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Strength-Load Ratio
An Index of Deep Slab Avalanche Conditions

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Abstract

Deep slab avalanches are often initiated by the catastrophic collapse of a weak basal layer under the overlying static load of snow.

Three winters of strength and load studies in the Bridger Range of Montana indicate that the Snow Resistograph and core sampling tube can be used effectively to anticipate deep slab avalanche conditions. The method involves measuring the strength-to-load ratio at the base of the pack. Whenever this ratio becomes less than 2 the snowpack is subject to sudden failure resulting from overloads. On a steep slope this often produces a deep slab avalanche.

Normal surface snow consolidation is the product of sintering and may be expressed as a power function of the age of the snow. The data suggest that both the rate of consolidation and the ultimate strength of the snow during the first month is predetermined by the physical conditions at the time of deposition.

Consolidation of the basal snow layer is very erratic because of metamorphic interference with the sintering process. In general the strength of the basal snow is guided by the rate of snow accumulation such that the rate of consolidation is approximately 1/2 the rate of loading. This produces a declining strength-to-load ratio at the base of the pack and leads in the direction of collapse.

Actual collapse therefore, depends in general upon the length of the season of snow accumulation, and the initial weakness of the basal layer at the time of burial. In detail the collapse depends upon the delicate interplay of load hardening and metamorphic weakening which occasionally produces short periods of extreme systemic fragility.

I. Introduction

Of the various types of snow avalanches common to the Northern Rocky Mountains, the most dangerous is the "climax" or "deep slab". Its danger lies not only in its massiveness and destructive power but in the problem of recognizing or evaluating the danger in advance of the event. Often, for no apparent reason, during the mid-to-late winter season, the entire snowpack on a steep slope will fracture down to the ground and move out with incredible swiftness. It starts almost as a single coherent slab which with movement progressively breaks up into a jumble of blocks suspended in the flowing matrix. Characteristically a deep slab avalanche leaves behind a nearly naked ground surface thinly covered by a layer of sheared granular ice. This surface then becomes a potential gliding surface for later avalanches of all kinds.

That these avalanches are associated with a fragile, basal layer of depth hoar has long been recognized (Seligman, 1936). However, to develop a scheme for prediction, it is necessary to first develop a precise hypothesis concerning the mechanism of snowpack failure. The hypothesis, to be useful, must be susceptible to testing by means of specific measurements.

In 1962 the Department of Earth Sciences at Montana State University at Bozeman, Montana began the development of instrumentation and methodology for testing one such hypothesis. First result were reported at the International Symposium on Snow and Avalanches at Davos, Switzerland, 1965 (Bradley, 1966).

Briefly, the hypothesis states that deep slab avalanches result primarily from compressional failure of the basal snow layer under the static overlying load of the snowpack. Vertical collapse of a snowpack lying on a slope results in tensional and shear failure along the perimeter of the slab. If the remaining factors of basal friction and angle of inclination are favorable, the avalanche will run. If not, the slab may creep a short distance opening up the tension crack, then come to rest. As a third alternative the collapse may not be followed by any lateral movement. A hairline fracture with slight vertical displacement may be the only visible result.

In any case, the initiating event is the collapse and the prediction of the collapse is the first matter to be tested rather than the prediction of the avalanche *per se*. This simplifies the problem down to the measurement of the crushing strength of the basal layer and the magnitude of the load overlying it.

This paper is a progress report in which we augment the observations and conclusions presented at Davos.

II. Instruments and Procedures

Measurement of snow load is readily obtained by a snow sampling tube. Snow strength may be evaluated by a Snow Resistograph, an instrument which plots a profile of snow strength as a function of snow depth (Bradley, 1964). During the winter of 1963–64, an east facing snow plot (1. 1) was selected for study. The plot was adjacent to an area known to have produced deep slab avalanches. The plot was sampled weekly from December through March. Observations elsewhere indicated that deep slab avalanches were most frequent on northeast facing slopes. On the basis of this, the study was expanded during the 1964–65 season to include two study plots, one facing southeast, (1. 2) the other facing northeast, (1. 3) and the season was extended from November through May. Each week resistograms were made in an effort to watch the slow changes of strength in the basal layers of the snowpack. At the same time the sampling tube was used to evaluate the accumulated load overlying the basal layer. In theory, the collapse of the pack would occur whenever the accumulated load exceeded the strength at the base of the pack. However, a more practical view would suggest that the closer the strength-to-load ratio approaches one-to-one, the more sensitive the system becomes to the influence of extraneous load factors such as a skier, a heavy gust of wind, thermal or sonic shock, etc.

The weekly resistograms and load measurements were plotted on a time base for study (Fig. 1). This information was recapitulated with special attention to strength and load changes at the base of the pack (Fig. 2). Later, the strength-to-load ratio (S/L) of all three plots were isolated and compared (Fig. 3).

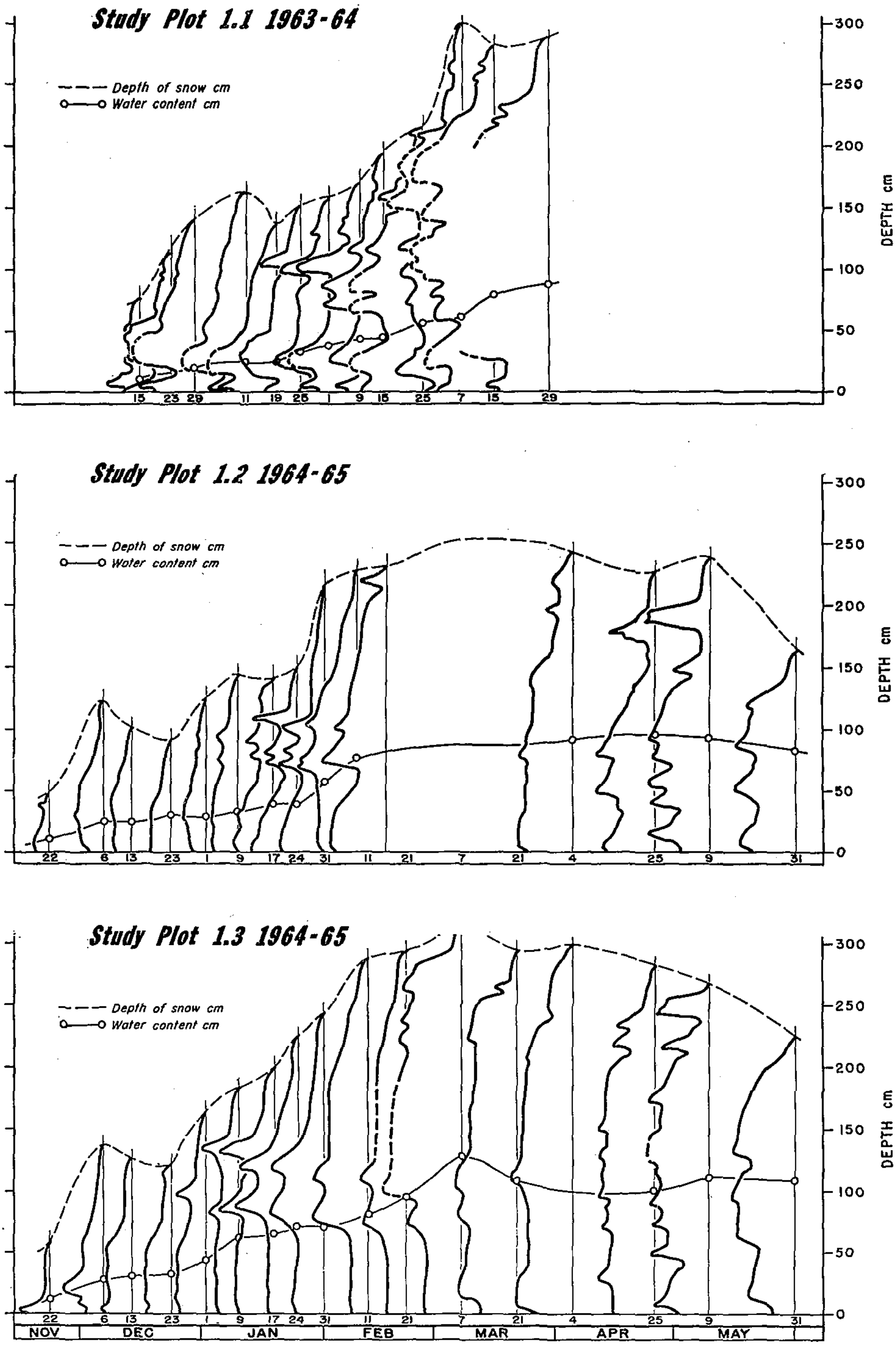

Fig. 1. Snow evolution as delineated by snow resistograph. *Bridger Range, Montana*

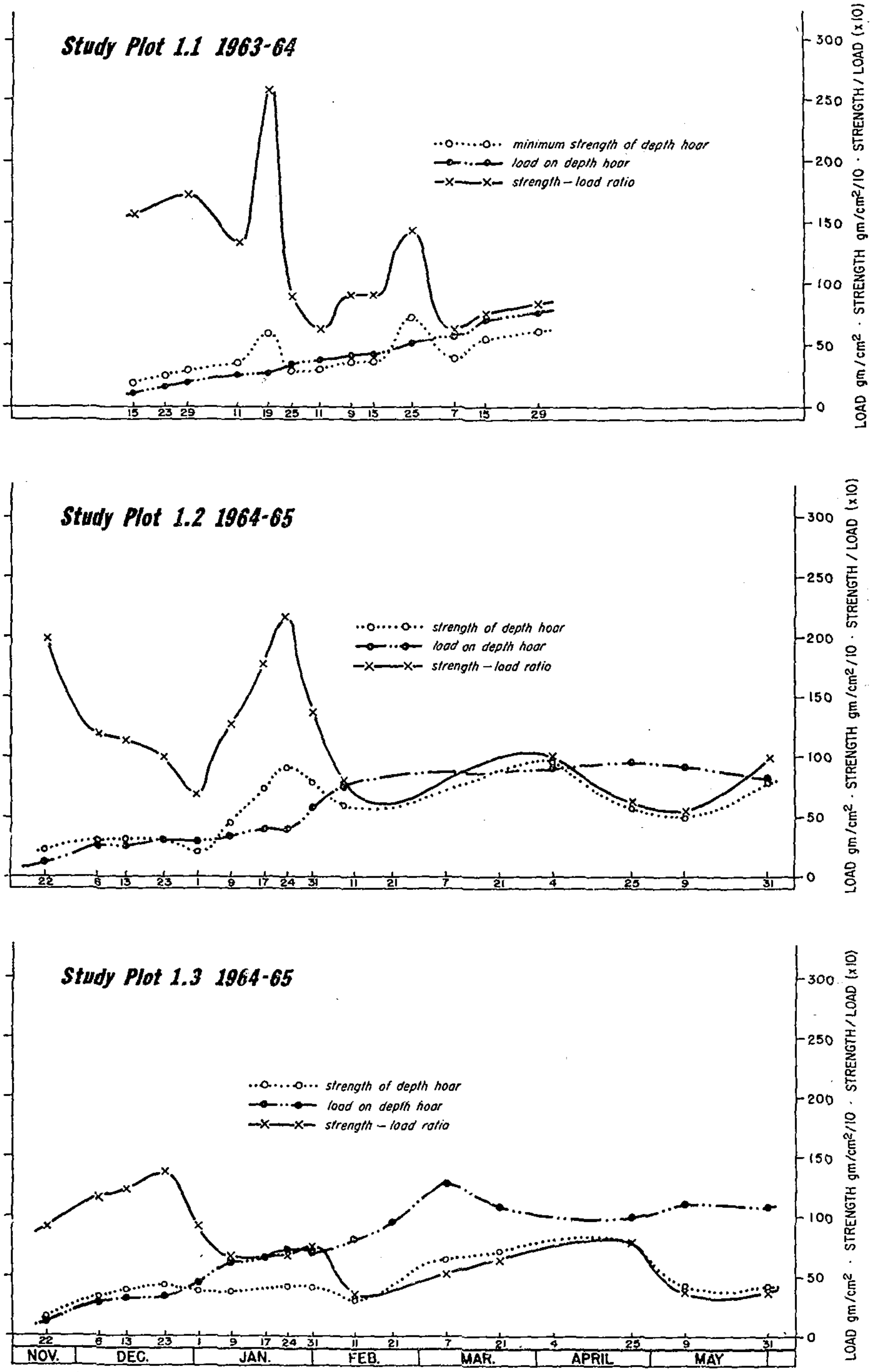

Fig. 2. Strength vs. load in the basal depth hoar.
Bridger Range, Montana

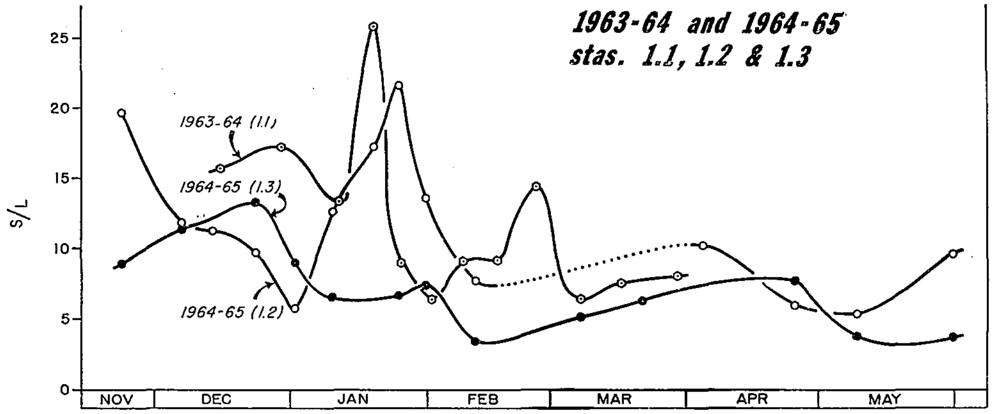

Fig. 3. Comparison of strength to load ratios in the basal depth hoar. Bridger Range, Montana

III. Observations

1. From Fig. 1 it may be seen that during the mid-season the weakest portion of the basal layer in study plots 1.1 and 1.3 characteristically shows a strength of 1/2 to 3/4 that of the portion of the snowpack immediately overlying it. Field observations indicated that well developed depth hoar is often, but not always the cause of this abnormal weakness. In study plot 1.3 the weakness appeared to be simply non-sintering of the granular snow, whose texture was otherwise indistinguishable from the well-sintered pack above. We conclude, therefore, that the metamorphic process next to the ground interferes, in some way, with the normal sintering process and that the abnormal weakness of the basal layer is a crude measure of this interference.

2. Figure 2 shows that the basal layers actually do gain strength with time, although the wide scatter of points begs for explanation. It should be said first that the recorded scatter is far too wide to be accounted for by either instrument or operator variability. That the scatter is, at least in part, a function of place is highly likely. Variability in ground cover and snow permeability would be expected to create variability in the metamorphic process and hence, variability in strength. Nevertheless, the scatter of the basal strength plots does not seem to be entirely random. In fact, the strength curve exhibits a kind of oscillatory pattern with a period in the neighborhood of 40 days. This confirms a previous observation (Bradley, 1966) that metamorphic weakening of the base, subsidence under load, and consolidation probably follow each other in a rhythmic cycle throughout the season. In a season of well developed depth hoar, catastrophic collapse would very likely replace the more common slow subsidence under an overload. Depth hoar, having a coarsely crystalline fabric and a minimum of sintering, would behave in a brittle, rather than a plastic manner (LaChapelle, personal communication).

3. Figure 3 compares strength-to-load ratio (*S/L*) curves for all three study plots. It should be noted here that again in spite of the scatter and apparent oscillations all three curves have a downward trend. The conclusion is inescapable, that even though the basal layer tends to strengthen with time, there is progressive systemic weakening

resulting from an overlying snow load which increases at a more rapid rate than the gain in basal strength. This can be seen better in Fig. 5.

Theoretical consideration of the process of snow sintering and the experimental work of various authors indicate, that snow consolidation is a power function of time, the exponent being in the vicinity of 0.40 (Hobbs, 1965). It was, therefore, necessary to test the resistograph against other methods and to test "normal" consolidation against that exhibited by the basal layer. To do this, three selected surface snow layers from each season were measured each week for a period of about a month after deposition. The measurements were plotted on log-log paper and equations derived for each curve (Fig. 4). The position of the curve was calculated by the method of least squares. In Fig. 5 strength, load and strength-to-load ratio in the basal layers are similarly plotted for comparison. From these illustrations, the following additional observations are pertinent.

4. Our normal (surface) snow plots in general show fairly good agreement with Hobbs theoretical calculation. The consolidation of each layer can be expressed by the equation $S_r = S_1 T^n$ where S_r = snow strength as measure by the resistograph, S_1 is the

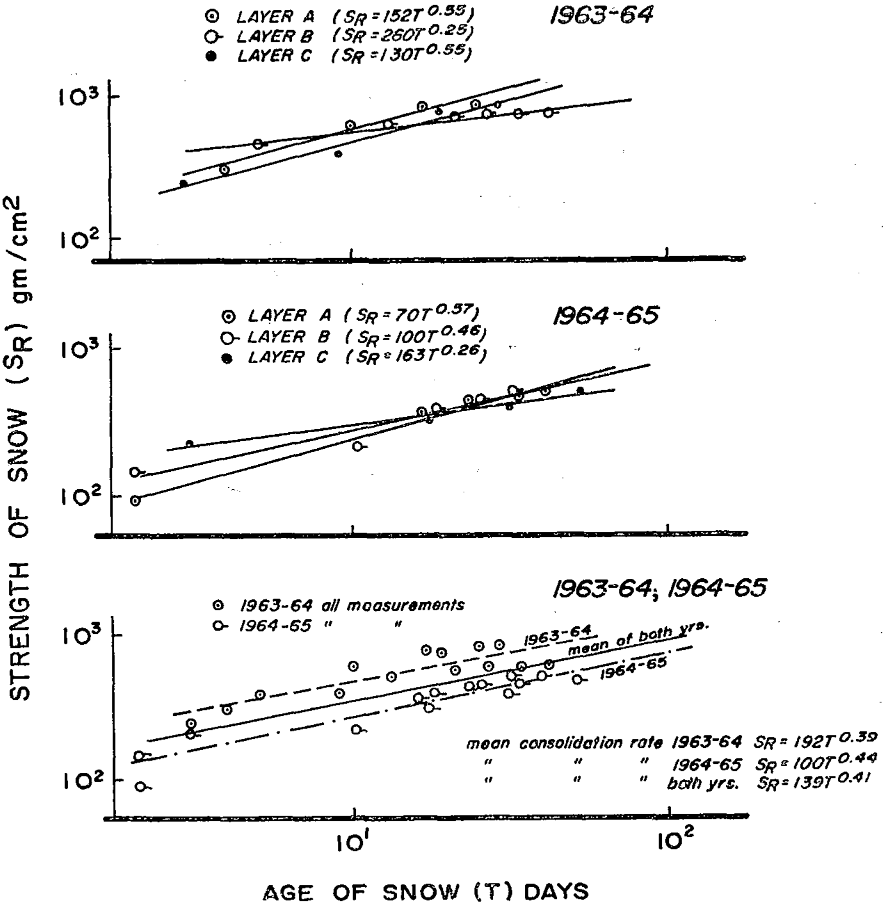

Fig. 4. General snow consolidation rates. Bridger Range, Montana 1963–64, 1964–65

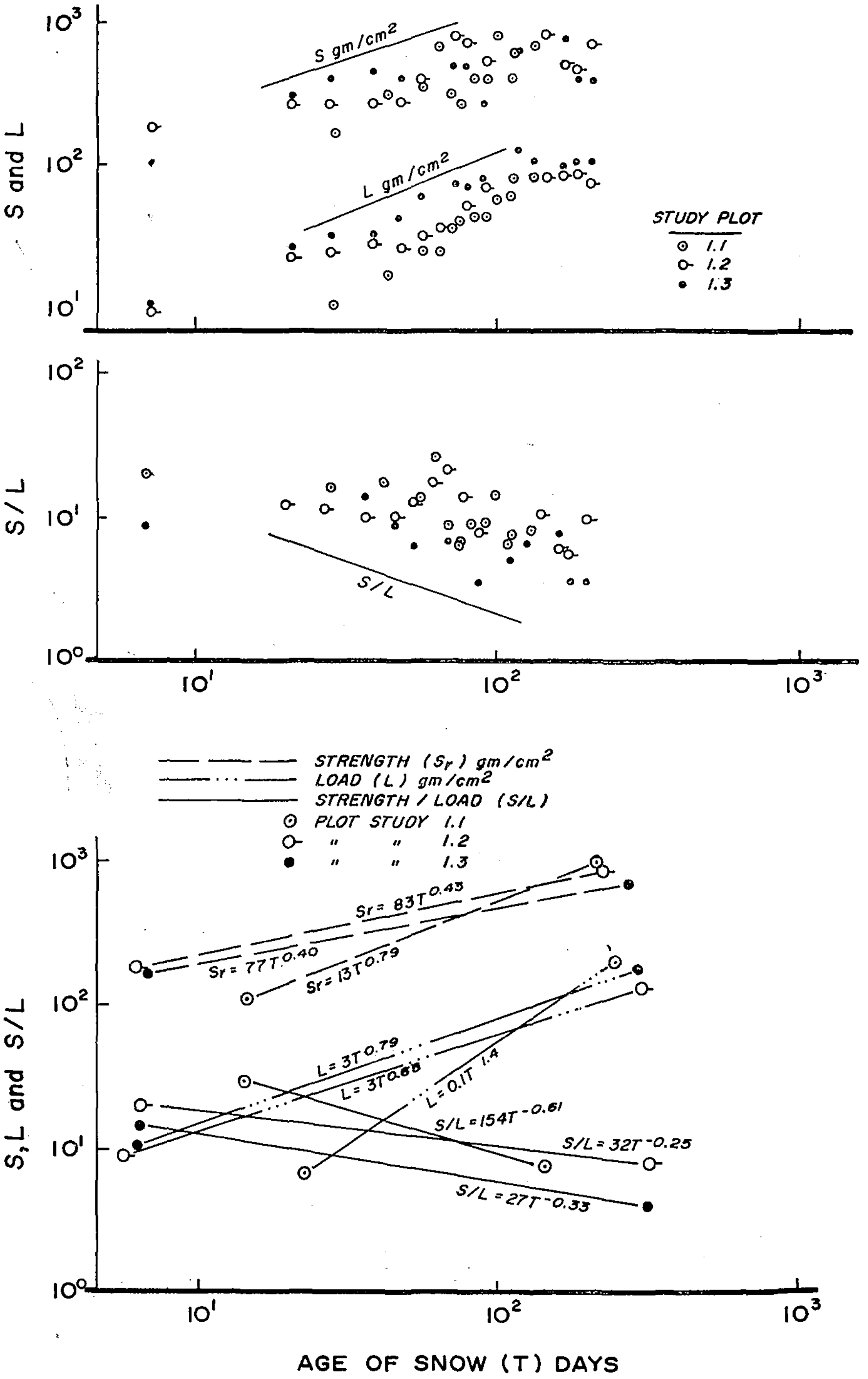

Fig. 5. Basal depth hoar strength and load measurements. Bridger Range, Montana 1963-64, 1964-65

apparent strength at the end of the first day following deposition. T is the age of the snow in days and n is an exponent emperically derived from the slope of the line. The mean slope for both seasons comes very close to $n=0.40$.

5. However, it can also be seen that S_1 and n are significantly different for each separate curve. This indicates that the physical conditions at the time of deposition tend to predetermine both the rate of consolidation and the ultimate strength of a particular layer. These physical conditions are probably mainly the original crystal shapes and the initial degree of packing, plus pertinent micro meteorological factors.

6. Lack of scatter in the measured points of the normal snow definitely points to an abnormal consolidation process in the basal layers to account for the erratic readings. That basal metamorphism interferes with normal consolidation is, of course, well known, but this analysis was necessary to explain the scatter in the readings.

7. The average rates (n) of consolidation of the normal snow are very similar for both seasons, but there is practically no overlap in the plotted points. The difference, therefore, lies in the initial strength of the snow (S_1). Since the two seasons varied greatly from each other in rate of snow fall, temperature and windiness, these probably had an effect, but only for a short period at the time of deposition. Thereafter, burial of the layer under newer snow would have insulated it from further wide microclimatic variations. Correlation of snow flake type with S_1 appears to be a fruitful line of inquiry. Such a study is being initiated as the next phase of this investigation.

8. The curve of best fit plotted for each of the basal layers in the 1964–65 study plots, shows a consolidation rate suprisingly "normal" ($n = 0.40$), in spite of the scatter of points. One would be tempted to conclude, therefore, that load had little effect on the process. However, the rate for the 1963–64 season was about twice normal ($n=0.79$). A glance at the loading curves shows that the rate of accumulation for the 1963–64 season was also about twice that of the 1964–65 season. Furthermore, in all three seasons the load appears to have gained at approximately twice the rate of consolidation. The evidence is strong for the conclusion that even though the metamorphism interferes with the sintering process at the base, the rate of consolidation of the base is actually guided in a gross way by the rate of loading.

9. Because the load increases at a higher rate than basal consolidation, the strength-to-load ratio (S/L) at the base is seen to decrease. From this, we generalize to say, that at least under the conditions of these studies, snow accumulation always proceeds *in the direction of* progressive systemic weakening and collapse. Whether collapse actually occurs depends in general upon the length of the season of snow accumulation and the initial strength of the basal snow at the time of burial. In detail, it also depends upon the delicate interplay of load hardening and metamorphic weakening, which occasionally produces short periods of extreme systemic fragility.

10. At no time, in any of the study plots, did systemic weakening even approach the theoretical minimum of 1. The weakest strength-to-load measurement for both seasons was 3.4 in study plot 1.3, February 11. The fact that neither season developed collapsing snow or deep slab avalanches near the study area is, therefore, consistent with the data, but does not really prove the reliability of the resistograph or the methodology. We therefore present data from outside the regular study plots and some material

derived from this last season of study to help close this gap.

In mid-March of 1964–65, on a slope outside the study area, the snowpack ruptured and slid or crept for about 1 m without avalanching, but leaving an open crevasse down to the bare ground. Two days later it was discovered. Resistograms and load studies were made on both sides of the fracture (Fig. 6). The undisturbed slab showed a basal strength-to-load ratio of 1. 4! In the slab that moved, the basal layer was apparently work-hardened to give a strength-to-load ratio of 4. 6. This isolated case, while strongly suggestive of methodological success, needs confirmation.

From the standpoint of this study, this last winter season of 1965–66 was most opportune. The heavy snows of mid-November were followed by a long, cool period with no precipitation during which the snow lay exposed and metamorphosed to a friable, coarse, granular layer. In December and early January, heavy snow storms buried the old layer. By January the basal snow was a well-developed, non-coherent mass of cup crystals so characteristic of depth hoar. A season of deep slab avalanches was obviously developing.

Regular study plots were abandoned and a search was conducted for critically weak areas, which could be watched for the onset of collapse. These were not hard to find. Between mid-January and mid-February, deep slab avalanches had run on most slopes and the resounding "crunch" of the snowpack suddenly collapsing under a skier was almost an everyday experience. By mid-February, this hair-trigger situation had stabilized with nearly all areas having collapsed either catastrophically or by subsidence, raising

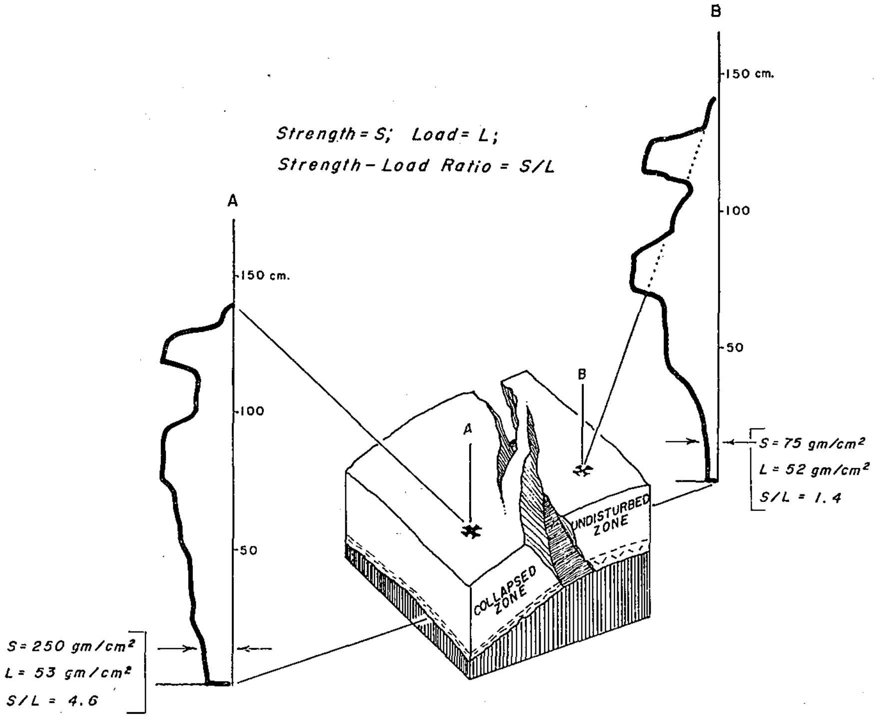

Fig. 6. Incipient deep slab avalanche. Bridger Bowl, March 21, 1965

the basal strength-to-load ratio to a safe 4–15. Figure 7 shows one of several situations similar to that of Fig. 6. A late January deep slab avalanche took place on the unskied upper slope of the main hill. After-the-fact measurements show the collapsed and consolidated remnant slab above the breakaway scarp. It also shows another portion of the slab in its original delicate condition.

VI. Summary of Conclusions

From the forgoing, the following conclusions appear to be justified for the dry cold conditions of the Northern Rocky Mountains:

1. The strength-to-load ratio as calculated from measurements with the resistograph and snow sampling tube can give a fairly reliable index of collapsing conditions. No collapse or deep slab avalanche has been observed, where the strength-to-load ratio was greater than 2. Several have been observed when the ratio was less than 2. Therefore, a strength-to-load ratio greater than 4 or 5 should represent a reasonable margin for safety purposes.

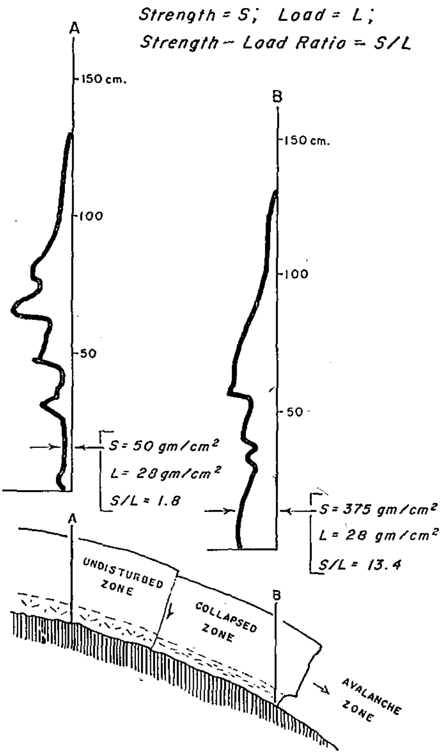

Fig. 7. Deep slab avalanche Bridger Bowl, Feburuary 6, 1966

Parenthetically it should be said that no ratio of less than 1 has been observed. Hence the errors which may inhere with the resistograph and sampling tube seem to effectively cancel themselves.

2. Snow consolidation in the first month following deposition is largely the result of sintering, with load hardening having a negligible effect. In this regard field measurements with the resistograph confirm the theoretical calculations of Hobbs (1965).

3. The normal rate of consolidation for a particular layer is a simple power function of the age of the snow. The data strongly suggest that both the rate of consolidation and the ultimate strength of the snow, during the first month, is largely predetermined by the physical conditions at the time of deposition. Most important of these conditions are probably crystal shape and initial packing.

4. Consolidation in the basal layer is mainly the result of load hardening, the normal sintering process being interfered with by metamorphism next to the ground. This interplay of processes produces erratic strength measurements and a crude rhythmic oscillation between systemic weakening and strengthening, which has a period of about 40 days.

5. In the basal layer, the rate of consolidation is largely controlled by the rate of loading, in such a way that the rate of consolidation is about 1/2 the rate of loading. This produces a progressive decline in the strength of the system (strength-to-load ratio)

at the base of the pack, as the season advances. Thus, we can say that the very process of snow accumulation leads in the direction of ultimate collapse of the basal layer under the overlying load.

6. Actual collapse of the snowpack depends in general upon the length of the season of snow accumulation, the early development of depth hoar and the initial weakness of the basal layer at the time of burial. In detail collapse depends upon the delicate interplay of load hardening and metamorphic weakening, which occasionally produces short periods of abnormal fragility. Catastropic collapse is probably favored by mid to late winter conditions wherein both the fragile depth hoar and the overlying pack are comparatively brittle as a result of the low temperature environment.

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