 p.

Matviyenko, V.S. and A.R. Gerber. 1974: The effect of explosion on a snow cover. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

McClung, D.M. 1974: Creep and the snow-earth interface condition in a seasonal alpine snowpack. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Mellor, Malcolm. 1974: A review of basic snow mechanics. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Miller, L. and D. Miller. 1974: The computer as an aid in avalanche hazard forecasting. Advanced Concepts and Techniques in the Study of Snow & Ice Resources, Proceedings of Interdisciplinary Symposium, Monterey, Calif., December 1973. National Academy of Sciences, pp. 356-363.

Moskalev, Y. 1974: On the origin of wind blasts and air jets caused by the motion of avalanches. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Perla, R.I. 1974: Stress and progressive fracture of snow slabs. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Perla, R.I.ed.: 1973: Advances in North American Avalanche Technology: 1972 Symposium. USDA Forest Service General Technical Report RM-3.

Perla, R.I. 1971: The slab avalanche. USDA Forest Service Alta Avalanche Study Center Report No. 100, 100 pp.

Plas, J.J. 1971: Les avalanches dans les Alpes français. 10 ans d'observations et de mesures. Annalen der Meteorologie, Neue Folge (5): 241-246.

Pont, A. 1972: Mattmark: les causes présumées de la chute catastrophique de 1965. Les Alpes. Revue du Club Alpin Suisse, 48e An., 2e Trimestre, p. 124-128.

Rieben, E. 1971: Les travaux de défense contre les avalanches. Les Alpes. Bulletin Mensuel du Club Alpin Suisse (11): 257-261.

Runich, A.V. and M. Ch. Zalikhanov. 1974: Structure and mechanical properties of the avalanche snow. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Runich, A.V. 1972: Metod rascheta davleniya lavinnogo potoka na prepyatstviye (A method for calculating the pressure of an avalanche flow upon an obstacle). Meteorologiya i Gidrologiya (5): 69-74 (English abstract, p. 74).

Salm, B. 1974: A constitutive equation for creeping snow. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Schaerer, P.A. 1974: Friction coefficients and speed of flowing avalanches. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Schmidt, R.A., jr. 1972: Sublimation of wind-transported snow - a model. USDA Forest Service Research Paper RM-90, 24 pp.

Schmilinsky, M. 1972: Description Systématique des avalanches. Les Alpes. Bulletin Mensuel du Club Alpin Suisse (1): 1-2.

Shimizu, H. and others. 1972: Kurobe kyōkoku shiai-dani no nadare kenkyū. I. Shiai-dani no nadre yobi chōsa (Study on the avalanche of Shiai-dani valley, Kurobe canyon. I. Preliminary observation.) Teion-kagaku: Low Temperature Science, Ser. A(30): 103-114, English summary, pp. 112-114.

Shoda, M. 1974: On the extension of Haefeli's one-dimensional theory of stress distribution within a sloping snow cover. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

St. Lawrence, W. and C.C. Bradley. 1974: The deformation of snow in terms of a structural mechanism. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Tochon-Danguy, J.-C., and E.J. Hopfinger. 1974: Simulation of the dynamics of powder avalanches. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Tollner, H. 1972: Suchgeräte zur Auffindung von Lawinenverschütteten. Wetter und Leben, Jahrg. 24, Ht. 9-10, pp. 208-211.

Tollner, H. 1971: Zum Problem Lawinen a bgang und Lawinen-Vorhersage in Österreich. Wetter und Leben, Jahrg. 23, Ht. 11-12, pp. 237-243.

Tushinskiy, G.K. ed. 1971: Karty lavinoopasnykh rayonov Sovetskogo Soyuza (Maps of avalanche risk regions of the Soviet Union). Moscow, Izdatel'stvo Moskovskogo Universiteta, 27 pp., 4 maps.

Tusima, K. 1972: Ondo ni yoru sekisetsu no kōdo henka. II. -5C kara -55C de no kōdo no sokutei (Hardness of snow as dependent on its temperature. II. Measurements of hardness from -5°C to -55°C). Teion-kagaku: Low Temperature Science, Ser. A(30): 47-52, English summary, pp. 51-52.

Tusima, K. 1971: Ondo ni yoru sekisetsu no kōdo henka (Hardness of snow as dependent on its temperature). Teion-kagaku: Low Temperature Science. Ser. A(29): 51-55, English summary, pp. 54-55.

Ushakova, L.A. and E.S. Troshkina. 1974: Role of the liquid-like layer in the snow metamorphism. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Voitkousky, K.F. and others. 1974: Creep-induced changes in structure and density of snow. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Voitkovsky, K.F. and others. 1974: Mass transfer and metamorphism in the snow cover. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

Wakabayashi, R. 1972: Schnee und Lawinen in Japan. Winterbericht des Eidgenössischen Institutes für Schnee- und Lawinenforschung (35): 163-167.

Wakabayashi, R. 1971: Beitrag zur Untersuchung von Lawinen im Waldgebiet Hokkaidos. Hokkaidō Daigaku Nōgakubu Enshūrin Kenkyū Hōkoku: Research Bulletins of the College Experiment Forests, College of Agriculture, Hokkaido University, 28(2): 259-323.

Zalikhanov, M.Ch. 1971: Snezho-lavinnyy rezhim i perspektivy osvoyeniya gor Kabardino-Balkariya (The snow avalanche regime and prospects for the development of the mountains of Kabardino-Balkarskaya A.S.S.T.). Nal'chik, Knizhnoye Izdatel'stvo "elbrus," 190 pp.

Ziegler, H. 1974: Continum mechanics, a powerful tool in solving ice and snow problems. IUGG-IASH International Symposium on Snow Mechanics, April 1974, Grindelwald, Switzerland.

LaChapelle, E.R. and T. Fox. 1974: A real-time data network for avalanche forecasting in the Cascade Mountains of Washington State. Advanced Concepts and Techniques in the Study of Snow and Ice Resources. Proceedings of Interdisciplinary Symposium, Monterey, Calif., December 1973. National Academy of Sciences, pp. 339-346.

APPENDIX 4

Reprinted from the Second Annual Report 1972-1973

CHAPTER 3: PHYSICAL CAUSES OF AVALANCHES IN THE SAN JUAN MOUNTAINS

With two winters of study completed, enough data on weather conditions and snow stratigraphy have accumulated to present an emerging picture of the basic snow conditions leading to avalanche formation in the San Juan Mountains. Many of the initial deductions concerning this causal relationship have been derived from the extensive number of snow pits dug over the past two winters at the regular Red Mountain Pass snow study site (25), in avalanche release zones (40), at avalanche fracture lines (24) and at miscellaneous sites throughout the research area (10). The basic procedures used and type of data acquired in these pit studies have been described in the 1972 Interim Report (Ives et al., 1972). Additionally, numerous partial pit and ram penetrometer profiles have been accumulated as supplementary information. This present discussion summarizes the insights gained to date and discusses the inferences which may be drawn from them.

The San Juan Snow Climate

The standard climatological records and the character of the 1972-1973 winter for the research area are summarized in Chapter 2. The influences of such basic weather elements as temperature, wind, cloud cover, radiation and precipitation are now examined as they affect internal structure and evolution of the snow cover.

The San Juan Mountains are an area of unusual interest for snow conditions, for they exhibit climatic extremes not found in more northerly latitudes where most practical and scientific knowledge of snow avalanche formation has been accumulated. The Red Mountain Pass snow study site, at 37°54'N, lies at the same latitude as the North Coast of Africa, some 1200 km (700 miles) closer to the equator than the Swiss Alps 240 and 320 km (150 and 200 miles) closer than Berthoud Pass, Colorado, and Alta, Utah, respectively, where most of the current knowledge about avalanche conditions in the internal ranges of the United States has been gained. The snow climate of the San Juan Mountains probably is closer to that of the High Atlas Mountains of North Africa than it is to the snow climate in much of the Alps or northerly portions of the United States. The avalanche release zones within the research area range in altitude from 2800 m (8,960ft) to almost 4000 m (12,800ft), with a mean altitude of 3400 (10,880ft). This combination of high altitude, low latitude and predominantly continental climate produces what we now define as a <u>radiation snow climate</u>.

At the summer solstice, the noon sun over Silverton stands within 14° of the zenith. Even at mid-winter, the noon sun rises 30° above the horizon, high enough to shine perpendicularly to south-facing slopes of 60°, well within the range of avalanche sluff zones. A substantial amount of solar energy is thus available to such slopes even at mid-winter and rises rapidly as spring approaches. At the same time, the combination of high altitude and frequent low humidity leads to intensive nocturnal radiational cooling of all exposures. Snowpacks with southerly exposures are subjected to rapidly varying and very intense near-surface temperature gradients while those with northerly exposures experience a persistent strong surface cooling and, consequently steep temperature gradients throughout the pack. The annual snow accumulation in the release zones, generally reaching depths of 1.5 to 3 meters, is not sufficient to suppress strong temperature gradients with the prevailing radiation regime. In the presence of such a temperature gradient, vapor transfer occurring along the gradient results in the formation of large and loosely packed snow crystals or depth hoar; this process, called constructive, or temperature-gradient (TG), metamorphism predominates in the snow cover. During the winter of 1972-1973, temperature-gradient metamorphism was noticeably less persistent than in the previous winter. However, 71% of the snow layers (total layer thickness in centimeters) in 21 release-zone pits dug through the snow cover prior to March 1 exhibited crystallographic evidence of either partial or advanced TG metamorphism. These same pits showed 18% new or partly-metamorphosed new snow and only 11% snow which was primarily produced by destructive, or equi-temperature metamorphism, a process by which the surface free energy of the snow particles is minimized by the formation of more nearly spherical particles. The percentage of snow reported as TG-derived drops to 55% for 18 pits in March and April, as would be expected when spring melt and equi-temperature metamorphism have destroyed some of the crystallographic evidence. Table 3 summarizes the distribution of snow types in these pits.

Depth hoar formation or TG metamorphism is more prevalent at lower elevations within the research area (below about 3200-3300 m) where snow accumulation is shallower and nocturnal radiational cooling leads to persistent temperature inversions in the valleys. On northerly slopes and in the forests a very weak depth hoar structure envelopes most of the snow cover. In the higher avalanche release zones, mature depth hoar is less extensive, although some is found in the lower parts of many pit profiles. During winters of light snow accumulation, such as 1971-1972, developed depth hoar layers appear more frequently in the release zones.

On the whole, snow cover in the release zones is mechanically weak throughout the winter. The deeper accumulation sites do ameliorate temperature gradients enough to allow some stabilizing gain in strength during the winter, but even at these sites certain weak layers tend to persist into spring. For the pit profiles cited in Table 3, the mean ram resistance of the 21 profiles prior to March 1 is only 6.1 kg. Ten of these 21 profiles have mean ram resistances of less than 5 kg, 7 lie between 5 and 10 kg, and only 4 lie between 10 and 20 kg. For the period March-April, the mean ram resistance rises to 13.8 kg. Throughout the winter, excluding new or partly-metamorphosed new snow, significant (over 5 cm) layers with ram resistances under 5 kg can be found in all but 4 pits, the latter exceptions occurring late in the spring. In 22 pits, a major part of the profile show a ram resistance of less than 2 kg, with half of these less than 1 kg. The pervasive influence of TG metamorphism apparently maintains low snow strengths even in those layers where its crystallographic effects cannot readily be distinquished.

TABLE 3. DISTRIBUTION OF SNOW TYPES BY LAYER THICKNESS

IN RELEASE ZONE PITS FOR WINTER OF 1972-1973

Total Layer Thickness (cm)	Λ	⏥	•O	+λ\	Complete Pit
To end Feb.	761	1633	368	619	3381
Mar.-Apr.	1216	874	1332	380	3802
Winter	1977	2507	1700	999	7183
Percent					
To end Feb.	23	48	11	18	100 (21 pits)
Mar.-Apr.	32	23	35	10	100 (18 pits)
Winter	27	35	24	14	100 (39 pits)

Temperature-Gradient Snow		Advanced Equi-Temperature	New and Partially
Advanced	Partial	Metamorphism	Metamorphosed Snow
Λ	⏥	•O	+λ\

At only two sites, a snowdrift accumulation area adjacent to Point 12,325 (anemometer site) and Molas Pass, did the snow cover in 1972-1973 develop a stratigraphic and ram resistance profile characteristic of hard slab, with a mean ram resistance of 70 kg in the top 190 cm at Pt. 12,325 and 30 kg in the mid-pack layer at Molas Pass. No avalanche occurred at these sites and only one of the avalanche fracture line profiles obtained in 1972-1973 exhibited the characteristics of hard slab (East Riverside, Appendix 1, Fracture Line Profile #15). Of a total of 182 slab avalanches recorded in the study area in this same winter, only 12 were identified as hard slab from external appearances.

Weak bonding between layers occurs frequently. This often appears as thin layers of low-cohesion snow between crusts. Intense surface radiational cooling and consequent recrystallization by strong TG metamorphism close to the snow surface appears to be the most common cause of such layers. Occasional falls of very soft, low density snow, sometimes only a centimeter or two thick, also contribute to this layer formation (Appendix 1, Fracture Line Profile #3). Crust disintegration through TG metamorphism also adds to poor layer bonding. In some instances, surface hoar layers have been identified as the lubricating layer in slab avalanches (Appendix 1, Fracture Line Profile #13 and #16). All of these factors stem from strong radiational cooling at the snow surface except the low-density new snow, and even this tends to be preserved by such cooling. The 1972-1973 Fracture Line Profiles compiled in Appendix 1 show many other examples of poor layer bonding, both at the glide plane and elsewhere in the profiles.

Remarkably little stabilization takes place on south-facing slopes in spite of the intense solar radiation at this latitude. Many sun crusts are developed, but these alternate with very weak layers of TG snow. There is some evidence of TG deterioration of crusts. Deeper layers of TG snow with low strength occur much more prominently than is normally found on south slopes in other climates. Figure 10 shows examples of this type of snow stratigraphy. In Appendix 1, Fracture Line Profiles #5 and #9 are also good examples. The controlling mechanism for inhibiting stabilization of slopes with southerly orientation appears to be intense TG metamorphism accompanying large diurnal fluctuations in radiation-determined temperature of the near-surface snow layers.

The general evolution of the snow cover during the winter season 1972-1973 is discussed in Chapter 2. That discussion is based on the evolution documented in detail at a single site, the Red Mountain Pass snow study site. Although this site was selected with care to be representative of snow and weather conditions at the 3400 m level in the San Juan Mountains, it has in fact proved to be only partially representative. Precipitation, snowfall types and air temperatures appear to characterize the research area rather well, but the snow cover evolution does not. The snow cover at the study plot has been singularly stable, with noticeably less TG metamorphism than elsewhere throughout the area, as well as significantly less evidnece of poor layer bonding. Most slope profiles collected in the avalanche release

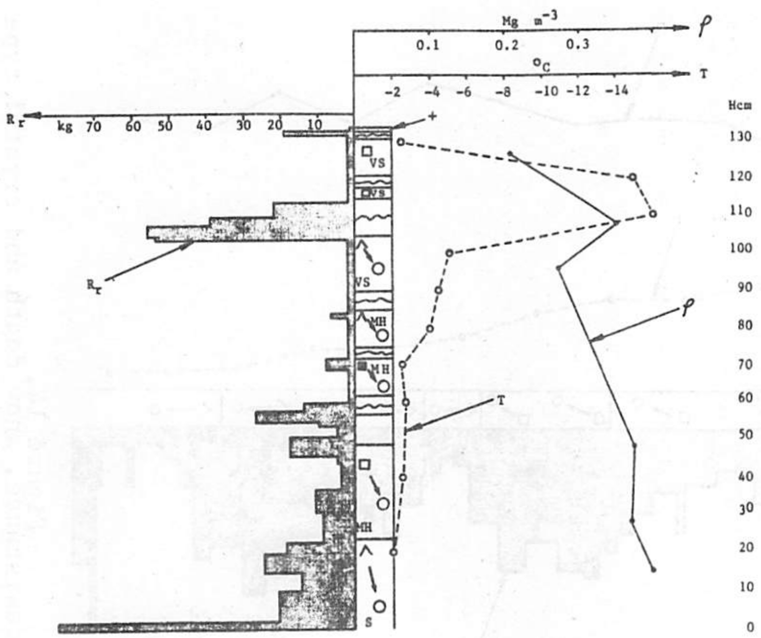

Figure 10. Stratigraphic data including density (Mg/m^3), temperature (°C), ram resistance (kg), crystal type, and snow height in cm (Hcm) from a snowpit located on a south-facing slope of Carbon Mountain (3500 m), February 16, 1973. For explanation of symbols, see Appendix 1.

zones as well as fracture line profiles show generally weak snow structure compared with the study plot. Furthermore, there is a large variability in the ram profiles among slope profiles themselves which on first glance ought to be similar. The difference in ram strengths between the study plot and slopes is clearly seen in Figures 11 and 12, where ram profiles at the study plot on two separate dates are compared with those on the same dates from slopes of various orientations immediately adjacent to the study plot. The strength contrast between otherwise comparable slopes is obvious in Figures 13 and 14 where slope profiles from two slopes of nearly identical orientation, elevation and snow depth, the Mill Creek A (Appendix 1, Misc. Pit #46) and North Carbon Site (Appendix 1, Misc. Pit #37) show entirely different ram profiles.

The strength variations among otherwise similar slope profiles are probably due to complex factors which may not all be perceivable from the existing data. Differences in wind influence no doubt play an important role. The local forest environment appears also to be a factor, with lower ram strengths appearing in more heavily timbered areas. The character of the ground surface may have some influence on the extent of TG metamorphism in the lower snow layers, and local variations in snow temperature regimes may be related to valley wind(katabatic, or drainage winds) patterns generated during nocturnal radiational cooling and the formation of local inversions.

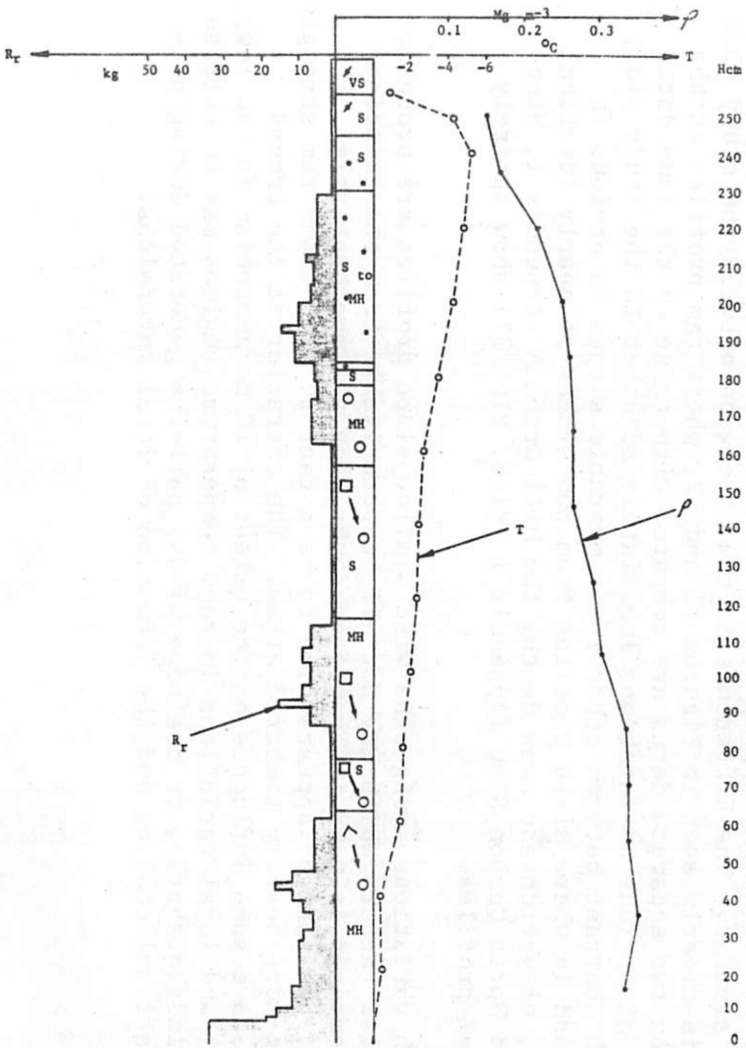

Figure 13.

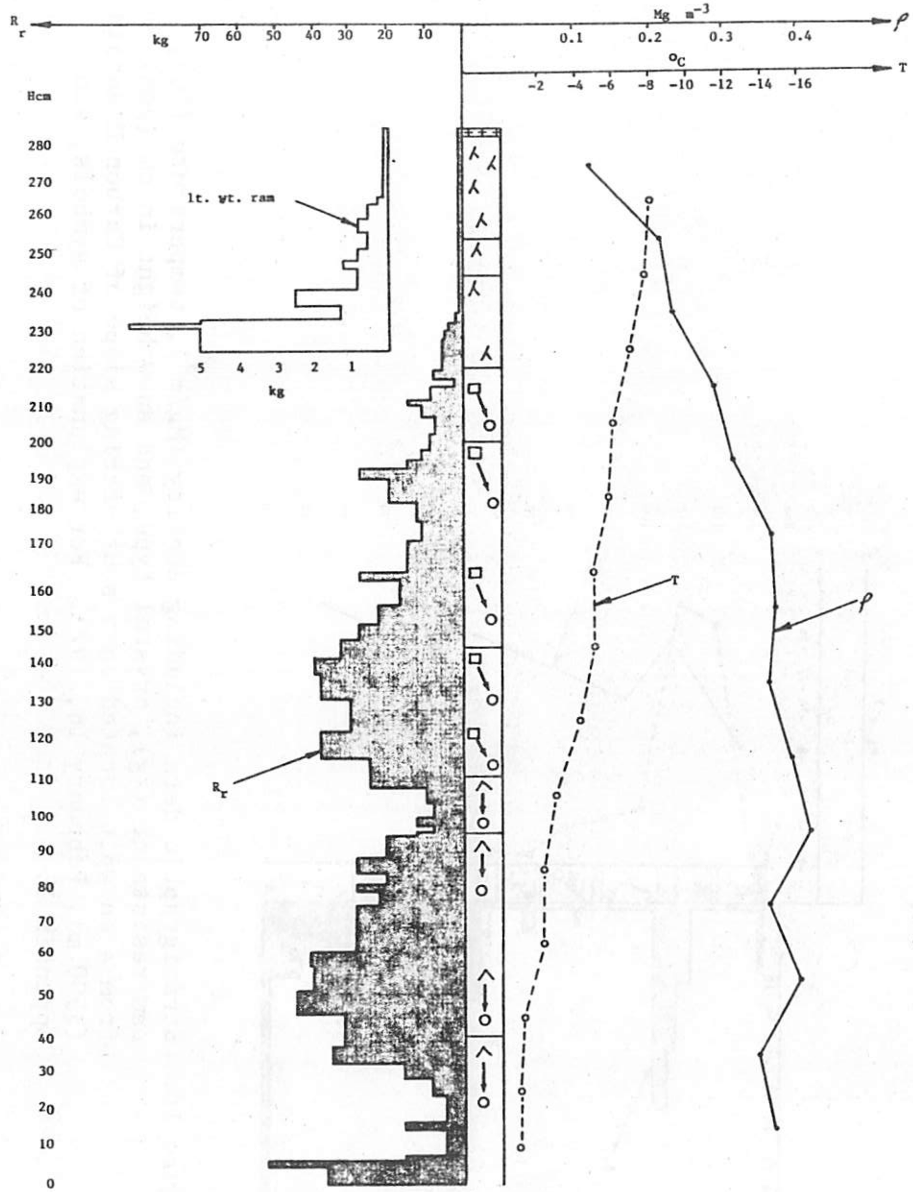

Figure 14.

Figure 13. Stratigraphic data, including density, temperature, ram resistance, snow depth and crystal type from a snowpit located on a north-facing slope within the Mill Creek Cirque (3600 m), April 6, 1973.

Figure 14. Stratigraphic data, including density, temperature, ram resistance, snow depth and crystal type from a snowpit located on a north-facing slope of Carbon Mountain (3500 m), March 8, 1973.

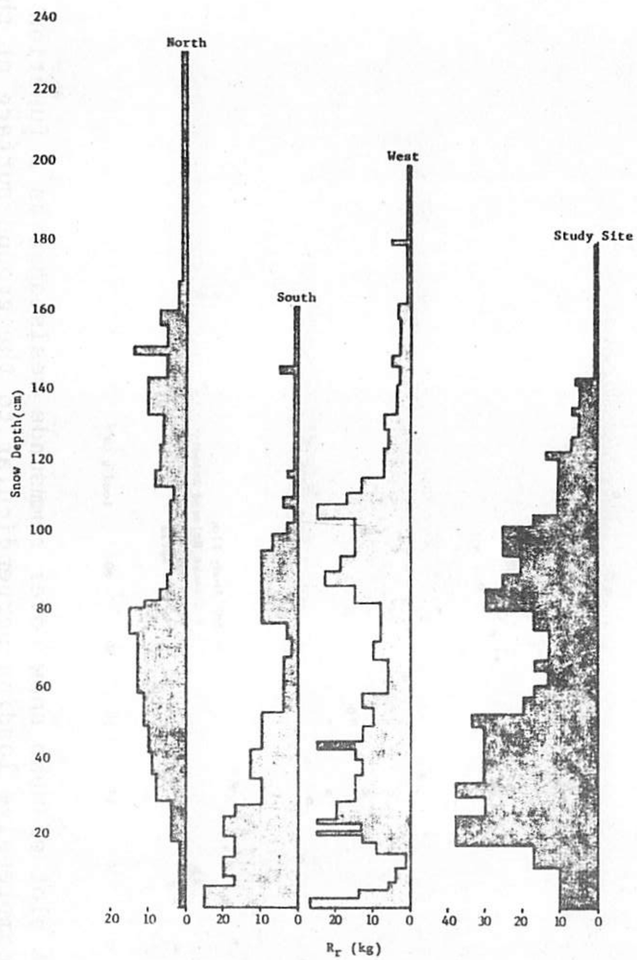

Figure 11.

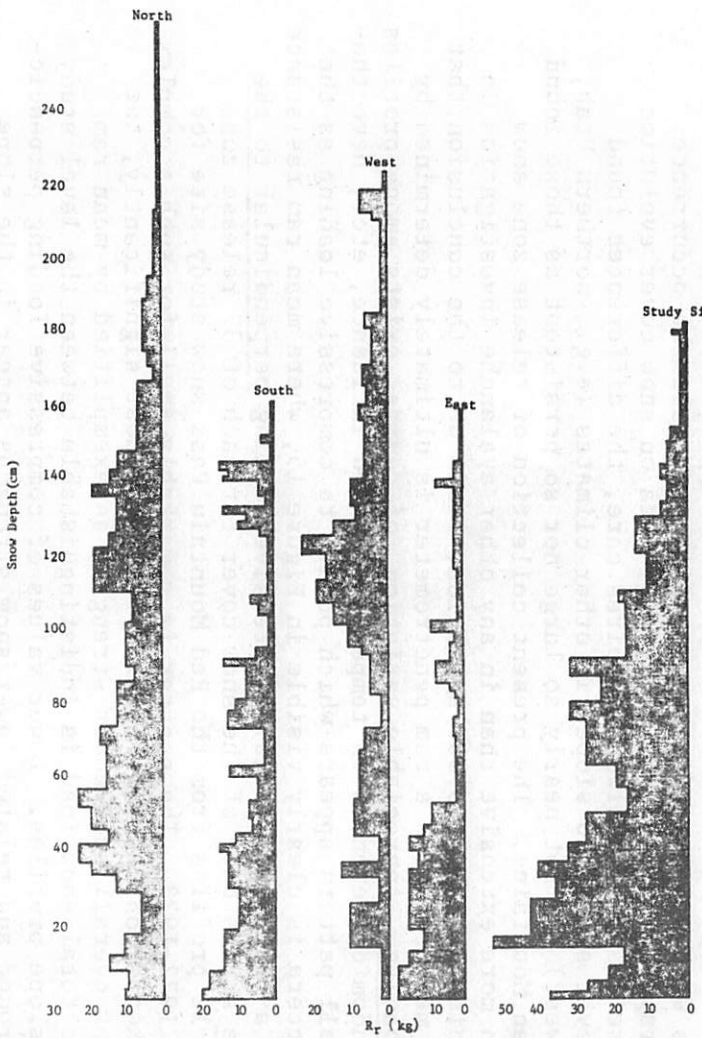

Figure 12.

Figure 11. Rammsonde resistance profiles obtained within the Red Mountain Pass snow study site and on north-, west-, and south-facing slopes adjacent to the study site, January 23, 1973.

Figure 12. Rammsonde resistance profiles obtained within the Red Mountain Pass snow study site and on north-, west, south-, and east-facing slopes adjacent to the study site, February 26, 1973.

Acquisition of many more slope profiles will probably be needed before this question of strength variability can properly be answered.

Our slope profile data appear to demonstrate a plausible explanation of the prevailing weaker snow found on slopes compared with that at the Red Mountain Pass snow study site. This situation has appeared during both of the past two years with widely different snowfall and avalanche occurrence. While the extrapolation of level study plot data on snow cover evolution to avalanche release zones always requires care, the differences found between the level sites and slopes in other climates (e.g., northern Utah, Pacific Northwest) are not nearly so large nor so persistent as those found in the San Juan Mountains. The present collection of release zone snow profiles, much more extensive than in any other avalanche investigation in any climate which has come to our attention, leads us to the conclusion that snow strength measured with a ram penetrometer is ultimately determined by compressive loading. Appreciable variation, of course, exists among profiles because of random differences in temperature, wind influence, etc., nevertheless, an overall pattern appears which points to compressive loading as the key. This pattern is clearly visible in Figure 15, where mean ram resistance is plotted as a function of total compressive loading perpendicular to the ground surface at the base of the snow cover for each of 37 release zone profiles plus 12 profiles from the Red Mountain Pass snow study site for the winter of 1972-1973. The scatter is remarkably small for such a complex geophysical phenomenon as snow cover evolution. Most significantly, the relationship of overall snow cover strength, as exemplified by mean ram resistance, to total snow load is indistinguishable between the level study plot and the slope profiles. Lower values of compressive loading perpendicular to the ground and related lower snow strengths appear in the slope profiles because only one component of the body forces in the snow cover, that modified by the cosine of the slope angle, is effective in this direction. The other component works parallel to the slope and produces creep

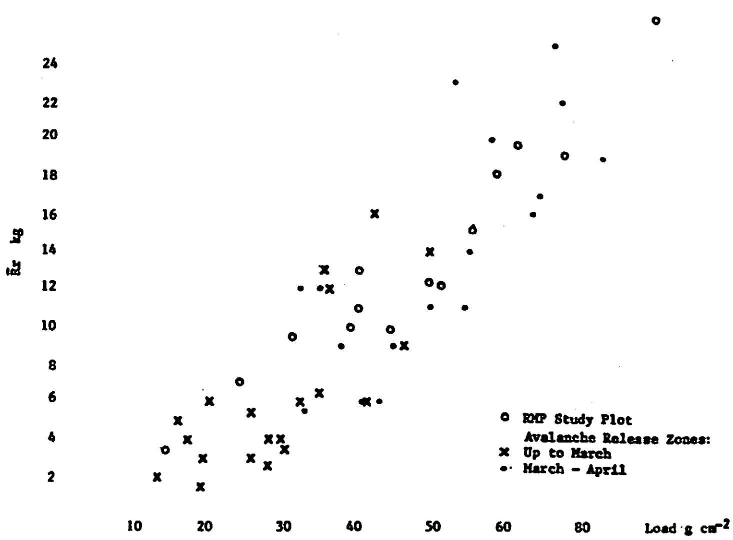

Figure 15. A plot of mean snow cover rammsonde resistance as a function of total compressive loading perpendicular to the ground surface at the base of the snow cover for each of 37 release zone profiles plus 12 profiles from the Red Mountain Pass snow study site for the winter 1972-1973.

deformation which does not generate a compressive load in the middle of an open slope. It now becomes apparent that the distribution of snow depths commonly found in the San Juan research area is such that compressive load values associated with higher snow strengths appear early in the winter on level ground but do not appear until much later in the winter on slopes above 30° which are characteristic of avalanche release zones.

Character of Avalanche Formation

The moderate snowfalls and radiation snow climate of the San Juan Mountains combine to produce a snow cover which in most avalanche release zones and for most of each winter is conditionally unstable. By conditionally unstable we mean that at any given time while the snow cover is at sub-freezing temperatures, it is only marginally unstable in respect to spontaneous slab avalanche release through internal causes, but it remains throughout each winter highly susceptible to either load-induced or thaw-induced avalanche release. The addition of new load to the snow cover (precipitation or wind-transport event), or the introduction of meltwater to subsurface snow layers (normally by thaw but also possible by rain) are in themselves necessary but not sufficient conditions for avalanche release. The conditionally unstable nature of the snow cover (predominantly low mechanical strength and poor layer bonds) is a sufficient condition to generate wet snow avalanches following introduction of meltwater, but it is neither necessary nor sufficient to generate load-induced avalanches, for load-induced avalanches may fall through instabilities in the new snow alone, while a snow cover existing prior to the load event remains stable and does not necessarily participate in the avalanche formation (direct-action avalanches). However, a conditionally unstable snow cover such as that so common to the San Juan Mountains can set the stage for load-induced avalanches which would not otherwise fall if the load had been deposited on stable snow.

During the winter of 1972-1973, a total of 17 avalanche fracture line profiles were collected in the research area. Two of these deal with spring conditions and wet snow; the rest relate to dry slab conditions and snow at sub-freezing temperatures. Of the 17 fracture lines visited, only three represented direct-action avalanches with the slab layer involving only newly-fallen or wind-drifted snow. The rest involved older snow in the sliding layer and hence fall into the category of climax avalanches, the basic type to be expected when load-induced avalanches occur in an unstable snow cover. Thicknesses of the sliding layers in these 17 profiles ranged from 19 cm (7.5in) to 122 cm (48in), with a mean thickness of 59.5 cm (23.4in). The mean ram resistance of the sliding layers ranged from 0.3 kg to 15 kg, with a mean for all 17 profiles being 3.3 kg. Only three profiles showed a mean ram resistance exceeding 10 kg and none of the remainder exceeded 4 kg. The predominant avalanche type was soft slab and only the three avalanches with mean slab layer ram resistance exceeding 10 kg can reasonably be called hard slab, although the maximum value of 15 kg is well below the hardnesses ranging up to 50 kg or more which are often associated with hard slab.

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