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NATIONAL RESEARCH COUNCIL
CANADA

THE STRENGTH OF SNOW IN COMPRESSION UNDER DYNAMIC LOADS

by

Lorne W. Gold

Report No. 55
of the
Division of Building Research

Ottawa
December 1954

PREFACE

Research into the problems related to snow and ice is a most important part of the work of the Division of Building Research since it is so peculiarly a Canadian problem.

The Division has just had completed a special cold room which was designed as a snow and ice laboratory -- one of the first such laboratories ever to be built. The work has already started in this laboratory and the Division looks forward to using this special facility for an immediate attack on the more urgent research problems in this field.

In advance of the completion of this facility Mr. Lorne Gold, the Head of the Snow and Ice Research Section, has been carrying out theoretical studies and has been using also the results of the Snow Survey of Canada for investigational work. The Snow Survey was initiated and is carried out through the Associate Committee on Soil and Snow Mechanics.

This paper ("The Strength of Snow in Compression under Dynamic Loads") presents the results of some of these preliminary studies and is a companion paper to that in D.B.R. Report No. 54 ("The Dependence of Snow Hardness on Specific Gravity"). These two papers are circulated in this preliminary form for criticism and comment. It is hoped that they may be published when suitably amended in the light of comments received.

Ottawa
December 1954

Robert F. Legget,
Director

THE STRENGTH OF SNOW IN COMPRESSION UNDER DYNAMIC LOADS

by Lorne W. Gold

The problems in Canada involving the strength of undisturbed snow, particularly in relation to transport, are mainly of a dynamic nature. That is, before the application of a load, the snow is relatively unstressed; when the load is applied, the forces involved are sufficient to cause the structure of the snow to collapse. An engineer working in this field is faced with a situation involving force of the order of 10 p.s.i., time of the order of one-fifth of a second and compression of the snow of the order of 6 inches. This problem is quite different from that involving the strength of snow under what could be called quasi-static conditions. Under quasi-static conditions, the snow cover is modified slowly by the action of gravity and other forces tending to bring about a state of thermodynamical equilibrium. If the snow lies on a slope, the structure of the snow might reach a critical state where the snow cover may be catastrophically released as an avalanche with the possible results of loss of life and damage.

In the dynamic problem, the engineer is interested in the relationships between equipment and the energy absorbing and load bearing capacity of the snow during the period of very rapid collapse; in the quasi-static problem, the engineer is interested in the modifications which occur within the snow cover that lead to critical values in the strength properties of the snow. Essentially the difference is one of emphasis on the particular aspects of metamorphism and strength studies of interest to the observer.

Extensive studies have been carried out and are still continuing on snow under quasi-static conditions. Few studies have been made on the behaviour of snow under dynamic loads. Problems involving the dynamic loading of snow have usually been approached empirically with little or no thought being given to the mechanical properties of snow and its behaviour when subject to such loads. This has led in many cases to needless or misguided effort with the resulting waste of money. Furthermore, because the mechanical properties of snow are not fully known or understood, a confidence is often placed in its mechanical behaviour which is not warranted.

There are many factors which affect the mechanical properties of snow. These factors, some of which cannot be readily assessed, interact to create conditions which in the final analysis are complicated in the extreme. The result is that, under practical conditions, the determination of the strength properties of snow cannot be an exact science. This is very evident in the analysis to be presented where a property, with the normally measured variables held constant, could vary by a factor of one hundred. Snow may be an ideal material for winter sport but it is not an ideal material from most engineering points of view.

There is a reason for the extreme variations in the strength properties of snow. Snow is made up of small ice crystals. Under natural conditions this ice is very near its melting point. This condition of the solid is very difficult to describe mechanically because of plastic effects and variations in strength properties with temperature in the vicinity of 0°C. Furthermore, the total ice surface area in the snow is very large and irregular with the result that, in a normal environment, the structure is thermodynamically unstable. Because of this, the structure and thus the strength properties are continually modified.

In order to gain an insight into the mechanical behaviour of snow under dynamic loading it was decided to construct an apparatus which would deform snow at a rate comparable to that caused by a ski or a tracked vehicle. With this apparatus and subsequent analysis it was hoped to:

1) study how the snow deforms under a dynamic load,
2) determine the primary variables involved in relation to the strength of the snow,
3) determine how the strength of the snow depends on these variables,
4) determine if these variables could be evaluated in a practical way,
5) determine if some practical working theory for the strength of snow could be developed,
6) evaluate the working theory in the light of the variability of the strength properties of the snow.

In order to obtain a clearer idea of how the proposed apparatus should act on the snow, what snow conditions it should be capable of dealing with and to obtain actual figures on which to base a design, a simple apparatus was constructed for preliminary investigations. The observations made with this apparatus proved very interesting and stimulated analysis of data collected by the Canadian Snow Survey which previously appeared to bear little relation to the dynamic strength of snow. The first part of this report deals with the observations made with the simple apparatus and the second part with the analysis precipitated by these observations.

Snow loading apparatus

Figure 1(a) and (b) is a sketch of the simplified apparatus used for preliminary observations on the collapse of snow under compressive loading. Figure 1(a) is in a plane perpendicular to the snow surface; Fig. 1(b) is in a plane parallel to the snow surface. By lever-action, a force is transmitted by a cable, through a compression spring to the push rod and loading plate acting against a vertical snow face. A tracing arm, Fig. 1(b), pivoted on a support rigidly attached to the spring container, is linked to the cable. This tracing arm records the forward movement of the push rod and the compression of the spring under load on a waxed paper. The maximum obtainable penetration with this instrument is about 8 inches. By using different springs, total load ranges of 0-50 lb., 0-100 lb. and 0-200 lb. were obtained. The loading plate, always circular in the observations carried out, was detachable so that the total load bearing area could be readily changed.

Figure 2 is a typical load - vs - penetration curve obtained with this apparatus. The scale is distorted because the tracing arm moves on the arc of a circle.

Observations

The apparatus was not completed until well on in the winter of 1953-54. Therefore, the number of observations and the types of snow in which the observations could be made were limited. Because snow conditions in the general Ottawa area are poor for this work, particularly in the late winter, the observations had to be carried out in drifts in order to obtain a sufficient depth of snow. For each test, the flat circular loading plate was placed against the vertical face of an exposed snow layer. Layers were chosen which appeared to be homogeneous and continuous though this is questionable, particularly in drifts, and certainly not always true for the tests carried out. The plate was then caused to penetrate horizontally into this layer at a rate in the order of 1 ft/sec.

Though the conditions for the tests were not ideal, the 75 observations made all produced curves similar to that of Fig. 2. At first the load increases with relatively little penetration. What penetration was observed was felt to be primarily due to unevenness of the surface and to the fact that the plate may not have been lying flat on the surface. At some well defined load, the snow structure begins to collapse and penetration begins. Thereafter, the load slowly increases with penetration.

For each snow type on which tests were run, the following properties were measured:

1) Temperature

The temperature was always in the range above -10°C. and therefore was not a significant variable in these tests.

2) Hardness

This was measured with the National Research Council gauge as described by Klein, Pearce and Gold (1).

3) Crystal size and type

This was measured and recorded, according to the procedure described in (1).

The following observations are given to show in a qualitative way the behaviour of snow under dynamic compressive loads. Each of the curves obtained in the tests were redrawn on normal rectangular co-ordinate paper with stress as ordinate and penetration as abscissa.

$$\text{Stress} \quad S = \frac{\text{Total Load}}{\text{Area of plate}} = \frac{Q}{A}.$$

It was found that the stress at which the snow began to collapse and the relative increase in stress, as measured at the bearing plate, with penetration was significantly related to the specific gravity of the snow. No dependence of these values on the area of the bearing plates could be detected. The bearing plates used had areas of 17.5 cm^2, 50 cm^2, 100 cm^2, 225 cm^2 and 300 cm^2. Figure 3 shows example stress vs. penetration curves for snow about 1 week old and in Fig. 4 are shown curves obtained in settling snow of medium specific gravity. In Fig. 5 is shown the curve obtained when the load was removed for one minute after penetration had begun, and then increased until the penetration was complete. The increased load required to cause penetration to begin again is appreciable. This demonstrates the very rapid rate at which the snow can regain its strength once it has been disturbed.

From Figs. 3 and 4 it is seen that it is possible to make an estimate of the stress at which the snow structure begins to collapse. Though the values of this stress varied from one test to another in the same snow layer, they were all of the same order of magnitude. Much of the variation is likely due to the non-uniform nature of the snow in drifts. For instance, it was found that the density of the snow was not constant in any one layer particularly in a direction normal to the main axis of the drift.

It was found that the estimated stress at the beginning of collapse, which will be called the ultimate compressive strength, kp, obtained from these observations was of the same order as the hardness number as measured by the hardness gauge. This is not unreasonable for the number recorded when using this gauge is the stress which exists across the plate of the hardness gauge when the snow makes its initial collapse. In Fig. 6 the estimated ultimate compressive strength is plotted against the measured hardness of the layer in which the test was run. The line kp = hardness has been drawn through the plotted points. There is a great deal of scatter of the points about this line but this may be due to the fact that the snow in which the observations were made did not have a truly uniform homogeneous structure. In many cases, the hardness readings were not made in the same immediate area in which the test was run. From Fig. 6 it was concluded that the hardness number was a good measure of kp. In the remainder of this paper, the hardness number will be assumed equivalent to kp.

In Fig. 7 the stress across the bearing plate is divided by kp and plotted against penetration. It will be seen that this relative increase in bearing load with penetration is practically a straight line relation for the conditions of test used. Though there is a considerable scatter in the slopes of the lines at any particular specific gravity, the slopes do tend to increase with increasing specific gravity.

For one series of observations, the snow in front of the penetrating plate was cut in sections at various stages of penetration in order to obtain an idea of what was happening. Figure 8, (a), (b), (c), (d), show sketches of these sections. The sections are normal to the plate and to the snow surface. The formation of a "bulb" of dense snow in front of the plate was readily observed and followed. The line of demarcation between the "bulb" and surrounding snow was clearly marked. A formed "bulb" could easily be broken away intact from the surrounding snow.

Some measurements were made on the specific gravity of the snow in the "bulb" directly in front of the plate. This specific gravity is plotted as a function of the original specific gravity of the snow in Fig. 9.

It must be remembered that the foregoing observations are of a qualitative nature only. These qualitative results do indicate some general relationships which exist for the strength of snow in compression. One of the most important of these relationships is that indicating that the number found with the National Research Council hardness guage is a good indication of the ultimate compressive strength of snow. This immediately places a new importance on the results of snow surveys using such instruments as they will be a source of data from which relationships between specific gravity, temperature, crystal size, crystal type and ultimate compressive strength of snow may be obtained. The remainder of this paper will deal with these relationships as observed from the results of the Canadian Snow Survey.

Canadian Snow Survey

In 1947 the Associate Committee on Soil and Snow Mechanics of the National Research Council initiated the snow survey of Canada. Since 1947, there have been at least ten observation stations located in various areas of Canada where pertinent information on snow cover has been collected. About twice a month a profile study of the snow cover is made at each station. During this study, a record is made of the various layers which make up the snow cover, their thickness and location with respect to the ground, their hardness, density, temperature and grain size and grain shape of the snow contained. This information was utilized in the following study.

Analysis of Data

For the first phase of the study, hardness was plotted against specific gravity (ρs) using the observations made at Aklavik, N.W.T.; Gander, Newfoundland; Ottawa, Ontario; Resolute, N.W.T. The result is shown on rectangular co-ordinate paper in Fig. 10. The area of each spot is approximately equal to the number of observations made at that specific gravity and range of hardness. The hardness values were grouped in steps of 100.

Though there is a spread of at least a factor of 10 to 100 in the values of kp for any one specific gravity, the general relationship between hardness and specific gravity is striking. The fact that specific gravity is one of the primary variables on which the strength of snow depends has been demonstrated (2, 3). Figure 11, where the same information of Fig. 10 is plotted on log-log paper, emphasizes this fact. Again, the area of a spot is approximately proportional to the number of readings taken at the value of ρs and range of hardness.

The scale of the National Research Council hardness gauge has 11 divisions numbered 0 to 10. The number indicated by the gauge when the snow first fails is multiplied by a scale factor of 1, 10, 100 or 1000, depending on the size of plate used, to give the hardness of the snow in gm/cm^2. This fact was utilized in the grouping of data for Fig. 11 and all subsequent presentations. For example, all points lying in the range $45\frac{1}{2}$ to $54\frac{1}{2}$ were grouped and given the hardness value of 50, all points in the range of $645\frac{1}{2}$ to $744\frac{1}{2}$ were given the hardness value of 700 etc. Those points at 45, 55, 650, 750 etc. were divided evenly between the two adjacent hardness groups.

By finding the mean density corresponding to each hardness range, a series of points were obtained through which the line "A" was drawn. It was assumed that this line very nearly gives the average dependence of hardness on specific gravity. From "A" it was found that the dependence of hardness on specific gravity is given roughly by:

$$\text{hardness} = 10^{6.7} \rho s^{7.7}.$$

This demonstrates the extreme dependence of the strength properties of snow on specific gravity.

To determine reasons for the spread in hardness values for any one ρs, these readings were plotted against other parameters measured in the snow survey. Figure 12 is a plot of hardness against temperature. In this display, the number of observations made within the range of hardness and temperature is given. The data have been further grouped by taking temperature steps of 3°C.

It was assumed that a relationship exists between hardness and temperature given by

$$\log\ (\text{hardness}) = a + bT \qquad (1)$$

where a and b are constants and T is the temperature. Since all specific gravities are represented in Fig. 12, "a" may not be a significant number when calculated from these data i.e. "a" may be a function of the specific gravity. To determine any dependence of hardness on temperature it is sufficient to determine b. It was assumed that b was independent of specific gravity. A rough check using points in the restricted specific gravity tange of 0.18 to 0.22 and 0.28 to 0.32 showed that this was a reasonable assumption.

A value for b was determined from the data of Fig. 12 using the method of least squares. It was found that

$$b = -0.0274$$

A correlation coefficient for the data was calculated and found to be 0.44. No attempt was made to reduce the spread in data due to variations in specific gravity when calculating this coefficient.

If we use the determined value for b in equation (1) then

$$\log \text{hardness} = a - 0.0274T$$

If snow at temperature T_1 and hardness H_1 is changed to temperature T_2, the resulting hardness $H_2$is given by

$$\log \frac{H_2}{H_1} = -0.0274\ (T_2 - T_1)$$

$$\frac{H_2}{H_1} = 10^{-0.0274\ (T_2 - T_1)}$$

and in terms of natural logarithms

$$H_2 = H_1\, e^{-0.0631\ (T_2 - T_1)} \qquad (2)$$

In Fig. 13, $e^{-0.0631\ (T_2 - T_1)}$ is plotted as a function of $T_2 - T_1$. It is seen that the hardness increases by a factor of approximately 1.88 for each 10°C. drop in temperature. It is unreasonable to think that this could go on indefinitely and therefore the above results must be applicable in a restricted temperature range i.e. 0 to -40°C.

This increase in strength with decrease in temperature is not due alone to the significant increase in the strength of ice with decrease in temperature near 0°C. (4). The snow tested in each case has had some chance to arrive at a state of thermodynamical equilibrium. As the temperature decreases, water vapour present in the voids of the snow will freeze out thus tending to increase the bonding between snow particles and therefore the strength of the snow. The increase in strength of the snow due to freezing out of vapour would be most significant in the temperature range 0 to -40°C. since it is over this range that the variation with temperature of the amount of vapour in equilibrium with an ice surface is appreciable.

When the temperature varies from 0°C. to -40°C., the hardness can change by a factor of 12.5. Referring to Fig. 11, we see that this variation is still not sufficient to account for the spread in hardness values i.e. hardness varies from 10 $\frac{gm}{cm^2}$ to 4000 $\frac{gm}{cm^2}$ at $\rho s = 0.25$. In Fig. 14 the number of observations for each of the hardness groups is plotted against the average crystal size. It is seen that there is no obvious increase or decrease in hardness as the crystal size varied. What is significant in Fig. 14 is the very large spread in hardness values at any one crystal size. In Table I, the number of readings lying in the hardness ranges of 10 - 100, 100 - 1,000, 1,000 - 10,000 $\frac{gm}{cm^2}$ for each crystal size is given as a percentage of the total number of readings taken for that crystal size. It is seen that only for the small average crystal sizes that an appreciable percentage of the readings have an ultimate strength in the range 1,000 - 10,000 gm/cm^2. Table I indicates that as the snow becomes more thermodynamically stable (larger average crystal sizes) the spread in hardness readings decreases the majority lying in the range 100 - 1,000 $\frac{gm}{cm^2}$.

TABLE I

Crystal Size	Per cent of readings in range 0-100,	100-1,000,	1,000-10,000	Total no. readings
0.5	11.4	39.5	49.1	220
1.0	23.9	50.0	26.1	272
1.5	19.9	61.2	18.9	111
2.0	28.9	65.5	5.6	90
2.5	36.1	55.6	8.3	36
3.0	35	62.5	2.5	40
3.5	38.8	55.6	5.6	18
4.0	14.0	81.4	4.6	43
4.5	14.2	85.8		7
5.0	10.8	86.5	2.7	37
5.5		50	50	2
6.0	5.9	94.1		17
7.0		100		2

In the Canadian Snow Survey, snow is classified into various types, namely:

1) new snow, type a;
2) snow in which the crystal structure can still be discerned, type b;
3) snow particles modified by melting, type c;
4) snow particles modified by sublimation, type d.

In Fig. 15, 16 and 17, these crystal types are plotted on a hardness vs.-specific gravity display. The observations in Fig. 15 were taken in tree-covered, sheltered areas; those of Figs. 16 and 17 at Goose Bay, Labrador. From these figures it is seen that if any difference exists between the hardness properties of snow of type c and snow of type d crystals, it is not sufficient to be of practical value to the engineer concerned with the strength properties of snow. These figures do show, particularly Fig. 17, that new snow generally has low hardness.

The foregoing analysis has shown the extreme variability that exists in the strength properties of snow. The dependence of the strength of snow on the normally measured snow properties does not account for this variability. One factor which can be discussed has not as yet been considered. In analysing the hardness of snow, no distinction was drawn between observations made in different areas of Canada except in the section dealing with snow type. The difference between snow in separated areas is due to variations in climate from region to region. Even within a region the climate can undergo extreme changes during the course of one winter. On top of the changes which occur in just one winter, there is the variation which occurs from winter to winter. Each climate fluctuation leaves its imprint on the snow cover.

As examples of the effect of meteorological conditions it was found that for Resolute, N.W.T., which has a very stable though cold climate throughout the winter, the hardness observations, plotted on the hardness-vs.-specific gravity display, lie in a much narrower band than say for Goose Bay, Labrador (Fig. 17) which has a climate subject to more extreme fluctuations. When considering observations from Fig. 11 which lie in the specific gravity range 0.28 - 0.32, it was found that the majority of readings of high hardness were taken at Resolute in drifted snow; the majority of low hardness readings were taken at Aklavik in old snow subjected to temperatures below -10°C. for a long period of time. It was interesting to note that for one series of observations when the layer temperature was below -10°C. for a long period of time, the hardness tended to decrease, yet for another series of observations for which the layer temperature was above -10°C. for a long period of time, the hardness tended to increase.

This very brief discussion on the effect of climate on hardness was introduced to show that the strength properties of snow are sensitive to the overall meteorological picture. Moreover, it has shown that the hardness of snow is dependent on a property which is not directly determined in the snow survey. This property is the bonding between crystals which is discussed in some detail in (2) and (5). The effect of bonding is clearly demonstrated by the difference in strength between wind blown snow and old snow approaching thermodynamic stability at low temperatures. Figure 14 and Table I also demonstrate the effect of bonding since they show that snow is more likely to have a hardness below 1000 gm/cm^2 when the average crystal size is greater than 2mm. As the snow ages, the surface irregularities which aid bonding disappear; the crystals become larger, more uniform in shape and tend to have fewer and weaker inter-connecting bonds.

The foregoing analysis has shown that the hardness of snow is primarily dependent on specific gravity, snow temperature and degree of bonding between particles. The dependence of hardness on crystal size and crystal type is not sufficient to be significant under practical conditions though a knowledge of these variables is necessary in order to obtain a complete understanding of the changes which can occur within the snow cover to yield the observed strength properties.

As has been stated, the above variables are continually changing with time; the degree and direction of change depending on the thermodynamic stresses acting. Interactions between these variables result in strength properties, the changes in which are very difficult to describe analytically even in isolated cases. The properties of the snow within a specified area of a layer in the snow cover can be determined at any one time, but these readings taken alone are not of much value to the man who must design equipment that will act on the whole snow cover and operate in many regions. It would thus appear that, because of the number of factors involved, individual measurements and exact relationships between variables begin to lose meaning as far as the design of apparatus to be utilized in snow is concerned. A more loose approach should be considered in which the average characteristics of the whole snow cover are derived statistically and the behaviour of the snow under dynamic load deduced from these average characteristics. Design of apparatus would then be based on these average characteristics keeping in mind the variations and interdependence of the individual readings.

This principle of approach is based not only on the observations given but also on the fact that the collapse of the snow during the application of a dynamic load cannot be conveniently described by the theory of elasticity or plasticity. By utilizing the average characteristics of a snow cover and estimating the dependence of these characteristics on the dynamic load it would be possible to deduce the characteristics of the snow just after collapse and the energy involved in the collapse process. It is this end point and associated energy related to the kinematics of the problem which is of primary interest in the dynamic situation.

Figures 18 and 19 have been given to show how certain general characteristics can be obtained for a snow cover. In Fig. 18 an attempt has been made to find, on the average, the relative depth of snow in a snow cover with hardness less than a given value. The layer depths for the observations of Fig. 11 were totalled as were the layer depths corresponding to each hardness range. The per cent of the total depth of the accumulated depths corresponding to the hardness values up to a given value were then calculated and plotted. The lines in Fig. 18 show the hardness ranges. Thus, if one wished to decide what per cent of a snow cover could be expected to have a hardness of 1000 gm/cm^2 or less, reference to Fig. 18 would give 70 per cent. If the particular application being designed was isolated to one area or type of area, a more correct dependence could be found from the relevant snow survey results or a correction factor for Fig. 18 estimated. One could then proceed on the basis that all snow of hardness less than 1000 gm/cm^2 would be affected by the particular application and all snow of hardness greater than 1000 gm/cm^2 would not be affected.

In Fig. 19, the average per cent of the snow depth with specific gravity less than a specified specific gravity has been plotted from the data used in Fig. 11 using the same procedure employed for Fig. 18. This type of general characteristics when averaged over a number of years in one region or regions could be of more value in design, when combined with an appreciation of the variability of the snow properties, than exact relationships set up between the snow properties.

Though Figs. 18 and 19 are derived from the same data, there is no direct relationship between them. They could not, therefore, be used together with Fig. 11 and a knowledge of the deformation for such problems as estimating the sinkage of a track or ski in a snow cover. Such problems could be approached if the average per cent of the snow depth corresponding to a limited range of hardness and specific gravity were known.

Conclusions

In the introduction certain ultimate goals for a proposed snow testing apparatus were laid down. Preliminary investigations and certain analysis of snow survey results have satisfied some of these goals.

It was found that the hardness of snow, which is assumed to be a direct indication of the strength of virgin snow in compression, is primarily dependent on specific gravity. At any one specific gravity, the hardness does depend significantly on temperature. Any dependence on crystal size or crystal type is insignificant for practical application except that new snow will probably have a low hardness. These variables are readily determined by methods now normally employed in snow mechanics. The hardness also depends significantly on the strength of the bonds between crystals. The degree of bonding is usually estimated from strength measurements, i.e. tensile strength tests. This fact makes it very difficult to estimate the ultimate compressive strength of a snow without resorting to direct measurement. All the foregoing variables are sensitive to the integrated meteorological conditions and therefore vary not only through the snow cover but also with time.

The general dependence of hardness on specific gravity and temperature was determined. The dependence of hardness on bond strength could only be briefly discussed qualitatively.

From these considerations it was concluded that it would be unrealistic to attempt to derive exact relationships between the strength of snow and the significant variables for the purpose of design. It was shown that certain average characteristics of the snow cover related to its strength could be obtained. A loose utilization of these characteristics along with an appreciation of the limits and variability of snow properties would likely be the best guide in design work. Essentially it amounts to estimating the stress strain relationships from pre-determined average snow strength and density distribution and their dependence on the dynamic load. An evaluation of this principle, which has been used consciously or otherwise by many engineers, is still to be carried out.

Acknowledgements

The author wishes to acknowledge the contribution of D.J. Alexander, who made most of the observations described in the first section, and the assistance of R. Armour in analysing the results of the snow survey.

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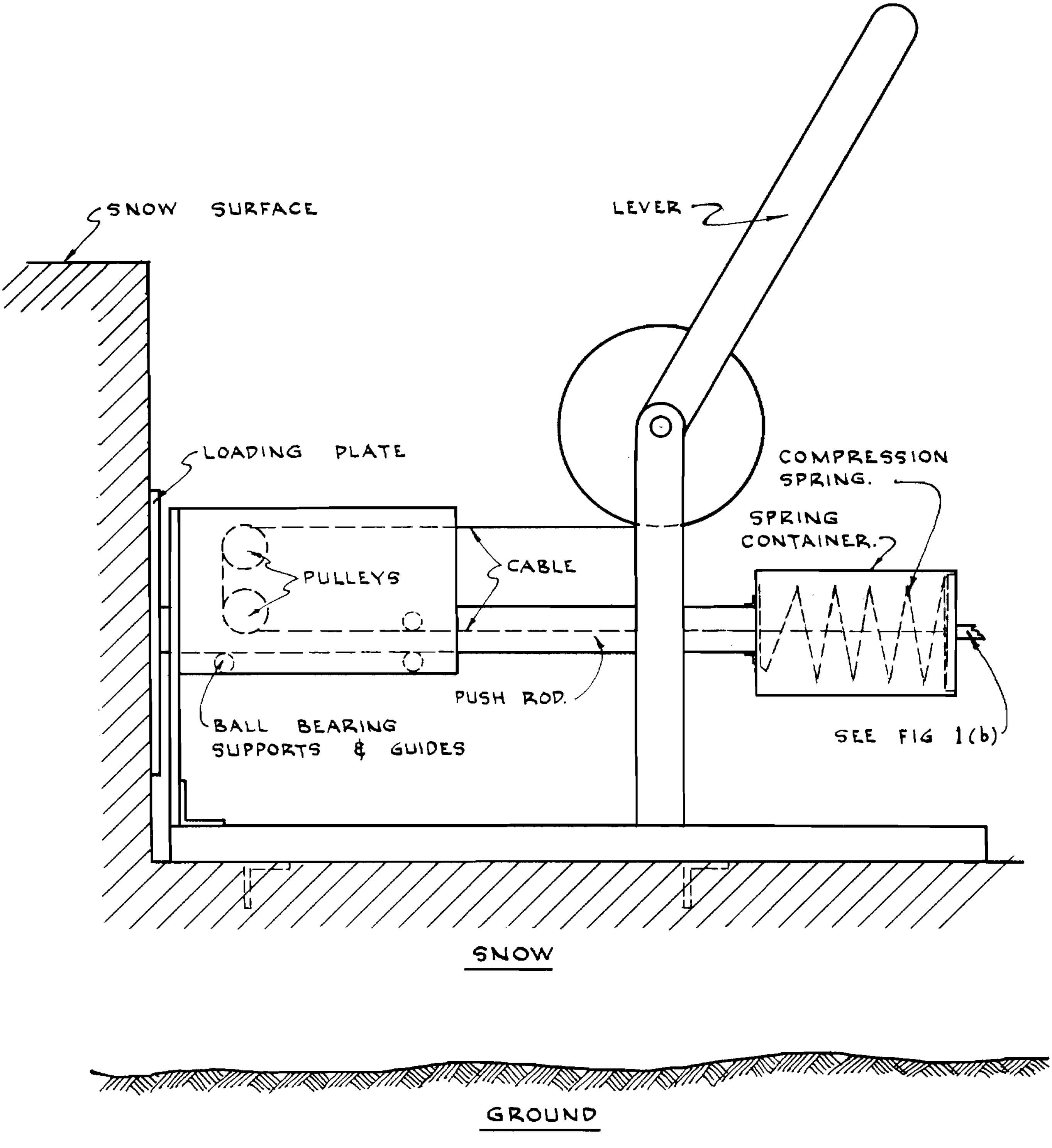

FIGURE 1(a). SIMPLE LOADING APPARATUS

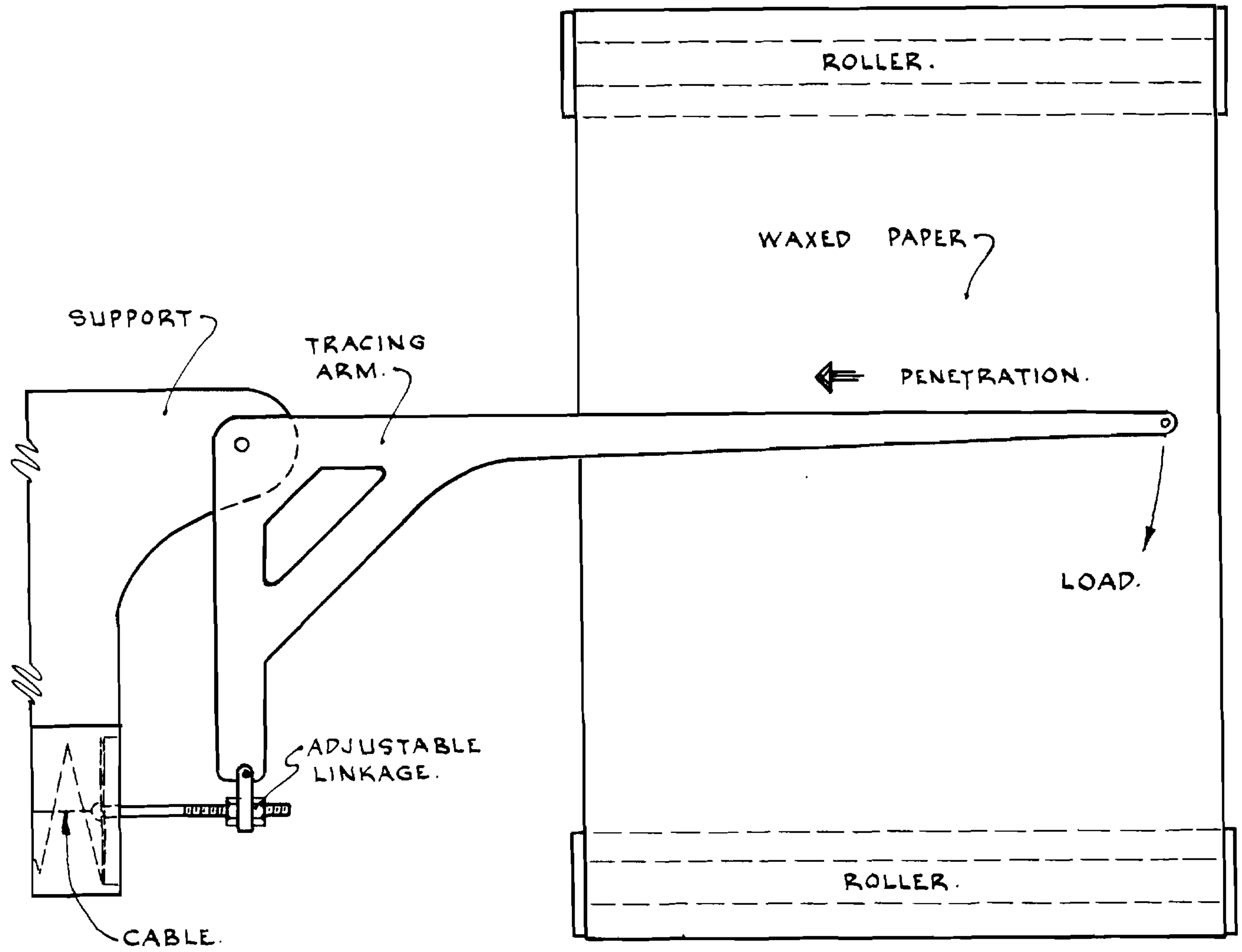

FIGURE 1(b). LOAD - PENETRATION RECORDING MECHANISM ON LOADING APPARATUS

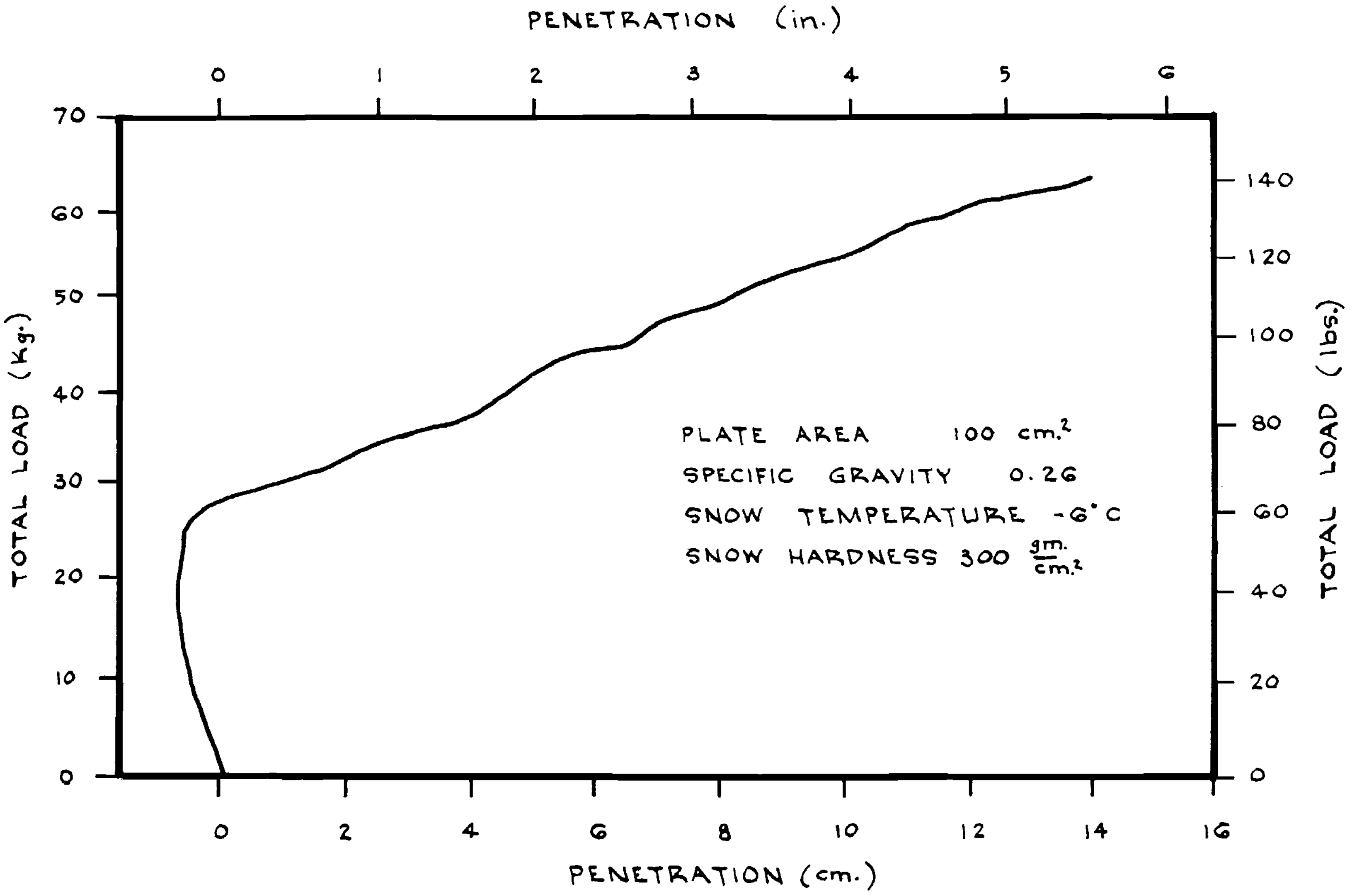

FIGURE 2. TYPICAL LOAD - PENETRATION CURVE OBTAINED WITH LOADING APPARATUS.

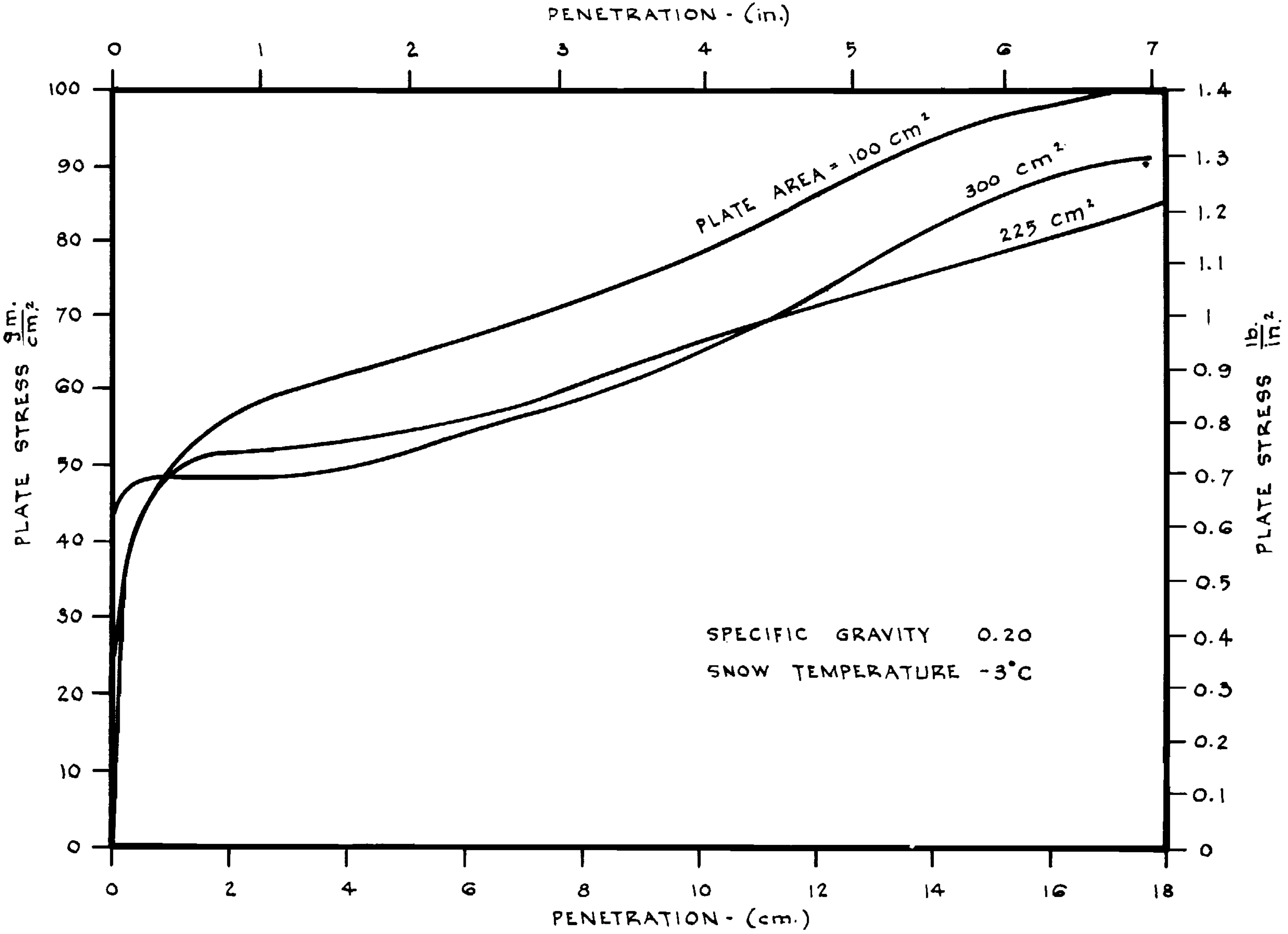

FIGURE 3. PLATE STRESS AS A FUNCTION OF PENETRATION FOR RELATIVELY NEW SNOW.

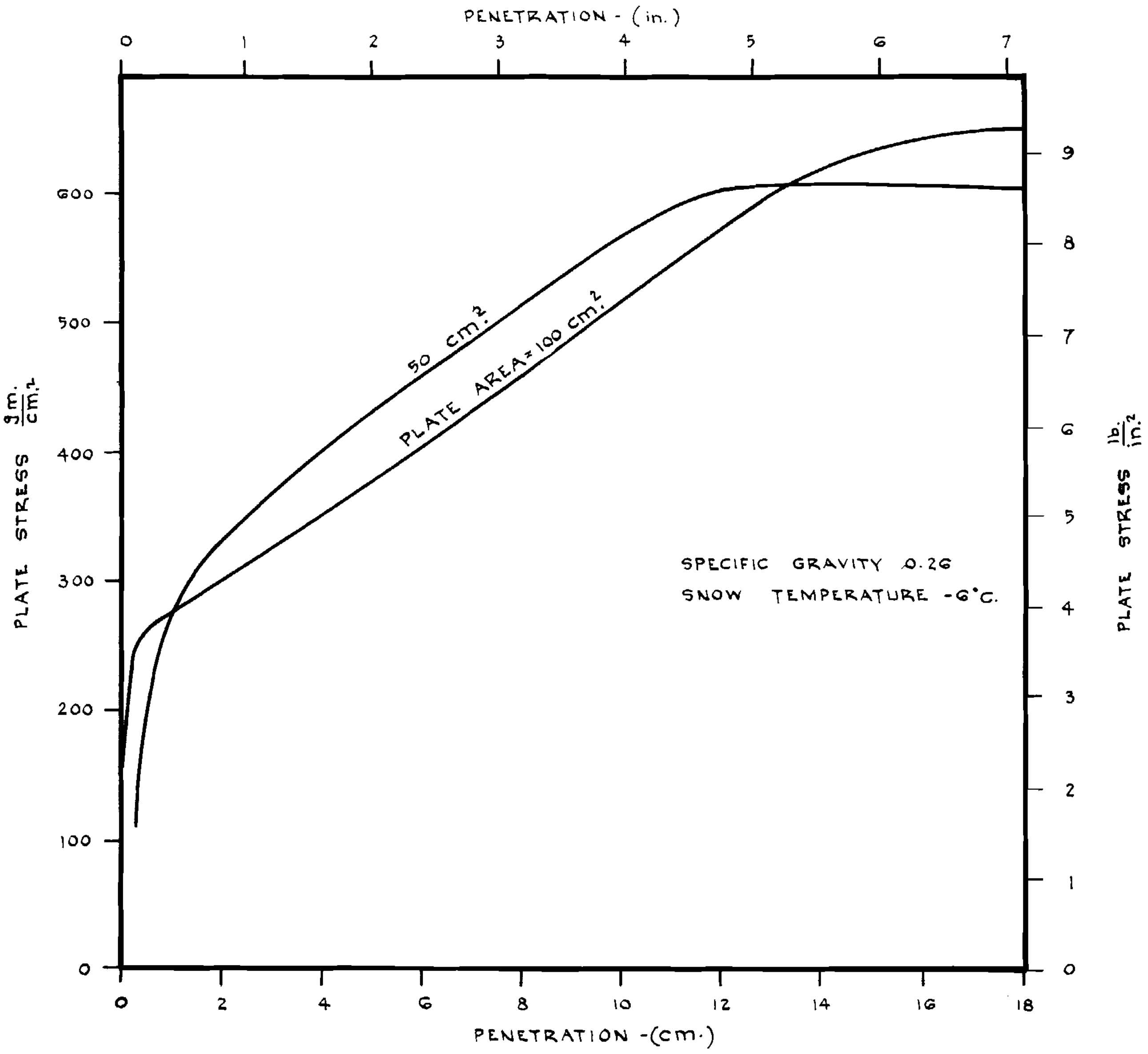

FIGURE 4. PLATE STRESS AS A FUNCTION OF PENETRATION FOR SETTLING SNOW.

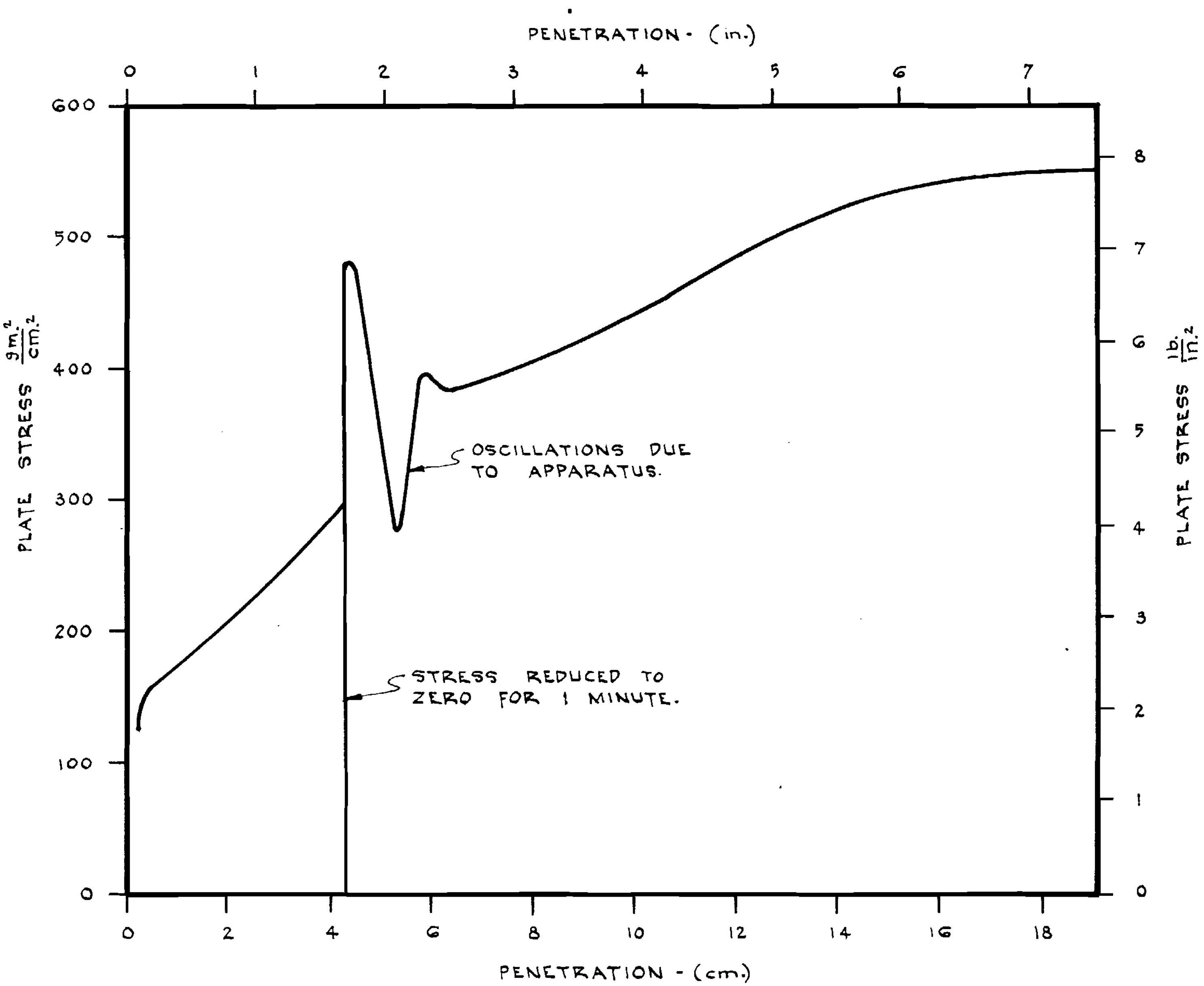

FIGURE 5. LOAD REMOVED FOR 1 MINUTE DURING PENETRATION AND THEN REAPPLIED.

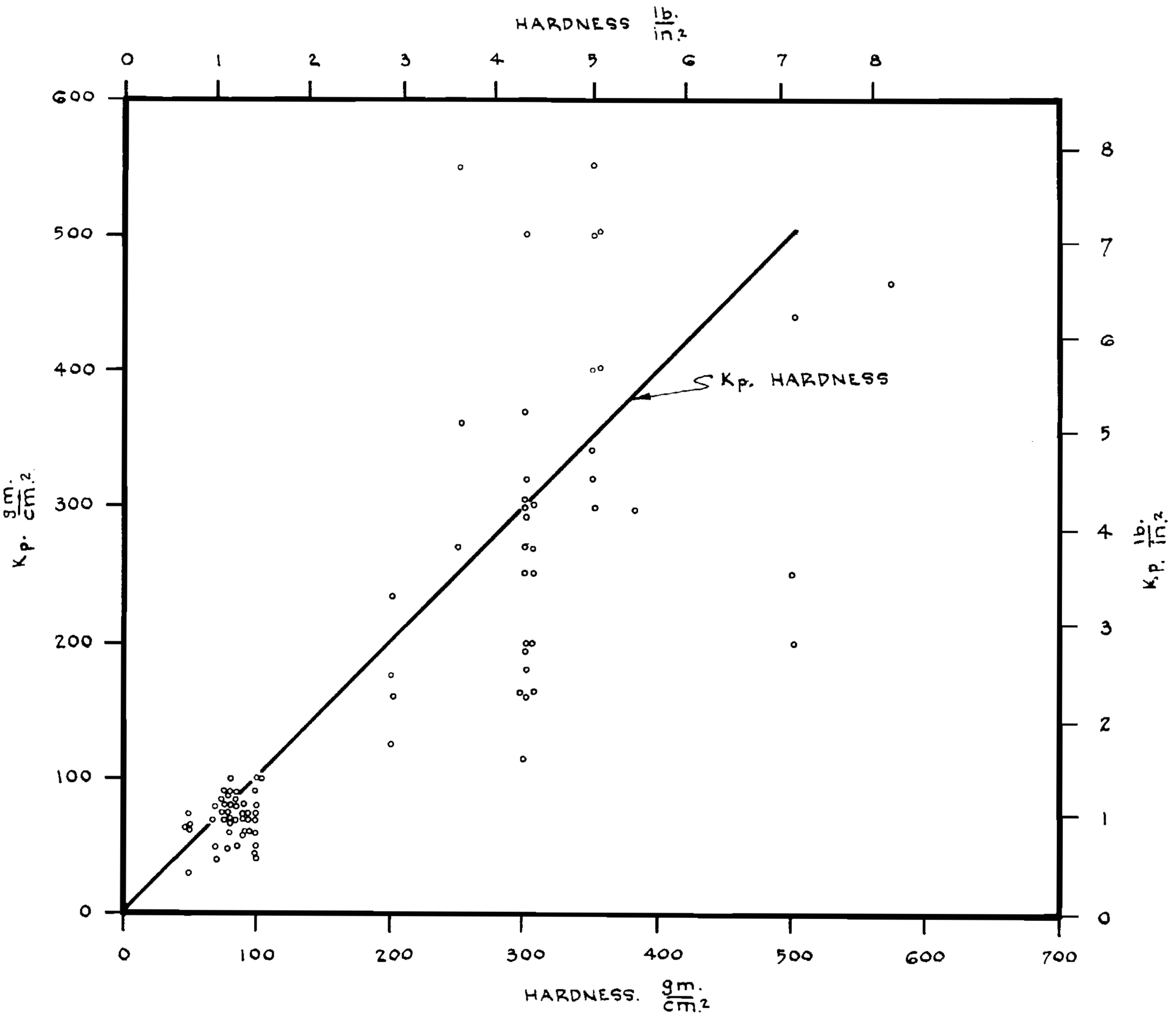

FIGURE 6. K_p AS A FUNCTION OF THE LAYER HARDNESS.

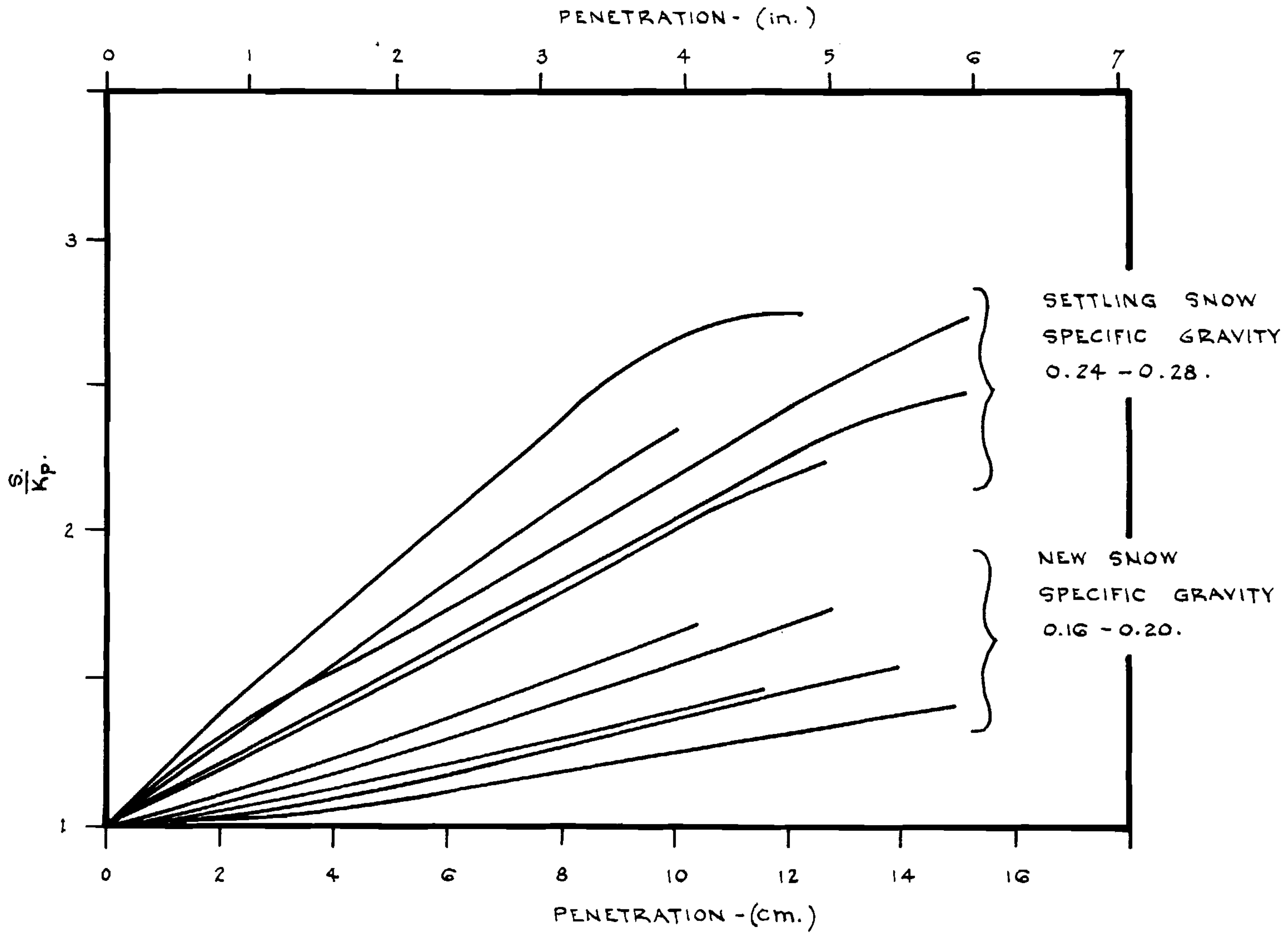

FIGURE 7. RATIO OF PLATE STRESS TO ESTIMATED ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF PLATE PENETRATION.

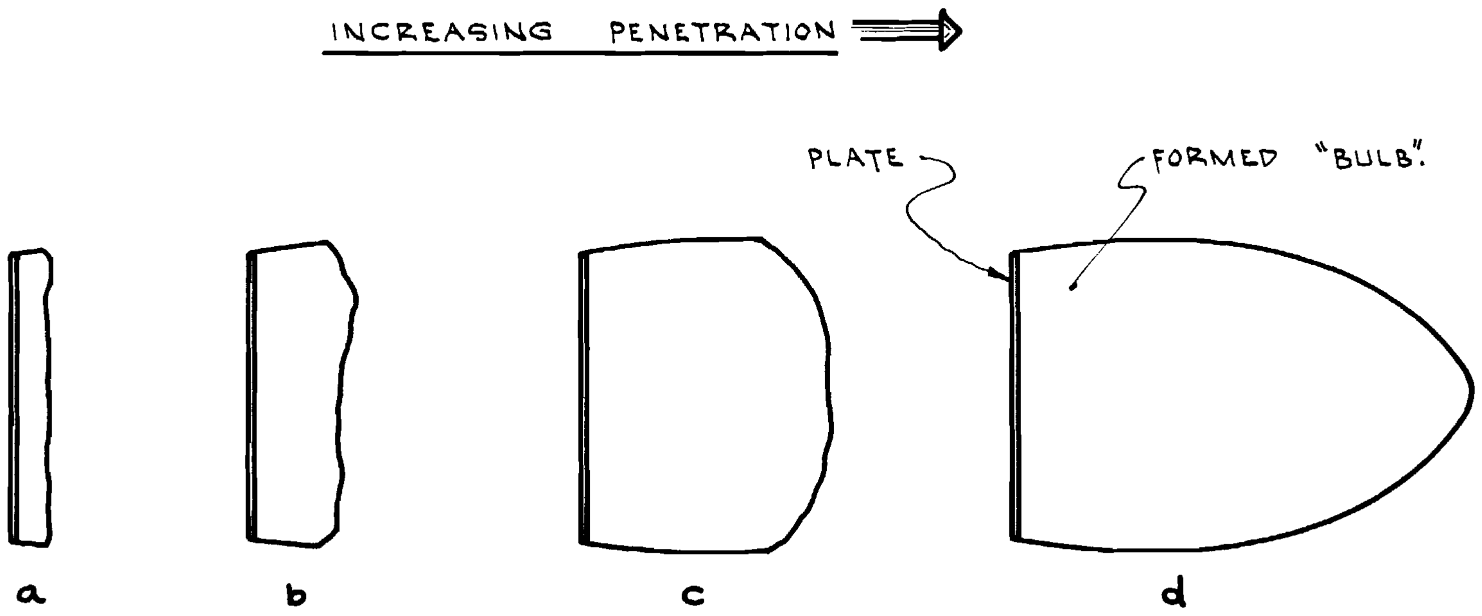

FIGURE 8. FORMATION OF "BULB" OF DENSE SNOW IN FRONT OF BEARING PLATE AS DEPTH OF PENETRATION IS INCREASED.

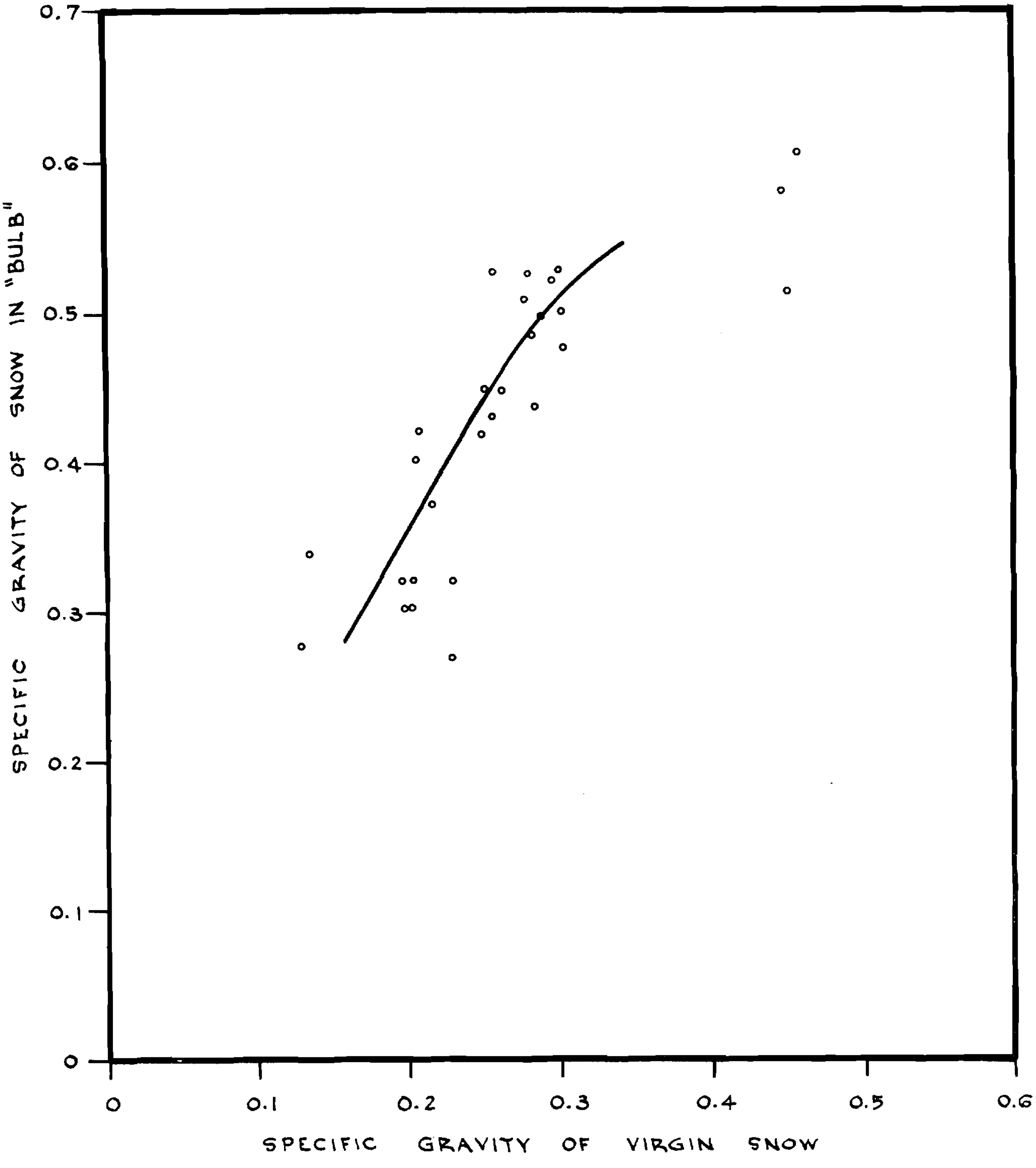

FIGURE 9. SPECIFIC GRAVITY OF SNOW IN "BULB" AS A FUNCTION OF SPECIFIC GRAVITY OF VIRGIN SNOW.

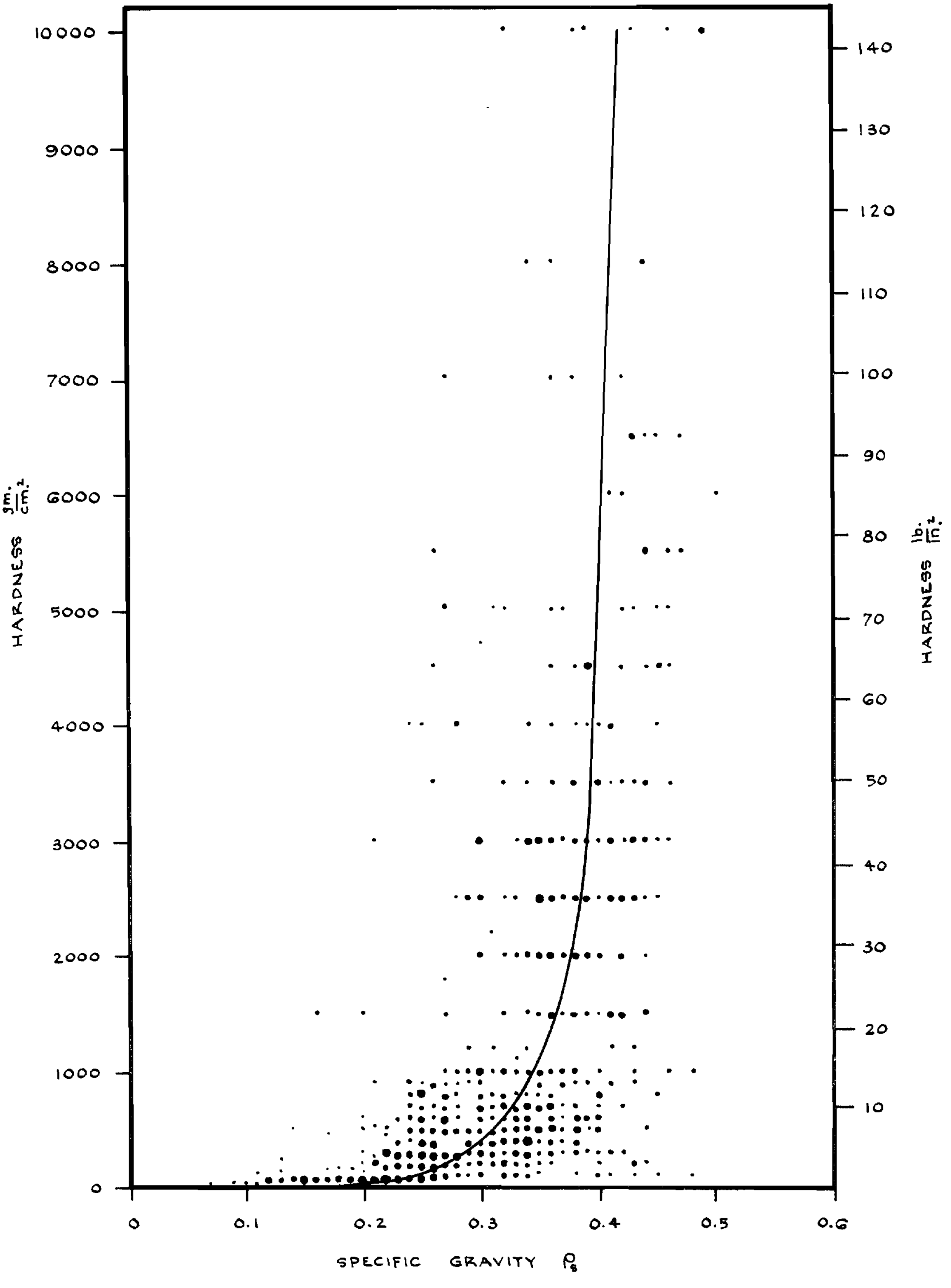

FIGURE 10. THE HARDNESS OF A SNOW LAYER PLOTTED AGAINST ITS SPECIFIC GRAVITY. THE AREA OF EACH SPOT IS APPROXIMATELY PROPORTIONAL TO THE NUMBER OF OBSERVATIONS MADE AT THAT POINT.

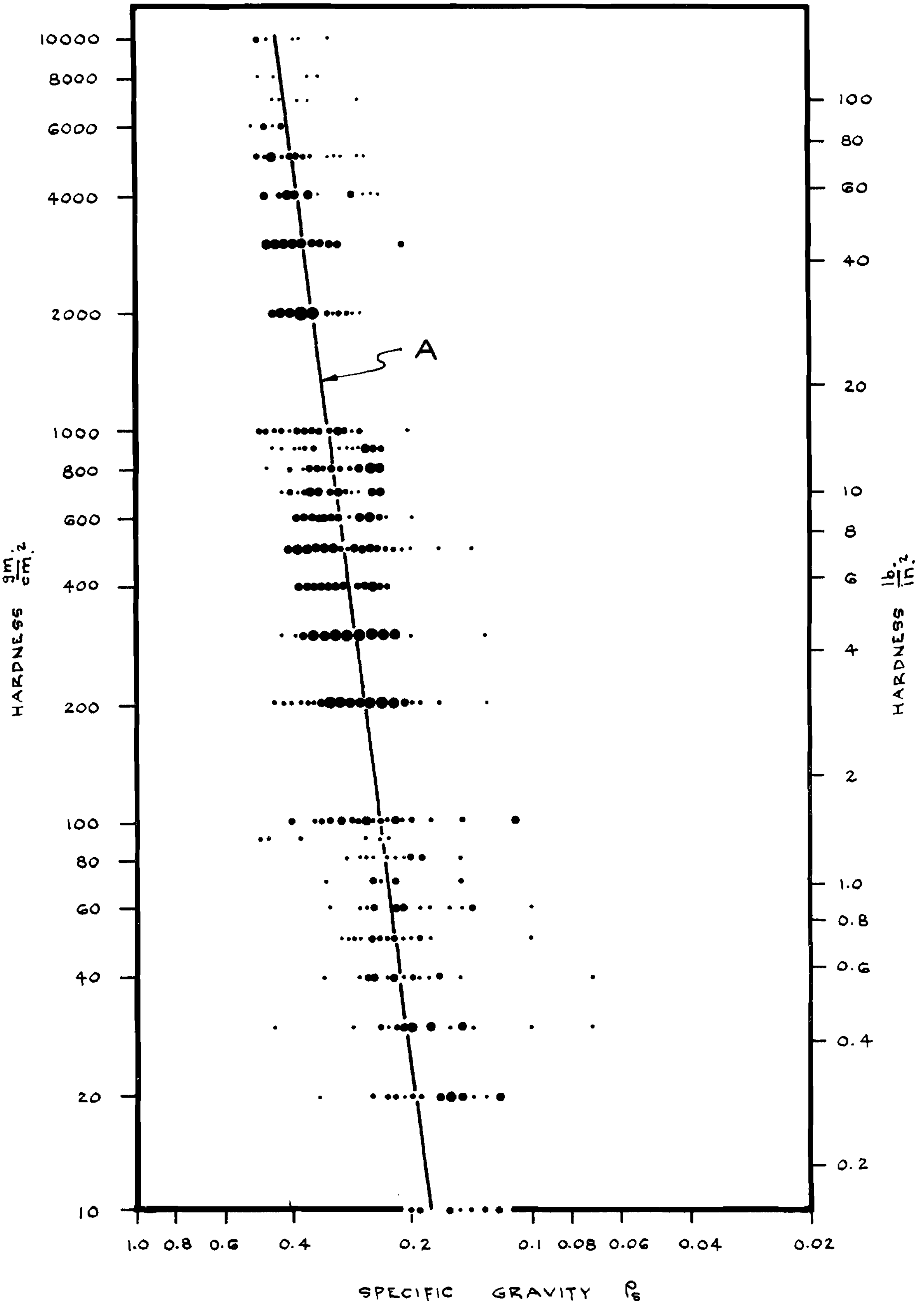

FIGURE 11. LOG HARDNESS PLOTTED AGAINST LOG SPECIFIC GRAVITY FOR RESOLUTE, AKLAVIK, OTTAWA AND GANDER.

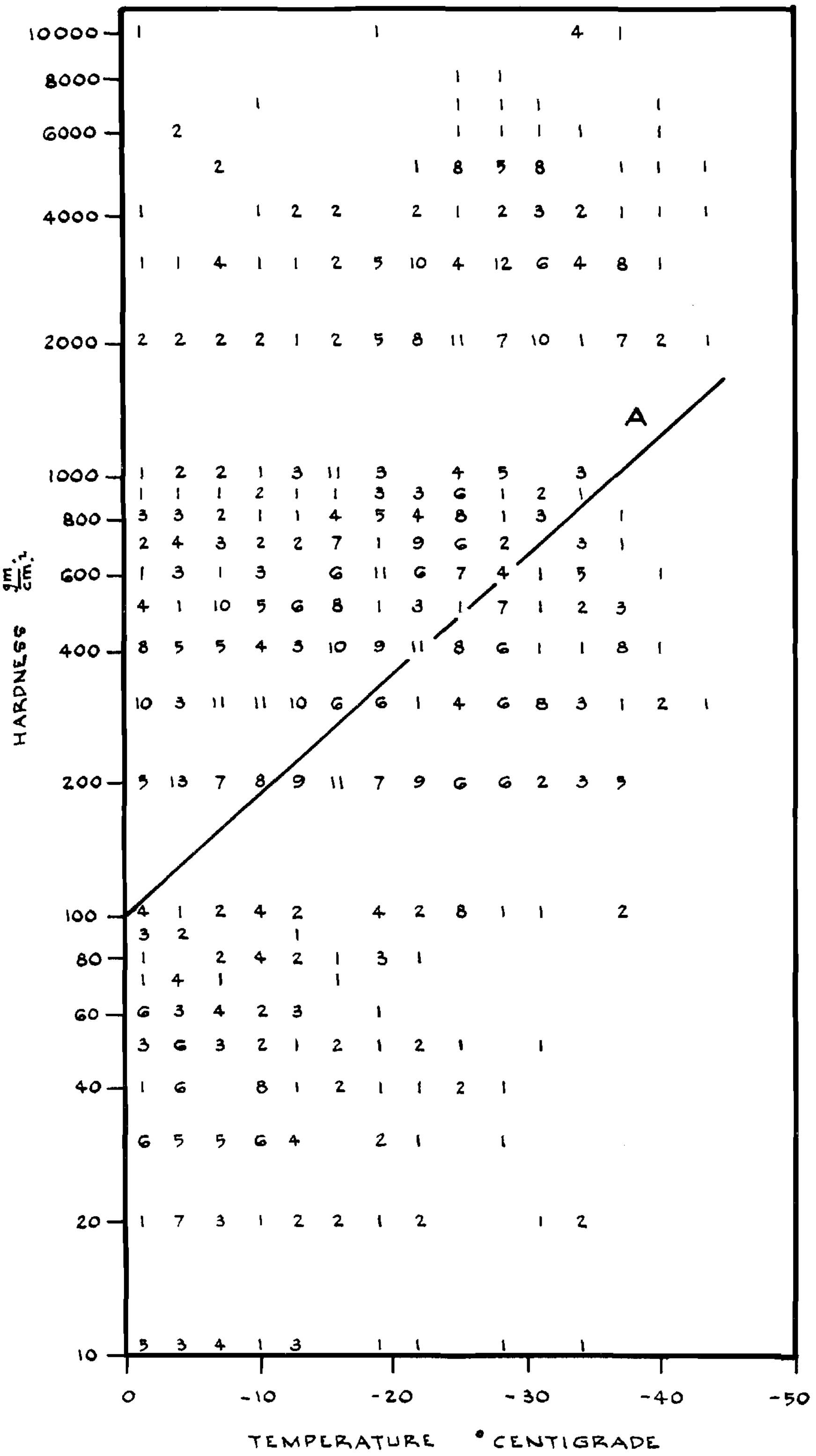

FIGURE 12. HARDNESS PLOTTED AGAINST SNOW TEMPERATURE. THE NUMBER OF OBSERVATIONS MADE IN THE SPECIFIED RANGE OF HARDNESS AND TEMPERATURE ARE GIVEN..THE LINE "A" HAS SLOPE DEFINED BY $H_2 = H_1 10^{b(T_2-T_1)}$, $b = -0.0274$.

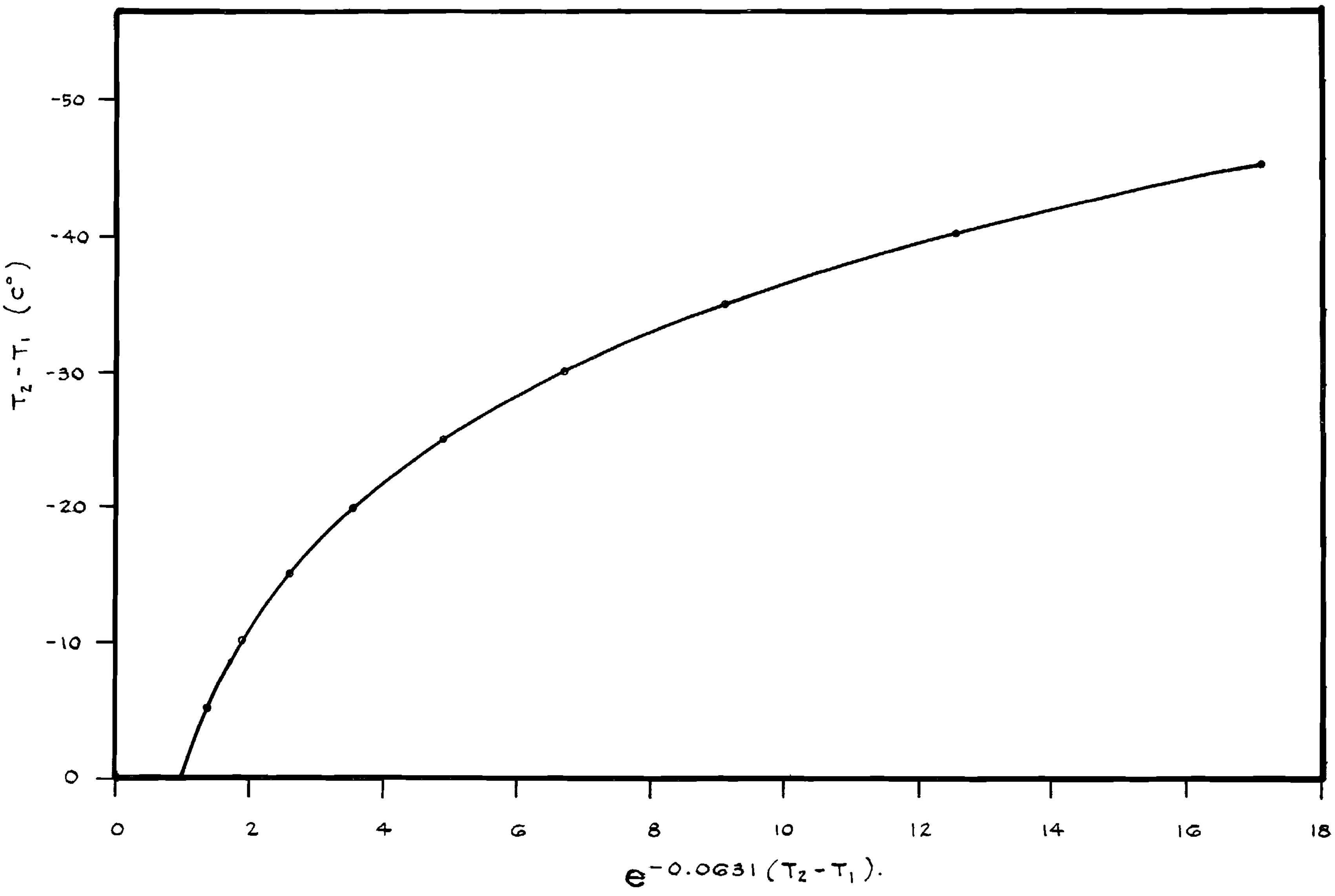

FIGURE 13. RELATIVE INCREASE IN HARDNESS WITH CHANGE IN TEMPERATURE.

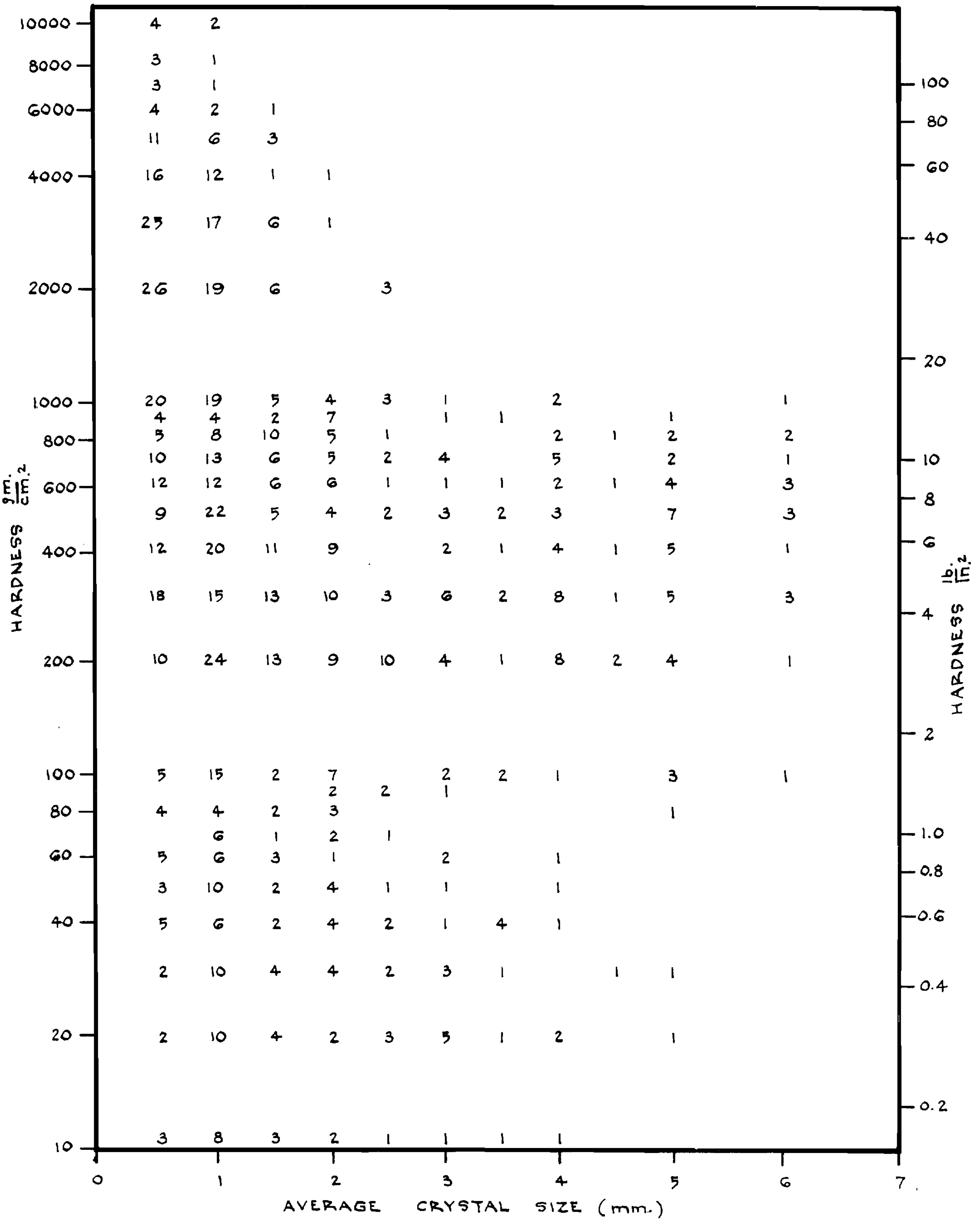

FIGURE 14.

HARDNESS PLOTTED AGAINST AVERAGE CRYSTAL SIZE

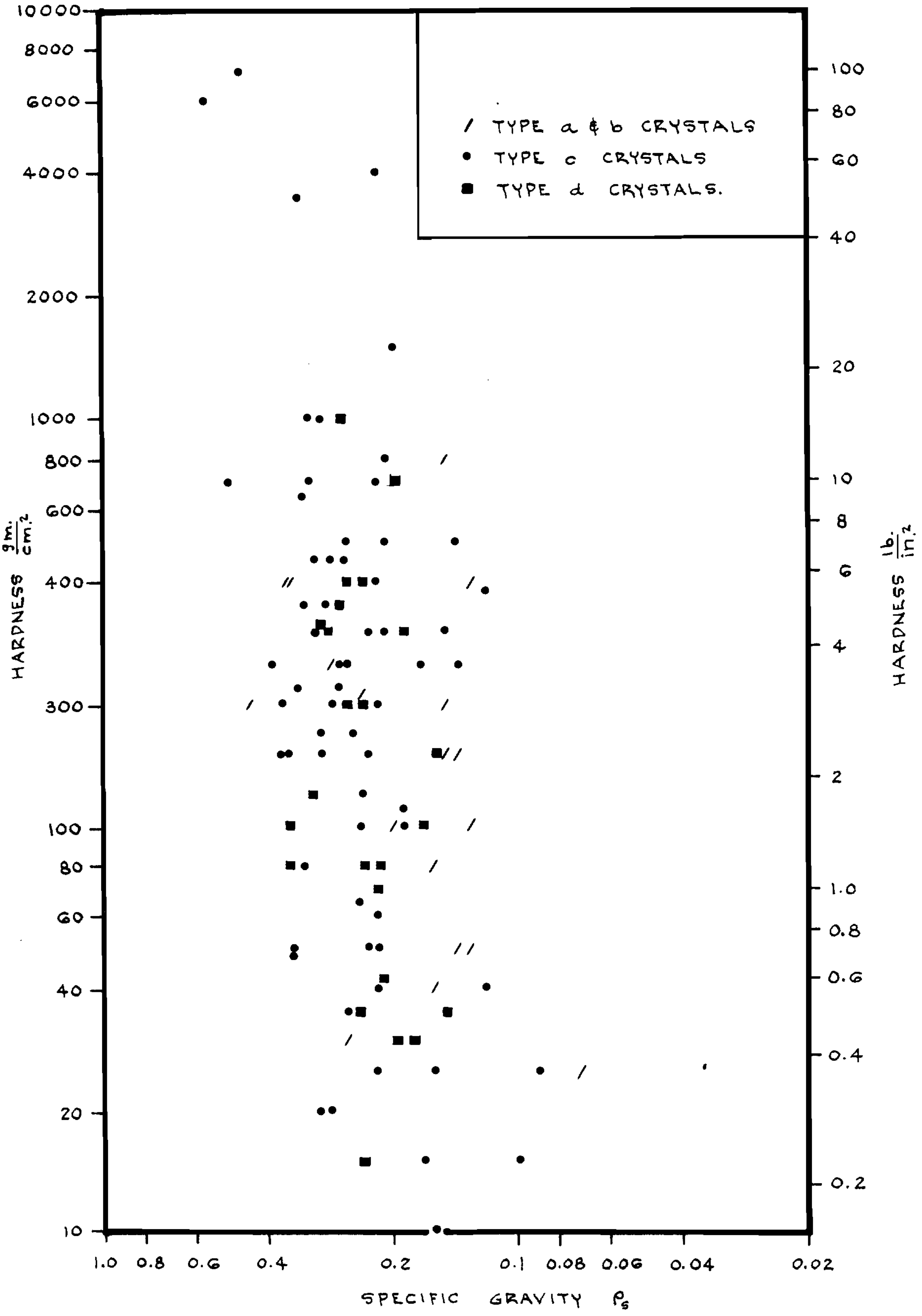

FIGURE 15. DEPENDENCE OF HARDNESS ON CRYSTAL TYPE FOR SNOW IN SHELTERED AREAS.

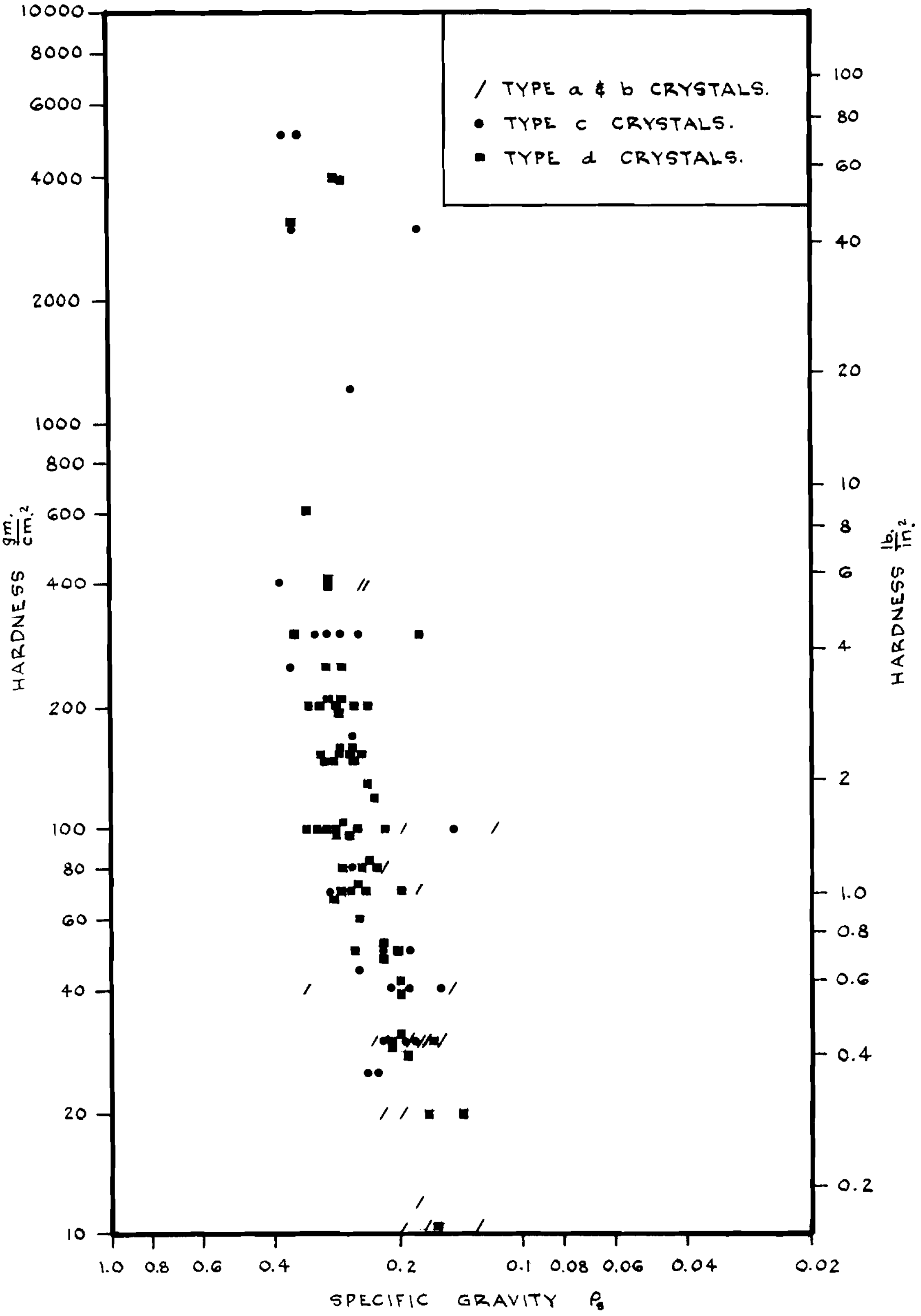

FIGURE 16. DEPENDENCE OF HARDNESS ON CRYSTAL TYPE OF SNOW OF AVERAGE SIZE LESS THAN 1.5 mm. THE OBSERVATIONS WERE MADE AT GOOSE BAY, LABRADOR.

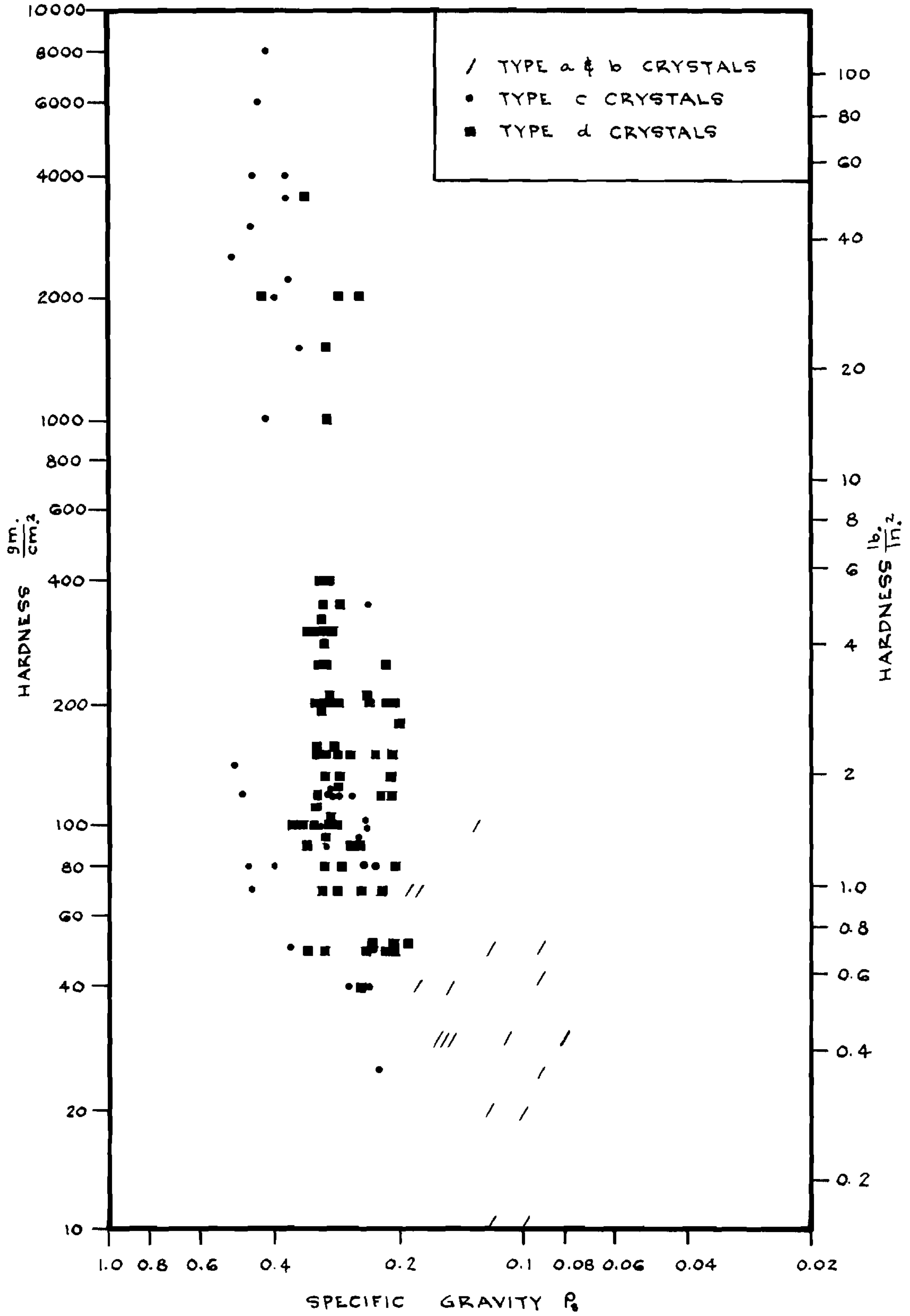

FIGURE 17. DEPENDENCE OF HARDNESS ON CRYSTAL TYPE OF SNOW OF AVERAGE SIZE GREATER THAN 1.5 mm. THE OBSERVATIONS WERE MADE AT GOOSE BAY, LABRADOR.

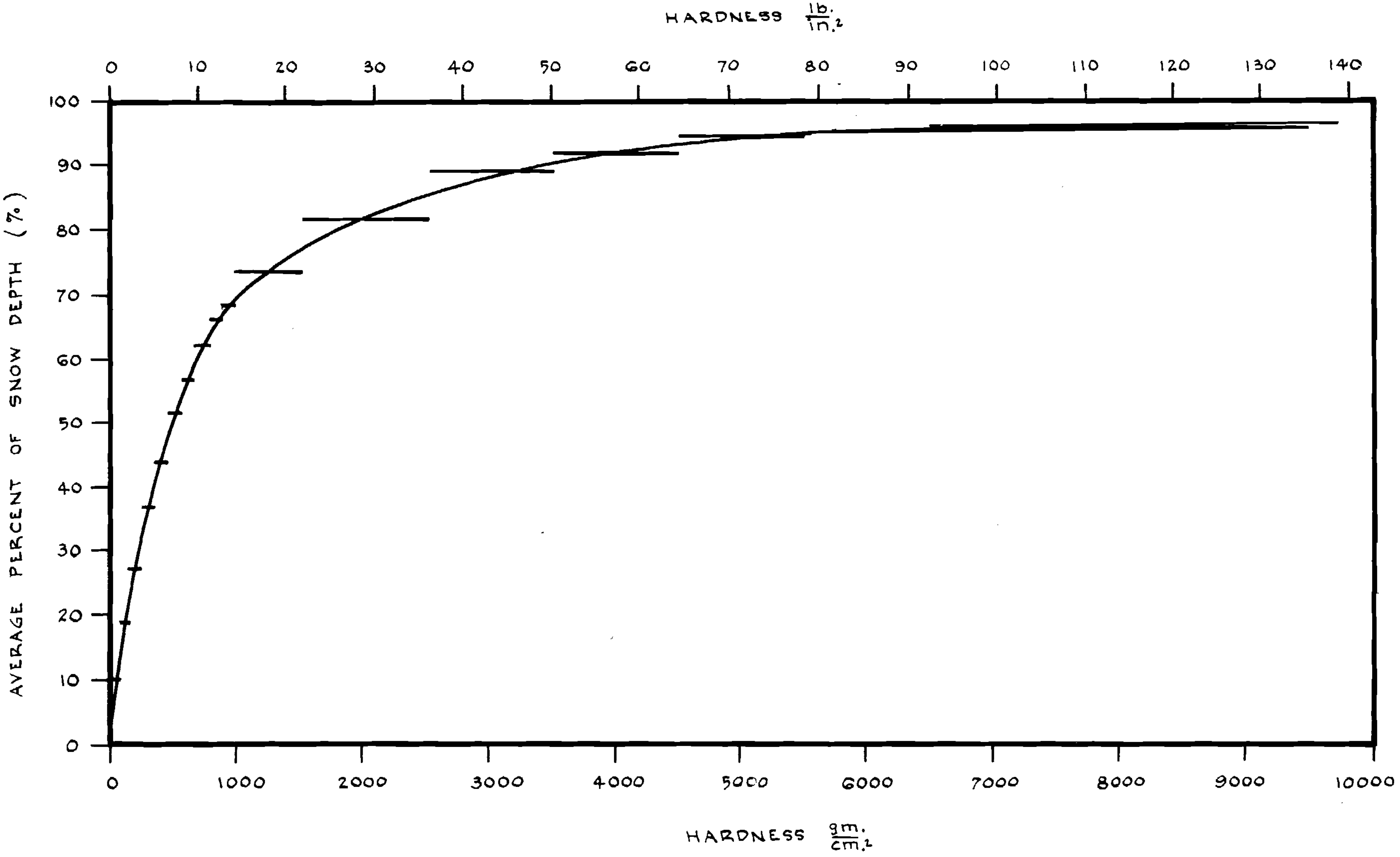

FIGURE 18. PERCENT OF SNOW DEPTH WITH HARDNESS LESS THAN GIVEN HARDNESS.

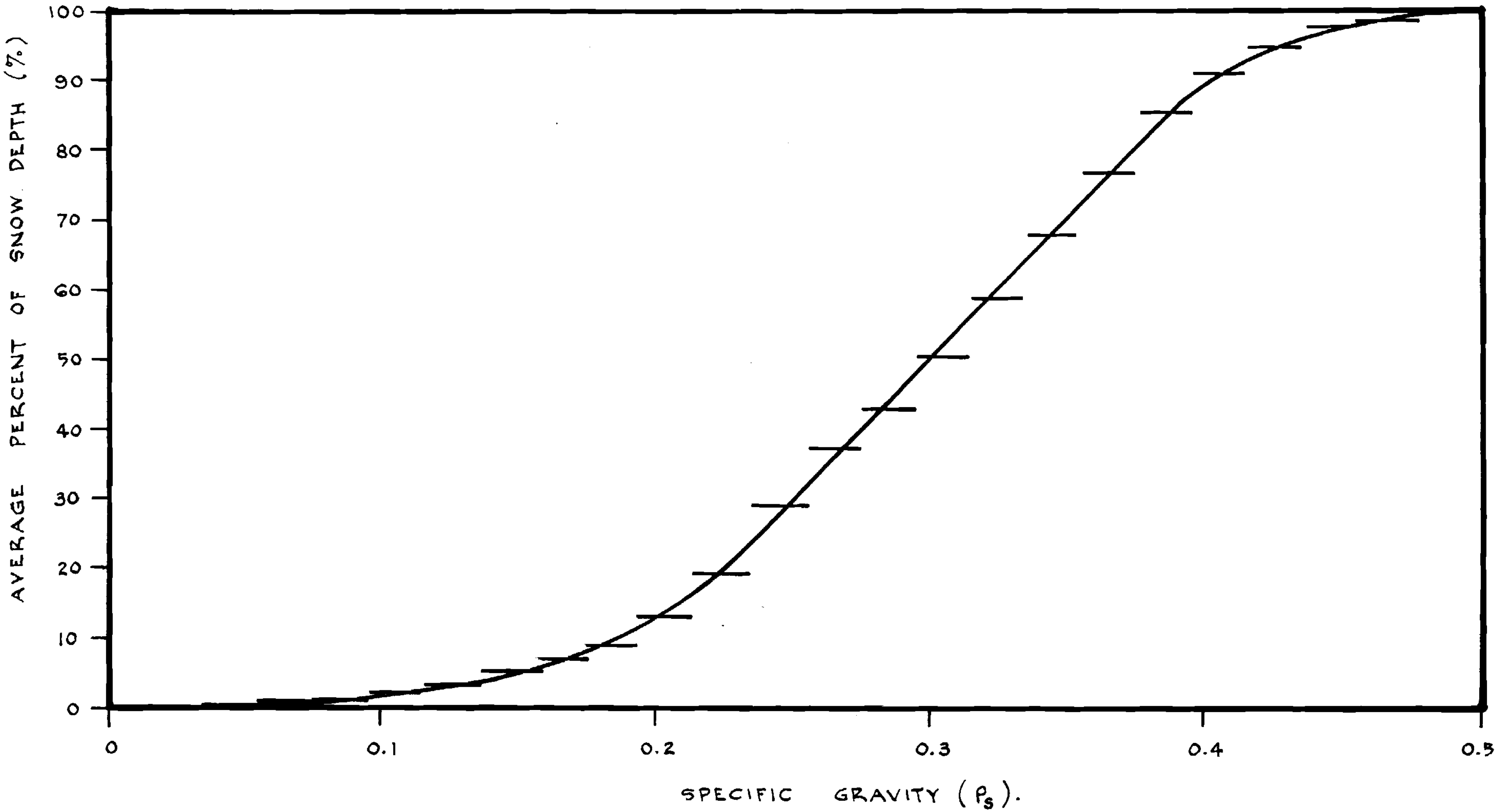

FIGURE 19. PERCENT OF SNOW DEPTH WITH SPECIFIC GRAVITY LESS THAN GIVEN SPECIFIC GRAVITY.