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SOME MECHANICAL PROPERTIES OF ALPINE SNOW, MONTANA 1964-66

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C.M. Keeler
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MARCH 1967

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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Erratum - USA CRREL Research Report 227

Page 26 – The following reference should be added to the list of "Literature Cited":

Bradley, C. C. and Bowles, D. A. (1966) Consolidation and metamorphic weakening. Opposing correlatives in avalanche initiation, International Conference on Low Temperature Science, Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan.

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PREFACE

This paper was prepared by C. M. Keeler and Dr. W. F. Weeks, glaciologists. It constitutes an interim report accomplished in conjunction with the U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) project on Mountain Snow Research (Snow and Ice Branch, Research Division). This project was supported by the Director's In-House Laboratory Independent Research Program.

The data discussed in this report were collected by the following people: winter of 1964, W. F. Weeks and D. L. Alford assisted by G. Thompson and D. Eberl, winter of 1965, W. F. Weeks and D. L. Alford assisted by D. Carter and S. Toth; and winter of 1966, C. M. Keeler and D. Bowles assisted by D. Carter.

The authors would like to thank W. K. Boyd, Chief Engineer, USA CRREL, for his support of the project; D. L. Alford, J. A. Bender, D. Carter, M. Mellor, and R. Ramseier for their critical comments on the manuscript; and D. L. Alford for allowing us to refer to his unpublished manuscript on the stratigraphic aspects of the 1964 Goose Lake, Montana, snow cover.

USA CRREL is an Army Materiel Command laboratory.

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SUMMARY

Data on the physical properties of seasonal alpine snow have been collected from the Beartooth Mountains near Cooke City, Montana (elevation ~ 3000 m) and the Bridger Range near Bozeman, Montana (elevation ~ 2200 m). Systematic measurements of snow density, temperature, structure, ram and Canadian hardness, centrifugal tensile strength and shear strength measured with a shear box and several types of shear vanes are included. Test results were grouped according to gross snow types (cohesive fine-grained "winter" snow, depth hoar, new snow, etc.) and whether the snow was wet or dry. Then interrelations between the different test parameters were studied. A plot of ram number vs density for winter snow gave a log-linear relation similar to that suggested for polar snows. Both shear vane and centrifugal tensile results when plotted as a function of porosity are well described by the negative exponential relation suggested by Ballard and Feldt. Depth hoar and wet snow invariably have lower strength values at any given density. There is an excellent one to one agreement between values obtained with the shear vane and the shear box. Limited observations are made on the change in mechanical properties with time.

Several field experiments were performed to study the sources of error in making in-situ mechanical tests on snow without utilizing a pit wall. Statistical analysis of the results shows that the main factor contributing to the experimental scatter is lateral inhomogeneity in the snow cover. There was no significant difference between the results of different operators. The standard deviation of a group of strength tests is shown to be directly proportional to the mean value of the group. This indicates that a $\log_e$ transformation should be made in handling snow strength results in order to stabilize the variance. It is emphasized that the systematic relations between snow properties invariably become obscured when different snow "types" are indiscriminantly grouped together.

SOME MECHANICAL PROPERTIES OF ALPINE SNOW, MONTANA 1964-66

by

C. M. Keeler and W. F. Weeks

INTRODUCTION

The USA CRREL Mountain Snow Research Project was initiated in 1964 to obtain additional information on the behavior of the "low" density snow that commonly forms the winter snowpack in mountainous regions. During and since the IGY, considerable information has been obtained concerning the properties of typically older and denser polar snows. It was hoped that the present project would be able to extend these studies into the low density range ($< 0.350\ g/cm^3$) using, when possible, tests identical to those used on polar snow. When this was not possible, it was planned to develop new tests. Because a wide lateral variation in snow depths and presumably physical properties was expected, attention was focused on tests that were reasonably portable or could readily be made so. It was then planned to establish as many interrelations as possible between the parameters measured by these tests. This would facilitate the rapid characterization of a given snowpack for any specific purpose by a minimum number of hopefully simple tests.

During the months of April and May 1964 and 1965, field studies were undertaken 19 km north of Cooke City, Montana, in the cirque basin occupied by Goose Lake (Fig. 1, 2). The area of the cirque is rougly 2.5 km² and a considerable portion of its floor exhibits a gently rolling relief ideal for snow studies. The general elevation of the cirque floor is 3000 m, placing the research site just above the tree line. A detailed description of the Goose Lake area is given in Alford and Weeks (1965).

Because Goose Lake basin has rarely been visited during the winter, little was known about its snow conditions. Based on the observations reported in this paper, 2.5 to 3 m is probably a reasonable estimate of the depth of the snowpack during an average winter. Snow accumulation usually starts in late October or early November and the pack does not become isothermal until early May. The weather systems supplying snow to the area come from the west and there is a pronounced orographic effect on the accumulation between Cooke City (2330 m) and Goose Lake (Fig. 3). Although Goose Lake proved to be an excellent location for snow studies, it was abandoned at the end of the 1965 field season because of the logistic difficulties in keeping it supplied during the winter.

The research program was continued during the winter of 1965-66 at Bridger Bowl, Montana, a small ski area located approximately 32 km northeast of Bozeman, Montana. This area has been instrumented for research by the Montana State University at Bozeman. The instrumentation includes a digital data gathering system which transmits data, via radio, to the computer center at the University. This system, which is administered by the Water Resources Research Center, can be adapted to accept data from a large variety of sensors.

The Bridger Range is a long steep ridge which runs north-south. The ridge crest is generally 2400 m in elevation and rises approximately 760 m above the surrounding country (Fig. 4, 5). The weather systems which supply snow to this area come from the west and northwest. Because of the abrupt rise of the range, snow accumulation is a pronounced function of elevation (Fig. 3). Although there are no long records of snow accumulation for the Bridger Bowl area, one can probably expect from 1.5 to 2 m of snow on the ground at the ski area in February and March. The snow is normally dry until April when it becomes isothermal.

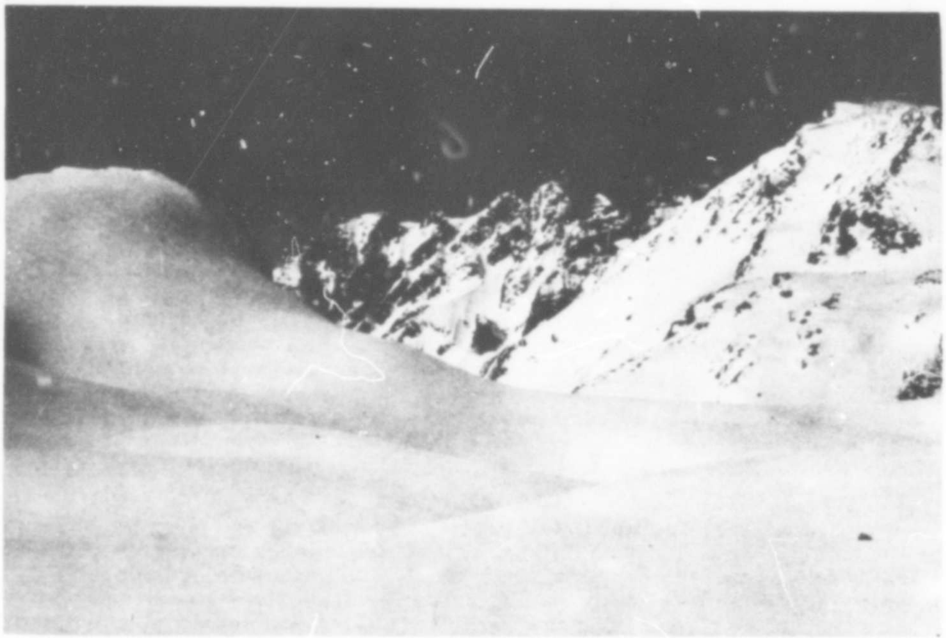

Figure 1. Goose Lake Basin, 1964: view north toward Wolf and Sawtooth Mountains.

Figure 2. Goose Lake Basin, 1965: view west toward Mount Fox.

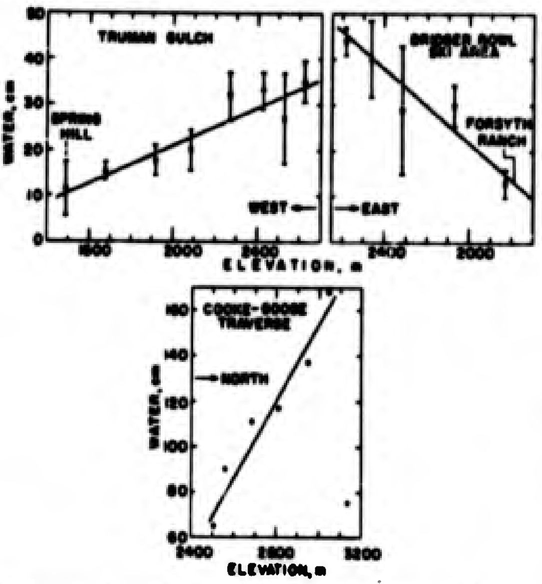

Figure 3. Snowpack water equivalent vs elevation. Top: Bridger Range, 15 March 1966; Bottom: Cooke City — Goose Lake Traverse, 30 April 1965.

The field season at Bridger Bowl occupied the months of February, March and April. Unfortunately, the snowpack was less than normal and warm weather prohibited implementing a more complete research program. In March of 1966 the Goose Lake site was revisited to make comparative measurements.

PREVIOUS WORK

The study of the properties of snow is a young discipline and the methodology has largely been adapted from other fields. Systematic measurements of the gross properties of a snow cover were first made by Seligman (1936) who was primarily interested in avalanche occurrence. Since that time the study of snow "in situ" via the "pit" method (i.e., the description of stratigraphy and the determination of density and temperature profiles) has been developed into a routine and is perhaps best described by Benson (1962). Pit studies have been used to study the broad regional variation of snow characteristics in Canada and the United States (Klein, 1949; Gold, 1958; Williams and Gold, 1958; Bilello, 1957, 1966), in Russia (Rikhter, 1945; Formozov, 1946; Dmitrieva, 1950) and in Japan (Ishiwara, 1955). In the Rocky Mountain area of the United States detailed continuing programs of routine pit measurements including grain size and ram hardness profiles have been carried out at Alta, Utah (Atwater et al., 1953-1956) and at Berthoud Pass, Colorado (Judson, 1965).

Measurements of the strength properties of mountain snow have been much more sporadic, particularly those coupled with detailed pit observations. After the initial studies by the Swiss who first successfully adapted soil mechanics tests to low density snow (Bader et al., 1939; Bucher, 1948; de Quervain, 1950) and the later studies by the Japanese using more refined techniques (Yoshida, 1955), strength studies have been made mainly on the higher density polar snows. The reasons for this emphasis are obvious: (a) most laboratory and field tests are much simpler to perform on the higher density snows (> 0.4 g/cm^3) and (b) snows with densities less than 0.35 g/cm^3 are rare in the polar regions (Mellor, 1964) where most recent field studies have been concentrated as a result of the IGY emphasis on polar glaciology. Typical references to recent studies of the mechanical properties of high density snows are Diamond (1956), Diamond and Hansen (1956), Butkovich (1956), Rula (1960), Ramseier (1963) and Mellor and Smith (1965). Unfortunately many of the test procedures used by these investigators necessitate removing specimens from the snowpack. Because of the extremely fragile nature of low density snow and the high air temperatures and large amounts of incoming short wave radiation encountered in temperate mountain regions, such tests are impractical. In addition many of the successful high density tests become insensitive to physical property variations in the low density range. This coupled with the naturally high variability in the characteristics of low density snow has resulted in its mechanical properties being quite poorly understood.

Figure 4. View west from the summit of Bridger Range.

Figure 5. View east from the summit of Bridger Range.

NATURE OF THE SNOWPACKS

A characteristic of seasonal snow in mountainous areas is its extreme variability both during a given winter and between different winters. The three winters reported in this paper are no exception, showing pronounced differences in average density, thickness and depth hoar development. To aid in the discussion of the strength data some representative pit data are included here (Fig. 6).

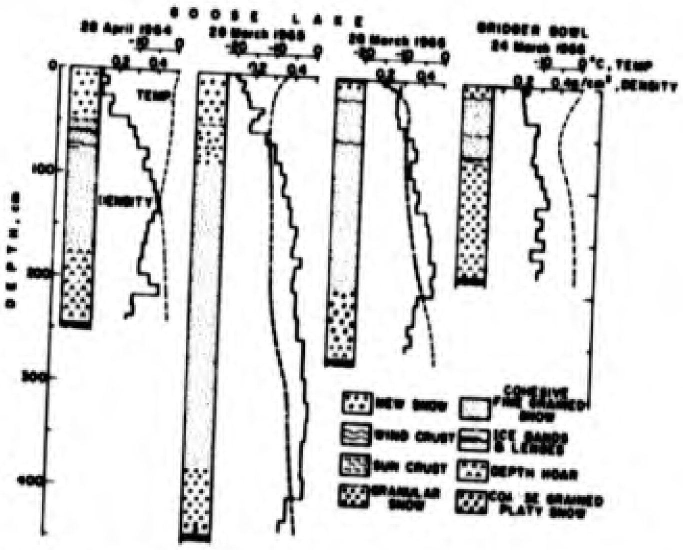

Figure 6. Representative pit observations from Goose Lake and Bridger Bowl.

Goose Lake, 1964

The winter of 1963-64, based on snow course information from Silver Gate, Montana, appeared to be a near average snow year. Snow depths in the Goose Lake basin measured on 16 April varied between 2.3 and 3.5 m with an average value of roughly 2.6 m. The winter in general was quite cold with no evidence of a pronounced densification of the snowpack until the period of warm weather in early April (D. Carter, personal communication). During the months of April and May when the pit observations were performed, three major stratigraphic units were distinguishable, both visibly and in the density and ram profiles. A layer of depth hoar roughly 0.7 m thick occurred at the bottom of the snowpack. This thick layer of hoar was presumably produced by large temperature gradients in the snow during the cold early part of the winter when the pack was still quite thin. Although this depth hoar showed no visible layering, the ram and density profiles showed the presence of layers with slightly different physical properties. The depth hoar layer gradually changed upward into a thick (1.0 m) layer of uniform fine grained snow showing a complete lack of either melt features or depth hoar development. This snow undoubtedly fell during the winter months when the air temperature was appreciably below 0C. Because the winter layer - depth hoar transition was gradational and difficult to fix visually, the boundary was usually located from the ram and shear strength data. The top of the winter layer was marked by a pronounced crust which formed during the few warm days preceding a storm on 11 to 14 April.

Above this crust was the new snow which fell while the field site was occupied. This snow was characterized by wide variations in physical properties and contained several sun crusts. The most pronounced stratigraphic marker in this new snow was a colored layer apparently produced by large amounts of dust in the storm accumulation of 24 April.

These stratigraphic units were sufficiently pronounced to be identifiable for several days after the snowpack became isothermal on 7 May 1966. Fortunately the great majority of the strength measurements reported in this paper were determined prior to 7 May so that stratigraphic interpretation was not a major problem. After the snowpack became isothermal, the gradual recrystallization and the ice lens formation produced mainly by percolating melt water gradually caused the earlier stratigraphy to become indeterminate.

Goose Lake, 1965

The winter of 1964-65 was a heavy snow year in Goose Lake and the northern Rockies in general. The average snow accumulation at Goose Lake was considerably more than that of the previous year (Fig. 6). The snow started to accumulate early and a heavy snowpack developed before extremely cold air temperatures were observed. For instance, it rained in December in Cooke City. There was, of course, no evidence of a rain crust in the pits at Goose Lake. This does, however, indicate that large amounts of snow were rapidly accumulating at Goose Lake at temperatures only slightly below freezing, effectively preventing the development of any significant depth hoar near the bottom of the pack. Instead a thick (0.8-m) layer of dense medium grained snow containing no pronounced stratigraphic markers was formed. This snow graded upward into 2.5 m of fine grained dense homogeneous snow. Above this there was, in general, 1 m of relatively new snow showing a few thin sun crusts.

Goose Lake, 1966

Goose Lake was visited on 28 March 1966 for the purpose of making comparative measurements. As was the case over the entire Rocky Mountain area, the first snowfalls of this winter were light and accompanied by cold temperatures which resulted in strong temperature gradients and the formation of a considerable layer of depth hoar. At Christmas time there was almost no snow at Cooke City (Dean Carter, personal communication) which is a highly unusual occurrence. The pit profile in Figure 6 is approximately 2/3 as deep and much less uniform that that of the previous year.

Bridger Bowl, 1966

The winter of 1966 was marked by low accumulation rates in the early season with the consequent formation of depth hoar. Heavy accumulation in February accompanied by relatively high temperatures caused the formation of numerous crusts. The pack went isothermal between late March and early April (depending on elevation). The extreme lateral variability of snow depth as a function of elevation over a small horizontal distance has been mentioned earlier (Fig. 3). Even at a single elevation, for example the 2000-m level, the snow depth varied from 1.5 to 2.5 m in a distance of 100 m due to wind effects.

RESULTS

Almost all of the physical property measurements were performed either on the wall of a pit or in the snow a few meters from a pit. This procedure was adopted in an attempt to provide as much supplementary data as possible for the interpretation of the strength results.

Ram hardness

The Rammsonde is a cone penetrometer which measures the "resistance to penetration" of a snow layer. A detailed description of the instrument is given by Haefeli (Bader *et al.*, 1939). The ram profile is quite easy to measure even under adverse weather conditions and the technique has been used for years as a rapid means of locating depth hoar layers in avalanche studies. Even though it has proved impossible to provide an exact physical interpretation of the meaning of the ram number (Nakaya, unpublished results), useful correlations have been obtained between the ram number and unconfined compressive strength (Abele, 1963) and density (Bull, 1956) for polar snows.

Figure 7 shows individual ram values obtained during 1964 and 1965 prior to the snowpack becoming isothermal plotted against snow density measured at the same level in a nearby pit. Depth hoar is excluded from this figure. If for comparative purposes a relation similar to that used by Bull (1956)

$$\log_{10} R = \alpha + \beta \rho \qquad (1)$$

is used to fit these data (403 points), one obtains by least squares $\hat{\alpha} = -0.8446$ and $\hat{\beta} = +6.399$ with a correlation coefficient $r = +0.941$. The 0.95 confidence limits on these estimates of α and β are ± 0.182 and ± 0.519 respectively. These values are quite comparable to those ($\hat{\alpha} = -0.6107$ and $\hat{\beta} = +5.3106$) obtained by Bull for a similar density range on the British North Greenland Expedition. It should be noted that in this type of plot considerable emphasis is given the lower ram values ($R < 3$). Unfortunately, the standard Rammsonde is not as sensitive to slight density changes in this low R range as at higher values. Figure 8 (top) shows a similar plot for depth hoar which indicates that for snow of a given density, depth hoar gives consistently lower ram values. This is quite reasonable in view of the pronounced decrease in cohesion associated with the development of depth hoar. It should be noted that the ability to discern the top of the depth hoar from the ram profile is more the result of the change in the ram number for a given density than it is due to basic density differences between these two snow types.

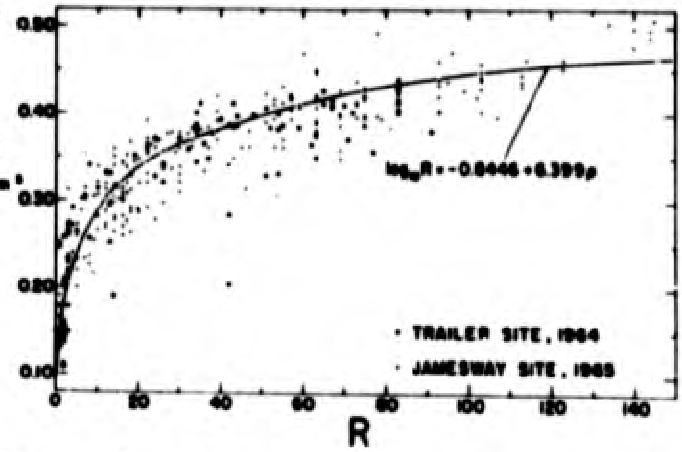

Figure 7. Ram number vs dry snow density (Goose Lake, 1964-65).

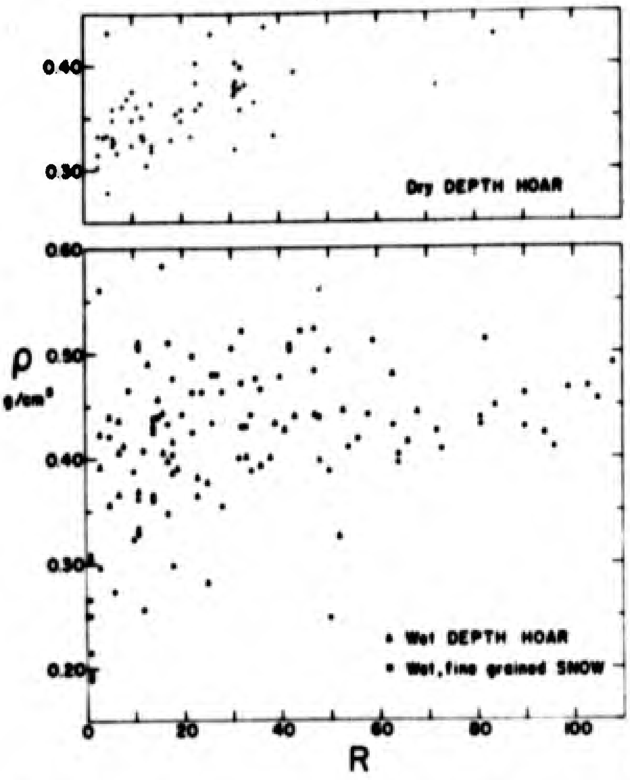

Figure 8. Above, Ram number vs dry depth hoar density; below, Ram number vs wet snow density; (Goose Lake, 1964).

Figure 8 (bottom) shows ram values obtained after the snowpack had become isothermal and in some cases water saturated. Although there is a pronounced increase in the scatter on this plot, it is evident that, in general, lower ram values occur for a given density. There are probably at least two reasons for this. One is the result of conversion of a percentage of the ice to water. As long as this water is not lost in sampling, there would be no change in density. However, the reduction in the total volume of the solid would definitely reduce the ram number. The other reason is that the majority of the melting occurs in the region of the bonds between grains, reducing the overall cohesion of the snow. The increase in the scatter in the values from the later isothermal pits is undoubtedly the result of the formation of numerous irregularly spaced ice lenses and glands which may be present at a given level in a pit and absent a fraction of a meter away where the ram profile was determined.

Centrifugal tensile strength

The centrifugal tensile test is first mentioned in the literature by Haefeli (Bader et al., 1939) and is more fully described by de Quervain (1950). The chief advantage of this test, in addition to its rapidity, is its ability to test very low density snow. In our apparatus (Fig. 9) the sample was pushed from a standard snow tube into a similar cylinder which is rotated about an axis normal to the axis of the cylinder. The sample is held in place by a two-pronged clip which reduces the cross sectional area of the center of the sample. The speed of rotation of the cylinder is then increased until the snow samples fails and the revolutions per minute at the time of failure are read from a calibrated ammeter. The failure strength of the sample is then determined by finding the force exerted on the cross sectional area of the failure surface and integrating over the half length of the cylinder. For the dimensions of the cylinder used, this reduces to

$$\sigma_t = 1.166 \times 10^{-9}\, M\, N^2 \tag{2}$$

where σ_t is the failure strength (kg/cm²), M is the mass of the sample and N is the number of revolutions per minute at failure. A nomograph for determining values of σ_t is given in Bader et al. (1951).

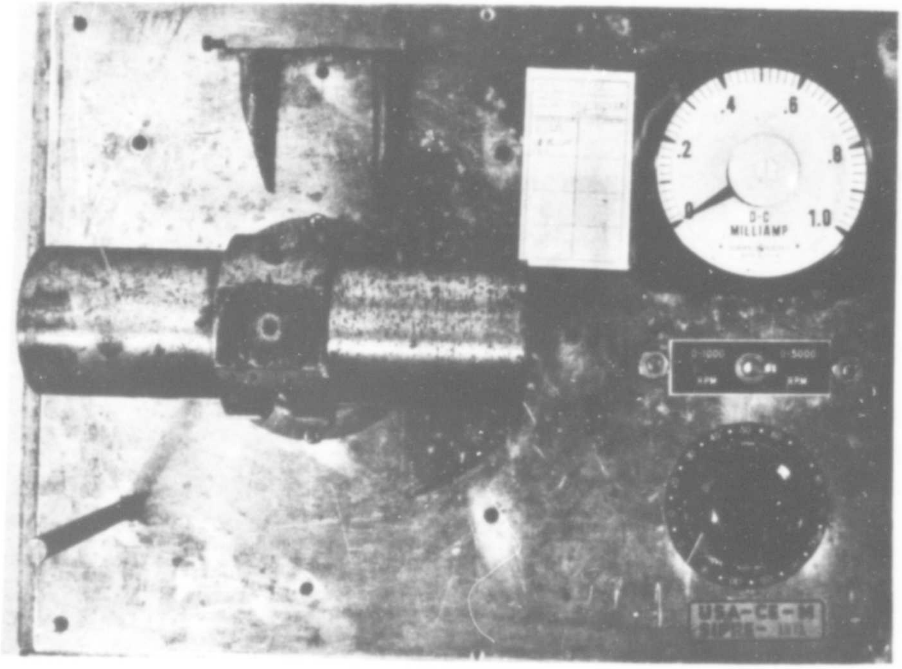

Figure 9. Centrifugal tensile tester.

Figure 10 shows a plot of σ_t vs porosity for new and winter snow from both the 1964 and 1965 seasons. The plot appears linear up to a porosity of roughly 0.60 when the σ_t values "tail off" towards a porosity of 0.87 at $\sigma_t = 0$. An extrapolation of the linear portion of the curve to $\sigma_t = 0$ yields a porosity of 0.65 which is somewhat higher than the n, of 0.56 which Ballard and McGaw (1965) obtained from the data of Butkovich (1956). This discrepancy is probably partially due to the range of porosities covered as this will affect the graphical appearance of the data.

Because of the obvious "tail" in Figure 10 it was decided to fit the relation

$$\frac{\sigma_t}{\sigma_i} = \exp\left[-\frac{2n}{1-n}\right] \tag{3}$$

where σ_i is the strength of fine grained bubble-free ice with a random orientation and n is the porosity. This relationship is a theoretical one suggested by Ballard

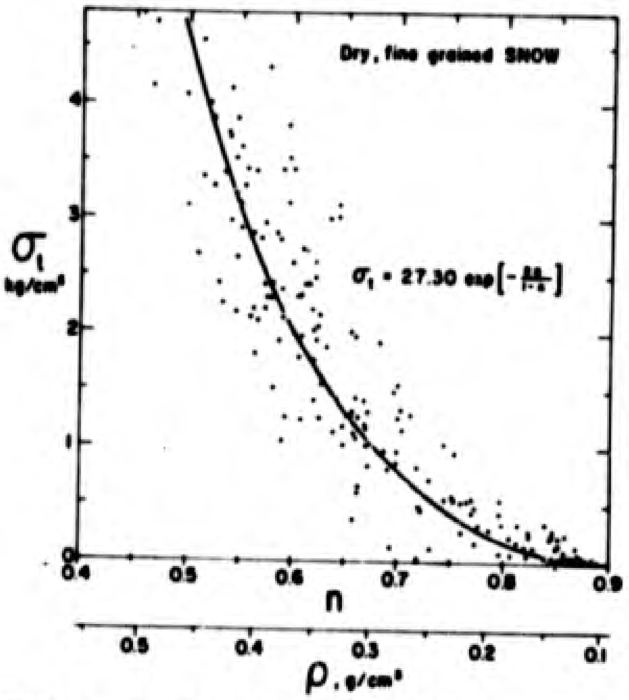

Figure 10. Tensile strength vs porosity of fine grained snow (Goose Lake, 1964-65).

and Feldt (1966). Because σ_i is unknown it was obtained by least squares by regressing σ_t on $\exp\left[-\frac{2n}{1-n}\right]$. The predicted value was 27.3 with a correlation of .867. This is in remarkable agreement with the value of 28.3 extrapolated by Ballard and McGaw (1965) from Butkovich's ring tensile data. This close agreement would indicate that the Goose Lake data (Appendix D) could well be used as the low density continuation of Butkovich's data.

Figure 11 shows a similar plot containing σ_t values for depth hoar. If Figures 10 and 11 are compared, it can be seen that the depth hoar has a lower σ_t value for a given porosity. This is quite reasonable inasmuch as the formation of depth hoar is invariably associated with a decrease in cohesion as constructive metamorphism proceeds.

It is interesting to compare the Montana σ_t values with the results of similar tests from the literature. The Montana snow appears consistently stronger by a factor of 2 to 3 over the results of Bucher (1948) and de Quervain (1950). It is presently not possible to explain this discrepancy. It is encouraging to note that the present tests show far less scatter and a much simpler relation to density than previous tests by the centrifugal method (see Bader, 1962, p. 36).

Shear strength

Shear box. Although the shear box has been mentioned in the literature for a number of years (de Quervain, 1950), it is only recently that any appreciable number of measurements have become available (Roch, 1965). The shear box measurements are normally made parallel to the stratification by cutting a "step" in the wall of a pit (Fig. 12). This prevents failure occurring over an area wider than the area of

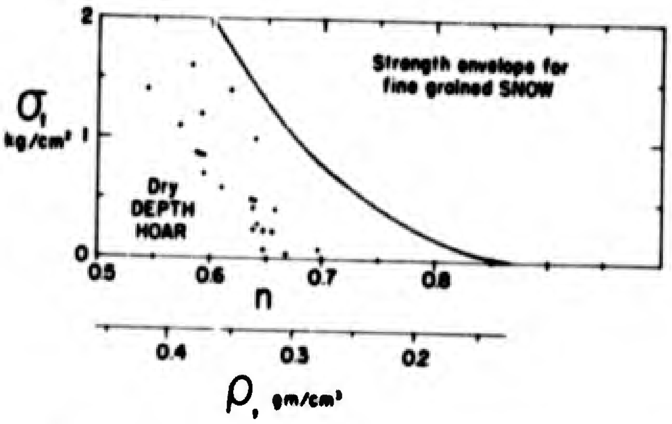

Figure 11. Tensile strength vs porosity of depth hoar (Goose Lake, 1965).

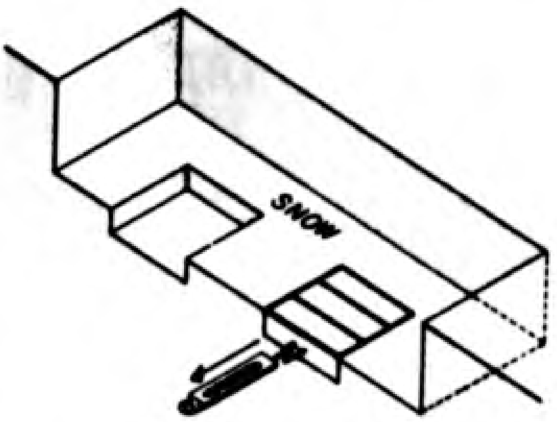

Figure 12. Schematic of shear box operation.

the shear box. The measurement of the force applied to the box at the time of failure was made with a Chatillon scale. Unfortunately the use of the shear box is limited to low densities and even at the lowest densities the failure surface was rarely planar.

Figure 13 shows the relationship between shear strength as determined using the shear box and porosity. It can be seen that the data extend only to porosities of about .6($\rho < .35$). The narrow range of the data makes curve fitting suspect. However, at the higher porosities a "tailing off" appears to be indicated in a fashion similar to that observed in the centrifugal tensile tests. The porosity of .61 proved to be about the limiting value for the use of the shear box.

The values for shear strength determined in this manner and reported by de Quervain (1950) are quite similar. His high value is .160 kg/cm² at a porosity of .65. Unfortunately the data of Roch (1965) are not directly comparable as he was concerned with the temperature dependence rather than the density dependence of the shear strength.

"In situ" shear vanes. Shear vanes have commonly been used in determining the "in situ" shear strength of soil. The general technique is well described by Cadling and Odenstad (1950). Recent preliminary studies by Haefeli and Brandenberger (1964) performed in conjunction with an EGIG field party have indicated that a simple shear vane may prove a useful tool in characterizing the vertical variation of shear strength in the near surface snow layers of the Greenland ice sheet. Their Figure 12 shows an excellent correlation between ram hardness and shear strength. In addition, Diamond and Hansen (1956) and Rula (1960) showed that reasonable correlations could be obtained between vane shear strengths and several other snow parameters. The prospect of successfully utilizing the shear vane is particularly attractive as the apparatus is both simple and portable. The EGIG shear vane is particularly desirable as a field instrument because it, like the Rammsonde, does not require the preparation of a snow pit.

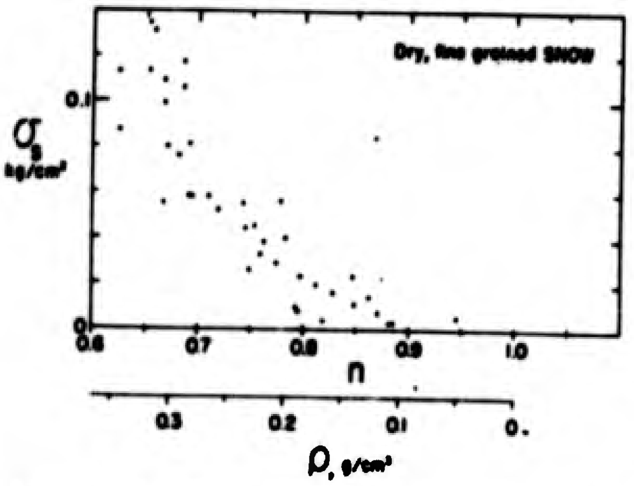

Figure 13. Shear box shear strength vs porosity (Goose Lake, 1965). Each data point represents the mean of at least 3 individual tests.

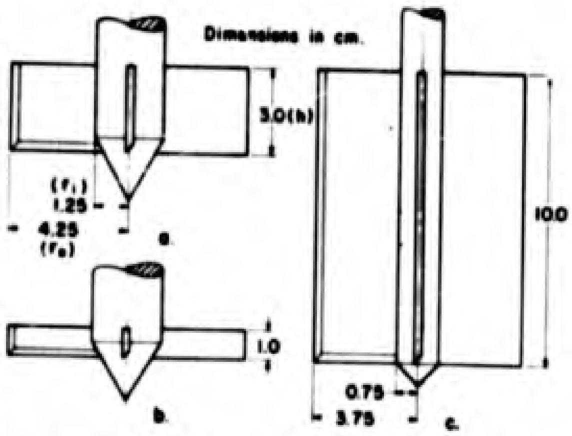

Figure 14. Schematic of shear vanes.

Several different types of shear vanes were used on this project (Alford and Weeks, 1965). During the 1964 field season, the general dimensions of the vane were based on the design of Haefeli and Brandenberger (1964). Both 3 x 3 cm (large) and 1 x 3 cm (small) vanes were used (Fig. 14a, b). The height of the vane was deliberately kept small to permit the sampling of thin homogeneous snow layers. The vanes were inserted to known depths in the snowpack using extension rods and kept at those depths during a given test by the use of a sliding ring equipped with a set screw which could be located at any point of the rod. This ring then rested on a flat aluminum plate which was set on the surface of the snow and through which the rod passed. The plate was used as the reference level during the tests. For convenience these vanes will be referred to as either the large or small EGIG shear vanes in this paper.

During the 1965 and 1966 field seasons a larger shear vane (3 x 10 cm), similar to those used in soils, was used (Fig. 14c). The vane was on the end of a short rod and was inserted horizontally into the walls of the snow pits. The use of pits allows one to avoid such disturbing influences as ice lenses and allows accurate depth determinations. This vane will be designated as the large shear vane.

The reduction of shear vane data is treated theoretically by Cadling and Odenstad and can be reduced to the following equation:

$$M_{max} = \sigma_s \left[(2\pi r_0 h)\, r_0 + 2(\pi r_0^2 - \pi r_i^2)(r_i + 2/3(r_0 - r_i))\right] \qquad (4)$$

where M_{max} is the torsional moment at failure read from the maximum deflection of the torque wrench, σ_s is the failure shear strength, r_0 and r_i are the outer and inner radii of the shear vane (see Fig. 14) and h is the height of the vane. In making these computations the effect of side friction is assumed to be negligible. The rotation rate of the vane, although not accurately controlled, is estimated to be roughly 90°/sec. There are undoubtedly considerable problems relating to the precise shape and constancy of the failure plane. Unfortunately no information was obtained on this problem because in these tests failure occurs some distance away from the free face.

EGIG shear vanes: The EGIG shear vane is located on the end of a rod with a diameter of 2.5 cm. The ends of the vanes are sharpened to minimize the disturbance of the snow as the vane is inserted. To determine whether the presence of the rod had a serious effect on the results, several tests were made at identical locations in which the vane was both (1) inserted directly into the snow and (2) inserted into a 2.5-cm predrilled hole. These results for dry snow are shown in Figure 15. Although there is an appreciable scatter, there does not appear to be any significant difference between the results obtained by these different methods for either the large or small vanes. In light of this, most subsequent tests were conducted without a predrilled hole. We feel that these results are inconclusive in indicating whether or not predrilling makes an appreciable difference as it is our impression that in the low density snow encountered at Goose Lake in 1964, the shear vane would not remain in the predrilled hole.

Next the results from comparable snow types using both the large and small shear vanes were compared. Figure 16 shows the relationship between strengths determined using the large and small vanes in fine grained dry snow. It is clear that on the average the large shear vane gives higher strengths than does the small shear vane. This is thought to be a reflection of the fact that the larger vane has a higher probability of encountering stronger layers as it samples a larger area at any given depth indicated on the extension rod. It is, therefore, very desirable to keep shear vane sizes constant when making comparative studies on the strength of snow or any other inhomogeneous material. Figure 17 shows a similar plot for wet snow. The pronounced distinction between results obtained from different sized vanes disappears. The authors have no explanation for this change.

Figure 18 is a plot of results obtained using the large and small vanes for both wet and dry "depth hoar." In this case there appears to be no apparent difference in strength, even for the case of dry "depth hoar." The explanation for this presumably lies in the fact that depth hoar is relatively homogeneous. It is interesting to note the considerably lower strength values due to the lack of cohesion in the depth hoar layer.

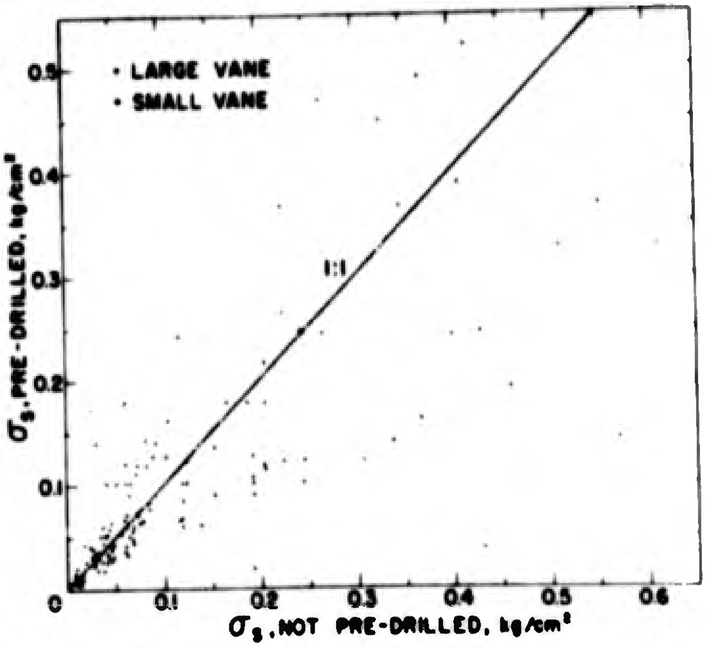

Figure 15. EGIG shear vane strengths: predrilled vs non-predrilled (Goose Lake, 1964).

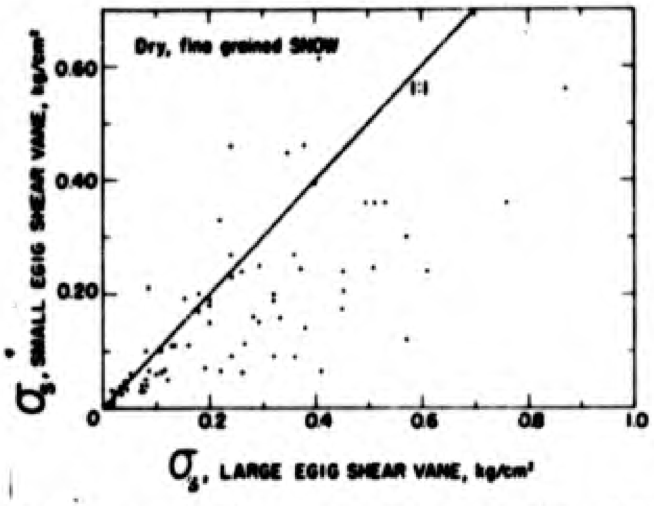

Figure 16. EGIG shear vane strengths: large vs small vane, fine grained snow (Goose Lake, 1964).

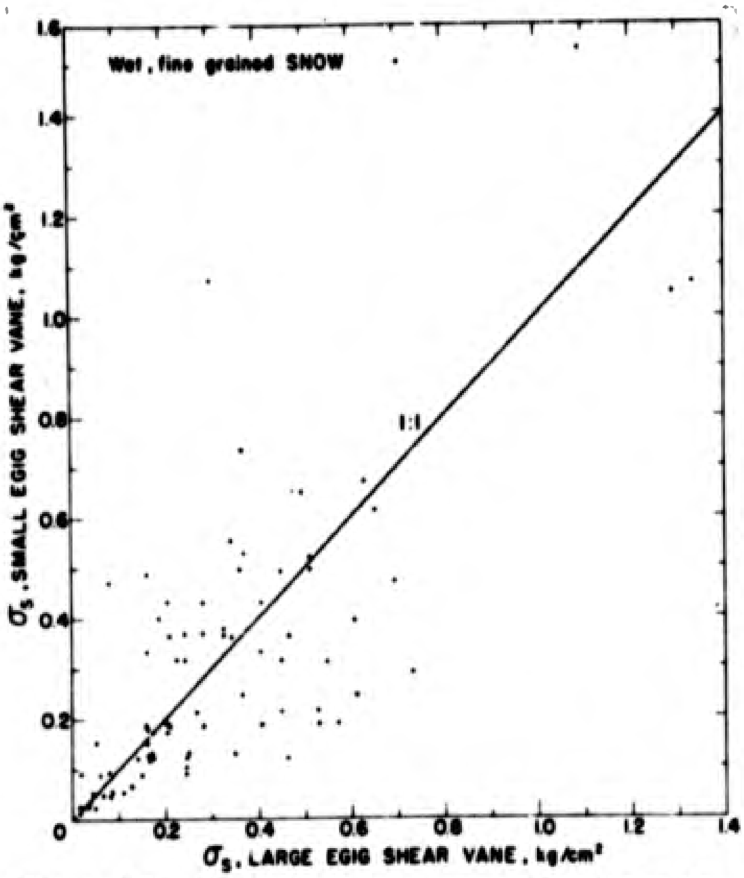

Figure 17. EGIG shear vane strengths: large vs small vane, wet snow (Goose Lake, 1964).

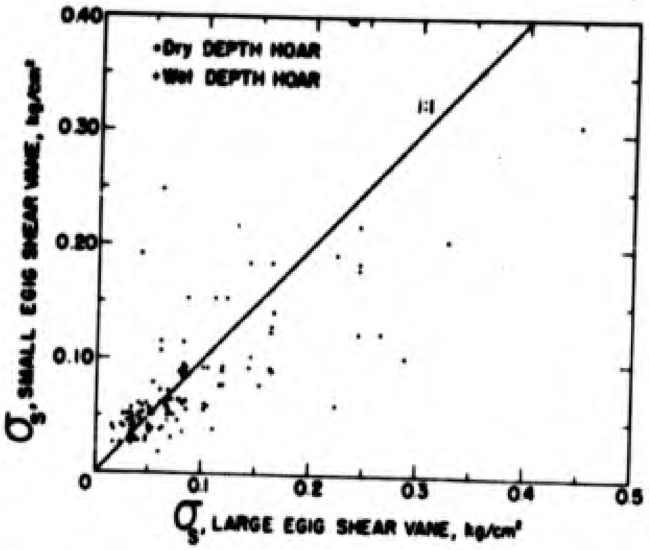

Figure 18. EGIG shear vane strengths: large vs small vane, depth hoar (Goose Lake, 1964).

In order to obtain some feel for the effects of the lateral variation of snow properties and differences due to different operators several experiments were performed. Between 15 and 18 May 1964, 11 ablation stakes that had been inserted at different locations in the Goose Lake cirque were visited and vertical profiles of shear strength were made. Because the snow depth varied from location to location (240-300 cm) it proved difficult to directly compare the results from specified levels. Therefore, to show the broad features of the vertical strength profile we used a non-dimensional thickness Z_N obtained by dividing the depth of a given sample Z by the total thickness of the pack H at that location. This assumes that the thickness of a given snow layer is proportional to the thickness of the snowpack. We then calculated the mean and variance of the 11 samples, one from each profile, that were located nearest to the normalized depth of interest. These results are presented in Figure 19 which shows the low average strength of the newer snow at the top of the pack, a stronger layer in the middle portion and the weak depth hoar layer at the base. The large variances encountered in the middle of the pack are presumably the result of the presence of inhomogeneities such as thin bedded ice lenses. The magnitudes of the variances appear to be directly related to the magnitudes of the average strength values (i.e., on the average, snow layers with a higher strength also show a greater scatter). This can be readily seen in Figure 20, which shows the mean shear strength plotted against the associated standard deviation at that depth. The relationship is linear, giving a constant coefficient of variation ($S_s/\bar{\sigma}_s$).

In order to assess the differences in the strength values due to differences in locations and operators, a 30 × 30 m grid was laid out. Locations on this grid were then established using a random number table and two operators determined two replicate shear profiles at each location. The sample size is admittedly small; however, it was thought best to complete these measurements in a short period of time to eliminate, as much as possible, variation due to time changes in the snow. Shear strength values were taken at 20 cm intervals starting at a depth of 10 cm and terminating at 190 cm. These profiles do not include measurements made in depth hoar.

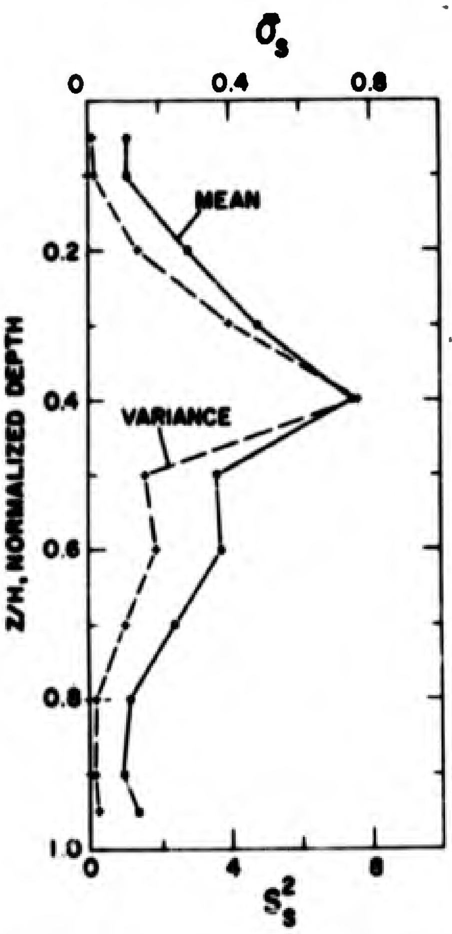

Figure 19. Variance and mean of large EGIG shear strengths vs normalized depths (Goose Lake, 1964).

The results from the sampling grid were analyzed for a given level using a three-level random nested analysis of variance (AOV) model.

$$Y_{ijk} = \mu + a_i + b_{ij} + c_{ijk} \qquad (5)$$

where i = 1 . . I, J = 1 . . J, and k = 1 . . . . K. This model states that any shear strength observation $\sigma_s = Y_{ijk}$ is equal to an overall mean μ plus the deviation of the i^{th} location mean from overall mean, plus the deviation of the j^{th} operator mean from the location mean, plus the deviation of k^{th} replicate from the operator mean (Krumbein and Graybill, 1965). The analysis of variance table for this model is given in Table I. In our specific case I = 6, J = 2 and K = 2. Because the standard deviation was shown to be directly proportional to the mean we used a ln transformation on the data to stabilize the variance before the AOV calculations were made (Brownlee, 1960, p. 114). The results of these calculations are presented in Table II. Here $\hat{\sigma}_a^2$, $\hat{\sigma}_b^2$ and $\hat{\sigma}_c^2$ represent the estimates of the variance components associated with differences between locations, between operators, and between replicates respectively. Inasmuch as it is reasonable to assume that in this case the variance associated with replication is very small, the values of $\hat{\sigma}_c^2$ are thought to represent scatter produced by small scale lateral inhomogeneities in the snow itself. The fact that the maximum value of $\hat{\sigma}_c^2$ is found at a depth in the pack where a large number of thin ice lenses occur tends to support this conclusion. Although there is considerable variation in Table II, in most cases the hypotheses that $\hat{\sigma}_a^2$ and $\hat{\sigma}_b^2$ equal zero are accepted. This indicates that the apparent variation between locations and between operations could (in the sense that the probability is greater than 1 in 20) be due to local scatter.

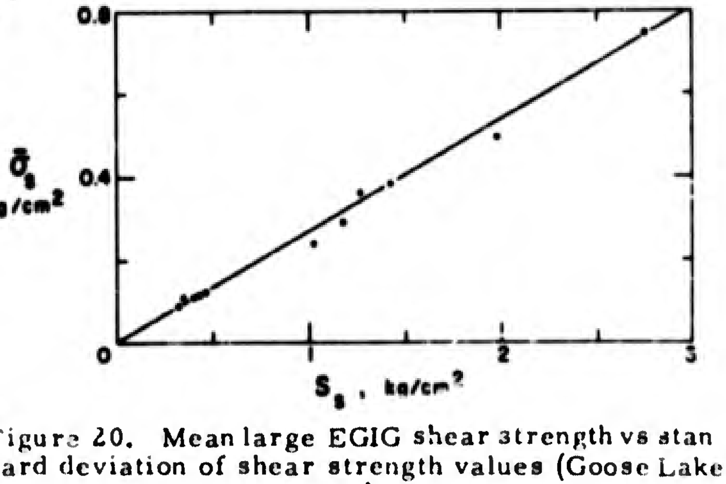

Figure 20. Mean large EGIG shear strength vs standard deviation of shear strength values (Goose Lake, 1964).

Table I. Analysis of variance table: three-level nested model.

Source	Degrees of freedom	Sums of squares	Mean square	Expected mean square
Between locations	$I-1$	$\frac{\Sigma_i Y_{i..}^2}{JK} - \frac{Y_{...}^2}{IJK}$	MS_a	$\sigma_c^2 + K\sigma_b^2 + KJ\sigma_a^2$
Between operators within locations	$I(J-1)$	$\frac{\Sigma_i \Sigma_j Y_{ij.}^2}{K} - \frac{\Sigma Y_{i..}^2}{JK}$	MS_b	$\sigma_c^2 + K\sigma_b^2$
Between measurements within operators within locations	$IJ(K-1)$	$\Sigma_i \Sigma_j \Sigma_k Y_{ijk}^2 - \frac{\Sigma_i \Sigma_j Y_{ij.}^2}{K}$	MS_c	σ_c^2
Total	$IJK-1$	$\Sigma_i \Sigma_j \Sigma_k Y_{ijk}^2 - \frac{Y_{...}^2}{IJK}$		

Table II. Hypotheses tests and variance estimates from the three-level nested EGIG shear vane experiment (variance estimates are presented on an untransformed scale).

	$H: \sigma_b^2 = 0$	$H: \sigma_a^2 = 0$	Estimated variance components		
	$F(6, 12, 0.05) = 3.00$	$F(5, 6, 0.05) = 4.39$	Between locations	Between operators	Local scatter
Z	Computed F	Values	$\hat{\sigma}_a^2$	$\hat{\sigma}_b^2$	$\hat{\sigma}_c^2$
10	2.15 NS	4.70	.015	.011	.012
30	-4.35 NS	-0.52 NS	.014	.007	.012
50	1.28 NS	0.68 NS	.004	.011	.02
70	2.30 NS	0.53 NS	.008	.013	.015
90	2.10 NS	2.01 NS	.011	.011	.013
110	0.37 NS	2.41 NS	.010	.009	.014
130	-3.64 NS	0.10 NS	.006	.035	.005
150	4.52	0.78 NS	.009	.010	.010
170	17.20	11.62	.013	.010	.010
190	-6.58 NS	-0.21 NS	.006	.017	.008

Since, during all the field experiments, it had become quite obvious that the the type of snow (i.e., fine grained, wet, depth hoar, etc.) being tested strongly affected the test results, it was decided to separate the data as much as possible by snow type. Figure 21 shows the relationship between shear strength, as measured using the large EGIG vane, and porosity for dry fine-grained snow. As was the case with tensile strength the plot shows a strong "tail off" at porosities higher than .60. Similar data gathered using the small EGIG vane gave slightly lower strength values and more scatter.

Figure 22 shows a similar plot except in this case the snow was isothermal and wet. The scatter is greater, perhaps because of inhomogeneities induced by diurnal freezing and thawing, and the strength values are lower. This is to be expected since in warm snow both the cohesion and the volume of ice are less. Similar plots were made for both dry and wet "depth hoar" (Fig. 23). It can readily be seen that the poor cohesion of the depth hoar results in low strengths at any porosity. The wet and water saturated cases do not appear to be appreciably different than the dry case.

Since it was shown earlier that a functional relationship exists between ram hardness and porosity (density), it might be assumed that there would be a relationship between ram hardness and shear strength. These data are plotted in Figure 24.

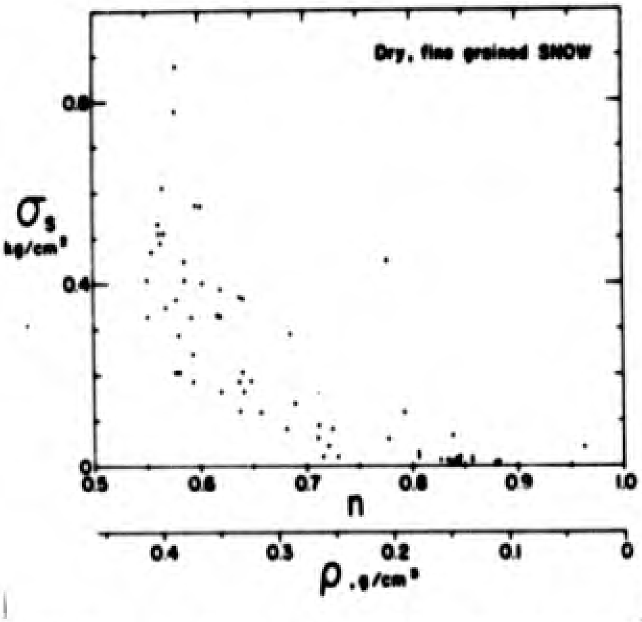

Figure 21. Large EGIG shear vane strength vs porosity for dry, fine grained snow (Goose Lake, 1964).

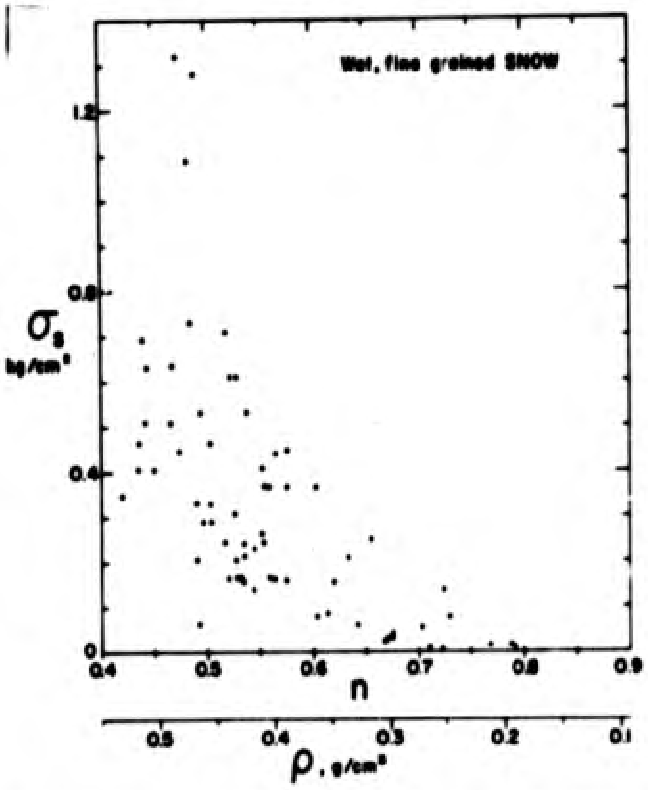

Figure 22. Large EGIG shear vane strength vs porosity for wet snow (Goose Lake, 1964).

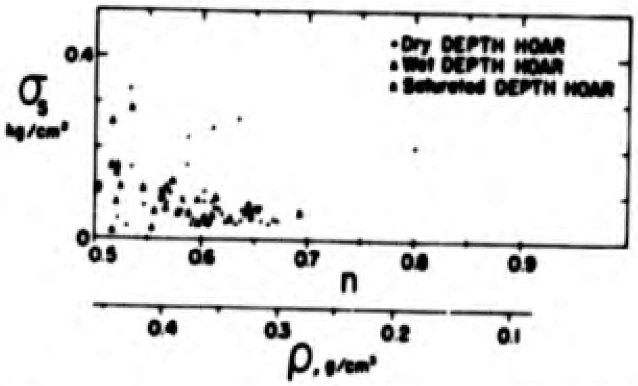

Figure 23. Large EGIG shear vane strength vs porosity for depth hoar (Goose Lake, 1964).

While there is a trend of increasing shear strength with increasing ram number, the scatter precludes an explicit statement of this relation. Similar plots for wet snow showed an even greater scatter. In all cases the depth hoar appears to have a lower shear strength at any specified ram number.

Large shear vanes: The experiments conducted with the EGIG shear vanes suggested that the scatter of data was primarily a function of inhomogeneities in the snowpack. In order to counteract these effects it was decided (1) to use an even larger shear vane which would, to some extent, average the strength values over a larger volume of snow and (2) to insert the vane horizontally into the pit wall making it possible to precisely locate the depth of sampling and make visual comparisons with the stratigraphic description. The possible errors resulting from this method of testing have already been discussed. This larger vane was used in the field seasons of 1965 and 1966 at Goose Lake and 1966 at Bridger Bowl. Its routine use throughout these periods has enabled us to amass quite an amount of data.

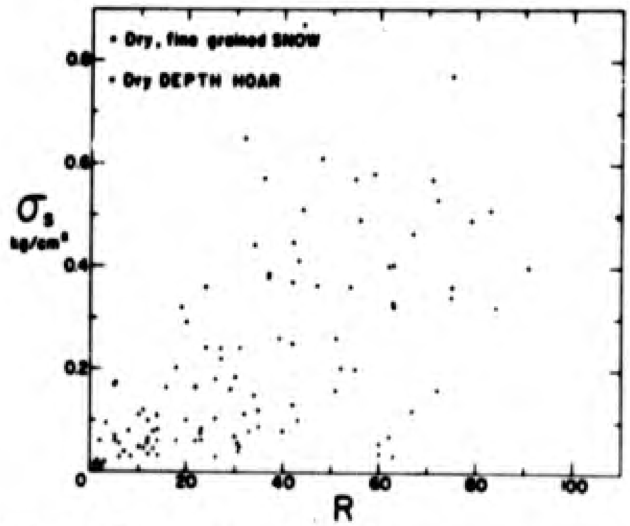

Figure 24. Large EGIG shear vane strength vs ram number (Goose Lake, 1964).

The shear strengths of the snow at Goose Lake in 1965 are plotted against porosity in Figure 25. The data show remarkably little scatter when the values for depth hoar are considered separately. This good relationship is thought to be in part due to improved measurement with the large shear vane and in part a testimony to the relative homogeneity of the snowpack that year. The range of porosities and strengths makes it possible to fit the data with the expression used earlier for the tensile strength data (eq. 3). In this case σ_i for shear is found to be equal to 4.15 kg/cm^2 when a least squares analysis is conducted. The correlation coefficient is 0.892.

The data from Bridger Bowl (Fig. 26) show considerable scatter. However, as they represent only a very limited porosity and strength range this scatter is not surprising and in fact would be expected due to the warm temperatures and extreme inhomogeneity of the snowpack that season.

The correlation between ram hardness and shear strength for the 1965 season at Goose Lake is very good (Fig. 27). By least squares $\alpha = 0.065$ and $\beta = 0.0038$ with $r = +0.868$. No physical significance can be attached to the value of the intercept as in all likelihood it should be zero; however, the curve was not forced through zero as we were not sure of the exact relationship. It is suspected that a relationship such as the one obtained could only be valid in a uniform snowpack. It should be noted that the Rammsonde measurement is not made at the same point in space as the shear vane measurement and consequently lateral variations in the snowpack affect the correlation.

Figure 28 shows a plot of shear strengths obtained using the shear vane and shear strengths obtained using the shear box. The agreement is good indicating that the same parameter is being measured in each case.

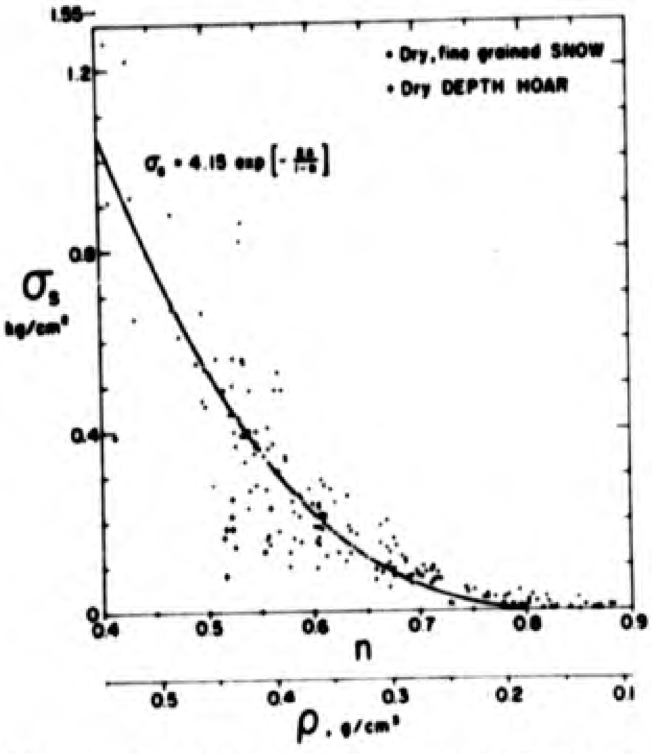

Figure 25. Large shear vane strength vs porosity (Goose Lake, 1965).

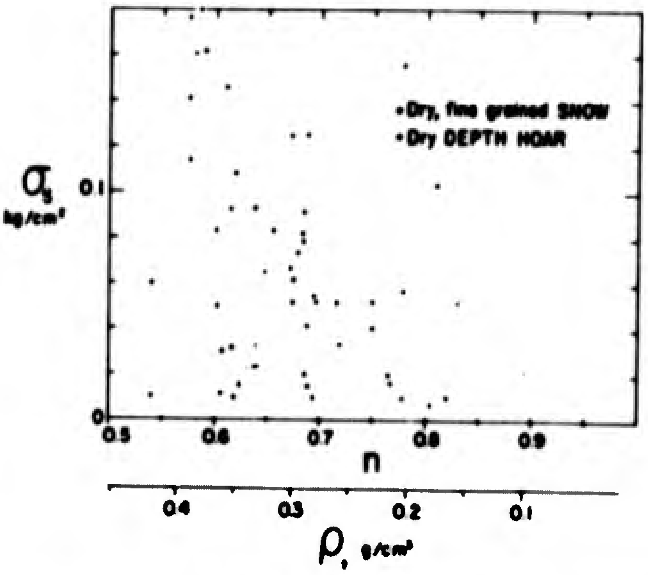

Figure 26. Large shear vane strength vs porosity (Bridger Bowl, 1966).

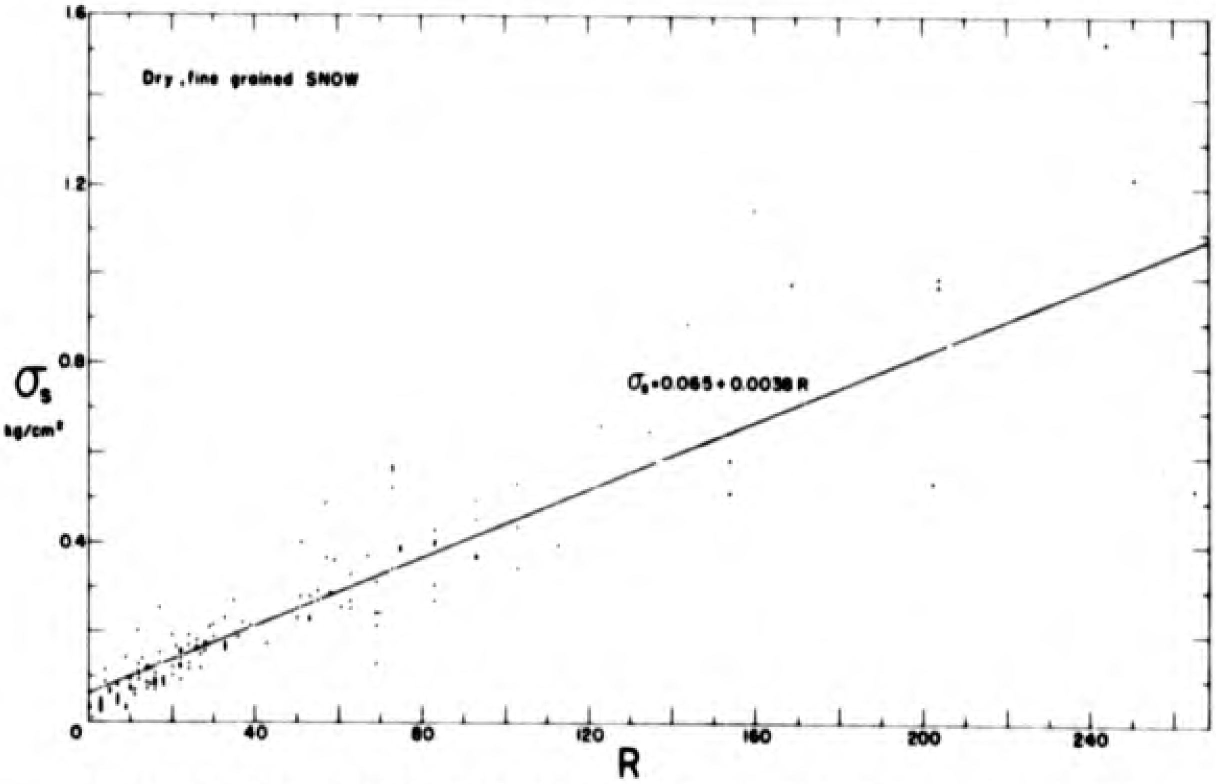

Figure 27. Large shear vane strength vs ram number (Goose Lake, 1965).

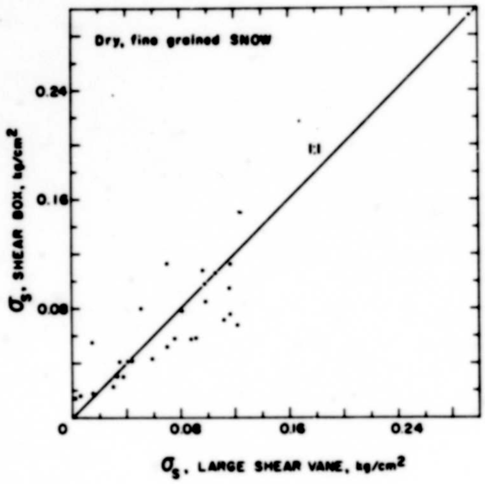

Figure 28. Large shear vane strength vs shear box strength (Goose Lake, 1965).

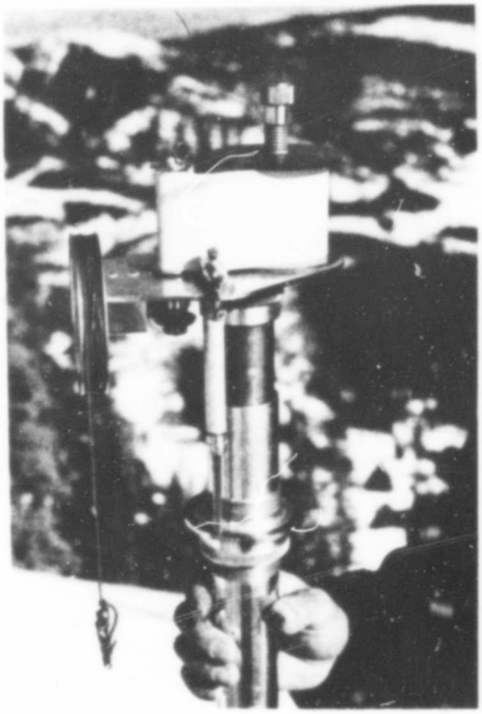

Figure 29. Recording head of snow resistograph.

Resistograph shear strength

During the seasons of 1965 and 1966 some comparative measurements of shear strength were taken using the large shear vane and a snow resistograph. The snow resistograph, designed and developed by Dr. Charles C. Bradley of the Montana State University, is a blade on a long probe, which is first inserted in the snow, then drawn upwards through the snowpack at a constant rate. The resistance encountered by the blade is balanced by a spring in the handle and transmitted to a scribe which records on a paper roll (Fig. 29). The paper unwinds at a rate controlled by the rate of withdrawal of the probe. The instrument is more fully described by Bradley (1965).

The curve plotted by the instrument, called a "resistogram," bears a strong resemblance to a ram profile. If the instrument is calibrated, the x axis can be read as strength and the y axis as depth. The instrument has been used to give a predictive index for avalanche hazard by determining the strength of the weakest layer. When this figure is compared with the load on this layer (determined by density measurements), the ratio of strength to load provides an indication of stability (Bradley and Bowles, 1966).

It was initially believed that the comparison of shear vane measurements to resistograph measurements should show a one to one correspondence; however, this does not appear to be the case. Figure 30 shows "shear" strengths measured

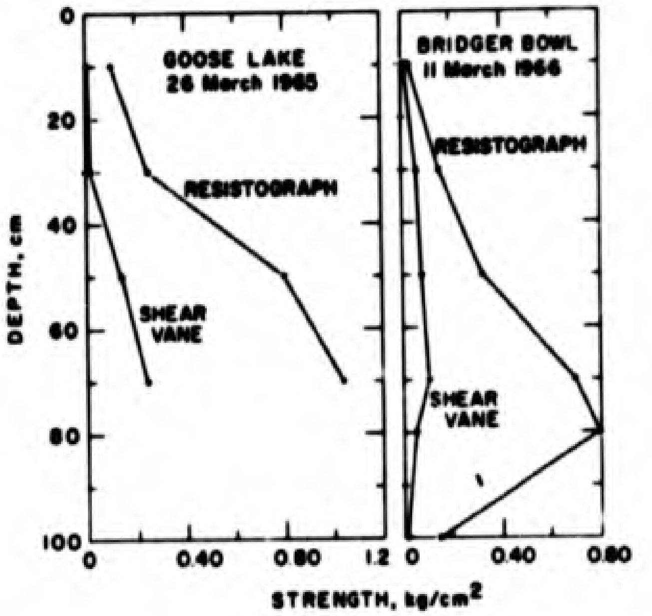

Figure 30. Comparison of large shear vane strength with snow resistograph strength.

both with the resistograph and with the large shear vane plotted as a function of depth for two locations. The ratio of the "strengths" measured by the two methods varies from 1:1 to 10:1 with the resistograph always indicating the higher strength. It is not the difference in the absolute values of the strengths but the changes in the strength ratios which are disturbing in that they suggest that the resistograph strength is neither proportional to the shear strength or to the tensile strength (which is itself a linear function of the shear strength—see Figure 33). Therefore, it is doubtful whether the (strength/load) ratio as utilized by Bradley and Bowles (1966) actually is a measure of the true value of this parameter. This criticism, however, in no way affects the usefulness of the resistograph in rapidly locating discontinuities in shallow, low density snowpacks. Furthermore, it should be noted that the strength/load ratio apparently serves as a reasonably accurate predictive index. Figure 31 shows composite resistograms (averages of three profiles) taken at four different elevations on the west side of the Bridger Range. The presence of crusts and a weak basal depth hoar layer is particularly evident.

Other results

Figure 32 shows the change with time of both the large shear vane strength σ_s and the centrifugal tensile strength σ_t in a given snow layer. A general increase in the strength values with time is indicated. The fact that these are not smoother curves is probably the result of difficulty in precisely locating identical snow layers in the different pits and the natural lateral variability of a snow layer at any given date. These curves are similar to the results of Roch (1965) from Swiss snows.

Figure 33 presents a comparison of shear vane measurements and centrifugal tensile strengths from identical snows. In general the tensile values appear to be roughly 10 times the shear values. Similar results have been obtained by Roch (1966) using a shear box. Butkovich, however, obtained comparable shear and tensile strengths for high density snow.

Figure 34 presents the observed change in the value of $\log_{10}$ (CN) vs porosity where CN is the hardness of the snow (g/cm^2) determined with a Canadian hardness gauge. The changes are quite systematic and within the range of the data may be approximated by the straight line $\log_{10}$ (CN) = 6.95 - 5.88 n with a correlation coefficient of -0.903.

CONCLUSIONS

We feel that the results presented in this paper are quite encouraging in that they demonstrate that the mechanical properties of low density snow can be investigated in the field using simple portable tests. The results show simple systematic relations with appreciably less scatter than would be anticipated from surveying the literature. Several excellent correlations are established between the results of different types of tests which should facilitate the rapid characterization of a given snowpack. It should be stressed that the systematic relations shown in this paper invariably become obscured when different "types" of snow are indiscriminantly grouped together. This points to the need for a more thorough study of the structural properties of low density snow and for an independent means of determining the degree of bonding in a snowpack. Only when such a technique is available will it be possible to adequately separate the different degrees of constructive metamorphism and incorporate the important process of depth hoar formation into an overall strength theory. The need for continued field studies using carefully controlled conditions is obvious.

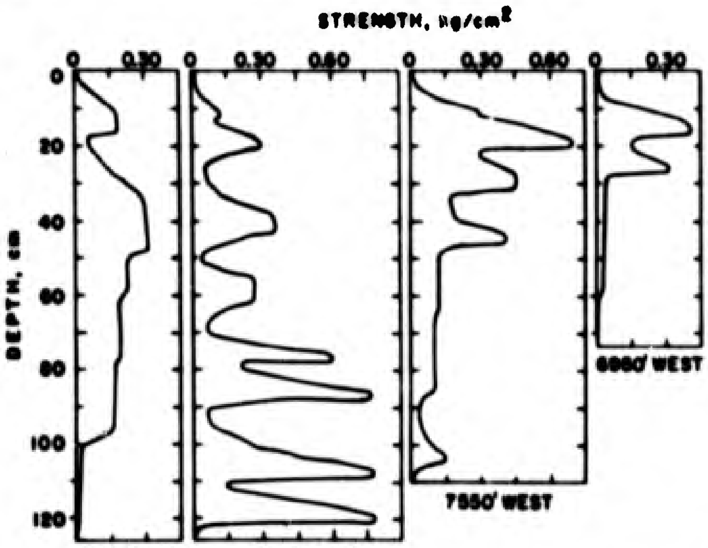

Figure 31. Areal variation of snow resistograms (Bridger Bowl, 1966).

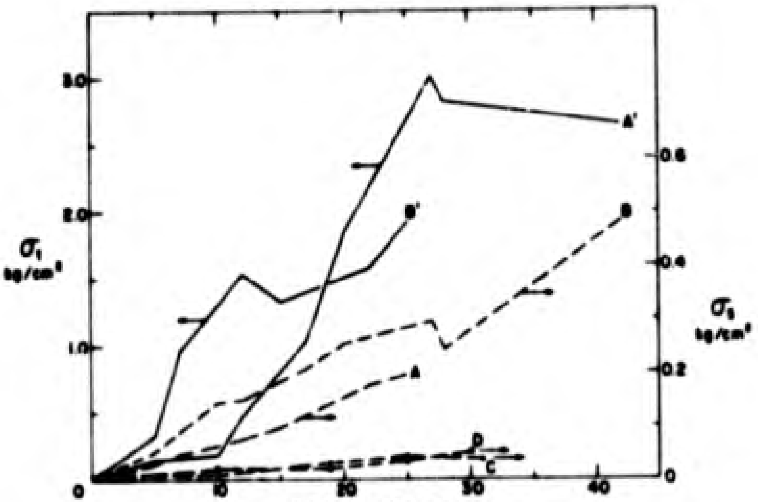

Figure 32. Time variation of strength properties (Goose Lake, 1965 and Bridger Bowl, 1966).

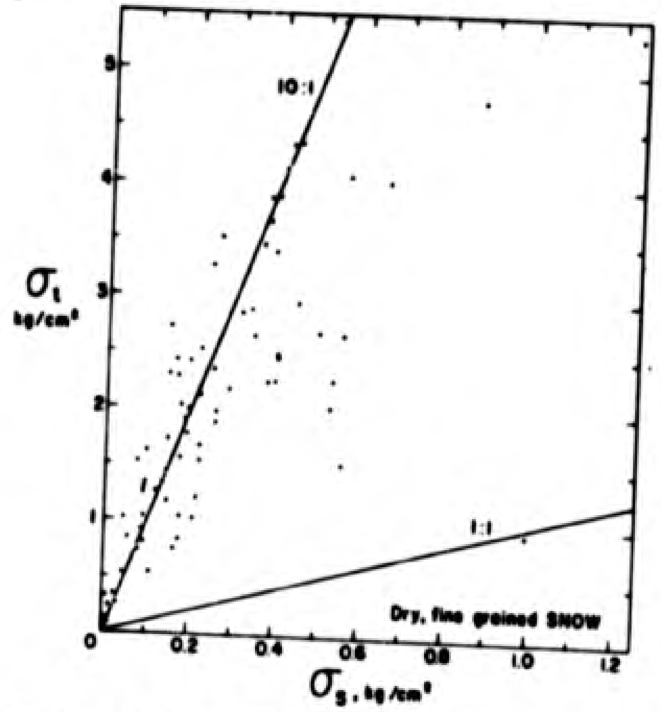

Figure 33. Centrifugal tensile strength vs large shear vane strength (Goose Lake, 1965).

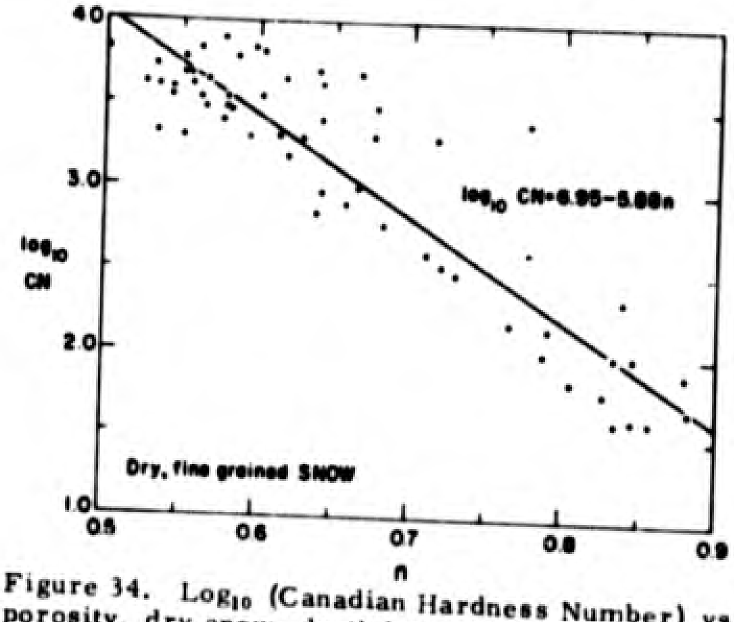

Figure 34. Log_{10} (Canadian Hardness Number) vs porosity, dry snow, depth hoar excluded (Goose Lake, 1964).

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APPENDIX A: EGIG SHEAR VANE STRENGTH MEASUREMENTS AND ASSOCIATED PIT DATA (GOOSE LAKE, 1964)

Notation: Z, vertical distance below snow - air interface (cm). σ_s, "in situ" shear strength (kg/cm^2) - the letters L and S indicate whether the test was performed with the large or the small shear vane, the letter D when used indicates that the hole was pre-drilled; ρ, snow density (g/cm^3). R, ram hardness (kg). CN, Canadian hardness number (g/cm^2).

Pit 2, 23 April 1964

Z	σ_s		LD	SD	ρ	R	CN	Depth hoar
	L	S						
10	.061	.051			.204	2	400	
20	.020	.026			.260	3	2000	
30	.041	.046			.304	7	3000	
40	.286	.153			.288	20	3000	
50	.449	.205			.204	42	2500	
60	.327	.179			.351	19	4500	
70	.367	.243			.331	54	5000	
80	.449	.179			.380	34	6000	
90	.408	.614			.364	62	6500	
100	.490	.368			.400	54	7000	
110	.776	.368			.387	75	8000	
120	.408	.061			.412	43	6000	
130	.469	.246			.407	67	5000	
140	.571	.123			.370	71	7000	
150	.263	.246			.406	51	4000	
160	.510	.368			.402	83	3500	
170	.102	.061			.394	43	3500	X
180	.224	.061			.381	31	2000	X
190	.082	.089			.358	23	7000	X
200	.061	.107			.384	23	8000	X
210	.327	[illegible]			.429	84	1500	X
220	.163	.141			.380	72	2000	X
230	.061	.038			.318	14	3500	X
240	.054	.051			.328	6	2500	X
250	.068	.056			.352	12		X
260	.105	.059			.348	20		X

Pit 3, 24 April 1964

10	.019	.013	.026	.005	.248	1	300	
20	.068	.023	.048	.041	.265	5	400	
30	.119	.102	.102	.061	.314	10	800	
40	.367	.090	.162	.090	.328	24.	950	
50	.204	.192	.119	.090	.329	18.	2500	
60	.878	.552	.327	.368	.386	44.	3000	
70	.571	.307	.143	.123	.365	36.	3500	
80	.612	.246	.327	.246	.398	48.	3000	
90	.510	.246	.327	.123	.397	44.	4500	
100	.245	.138	.245	.061	.340	42.	2000	
110	.245	.123	.102	.102	.358	27.	1500	X
120	.224	.192	.122	.107	.379	27.	1100	X
130	.061	.038	.041	.051	.328	18.	1100	X
140	.068	.064	.043	.051	.316	7.5	4500	X
150	.060	.018	.037	.020	.330	6.5	5000	X

Pit 3, 24 April 1964 (Cont'd)

Z	σ_s		LD	SD	ρ	R	CN	Depth hoar
	L	S						
150	.060	.018	.037	.020	.330	6.5	5000	X
160	.048	.028	.031	.031	.304	13.	3000	X
170	[illegible]	.028	.034	.031	.315	3.	3000	X
180	.043	.046	.031	.028	.332	4.5	5000	X
190	.048	.061	.043	.035	.324	10.	5500	X
200	.073	.051	.119	.051		5.		X

Pit 3A, 26 April 1964

10	.010	.008	.020	.015	.108	2.	50	
20	.009	.010	.009	.005	.110	2.	80	
30	.012	.008	.009	.008	.152	2.	100	
40	.010	.008	.012	.008	.151	2.	40	
50	.014	.013	.010	.010	.144	2.	40	
60	.012	.031	.012	.018	.159	2.	60	
70	.119	.067	.060	.056	.190	14.		
80	.085	.064	.077	.090	.252	13.		
90	.136	.116	.128	.243	.284	42.		
100	.187	.205	.179	.179	.322	26.		
110	.163	.166	.163	.179	.328	51.		
120	.327	.192	.327	.128	.349	63.		
130	.327	.205	.449	.217	.374	63.		
140	.408	.399	.388	.243	.380	91.		
150	.347	.428	.367	.246	.396	75.		
160	.531	.368	.653	.491	.402	72.		
170	.265	.123	.245	.123	.333	39.		X
180	.082	.089	.082	.128	.365	35.		X
190	.041	.192	.102	.090	.374	31.		X
200	.068	.056	.068	.054	.320	31.		X
210	.077	.046	.065	.064	.330	12.		X
220	.068	.072	.060	.072	.332	22.		X
230	.017	.026	.043	.038	.278	5.		X
240	.034	.046	.051	.041	.324	14.		X
250	.037	.043	.037	.043	.330	12.		X
260	.044	.059	.058	.067		16.		X
270	.119	.077	.085	.064		7.		X

Near Pits 3A and 4, 27 April 1966

Z	σ_s		LD	SD	ρ	R	CN	Depth hoar
	L1	L2						
10	.009	.012				2.	100	
20	.007	.007				2.	40	
30	.009	.017				2.	70	
40	.015	.027				2.	220	
50	.012	.017				2.	350	
60	.048	.094				2.	600	
70	.068	.128				12.	700	
80	.128	.204				11.	2000	
90	.163	.449				16.	1500	
100	.163	.449				22.	3500	
110	.367	.449				47.	3000	
120	.204	.816				55.	4000	
130	.408	.490				63.	4000	

Near Pits 3A and 4, 27 April 1966 (Cont'd)

Z	σ_s		LD	SD	ρ	R	CN	Depth hoar
	L1	L2						
140	.367	.714				75.	2000	
150	.490	.163				79.	2000	
160	.122	.286				67.	2000	
170	.128	.204				35.	2000	
180	.170	.082				34.	500	
190	.060	.017				30.	400	
200	.051	.077				18.	800	
210	.071	.085				9.	300	
220	.327	.163				20.	200	
230	.017	.020				5.		
240	.043	.051				14.		
250	.043	.060						
260	.043	.085						

Pit 4, 28 April 1964

Z	σ_s		LD	SD	ρ	R	CN	Depth hoar
	L	S						
10	.020	.020			.144	1.	100	
20	.017	.015			.131	1.	40	
30	.020	.015			.178	1.	70	
40	.015	.013			.148	1.	220	
50	.043	.033			.256	2.5	350	
60	.077	.041			.292	2.	600	
70	.102	.067			.332	12.	700	
80	.245	.230			.372	24.	2000	
90	.163	.115			.348	29.	1500	
100	.367	.276			.386	42.5	3500	
110	.204	.184			.384	52.	3000	
120	.286	.246			.418	57.	4000	
130	.245	.276			.426	65.	4000	
140	.327	.092			.412	65.	2000	
150	.082	.089			.383	33.	2000	X
160	.082	.115			.403	23.	2000	X
170	.051	.038			.376	31.	2000	X
180	.048	.030			.361	11.	500	X
190	.037	.031			.348	6.	400	X
200	.119	.090			.359	6.5	800	X
210	.034	.036			.431	26.5	300	X
220	.034	.026			.333	3.	200	X
230	.043	.046			.303	3.		X
Near Pit 4, 29 April 1964								
10	.017	.015			.144	2.		
20	.020	.013			.131	2.		
30	.036	.018			.178	3.		
40	.068	.028			.148	3.		
50	.088	.056			.256	8.		
60	.085	.046			.292	14.		
70	.184	.179			.332	14.		
80	.184	.079			.372	30.		
90	.388	.460			.348	37.		
100	.204	.153			.386	55.		

Near Pit 4, 29 April 1964 (Cont'd)

Z	σ_s		LD	SD	ρ	R	CN	Depth hoar
	L	S						
110	.286	.166			.384	59.		
120	.265	.115			.418	75.		
130	.388	.141			.426	83.		
140	.122	.056			.412	35.		
150	.082	.036			.383	31.		X
160	.111	.038			.403	31.		X
170	.037	.031			.376	10.		X
180	.039	.028			.361	8.		X
190	.054	.079			.348	10.		X
200	.031	.046			.359	20.		X
210	.027	.041			.431	5.		X
220	.034	.041			.333	5.		X
Pit 5, 30 April 1966								
10	.009	.013	.010	.010	.264	3.		
20	.029	.038	.031	.018	.272	3.		
30	.036	.028	.027	.023	.232	3.		
40	.037	.430	.044	.038	.340	8.5		
50	.105	.061	.162	.061	.340	26.		
60	.119	.115	.068	.067	.359	32.		
70	.153	.192	136	.102	.344	34.		
80	.082	.205	.119	.115	.394	40.		
90	.245	.460	.245	.192	.382	54.		
100	.224	.338	.265	.141	.410	70.5		
110	.224	.061	.367	.120	.415	83.		
120	.245	.092	.245	.141	.356	77.		
130	.265	.061	.469	.179	.387	34.5		
140	.082	.102	.143	.128	.401	35.		
150	.085	.153	.082	.090	.398	37.		X
160	.071	.031	.111	.141	.354	19.		X
170	.037	.038	.060	.051	.369	14.		X
180	.024	.046	.068	.038	.369	9.		X
190	.065	.061	.102	.072	.437	37.		X
200	.031	.028	.036	.026	.363	24.		X
210	.026	.041	.031	.026	.324	6.		X
220	.031	.051	.031	.102		14.		X
Pit 6, 7 May 1964								
10	.037	.031			.215	1.	150	
20	.020	.090			.192	1.	150	
30	.031	.026			.194	1.	100	
40	.051	.153			.306	1.	1000	
50	.068	.046			.304	1.	5000	
60	.082	.056			.298	18.5	2000	
70	.128	.064			.328	11.	4000	
80	.170	.174			.354	28.	2000	
90	.245	.123			.418	56.	3500	
100	.163	.123			.388	50.5	2500	
110	.143	.123			.430	90.	5500	
120	.347	.123			.408	73.	5000	
130	.204	.368			.466	99.	6500	
140	.204	.184			.432	81.	4000	

Pit 6, 7 May 1964 (Cont'd)

Z	σ_s L	σ_s S	LD	SD	ρ	R	CN	Depth hoar
150	.245	.092			.426	72.	2200	
160	.286	.102			.428	41.	2500	X
170	.082	.090			.402	33.	3000	X
180	.163	.128				31.4	1500	X
190	.082	.090			.406	16.	600	X
200	.061	.072			.336	7.5	400	X
210	.068	.046			.397	17.5	1000	X
220	.048	.046			.406	41.5	1000	X
230	.111	.153				9.	400	X
240	.051	.056				9.	400	X
250	.053	.054						X

Pit 7, 12 May 1964

Z	σ_s L	σ_s S	LD	SD	ρ	R	CN	Depth hoar
10	.017	.013			.251	1.	100	
20	.017	.026			.266	1.		
30	.119	.056			.256	12.	500	
40	.043	.056			.296	3.	500	
50	.245	.102			.323	10.		
60	.367	.522			.388	10.	3000	
70	.163	.123			.430	32.		
80	.449	.491			.388	34.	4500	
90	.204	.430			.425	22.		
100	.449	.215			.397	64.5	5000	
110	.163	.123			.430	33.		
120	.469	.368			.450	84.	6000	
130	.286	.184			.462	90.		
140	.286	.368			.457	111.	6000	
150	.265	.215			.411	96.		
160	.102	.092			.416	66.	3000	X
170	.102	.092			.399	48.		X
180	.122	.153			.393	36.	3000	X
190	.061	.115			.378	25.5		X
200	.041	.051			.364	23.	1000	X
210	.051	.038			.416	18.5		X
220	.016	.041			.444	16.	2000	X
230	.060	.248			.326	52.		X
240	.017	.038				14.	800	X
250	.068	.051				6.		X

Pit 8, 15 May 1964

Z	σ_s L	σ_s S	LD	SD	ρ	R	CN	Depth hoar
10	.153	.092			.348	17.	400	
20	.051	.026			.274	6.	300	
30	.204	.179			.334	11.		
40	.082	.051			.362	14.	400	
50	.163	.153			.440	15.		
60	.163	.179			.400	31.5	1000	
70	.367	.430			.404	18.		
80	.408	.430			.410	54.	4000	
90	.163	.123			.404	64.		
100	.531	.184			.424	94.	6000	
110	.327	.368			.456	105.		
120	.510	.522			.490	108.	4500	

Pit 8, 15 May 1964 (Cont'd)

Z	σ_s L	σ_s S	LD	SD	ρ	R	CN	Depth hoar
130	.327	.368			.468	103.		
140	.612	.246			.432	63.	3500	
150	.163	.123			.440	43.		X
160	.163	.092			.442	47.5	2500	X
170	.163	.092			.480	63.		X
180	.082	.092			.434	39.	2000	X
190	.082	.061			.399	19.		X
200	.034	.056			.368	11.5	1000	X
210	.051	.041			.386	18.		X
220	.085	.056			.356	5.	1500	X
230	.051	.036				42.		X
240	.051	.051						X

Pit 9, 19 May 1966

Z	σ_s L	σ_s S	LD	SD	ρ	R	CN	Depth hoar
10	.082	.092			.248	50.		
20	.367	.246			.364	14.		
30	.408	.184			.504	11.		
40	.612	.399			.438	14.		
50	.449	.307			.480	26.		
60	.531	.215			.464	28.		
70	.735	.276			.472	32.		
80	.306	1.074			.434	23.		
90	.694	.460			.532	44.		
100	.510	.491			.512	59.5		
110	.469	.122			.514	82.		
120	.245	.368			.442	58.		
130	.163	.184			.440	48.		X
140	.245	.184			.446	53.		X
150	.143	.184			.444	68.		X
160	.082	.092			.400	38.		X
170	.082	.061			.382	23.		X
180	.041	.061			.362	11.		X
190	.082	.061			.426	14.5		X
200	.061	.061			.282	25.		X

Pit 10, 23 May 1964

Z	σ_s L	σ_s S	LD	SD	ρ	R	CN	Depth hoar
10	.245	.123			.408	12.	600	
20	.061	.092			.466	9.	2000	
30	.163	.491			.442	5.		
40	.653	.614			.492	12.	1200	
50	.163	.184			.434	17.5		
60	.408	.338			.518	17.	1500	
70	1.286	1.044			.468	22.		
80	.714	1.504			.442	34.	2500	
90	.490	.645			.502	50.		
100	.571	.184			.562	47.	3500	
110	.245	.179			.584	17.5		X
120	.245	.217			.490	13.	2200	X
130	.449	.307			.502	11.		X
140	.143	.092			.426	14.	1000	X
150	.153	.077			.404	5.5		X
160	.034	.051			.560	3.	500	X

Pit 10, 23 May 1964 (Cont'd)

Z	σ_ϕ		LD	SD	ρ	R	CN	Depth hoar
	L	S						
170	.145	.102			.424	3.		X
180	.068	.051			.392	3.	1000	X
190	.071	.064				3.		X
Pit 11, 26 May 1964								
10	.347	.552			.438	81.		
20	.163	.338			.442	20.		
30	.204	.184			.476	18.		
40	.367	.491			.506	30.		
50	.551	.307			.498	22.		
60	.347	.368			.532	32.		
70	.633	.675			.510	42.		
80	1.327	1.074			.484	47.		
90	1.082	1.688			.476	35.		
100	.245	.307			.478	40.5		
110	.224	.307			.466	36.		
120	.184	.400			.480	27.		
130	.367	.737			.504	42.		
140	.082	.460			.464	24.		
150	.119	.092			.436	7.5		X
160	.026	.051			.412	8.		X
170	.119	.077			.456	15.		X
180	.043	.051			.406	7.5		X
190	.034	.051				7.		X
200	.077	.064				11.		X

APPENDIX B: EGIG SHEAR VANE STRENGTH MEASUREMENTS FROM A SAMPLING GRID (8 May 1964, GOOSE LAKE)

Notation: see Appendix A. The operators are designated by number after the shear vane size designation.

Location 1. Time 1245

Z	L1	L1	L2	L2
10	.041	.068	.128	.245
30	.020	.051	.037	.082
50	.286	.068	.085	.041
70	.143	.153	1.531	.122
90	.490	.490	.143	.531
110	.327	.347	.327	.408
130	.265	.306	.408	.224
150	.286	.327	.408	.469
170	.163	.163	.245	.245
190	.245	.306	.408	.327

Location 2. Time 1500

10	.043	.051	.264	.085
30	.094	.037	.082	.037
50	.094	.060	.041	.082
70	.224	.204	.714	.408
90	.531	.163	.245	.204
110	.245	.224	.490	.408
130	.204	.265	.531	.612
150	.286	.286	.449	.245
170	.245	.245	.143	.143
190	.224	.245	.245	.429

Location 3. Time 1545

10	.037	.051	.714	.145
30	.051	.037	.041	.026
50	.022	.102	.327	.102
70	.143	.143	.367	.184
90	1.225	.490	.122	.327
110	.245	.245	.143	.163
130	.327	.367	.714	.776
150	.286	.327	.612	.510
170	.347	.245	.184	.408
190	.163	.184	.347	.408

Location 4. Time 1645

10	.085	.043	.119	.017
30	.051	.026	.034	.034
50	.136	.051	.128	.224
70	.367	.286	.060	.347
90	.327	.367	.204	.184
110	.327	.204	.449	.347
130	.388	.408	.673	.653
150	.347	.510	.469	.510
170	.714	.490	.612	1.120
190	.408	.571	.286	.490

Location 5. Time 1900

Z	L1	L1	L2	L2
10	.119	.077	.136	.367
30	.094	.060	.026	.306
50	.051	.094	.063	.082
70	.286	.327	.051	.082
90	.163	.163	.245	.224
110	.286	.327	.388	.286
130	.327	.408	.469	.714
150	.327	.408	.694	.612
170	.490	.612	.653	.510
190	.408	.408	.714	.592

Location 6. Time 2000

10	.051	.119	.085	.184
30	.043	.060	.020	.020
50	.102	.128	.051	.163
70	.119	.184	.163	.714
90	.224	.102	.163	.102
110	.163	.184	.163	.184
130	.408	.429	.265	.694
150	.449	.367	.306	.490
170	.265	.490	.490	.327
190	.327	.265	.408	.510

APPENDIX C: EGIG SHEAR VANE STRENGTH MEASUREMENTS AT ABLATION STAKES (15-18 May 1964, GOOSE LAKE)

Notation: see Appendix A. Ablation stake number given first followed by vane size; Z_N, the sample position in the snow pack measured from the snow-air interface divided by the total thickness of the pack.

Z_N	1S	2S	3S	4S	5S	6S	7S	8S	9S	12S	13S
.05	.128	.153	.077	.217	.153	.056	.128	.230	.153	.077	.077
.1	.051	.051	.179	.051	.051	.128	.090	.179	.153	.179	.230
.2	.215	.230	.246	.767	.153	.133	.051	.767	.077	.256	.179
.3	.184	.184	1.228	.307	.215	.600	.614	.184	1.258	.184	.338
.4	.552	.246	1.074	.737	.307	.614	.368	.368	1.074	1.535	1.368
.5	.522	.491	.184	.153	.491	.400	.184	.123	.614	.307	.491
.6	.215	.368	.921	.522	.123	.184	.061	.460	.246	.368	.614
.7	.064	.123	.307	.064	.077	.092	.205	.123	.338	.737	.491
.8	.179	.064	.179	.038	.064	.061	.054	.051	.217	.184	.090
.9	.077	.077	.051	.077	.038	.060	.077	.077	.152	.102	.217
.95	.179	.051	.179	.153	.001	.051	.217	.192	.090	.179	.102

APPENDIX B: EGIG SHEAR VANE STRENGTH MEASUREMENTS FROM A SAMPLING GRID (8 May 1964, GOOSE LAKE)

Notation: see Appendix A. The operators are designated by number after the shear vane size designation.

Location 1. Time 1245

Z	L1	L1	L2	L2
10	.041	.068	.128	.245
30	.020	.051	.037	.082
50	.286	.068	.085	.041
70	.143	.153	1.531	.122
90	.490	.490	.143	.531
110	.327	.347	.327	.408
130	.265	.306	.408	.224
150	.286	.327	.408	.469
170	.163	.163	.245	.245
190	.245	.306	.408	.327

Location 2. Time 1500

Z	L1	L1	L2	L2
10	.043	.051	.204	.085
30	.094	.037	.082	.037
50	.094	.060	.041	.082
70	.224	.204	.714	.408
90	.531	.163	.245	.204
110	.245	.224	.490	.408
130	.204	.265	.531	.612
150	.286	.286	.449	.245
170	.245	.245	.143	.143
190	.224	.245	.245	.429

Location 3. Time 1545

Z	L1	L1	L2	L2
10	.037	.051	.714	.145
30	.051	.037	.041	.026
50	.022	.102	.327	.102
70	.143	.143	.367	.184
90	1.225	.490	.122	.327
110	.245	.245	.143	.163
130	.327	.367	.714	.776
150	.286	.327	.612	.510
170	.347	.245	.184	.408
190	.163	.184	.347	.408

Location 4. Time 1645

Z	L1	L1	L2	L2
10	.085	.043	.119	.017
30	.051	.026	.034	.034
50	.136	.051	.128	.224
70	.367	.286	.060	.347
90	.327	.367	.204	.184
110	.327	.204	.449	.347
130	.388	.408	.673	.653
150	.347	.510	.469	.510
170	.714	.490	.612	1.120
190	.408	.571	.286	.490

Location 5. Time 1900

Z	L1	L1	L2	L2
10	.119	.077	.136	.367
30	.094	.060	.026	.306
50	.051	.094	.063	.082
70	.286	.327	.051	.082
90	.163	.163	.245	.224
110	.286	.327	.388	.286
130	.327	.408	.469	.714
150	.327	.468	.694	.612
170	.490	.612	.653	.510
190	.408	.408	.714	.592

Location 6. Time 2000

Z	L1	L1	L2	L2
10	.051	.119	.085	.184
30	.043	.060	.020	.020
50	.102	.128	.051	.163
70	.119	.184	.163	.714
90	.224	.102	.163	.102
110	.163	.184	.163	.184
130	.408	.429	.265	.694
150	.449	.367	.306	.490
170	.265	.490	.490	.327
190	.327	.265	.408	.510

APPENDIX C: EGIG SHEAR VANE STRENGTH MEASUREMENTS AT ABLATION STAKES (15-18 May 1964, GOOSE LAKE)

Notation: see Appendix A. Ablation stake number given first followed by vane size; Z_N, the sample position in the snow pack measured from the snow-air interface divided by the total thickness of the pack.

Z_N	1S	2S	3S	4S	5S	6S	7S	8S	9S	12S	13S
.05	.128	.153	.077	.217	.153	.056	.128	.230	.153	.077	.077
.1	.051	.051	.179	.051	.051	.128	.090	.179	.153	.179	.230
.2	.215	.230	.246	.767	.153	.133	.051	.767	.077	.256	.179
.3	.184	.184	1.228	.307	.215	.600	.614	.184	1.258	.184	.338
.4	.552	.246	1.074	.737	.307	.614	.368	.368	1.074	1.535	1.368
.5	.522	.491	.184	.153	.491	.400	.184	.123	.614	.307	.491
.6	.215	.368	.921	.522	.123	.184	.061	.460	.246	.368	.614
.7	.064	.123	.307	.064	.077	.092	.205	.123	.338	.737	.491
.8	.179	.064	.179	.038	.064	.061	.054	.051	.217	.184	.090
.9	.077	.077	.051	.077	.038	.060	.077	.077	.152	.102	.217
.95	.179	.051	.179	.153	.001	.051	.217	.192	.090	.179	.102

APPENDIX D: LARGE SHEAR VANE STRENGTH MEASUREMENTS, CENTRIFUGAL TENSILE STRENGTH MEASUREMENTS, AND ASSOCIATED PIT DATA (GOOSE LAKE, 1965)

Notation: same as Appendix A except that σ_s is "in situ" shear strength (kg/cm^2) as measured with large shear vane and σ_t is tensile strength (kg/cm^2) as measured with centrifugal tester.

Pit of 28 March 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
5	.108	.010		1
10	.146	.005		1
15	.136			1
20	.162	.005		1
25	.164			1
30	.248	.015		1
35	.220			1
40	.184	.015		1
45	.184			1
50	.132	.010		1
55	.128			1
60	.260	.074		1
65	.252			9
70	.314	.091		7
75	.306			10
80	.320	.132		17
85	.352			17
90	.346	.132		24
95	.342			41
100	.362	.224		23
110	.352	.270		43
120	.392	.343		43
130	.394	.490		55
140	.400	.490		95
150	.438			93
160	.426	.857		99
170	.418			113
180	.428	.820		93
190	.458			133
200	.426	.551		174
220	.440	.490		114
240	.468	.551		184
300	.510	.612		164
320	.522	.673		174
340	.522			155
350	.522			305
360	.488			355
370	.514			205
380	.530			245
390	.530			205
400	.500			196
410	.520			226
420	.514			226
430	.428			226

Pit of 3 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
5	.106		.009	1
10	.166		.062	1
15	.126		.045	1
20	.126	.002	.035	1
25	.146		.041	1
30	.158	.006	.132	1
35	.164		.137	1
43	.250	.015	.705	1
50	.302	.051	.852	7
55	.236		.550	8
60	.226		.258	8
65	.272		1.156	5
70	.266	.091	.820	10
75	.318		.650	14
80	.318		.600	10
85	.318		1.251	12
90	.338	.112	.504	10
95	.342		1.561	16
100	.344		2.053	19
105	.346		1.938	20
110	.384	.164	2.437	33
115	.382			35
120	.392		2.488	63
125	.394		2.813	197
130	.378	.254	3.524	189
135	.388		3.265	194

Pit of 4 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
6	.124		.047	
15	.130		.081	
28	.154		.191	
40	.325		1.191	
60	.286		.971	
90	.360		1.978	

Pit of 5 April 1965 (Trailer site)

Z	ρ	σ_s	σ_t	R
10	.170	.003		
20	.194	.013		
30	.266	.060		11
35	.278			9
40	.226			9
45	.252			6
50	.308	.084		15
55	.352			8
60	.348			18
65	.314			10
70	.314	.070		10
75	.358			12
80	.364			18
85	.362			26
90	.364	.096		22
95	.358			30
100	.372			22

APPENDIX D

Pit of 5 April 1965 (Trailer site) (Cont'd)

Z	ρ	σ_s	σ_t	R
110	.438	.270		35
120	.440			57
130	.388	.133		43
140	.406			23
150	.406	.173		33
160	.446			27
175	.388	.192		45
180	.430			39
190	.482	•		63
200	.438	.162		70
210	.444			60
220	.444	.081		52

Pit of 8 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
5	.116		.024	1
10	.174		.082	1
15	.168		.047	1
20	.182	.001	.106	1
25	.140		.366	1
30	.202	.003	.301	1
35	.198		.295	1
40	.228	.046	.531	3
45	.288		.329	6
50	.296	.143	.172	13
55	.344		1.252	16
60	.276	.082	.926	18
65	.274		1.252	12
70	.306	.097	1.300	10
75	.300		.699	18
80	.336	.128		12
85	.350		2.499	14
90	.362	.149	2.735	22
95	.354		1.735	22
100	.364	.149	2.301	22
105	.368		2.336	25
110	.380	.216	2.128	39
115	.420		2.999	39
120	.426	.390	3.400	75
125	.406		1.725	67
130	.406	.335	2.899	63
135	.404		1.846	57
140	.414	.376	3.671	57
145	.426		3.777	69
150	.426	.557	1.552	99
155	.448			103
160	.436	.398	3.866	113
165	.420			93
170	.416	.281	2.182	53

Pit of 10 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
5	.120		.034	1
10	.118		.033	1
15	.122	.011	.057	1
20	.138		.232	1
25	.216	.029	.454	1
30	.186		.212	1
35	.166	.030	.247	1
40	.230		.977	1
45	.236	.049	1.003	3
50	.264		.498	5
55	.304	.146	1.198	9
60	.340			14
65	.322	.120	1.269	22
70	.278		.857	28
75	.314	.146	1.435	16
80	.308		1.034	16
85	.330	.171	1.108	22
90	.358		2.412	14
95	.358	.196	2.412	22
100	.372		3.131	24
105	.360	.213	1.208	29
110	.376		2.387	27
115	.384	.221	1.513	37
120	.402		2.109	39
125	.422	.404	4.135	51
130	.416		3.502	75
135	.416	.373	3.880	67
140	.410		3.272	59
145	.406	.365	3.417	59
150	.412		3.112	55
155	.428	.396	2.245	75
160	.436		3.294	95
165	.452			123

Pit of 15 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
5	.148		.031	1
10	.186	.010	.313	1
15	.162		.272	1
20	.174	.021	.358	1
25	.228		.531	1
30	.210	.028	.160	3
35	.214		.517	3
40	.274	.076	1.535	3
45	.264		1.293	14
50	.304	.207	1.020	12
55	.344		2.184	22
60	.376			32
65	.362			47
70	.298	.166	.755	26
75	.342			26
80	.336			26
85	.370			22
90	.366	.188	1.794	30
95	.378		1.032	34

Pit of 15 April 1965 (Jamesway site) (Cont'd)

Z	ρ	σ_s	σ_t	R
100	.376		1.262	38
105	.392		2.962	39
110	.380	.257	1.993	63
120	.432		2.420	55
130	.426	.330		83
140	.406			63
150	.450	.563	2.686	73
160	.444			113
170	.418	.345	2.658	103
180	.446		3.370	63
190	.438	.498	2.951	93
200	.460		3.100	93
210	.488	.884	4.782	144
220	.496			164
230	.524	1.225		254
240	.494		4.158	234
250	.496			144
260	.506	.514		154
270	.504		3.808	134
280	.542	1.261	5.311	164
290	.542			224
300	.548	1.550		244
320	.550			325
340	.554	.906		325
360	.508			335
380	.520	.649		135
400	.508			145

Pit of 18 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
5	.168		.035	
10	.186	.011	.069	
15	.182			
20	.138	.029	.157	1
25	.168		.191	1
30	.178	.036	.203	1
35	.210		.489	1
40	.186	.045	.524	1
50	.212		.494	3
55	.220		.513	5
60	.272	.098	1.333	4
65	.302		1.190	6
70	.338	.255	1.893	17
75	.366		3.414	18
80	.336	.188	2.005	36
85	.314		1.993	46
90	.334			36
95	.322		1.269	30
100	.348	.174	2.017	43
105	.364		2.310	23
110	.368		2.196	39
115	.380		2.871	47
120	.370	.270		55

Pit of 25 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
10	.198	.035	.226	1
15	.226		.426	1
20	.220	.026	.467	3
25	.240		.274	4
30	.282	.079	.705	10
35	.314		1.144	15
40	.298	.078	.745	14
45	.304		1.389	14
50	.304	.097	1.595	18
55	.300		.846	16
60	.308	.097	1.606	16
65	.270		1.064	16
70	.278	.088	1.095	14
75	.286		2.160	18
80	.260	.085	1.270	16
85	.282		1.288	14
90	.270	.088	.761	16
95	.314		.785	12
100	.336	.178	1.535	28
105	.360		3.192	37
110	.360	.294		55
115	.384			81
120	.358	.214	3.508	69
125	.394		4.063	53
130	.362	.235		53
135	.384			43
140	.418	.269		63
145	.410			53
150	.410	.343		73
155	.424			83
160	.416	.367		83
165	.420			63
170	.460	.455		93
175	.402			103
180	.434	.367		93
185	.438			83
190	.440			83

Pit of 26 April 1965 (Jamesway site)

Z	ρ	σ_s	σ_t	R
10	.234	.042	.230	7
15	.232		.228	5
20	.216	.030	.170	9
25	.200		.336	5
30	.258	.070	.150	5
35	.302		1.691	15
40	.282	.076	.946	16
45	.268		.826	12
50	.288	.113	1.316	12
55	.312		1.862	18
60	.292	.122		22
65	.320		1.462	20
70	.288	.106	1.511	20
75	.292		.979	18
80	.264	.098	.744	18

Pit of 26 April 1965 (Jamesway site) (Cont'd)

Z	ρ	σ_a	σ_t	R
85	.278		1.181	14
90	.302	.107	1.283	16
95	.330		2.224	30
100	.368	.239	3.263	33
105	.394		2.813	79
110	.348	.241	2.345	69
115	.390		3.112	51
120	.386	.242	1.640	69
125	.400		3.022	69
130	.398	.314	2.842	69
135	.404		3.052	93
140	.396	.526	2.077	73
145	.414		2.628	73
150	.406	.406		83
155	.412		2.942	73
160	.416	.400	2.483	83
165	.436		3.670	73
170	.438	.437	3.687	103
175	.428		3.233	103
180	.426	.428	4.383	83
185	.426		4.174	83
190	.436	.563	4.067	73
195	.442		4.548	103
200	.462	.661	4.096	123

Pit of 10 May 1965 (Jamesway site)

Z	ρ	σ_a	σ_t	R
10	.120	.005	.025	1
15	.118		.116	1
20	.110	.010	.231	1
25	.118		.024	1
30	.164	.016		1
35	.166		.217	1
40	.182	.022	.383	1
45	.186			1
50	.216		.503	3
55	.312		.451	3
60	.360	.178	.839	24
65	.378		.795	30
70	.338			30
75	.310		.652	30
80	.392		2.799	22
85	.362	.183	1.899	26
90	.366			22
95	.360	.219	1.675	30
100	.360		1.764	30
105	.360		2.016	45
110	.360		1.888	45
120	.362	.163	2.585	33
130	.378		2.399	33
140	.422	.499	2.697	57
150	.396		1.560	107
160	.402	.379	2.252	93
170	.426		3.777	113
180	.436	.526	2.287	103

Pit of 10 May 1965 (Jamesway site) (Cont'd)

Z	ρ	σ_a	σ_t	R
190	.456		5.146	103
200	.460	.539	5.430	203
210	.460			96
220	.452			78
230	.472			114
240	.462			114
250	.468	.453		60
300	.522	.918		204
340	.504	.980		169
380	.538	.392		217
400	.556			277

APPENDIX E: SHEAR STRENGTH AS MEASURED USING SHEAR BOX (GOOSE LAKE, 1765)

Notation: σ_{max}, maximum shear strength; σ_{min}, minimum shear strength; σ, mean shear strength (usually the mean of from 3 to 6 measurements at the specified depth). ρ, snow density (g/cm^3).

Z	σ_{max}	σ_{min}	σ	ρ
		28 March 1965		
1	.006	.003	.005	.050
5	.011	.005	.008	.188
30	.021	.014	.018	.172
40	.072	.045	.055	.236
60	.120	.107	.113	.344
		3 April 1965		
10	.004	.004	.004	.116
20	.015	.012	.014	.126
30	.020	.013	.016	.158
40	.061	.048	.056	.203
50	.084	.073	.080	.302
60	.052	.036	.045	.226
70	.066	.045	.058	.266
80	.123	.095	.113	.318
90	.093	.064	.072	.338
100	.093	.082	.087	.344
		8 April 1965		
5	.004	.002	.003	.108
15	.004	.003	.003	.106
25	.010	.009	.009	.190
35	.027	.015	.023	.140
45	.033	.024	.029	.206
55	.117	.092	.105	.306
65	.140	.129	.134	.318
		10 April 1965		
10	.008	.006	.007	.118
20	.014	.009	.011	.138
30	.026	.019	.023	.186
40	.027	.023	.026	.230
		25 April 1965		
10	.048	.032	.041	.198
20	.040	.022	.033	.220
30	.109	.045	.081	.282
50	.114	.069	.098	.304
60	.113	.103	.108	.308
70	.067	.044	.058	.278
80	.117	.077	.099	.260
95	one value only		.131	.314
100	one value only		.294	.360

26 April 1965

Z	σ_{max}	σ_{min}	σ	ρ
10	.070	.026	.044	.234
20	.050	.029	.038	.216
30	.061	.041	.052	.258
40	.070	.045	.058	.282
50	.154	.099	.117	.288
60	.088	.065	.076	.292
70	.126	.092	.106	.288

APPENDIX F: LARGE SHEAR VANE MEASUREMENTS AND ASSOCIATED DENSITIES (BRIDGER BOWL, 1966)

Site A			Site B		
Z	ρ	σ_s	Z	ρ	σ_s
1 March 1966					
15	.130	.024	40	.252	.031
30	.204	.057	60	.266	.050
50	.282	.078	80	.314	.061
75	.326	.065	100	.360	.030
100	.286*	.015	110	.360*	.012
11 March 1966					
10	.212	.016	10	.176	.010
30	.276	.052	20	.252	.027
50	.288	.083	30	.272	.069
70	.320	.108	50	.288	.081
80	.270	.053	70	.304	.074
100	.288*	.020	90	.366	.055
			110	.344	.043
			130	.300*	.015
21 March 1966					
20	.156	.052	25	.102	.010
40	.180	.104	40	.201	.026
60	.204	.156	60	.210	.041
80	.228	.041	70	.260	.057
100	.228	.052	80	.293	.078
120	.300	.067	100	.340	.140
140	.300	.125	120	.310	.109
160	.366	.146	140	.370	.119
180	.360*	.083	160	.366*	.093
200	.332*	.093	180	.353*	.034
220	.316*	.083			
240	.350*	.010			
23 March 1966			**24 March 1966**		
20	.240	.010	10	.204	.010
40	.256	.036	20	.216	.020
60	.264	.057	40	.288	.041
80	.352	.125	60	.276	.052
100	.392	.166	80	.288	.125
120	.376	.156	100	.340	.114
150	.308*	.030	120	.296	.062
			140	.300*	.052
			160	.276*	.010

*indicates depth hoar

30 March 1966

Site A			Site B		
Z	ρ	σ_s	Z	ρ	σ_s
20	.350	.015			
40	.360	.093			
60	.392	.177			
80	.382	.177			
100	.416*	.062			
120	.420*	.010			

*indicates depth hoar

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U. S. Army Cold Regions Research and
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13 ABSTRACT

Data on the physical properties of seasonal alpine snow have been collected from the Beartooth Mountains near Cooke City, Montana, and the Bridger Range near Bozeman, Montana. Systematic measurements of snow density, temperature, structure, ram and Canadian hardness, centrifugal tensile strength and shear strength measured with a shear box and several types of shear vanes are included. Test results were grouped according to gross snow types and whether the snow was wet or dry. Interrelations between the different test parameters were studied. Experiments were also conducted to study the sources of error in making in-situ mechanical tests on snow without utilizing a pit wall. The main factor contributing to the experimental scatter is lateral inhomogeneity in the snow cover. However, the standard deviation of a group of strength tests is shown to be directly proportional to the mean value of the group. The systematic relations between snow properties invariably become obscured when different snow "types" are indiscriminantly grouped together.

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Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Snow cover-- Montana						
Snow cover-- Physical properties-- Measurement						
Snow surveys--Montana						

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