RELATIONSHIPS BETWEEN SNOW STRUCTURE AND AVALANCHE RELEASE

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Introduction

Each winter, from 100 to 200 avalanches affect the highways within the San Juan Mountains of southwestern Colorado. The University of Colorado Institute of Arctic and Alpine Research (INSTAAR), has been studying the nature and causes of these avalanches for five winters in order to develop a forecast model. Results of the study have shown that accurate avalanche forecasting is strongly dependent on the structure of the snow cover as well as on meteorological parameters. Poor relationships between avalanche magnitude and frequency and precipitation amount are modified to include snow structure data, resulting in clearer understanding of the timing of slab failure. The character of several avalanche seasons is described to demonstrate the strong dependency of avalanche release on snow structure in both subfreezing and melting snow. Conventional and statistical methods of avalanche forecasting are discussed in terms of snow structure parameters as input variables.

Meteorological Parameters, Snow Structure and Forecasting

Avalanches within the study area are primarily precipitation triggered; over 90% of the mid-winter events occur during storm periods. Consequently the discriminate function analysis utilized by INSTAAR (Bovis, 1976) as a statistical method to forecast avalanche occurrence in the San Juan Mountains indicates precipitation values as the optimum discriminator between avalanche and non-avalanche periods. However, the current numerical forecast model relies entirely on meteorological variables to the exclusion of snow structure. When the model was developed, the importance of snowcover variables was indeed recognized. However, the frequent and extreme stratigraphic variation in snow strength and structure proved too complex to allow such variables to be included in the initial model. A strong relationship between old snow structure and avalanche activity is in fact apparent from fracture line data associated with actual avalanche releases. These studies indicate that 86% of the mid-winter releases occurred within the old snow structure (climax-type avalanche) and 75% of the cases involved lubricating layers identified as recrystallized temperature-gradient snow.

While precipitation rates and amounts correlate well with the occurrence of avalanches, such values often do not correlate consistently with the type and magnitude of the release. Correlations between individual storm precipitation amounts and large slab releases were poor, often resulting in r^2 values of less than 0.10. An example of this condition is shown in Fig. 1. If snow structure actually controlled the type and depth of avalanche release, a pattern should emerge if snow structure conditions were monitored throughout the avalanche season. In Fig. 2, when one winter season is divided into four parts according to the intensity of the (temperature-gradient-driven) recrystallization process acting within the snowcover, the precipitation vs. avalanche event data conform to a systematic pattern. The periods are subdivided by date based on four temperature-gradient regimes as measured within the snowcover at the Red Mountain Pass study site. The mean temperature gradients for each period appear below the appropriate dates in Fig. 2. Figure 3 contains the variation in integrated rammsonde resistance with time to further illustrate the respective snow strength regimes associated with each time segment during this particular winter season.

The period November 1st to December 16th indicates the steepest temperature gradient and, while the general snow structure is weakening in response to this condition, it is not until the period December 17th to January 12th that the weakness attains a maximum, creating the pattern of large numbers of avalanches resulting from relatively little precipitation. Figure 4 contains an example of a fracture-line profile obtained during this period; it shows the extremely weak structure of the old snow. The strength data were recorded with a light-weight (0.1 kg) rammsonde. The period January 13th to March 5th represents a period of transition with the snowcover gaining strength as the temperature gradient decreases. The final period represents the snowcover as it approaches an isothermal condition. Linear regression r-values appear for each relationship in Fig. 2 and the instability of the snow structure associated with each period is depicted by the slope value for the appropriate avalanche-precipitation relationship (Fig. 2d, inset).

The deviation of data points A in Fig. 2a, B in Fig. 2c and C in Fig. 2d can be appropriately dealt with as individual cases based on the following supplemental data. Point A represents an early precipitation episode when new snow was accumulating on bare ground or shallow old snow. In case B, February 23, 1975, although little direct precipitation was recorded, additional loading did occur as the result of a wind transport episode with a duration of 18 hours and a mean wind speed of 13 m/sec. Case C, April 13, 1975, occurred when numerous, small soft slab events occurred within the new snow. During the last 12 days preceding this cycle, 95 mm of precipitation had been recorded at the Red Mountain Pass study site without significant avalanche activity. The structural regime represented by Fig. 2d is that of new snow collecting on an exceedingly stable, near-isothermal snowcover. Failure within the older snow structure was, therefore, precluded and a shear failure plane developed in conjunction with a freeze-thaw crust that was established during a brief clear weather episode within the longer period of heavy precipitation. This cycle is an isolated example of slab releases within new snow, an avalanche pattern which frequently occurs in climates where stable old-snow structure prevails, but is the exception within the San Juan snow climate. Figure 5 shows the influence of general snowcover strength on the relationship between larger slab avalanches observed during five winter seasons and individual storm precipitation ("large" being defined as avalanches that are at least capable of damaging an auto or wood-frame house). The data separate into two groups, one reflecting a generally weak snowcover and the other a stronger structure. The location of each data point with respect to either group (separated by dashed line) can be explained in 83% of the cases by a study site mean rammsonde value of <10.0 kg/cm or >10.0 kg/cm respectively.

Genesis of Local Snow Structure

Having established that snow structure exhibits significant control over the nature of avalanche release, what then are the physical conditions which create such a stratigraphy? Investigations of snow structure within avalanche release zones have indicated the dominant snow type to be the result of temperature-gradient metamorphism. The basal layer of temperature-gradient snow or "depth hoar" common to sites in the Rocky Mountains is also prevalent in the San Juan Mountains, with the average thickness of the well-developed layer being from 30-60 cm. Once a substantial basal layer of mechanically weak depth hoar has formed within a release zone, only a significant avalanche cycle can eliminate this condition. Minimal intergranular bonding prevails and, even as the depth and thus load of the overlying snowcover increases and the initial and the initial steep temperature gradient is diminished, only minimal improvement in intergranular cohesion occurs with time.

Figure 3 shows the increase in strength with depth within the mid-pack layers and the sharp break in this relationship as the lower depth-hoar layers are reached. Figure 6 shows the limited densification with time of the depth-hoar layer (shaded zone) compared to the layers above which were exposed to less steep temperature gradients. Figure 7 demonstrates the resistance to settlement exhibited by advanced temperature-gradient snow (settlement curve #1). Curves 2 through 4 represent the settlement rate of mid-winter snow layers exposed to a lesser temperature gradient (0.08 to 0.15°C/cm) and curves 5 through 7 represent the settlement of snow layers at or very near an isothermal condition (0.02 to 0.07°C/cm).

Restricted settlement within specific snow layers may be due to low temperatures (-15.0 - 25.0°C) as well as minimal overburden pressure. Low density, shallow snowfalls are common to this area with the average storm depth being 17 cm and an average mid-winter density of .065 mg/m^3. This situation differs from climates where snowfall amounts are greater and temperatures are closer to freezing. Relationships between overburden pressure, temperature and layer densification have been analyzed elsewhere (deQuervain 1957, Kojima 1974) with the unconsolidated and shallow temperature-gradient layers showing minimal or no increase in density or strength with time. Only substantial loading may cause strength increases but, in terms of avalanching, shear failure may well occur beforehand.

If, in a given release zone, the basal depth-hoar layer is not removed by mid-winter avalanching, it may provide a structure which increases the probability of wet slab avalanches in the spring. As percolating melt water comes in contact with a snow structure which has been developing over several months, optimum shear boundary conditions are created for slab-type releases. As a result of minimal avalanche activity during the 1972-1973 season in the San Juan Mountains, a major portion of the winter's snow structure remained within the release zones at the time the snowcover became isothermal. Wet slab avalanches were numerous and of sufficient magnitude to block the highway at 60 points. In contrast to this situation, a winter with frequent, deep avalanching results in the removal of a major portion of the snowcover metamorphosed under early to mid-winter conditions. Subsequent snowfalls in late winter and early spring are exposed to less significant temperature-gradient metamorphism and thus comprise a more homogeneous and stable structure.

While the occurrence of a basal temperature-gradient layer is often a common condition in high altitude, continental snow climates, consistent recrystallization of near-surface snow layers may not occur as frequently in other locations with a more northerly latitude. The San Juan Mountains are located at a latitude of 37°, the same latitude as the North Coast of Africa, some 1200 km closer to the equator than the Swiss Alps, 240 and 320 km 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 altitudes from 2800 m to almost 4000 m with a mean altitude of 3400 m. This combination of high altitude, low latitude and predominately continental climate produces what we define as a radiation snow climate (LaChapelle 1974).

A substantial amount of solar energy is available to slopes with a southerly aspect, even at midwinter, and this increases as spring approaches. This slope aspect includes a majority of the avalanche release zones in the study area. At the same time, the combination of high altitude and low atmospheric moisture leads to the intense nocturnal radiation cooling of all exposures. The annual snow accumulation within the release zones generally amounts to depths from 1.5-3.0 m and is not sufficient to supress the development of significant temperature gradients. While the mean internal temperature gradients of north- and south-facing slopes do not differ to a significant extent, such values being a function of long-term mean daily air temperatures, it is within the near surface layers that the radical contrast exists. Slopes with a southerly exposure experience subsurface warming due to the penetration and absorption of solar radiation. At any time during the winter season this warming can be sufficient to cause the snow temperature to reach the melting point with the eventual formation of a freeze-thaw crust. Even at the warmest point in the diurnal temperature cycle, when melt is occurring 1.0-2.0 cm beneath the surface, the temperature of the snow-air interface, due to radiation cooling, often remains well below freezing, creating an extremely steep temperature gradient within this near-surface layer. This combination provides optimum conditions for temperature-gradient recrystallization; mean snow temperatures at or near freezing providing maximum water vapour supply, snow structure of low density allowing maximum vapour diffusion and a temperature gradient as high as several degrees per centimenter. Vapour pressure gradients within these surface layers may commonly be as high as 0.60 - 0.80 mb/cm, values which are three to four times greater than those gradients found within basal depth hoar layers. Consequently, advanced temperature-gradient recrystallization may occur within 24 hours. This process has been called radiation recrystallization by LaChapelle (1970) and has been frequently observed in the San Juan Mountains (Armstrong and Ives, 1976). This condition, initially created near the surface of the snow-cover, is buried by subsequent snowfalls and, as the thaw layer freezes, an ideal sliding surface is provided with a lubricating layer of "depth hoar" above. A delicate radiation balance is required to develop this near-surface snow structure. Too much solar radiation or too little infrared cooling will result in firnspiegel or a melt-freeze crust only. In this situation poor adhesion between the slab layer and the sliding surface appears to contribute towards the failure, rather than a separate and distinct weak layer of substantial thickness. Figure 8 shows the relationship between the calculated shear stress of the slab and the measured density of the lubricating layer below. Density samples were limited to average values across 50 mm layers, whereas the actual shear failure zone may often have been less than 10 mm in thickness.

The large diurnal fluctuations in the radiation-determined temperature of the near-surface snow layers continue throughout the winter and a highly complex stratigraphy develops, characterized by large variations in structure and strength. Layers of relatively homogeneous, stronger snow, comprising the individual precipitation increments, are separated by thin layers of temperature-gradient snow and freeze-thaw crusts that have developed during clear weather periods between storms. Poor layer bonding is prevalent in these situations and the snowcover can be described as conditionally unstable, i.e., highly susceptible to load-induced or thaw-induced avalanche release. The general concept of the stabilization of southerly slopes associated with the effect of solar radiation simply is not applicable in the San Juan Mountains. A more detailed analysis of the effect of near-surface temperature gradients can be found in LaChapelle and Armstrong (in preparation).

Conclusions

As mentioned at the beginning of this paper, statistical or objective avalanche forecast models as yet have not included snowcover stratigraphy to any significant extent. In the case of the conventional or subjective forecast, however, it is generally assumed that the person compiling the forecast does take pertinent snowcover parameters into consideration. While it is difficult to make quantitative comparisons of various forecast techniques, attempts have been made during the INSTAAR project (Armstrong and Ives 1976) with the conclusion being that the level of accuracy of the two methods, statistical and conventional, was comparable. It would appear, then, that the methodology which might result in the highest level of accuracy would involve a numerical method combining snowcover and meteorological parameters. I would also stress that the optimum procedure would combine such a statistical approach with the talents of a trained field observer, well versed in the general concepts of the physical and mechanical properties of snow, and especially how these properties are influenced by the local snow climate. As long as the complex nature of snow structure defies accurate physical modelling, and statistical data banks contain samples not populations, be they 10-year or 100-year records, the subjective interpretation of input variables by a skilled observer will continue to be invaluable.

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<u>Discussion</u>

ANDERSON: Can you please explain the phenomenon of radiation-recrystallization that you observe in the upper layers of your snowpack?

ARMSTRONG: Radiation recrystallized grains may form at or just below the snow surface and result from a very steep temperature-gradient which may develop across the near-surface layer. This condition is caused by the penetration and absorption of some small amount of solar radiation at a depth of about 1.0 to 2.0 cm beneath the surface of the snowcover. At the snow-air interface, just above this relatively warm layer, the temperature is controlled by outgoing long-wave radiation and may be several degrees cooler. It is difficult to monitor this process due to the problems associated with accurately measuring snow surface temperatures during periods of strong incoming solar radiation.

FITZGERALD: We believe we also observe this phenomenon at Snowbird. Is radiation the main contributing factor to the formation of these layers?

LACHAPELLE: Radiation recrystallization requires the correct balance between radiation and air temperature, which is generally below freezing when the grains form. Apparently, the balance occurs only for a narrow range of conditions. The low latitude and high altitude of the San Juans seems to favor the necessary balance - at least in comparison to other mountain ranges where I have made observations. The phenomenon is not observed in the absence of solar radiation. For example, it is not observed on shaded north-facing slopes.

KOEDT: How are radiation recrystallized layers related to surface hoar?

ARMSTRONG: They are not the same. During surface hoar formation, the vapour is deposited from the atmosphere down onto the snow surface. During the formation of radiation recrystallized grains, the vapour source is within the snowcover and the vapour flow is upwards, across the layer, experiencing the strong temperature-gradient which I described previously.

ARMSTRONG: At this point I would like to add a comment with respect to the numerical prediction of avalanches with statistical models. It appears from our work in the San Juans, from the recent models proposed by the Swiss Institute, from the models proposed by the Forest Service at Fort Collins, and from the work of Salway, just reported, that numerical prediction is approaching a level comparable to the subjective level of the man in the field. Up to the present, the numerical models have incorporated only meteorological variables, and it would seem that if we could somehow introduce snow structural parameters into the predictive equations, then the equations could possibly move ahead of the subjective approach.

SIMMS: It is difficult to see the practical value of a single predictive equation. At Jackson, we are presently working on a different type of aid to the field man. We are using the computer to store about 500 patterns of input data which represent conditions of varying avalanche intensity. The patterns are established from historical data. If an operational decision is required, we can check to see which historical day best matches the current situation. This is essentially the process of reasoning a field man uses to bring experiences from his memory.

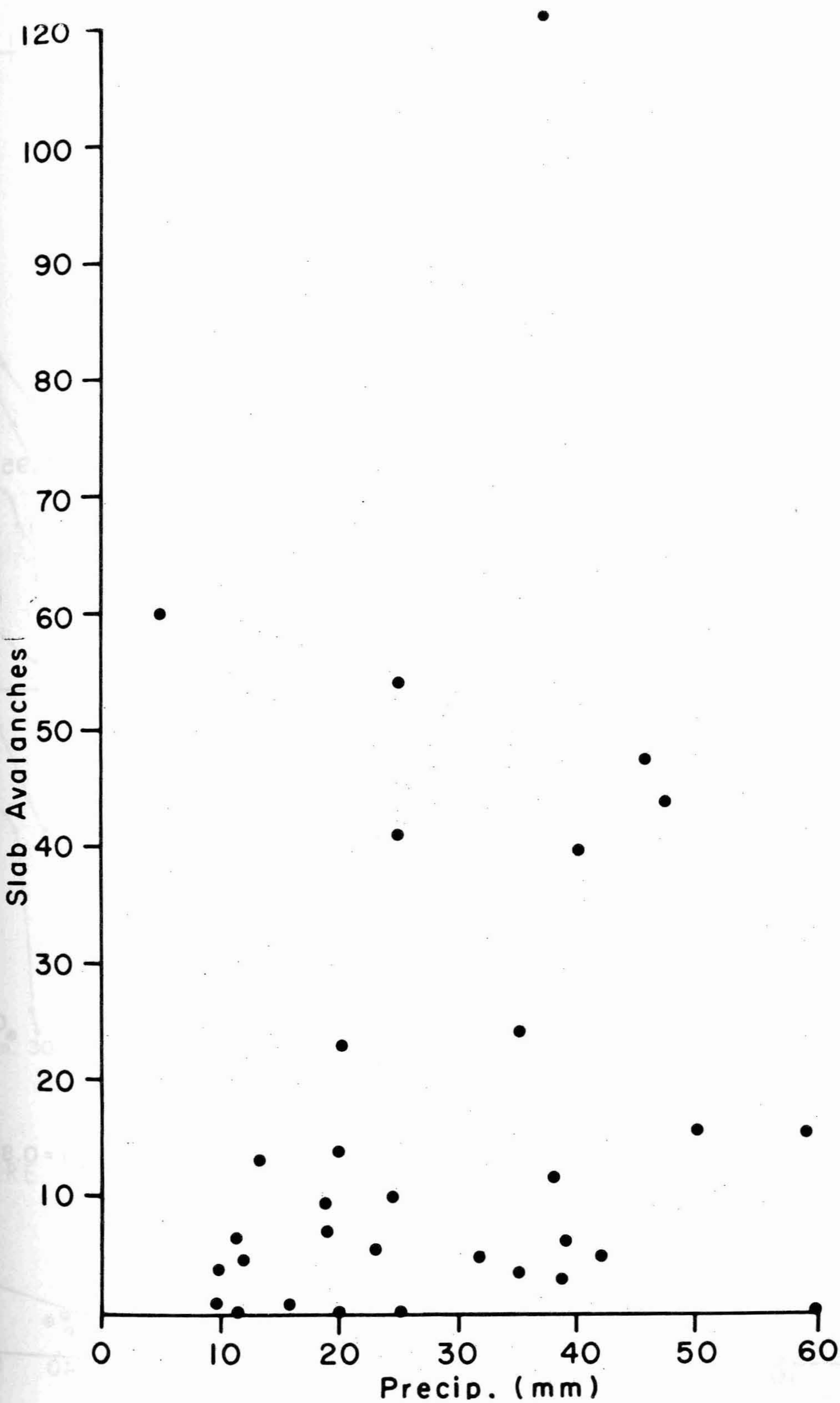

FIGURE 1 RELATIONSHIP BETWEEN STORM PRECIPITATION TOTALS (mm WATER EQUIVALENT) AND SLAB AVALANCHES FOR THE 1974-1975 WINTER

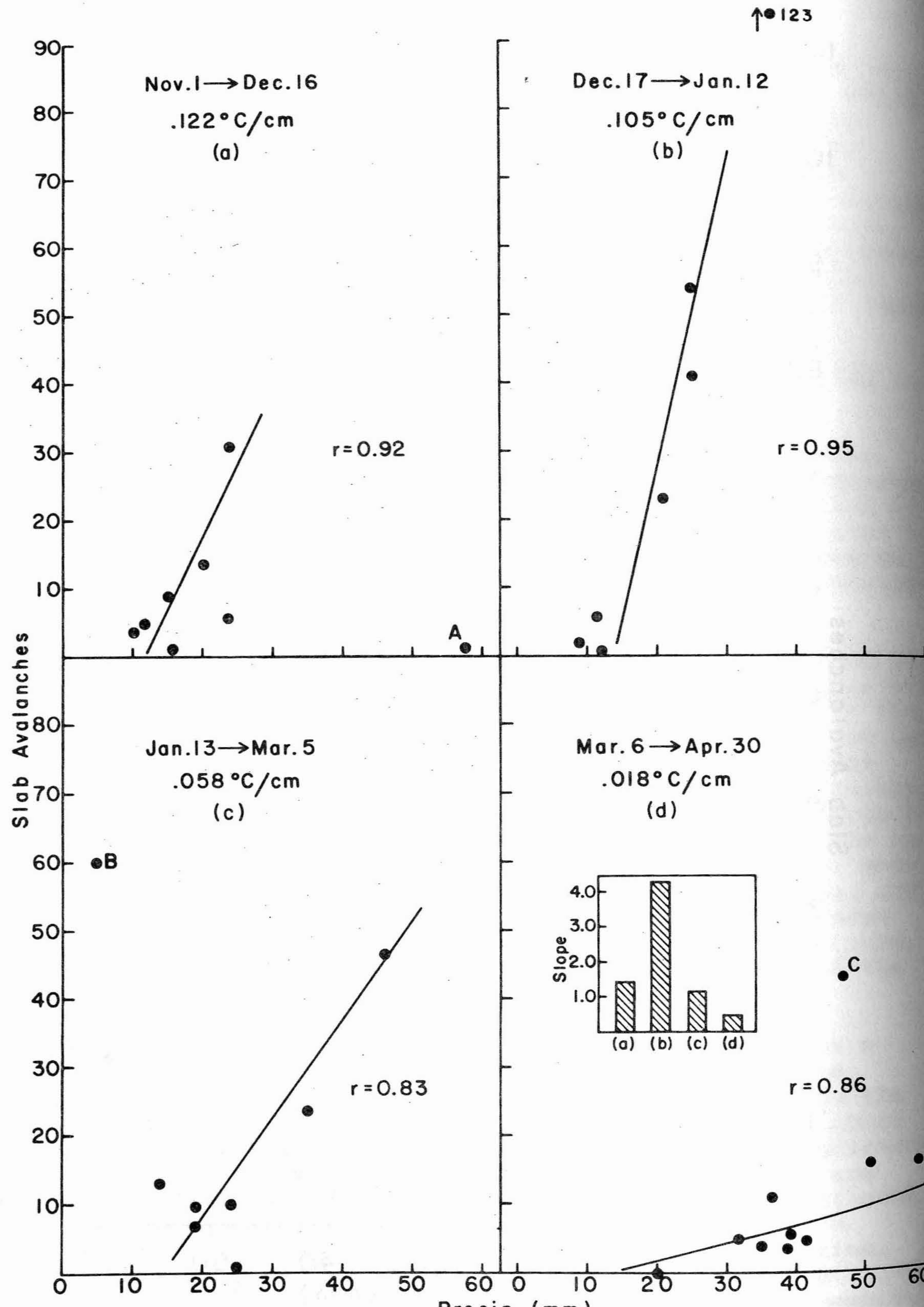

FIGURE 2 RELATIONSHIP BETWEEN STORM PRECIPITATION AND SLAB AVALANCHE EVENTS SUBDIVIDED INTO FOUR PERIODS ACCORDING TO PROGRESSIVE CHANGES IN SNOW STRUCTURE

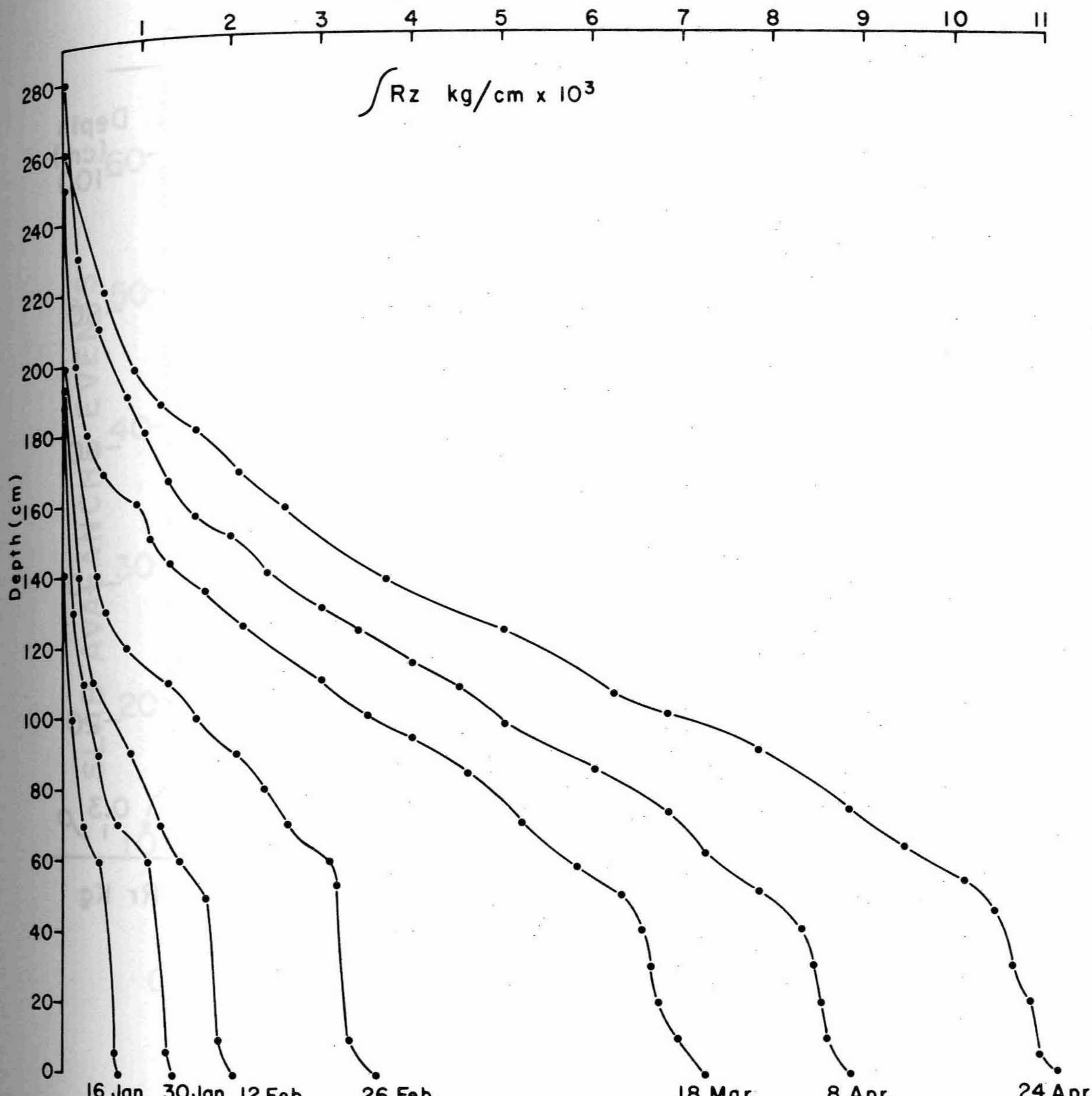

FIGURE 3 INTEGRATED RAMMSONDE VALUES - RED MOUNTAIN PASS

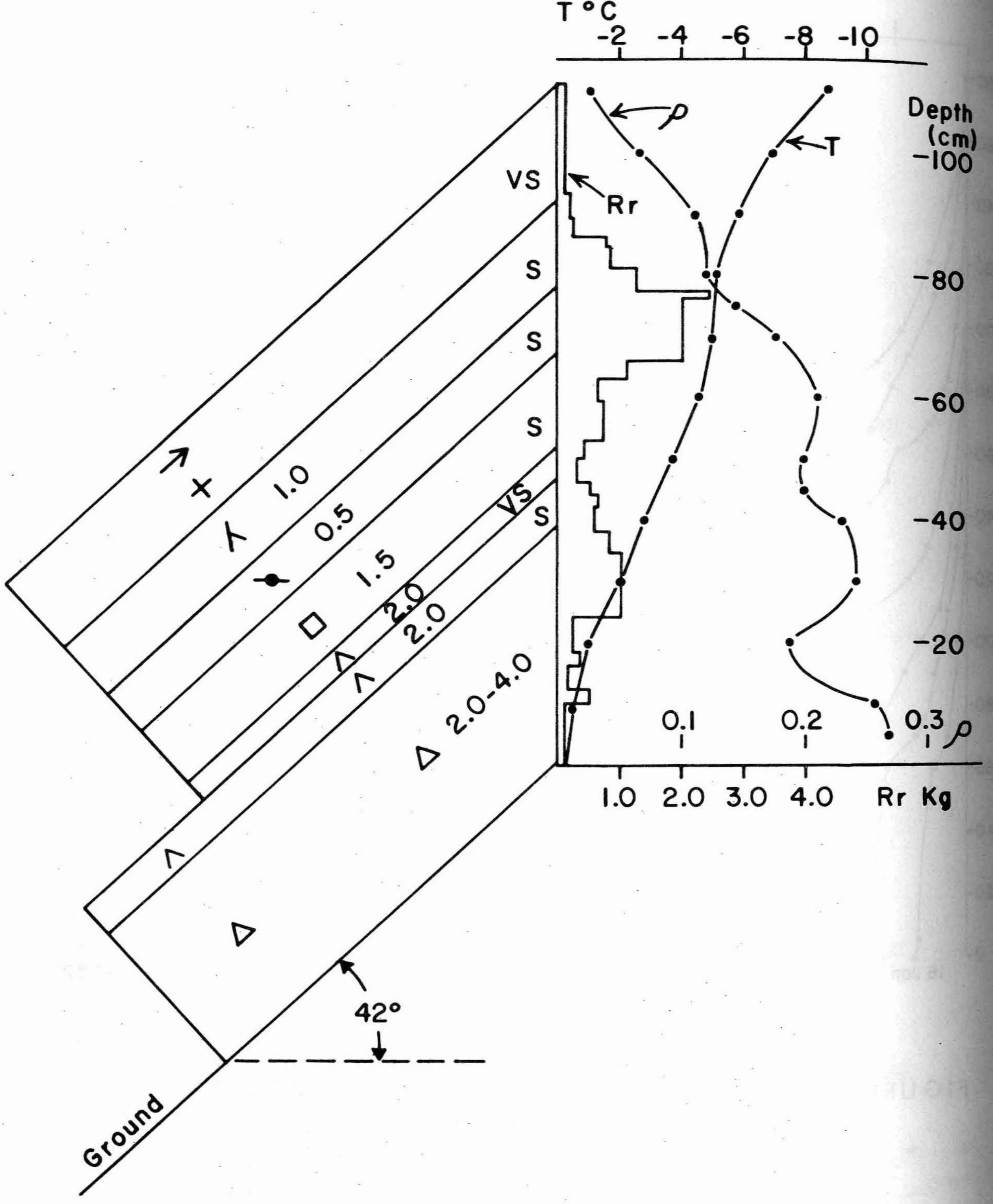

FIGURE 4 FRACTURE LINE PROFILE, SOFT-SLAB RELEASED TO GROUND, 22 DEC. 1974

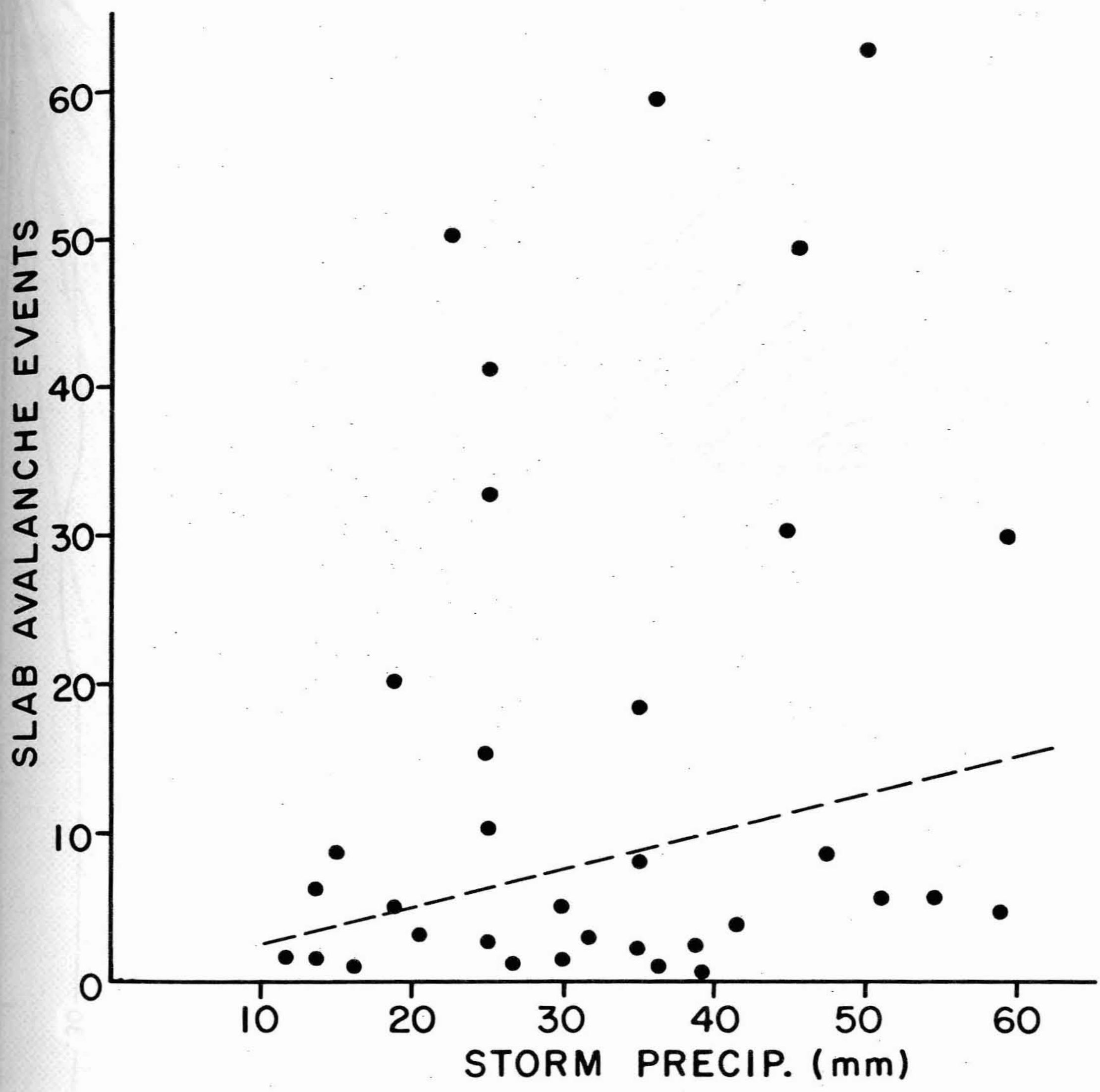

FIGURE 5 LARGE SLAB AVALANCHES AS A FUNCTION OF PRECIPITATION AND SNOW STRUCTURE

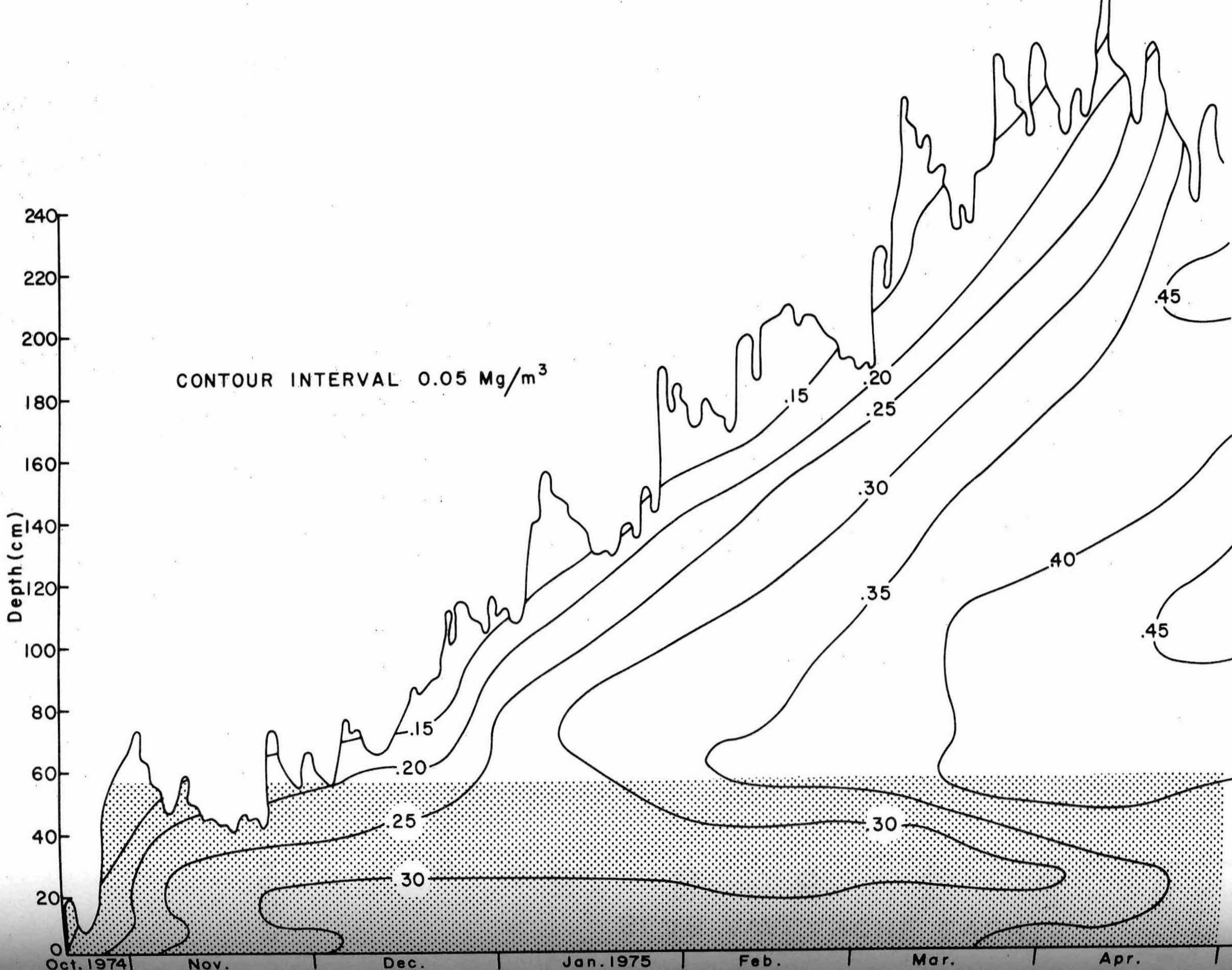

FIGURE 6 TIME-STRATIGRAPHIC DENSITY VARIATION - RED MOUNTAIN PASS

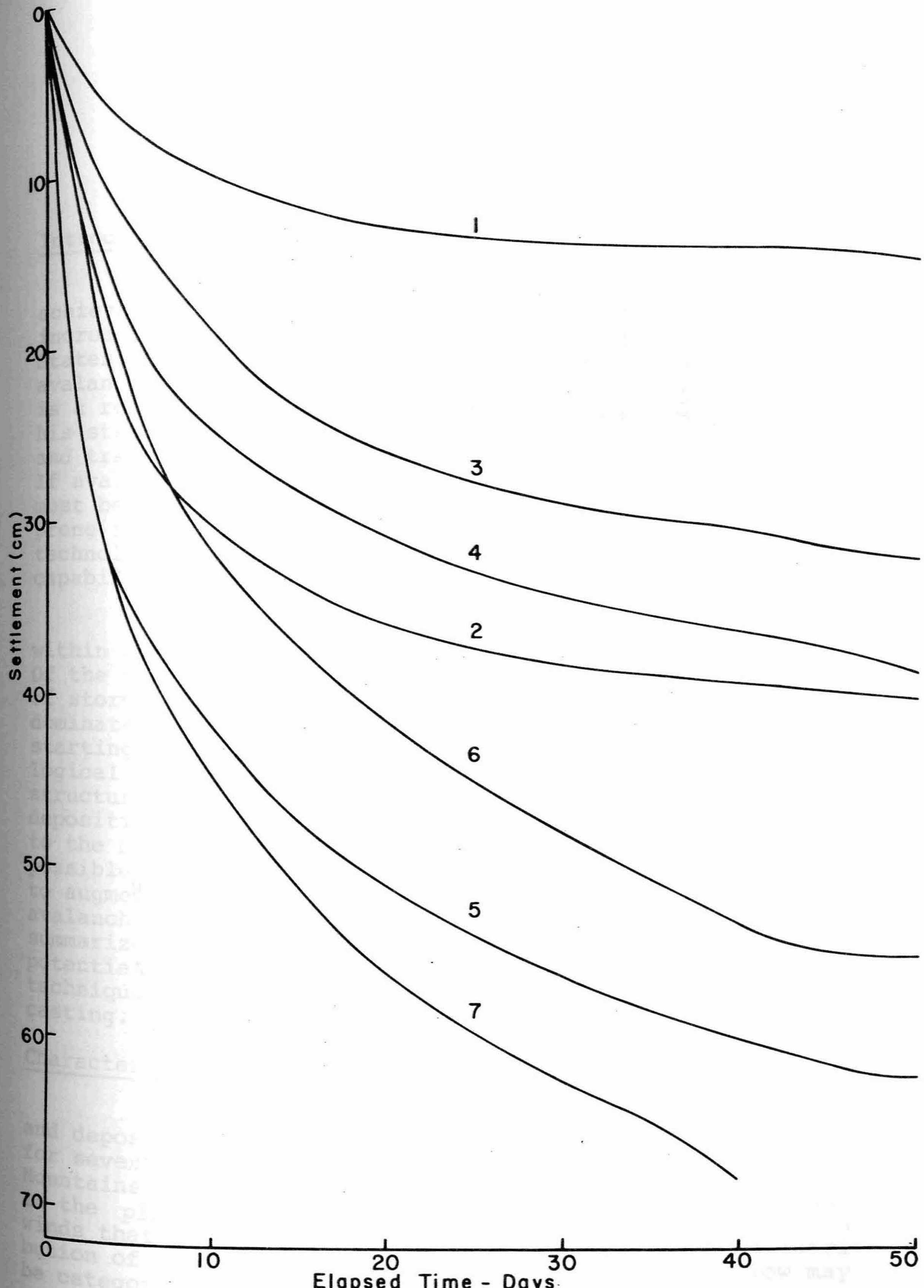

FIGURE 7 SNOW SETTLEMENT AS A FUNCTION OF TIME AND SNOW STRUCTURE TYPE

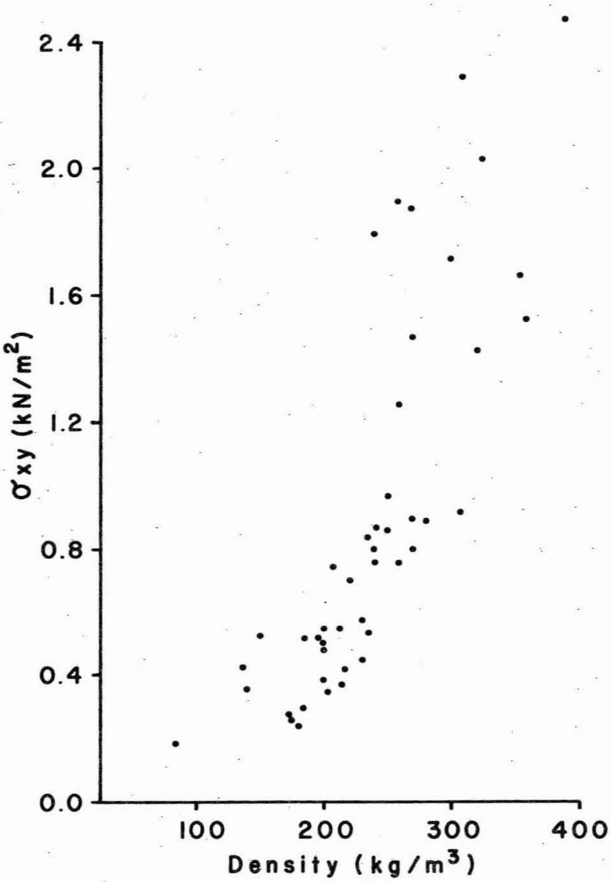

FIGURE 8 RELATIONSHIP BETWEEN CALCULATED SLAB SHEAR STRESS AND MEASURED DENSITY OF THE LUBRICATING LAYER AT THE BASE OF THE SLAB