The Physics of Skiing, the preliminary and general Survey.*

By

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(Plates I–V)

1. Introduction

Physical investigations into ski-running are of remarkable importance in discussing the problems of winter transport in districts where the whole land is covered with snow in winter. Scientific research in this line, however, has been very rarely attempted. The authors started in the winter of 1934–35 to study this problem along physical lines. The experiments during that season were conducted in order to carry out the general survey of the diversified phenomena relating to this problem, and the supplementary experiments were continued in the winter of 35–36.

Before entering into the mechanism of ski-running, it is important to get some knowledge of the physical nature of ground snow. The first experiments were designed for the purpose of obtaining this knowledge and, later, investigations were made into the mechanism of ski-running. The results obtained in the two seasons will be summarized in this paper, although they are at present of a preliminary character.

Part I. THE PHYSICAL NATURE OF GROUND SNOW

2. Transformation of crystals preserved in ground snow

The results of our investigations into the snow crystals observable in our climate are fully described in the foregoing papers in this Journal. As is well known, those crystals of delicate form and structure undergo a marked transformation while they are preserved in the ground snow. In order to simplify the condition, we shall deal in this paper only with cases when the atmospheric temperature is below freezing-point. The

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* Investigations on snow, No. 9.

climate half way up Mt. Tokati, 1060 metres above sea level, just satisfies this condition; that is, in its vicinity the temperature is normally between $-5°C$ and $-15°C$ during the four winter months. It must be noted here that the discussions in this paper are limited throughout to the results of the experiments carried out on the snow at that particular place.

In such a climate, the transformation of the crystal is chiefly due to the sublimatic action of ice. The vapour pressure of ice is moderately high, being 4.58 mm Hg at $0°C$ and 1.97 mm Hg even at $-10°C$. These values mean the vapour pressure which is in equilibrium with the plane surface of ice, and the tension of vapour, which is in equilibrium with a pointed portion or a sharp edge of the crystal, must be much higher than these values, owing to the action of the surface tension of the solid. Then the molecules of ice sublimate from the pointed portion of the crystal and condense on to the dented part or the plane surface. As a result, first, the designs observable in the crystal, which are due to minute canals or ridges on the body of the crystal, disappear, and the sharp outline of the crystal changes into a simpler and more rounded form. Then some branches begin to detach themselves from the crystal and the constituents of the snow layer become an assemblage of ice particles of slender and simple form. These slender particles again change into heaps of granular particles. In other words, these processes may be explained as examples of the general rule to the effect that the smaller the surface of a crystal, the greater its stability.

When one examines under a microscope the forms of snow particles in the different strata of a snow layer, one sees that the process of transformation above described is nicely observable in the case of snow. KURODA[1] has already noticed this process of transformation and some microphotographs of those snow grains are given in his paper. The observations which were made by the present authors at Mt. Tokati also showed the phenomenon very nicely. A series of microphotographs are shown in Photos. 1 *a-d*, Pl. I. 1*a* shows the structure of the snow particles of ground snow at a depth of 5 cm from the surface. 1*b* shows the structure 30 cm from the surface; the slender particles of snow above mentioned may be observed, mixed with grains of ice. At a depth of 60 cm, (Photo. 1*c*), all the particles are seen to have grown up into granular form of considerable size, as would be expected from the theory described above. 1*d* shows the grains at a depth of 100 cm. One sees no marked difference

1) M. KURODA, Sci. Pap. Inst. Phy. Chem. Res., Tokyo, **12** (1929) 69.

between the structures of grains at depths of 60 cm and 100 cm.

Roughly speaking, when the climatic condition is such that the temperature is always kept below freezing-point, the ground snow beneath a point 30 cm from the surface consists of an assemblage of ice grains. These photographs were taken at the beginning of January when the snow is still "new". If the snow becomes "old", say, towards the end of March, the particles in the shallower strata of the ground snow also take the form of ice grains. The investigations into the mechanism of ski-running described in this paper were mostly made on "old" snow, the whole being made up of an assemblage of ice grains except the layer near to the surface, perhaps, 10 cm in thickness.[1)]

3. The stratigraphic structure of ground snow

In a warmer climate, the ground snow is sometimes exposed to a temperature above freezing-point, or soaked by an occasional shower. In such a place the surface layer of the snow is thawed each time and refreezing takes place, giving rise to many layers of "icy crust" inside the snow. If a vertical section is made of such snow, one can usually see its stratigraphic structure.

At the spot where the following experiments were made, the atmospheric temperature was always below 0°C, and so the snow showed such a homogeneous character that any vertical section represented only a uniform, white wall of snow. The authors, however, found by chance that the ground snow in such a place also had a stratigraphic structure. This structure can only be made visible if a blazing fire is made at the bottom of a hole dug in the snow. The hole must be of considerable size, say, one or two metres in diameter, and must be chosen so that the section of snow to be examined forms one side wall of the hole. If one waits about five minutes after starting the fire, one will see that many horizontal layers become visible in the formerly uniform, white wall of snow. The general appearance of this stratigraphic structure is shown in Photo. 2, Pl. I. A close examination of the strata shows that in the *white* layer the snow particles remain unchanged, while in the *grey* layer they are soaked with thawed water, resulting in a bluish-grey tint. The thickness of these *white* and *grey* layers varies from a few millimetres to several centimetres, and no regularity is found in their distribution and thickness.

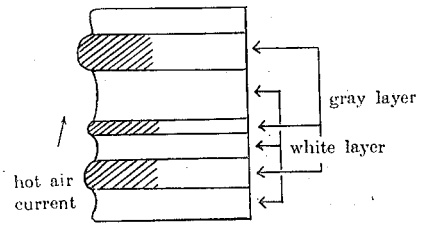
1) Detailed explanation of the nature of ground snow in Alpine districts will be seen in SELIGMAN's book, "Snow structure and ski fields", 1936, London.

This stratigraphic structure was found not only in the snow at Mt. Tokati, but also in that at Sapporo, and the authors consider that the ground snow at any place will show this structure more or less markedly. This method of making the strata visible was found to give a powerful clue in the investigations into the mechanism of ski-running, which will be fully described in Part II. Recently we received a most fascinating book of Mr. Seligman's on snow, "Snow structure and Ski fields", in which the stratification of snow deposits was treated in full detail, except this "blazing fire method" of making the structure visible. It seems to the authors that this method has not received much attention from workers in this line.

4. The physical nature and origin of the white and grey layers

In order to examine the mechanism of these strata, a block of snow about 30 cm square was cut out. It was brought near a stove and the white and grey layers were made to appear by sending a hot air current to one side of the block. The change in the surface of the block is shown schematically in Fig. 1. The surface of the white layer was dented as shown in the Figure, and the snow particles of the layer remained in a dry state. In the grey layer it was found that the thawed water had soaked through the block, as is shown by the shaded parts in the Figure. Thus the difference between the inner structures of these two layers consists chiefly in the difference of their powers to soak up the liquid.

Fig. 1

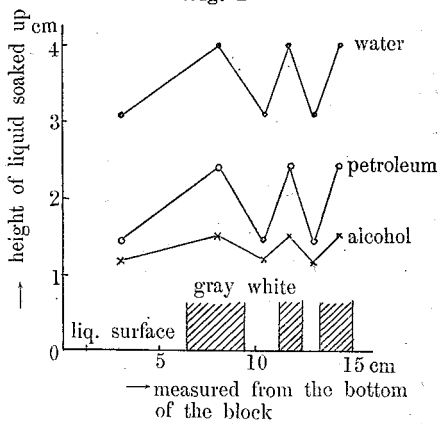


i) The soaking power of the layer

The "soaking power" of the layer was measured by the height to which the liquid inside the block rose when the block was held vertically and its bottom momentarily immersed in the liquid. A suitable block was chosen, the distribution of the white and grey layers was first examined by the method described above, and then the thawed surface was cut off. This block was held in such a manner that the originally horizontal layer was in a vertical position, and one side was made to touch the surface of water for 30 sec. The height to which the water rose was quite different

for the two kinds of layer. Two more series of similar experiments were carried out with alcohol and petroleum respectively. The results were qualitatively the same for all cases and are shown in Fig. 2. This phenomenon is no doubt due to differences in the capillary actions of the fine interstices in the granular structure of snow.

Fig. 2

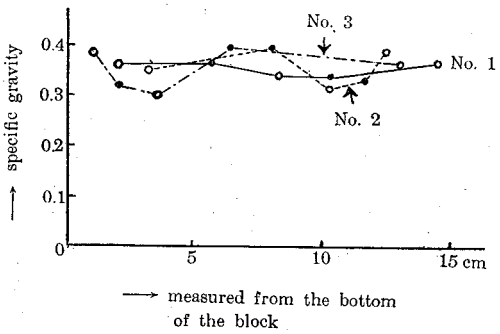


ii) The specific gravity and hardness of the two layers.

In order to discover whether besides the soaking power described above, there is any difference in the physical natures of the white and grey layers, the specific gravity and the hardness were measured for both layers.

For the measurement of the specific gravity, the required layer was cut into a thin circular disc, 10 cm in diameter and 2 cm in thickness, and its weight was measured. The results obtained from three specimens are plotted in Fig. 3, in which ○ marks show the values for white layers and ● marks show those for grey ones. From the results shown in the Figure, one sees that no marked difference is observable between the two layers in respect of specific gravity. Thus the difference in soaking power cannot be due to difference in the closeness of the packing of snow grains in the layer.

Fig. 3



For the measurement of the hardness, an apparatus was designed which was similar in principle to that used by Mr. KURODA[1]. It was designed so as to be conveniently used on a vertical snow wall. The schematical sketch is given in Fig. 4, in which A is a brass cone with a semi-vertical angle of 45° and W is a weight movable in the direction of the arrow. This apparatus is held in such a manner

1) KURODA, ibid.

that the vertex of the cone just touches the surface of the snow wall, and W is let go from a fixed height in order to give a definite impulse to the cone. The diameter d of the circle thus made by the cone on the snow wall was measured, and $1/d$ was taken to represent qualitatively the hardness of snow at that point. The hardness was thus measured at many points at various depths, and the specific gravity was also measured at the corresponding strata. After taking these data, a fire was made to see the distribution of the white and grey layers. One example of the results is shown in Fig. 5, from which one understands that the difference in the hardness, if any, is much smaller than that due to the depth of the layer. Generally speaking, there is little difference between the white and grey layers as regards specific gravity and hardness.

Fig. 4

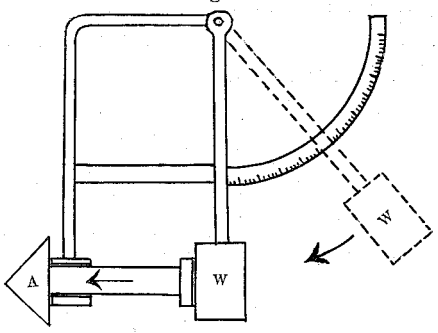
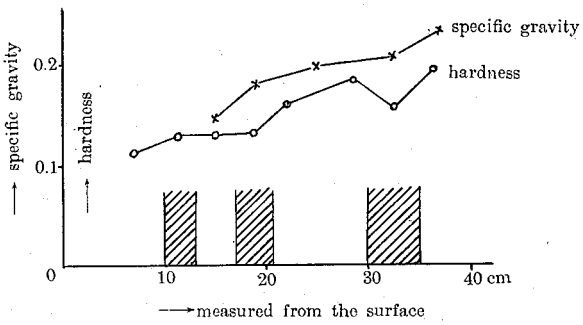


Fig. 5



iii) The structures of two layers examined under a microscope.

Two very thin plates of snow were cut out from the white and grey layers respectively and were examined under a microscope with a combined illumination of transmitted and reflected light. The difference in the granular structures of the two layers was most clearly observed when the specimen was soaked with a small quantity of water. Two microphotographs representing the structures of the two layers are shown in Photos. 3 *a, b,* Pl. II, *a* showing the grey layer and *b* the white one. In the photographs one sees clearly the difference in the structures. In the former, the grains are distinctly defined and most of them have a hexagonal form, indicating that each grain is a single crystal of ice. In the latter, the boundaries of the grains are not so distinct as before, and accordingly the interstices between the grains are not sharply defined.

From these structures it is understood that the grey layer must have

a high soaking power because of the capillary action of the well defined interstices among the grains, while in the white layer the water is absorbed with difficulty, as the interstices are not connected to form a fine capillary bore. The factors governing the origin of the difference in the structures of the two layers will be very complicated. The crystal form, the atmospheric temperature, the sun-shine, the mechanical action due to wind, etc. will each play some rôle in producing these two types of grain form. This problem will not be discussed in this paper.

After finishing this work, Mr. SELIGMAN's book, in which the crusty strata were studied by using dyed water, came to our notice. It is quite true that this stratification is increased, as he describes, by alternate thaws and frosts. In February 1936 we experienced a heavy snowfall that cintinued for two days and gave a deposit about 60 cm in depth. In this case also we could see, using the blazing fire method, more than ten strata in the newly fallen snow. The stratification in such a case will be due to a continual fluctuation in the wind speed, which produces various degrees of wind packing, and to the variation in the form of the prevailing crystal at every moment during the snowfall. These laminations of the deposit will give rise to the beautiful parallel markings afterwards in the form of erosion when the deposit becomes a solid crust, as pointed out by SELIGMAN in his book, pp. 227–231. The chief feature of our blazing fire method is that it can make even slight traces of stratification visible, and we can see the strata while the snow is still soft or in a powdery condition, a great advantage when we are studying ski-running.

Part II. MECHANISM OF SKI-RUNNING

5. The mode of snow-compression caused by ski-running, the preliminary experiments

The homogeneous ground snow which is being discussed in this paper is called by skiers "powder snow". When the snow is of a perfect powdery nature the ski runs beneath the surface of the snow. The snow beneath the ski is compressed by the weight of the skier and it is carried forward by the moving ski, and the soft snow near the track is scattered so that it appears like smoke. In such a case the resistance of the snow to the moving ski is very complicated. Besides the friction between the underside of the ski and the surface of compressed snow, there is another sort of resistance which is similar in nature to a hydrodynamical resistance. The latter involves many factors; for example, a portion of snow in the track

must be moved aside, another portion of snow under the ski must be pressed down, the layer compressed by the ski must be dragged along, the snow in and around the track must be scattered, etc. This phenomenon, therefore, must be treated as a problem of "the dynamics of powder". Difficulty arises from the fact that in this case the material is very easily compressible and a method of investigation must be chosen quite different from that which would be used in the case of "incompressible" material, such as sand or ordinary powder. In the following the method of investigating the mode of compression will be described.

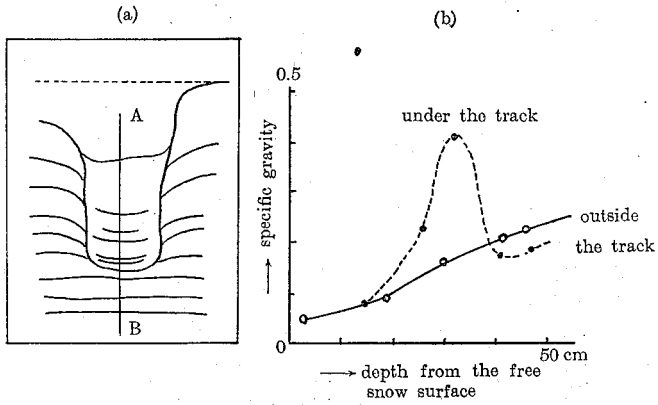
For this purpose the blazing fire method of making the stratification of snow visible was found to be very convenient. A suitable slope of virgin snow is chosen and a straight run on skis is made. Then a hole is dug in the track, so that a vertical section of snow is made perpendicular to the direction of the track. By making a fire at the bottom of the hole, one is able to see the way in which the snow has been compressed beneath the ski. Photo. 4, Pl. II, shows one example of such a section; in this case the atmospheric temperature was $-6.0°C$, the temperature of the air just above the surface of the snow was $-2.8°C$ and the velocity of the ski was 6.3 m/sec. As seen in the photograph, a portion of snow under the ski is detached from the other part and is made to subside as a separate block, which is itself compressed to a considerable extent by the weight of the skier. The total depth to which the compression of the snow reaches is in usual cases between 20 cm and 30 cm from the free surface of the snow. Below that depth little pressure appears to be exerted and the weight of the skier is sustained by the shear along the side walls of the subsiding block.

From the form of the subsiding block one can infer the direction and distribution of the stress inside the snow, showing that this method is applicable in the scientific investigation of ski-technics. For example, in Photo. 4, one can see that the ski on the right side exerted a normal pressure inside the snow, while that on the left side must have been "rolling". The possibility of applying this method to the scientific investigations into ski-technics will be published later as a separate paper.

The mode of snow-compression will be studied also from the measurement of the specific gravity of the snow under the ski at various depths. Fig. 6*a* shows a sketch of the section, in which case the pressure was exerted normally. The specific gravity was measured at various points along the central line AB of the depressed block. The results are shown by a dotted line in Fig. 6*b*, in which the full line represents the specific gravity of snow

outside the track. One sees that the specific gravity exhibits a maximum at the bottom of the block, showing that the compression of snow occurs most markedly in this layer. Below this layer the specific gravity of the snow appears to be a little less than that of the corresponding layer outside the track. This peculiar phenomenon was sometimes observed and does not seem to be due to a simple experimental error. This phenomenon must be studied in detail in the later investigations.

Fig. 6



Besides the compression above described, the actual motion of snow is such that this depressed block is pushed forwards at a velocity varying with the depth. This sort of motion was treated by a different method and will be discussed in the following section.

6. The flow of snow caused by the motion of the ski

The flow of snow caused by the motion of the ski belongs to the problem of the dynamics of powder. This is a branch of physics which has not been studied thoroughly yet. For several years Prof. T. TERADA and his collaborators have been studying this problem and he put forward a hypothesis on the dynamical nature of a heap of powder, which states that a mass of powder shows a displacement similar to a plastic deformation, or to a viscous fluid when the latter receives a force within a certain limit. This same heap of powder behaves like a perfect fluid when an accerelation beyond a critical limit is given to the particle. The authors began to study the problem of the flow of snow caused by the motion of a ski, taking this suggestion as a working hypothesis.

A suitable slope is chosen and a large glass plate is pushed into the

snow vertically to a depth of 30 or 40 cm from the free surface, the plate being perpendicular to the line of the greatest slope. Then the plate is removed and some soot or red ochre is poured into the narrow chink. A straight run is made so that the ski cuts its way through the sheet of soot. Then the distribution of the soot after the passing of the ski is examined by making a vertical section of snow along the middle line of the track. One example of the distribution of soot is shown in Fig. 7 and a photograph in Photo. 5, Pl. II. In Fig. 7, OP is the original surface of snow and QR is the surface of the track. The soot that was originally in the position AB drifts so as to make the line ACS and another portion of soot is distributed in the region E by being mixed with the snow. The point of interest is that the flow of soot takes nearly a parabolic form near the point C. The distribution of the displacement inside the snow is seen from this form to be similar to the velocity distribution in a viscous fluid. The snow in this region, therefore, may be taken as showing the nature of a viscous fluid. The line CS was found by a later experiment to show the plane in which the under-side of the ski slid on the surface of the compressed snow, as will be described in Part III. The length of this flow CS of soot or red ochre varies from a few to several metres. A few examples will be shown in Table I.

Fig. 7

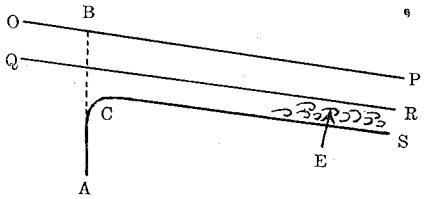


Table I

	Vel of ski in m/sec	CS in m	Temperature in °C	Hardness of snow in arbitrary unit
red ochre	5.6	1.20	−5.9	32
	10.0	5.45	−5.6	33
	7.1	6.96	—	42
soot	6.3	6.75	−2.8	33
	6.3	2.60	−6.0	32

In the region E the soot or red ochre is well mixed with the snow. The soot that was originally near the point B is pushed forwards and mixes with the snow after travelling for a few to several metres. The snow in this portion, therefore, may be considered as showing a dynamical nature similar to a perfect fluid. From this simple experiment we found

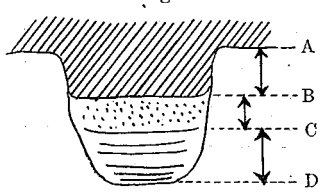
that Prof. TERADA's theory of the mechanical nature of a system of powder holds also in the case of snow such as is treated in this paper, that is, snow in a perfect "powder" condition with the temperature always below 0°C.

7. Further experiments on the compression of snow by using a sled

In the case of ski-running some human influence is liable to get in the way of a quantitative investigation. We constructed a sled in the form of a ski with both ends bent upwards. It measured 114 cm in length and 20 cm in breadth, weighing 8 kg. The under-side of the sled was coated with sliding wax. Ten iron weights, each 8 kg in weight, were prepared. This sled, loaded with various weights, was made to run down a slope and the mode of snow-compression was investigated under various conditions. This experiment was also carried out at Mt. Tokati in March 1935, the temperature being normally between −5°C and −10°C throughout the investigation. One morning the temperature rose to +2°C and we could see the behaviour of wet snow as well. The size of the sled and the manner in which the experiment was carried out will be seen in Photo. 6, Pl. III.

The mode of snow-compression in this case was qualitatively the same as in the case of the ski, the only difference being that the structure of the depressed block could be more clearly observed by the blazing fire method in the present case. One good photograph showing the structure is represented in Photo. 7. In this case the temperature was −8°C, the total weight was 32 kg and the velocity of the sled at this point was 9.2 m/sec. It will be clearly seen in the photograph that the depressed block is composed of two parts, the upper part being composed of disturbed snow and the lower showing the original stratification in a compressed state. For future reference we shall call the upper part the "disturbed layer" and the lower the "compressed layer". The schematic diagram is given in Fig. 8. For later convenience it will be described as follows:

Fig. 8



AB: the depressed amount (the distance between the free snow surface and that of the track),
BC: thickness of the disturbed layer,
CD: thickness of the compressed layer,
AD: the compression depth, or the yielding depth.

Many experiments were carried out with this sled for different temperatures, varying the velocity of the sled and the number of the weights. For 21 experiments the depressed amount, the disturbed layer and the compressed layer were measured and the results are tabulated in Table II. For the measurement of the velocity, thin threads were stretched horizontally at definite intervals, usually 2 metres apart. The time moments, at which they were cut successively by the sled, were recorded by an electromagnetic device on a rotating drum. All the recording instruments were enclosed in a wooden box with a glass window, so that the measurement could be done safely in an open field even when the snow was falling.

The relations between the amount of AB, BC, CD and the temperature, weight and velocity may be studied from the data in Table II.

Table II

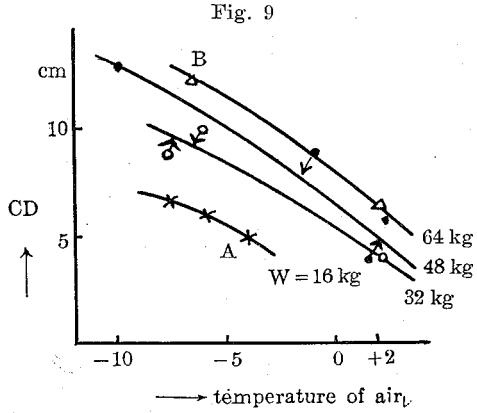
Date	Photo. No.	Temp. in °C	Weight in kg	Velocity in m/sec	AB cm	BC cm	CD cm	AD cm
III 14, 15h	3	−6.0	32	6.0	13.0	6.0	10.0	29.0
15.30	4	−6.0	16	—	7.5	4.5	6.0	18.0
III 15. 10	5	−7.5	16	—	7.0	8.5	8.5	24.0
,,	6	−7.5	16	—	6.0	9.5	5.0	20.5
10.15	7	−7.5	32	7.7	10.5	7.5	7.0	25.0
,,	8	−7.5	32	7.2	8.5	9.0	9.0	26.5
10.30	9	−7.5	32	—	7.0	—	—	—
,,	10	−7.5	32	—	6.5	13.5	5.5	25.5
11	11	−7.5	32	—	11.0	—	—	—
15	14	−10.0	48	4.5	14.5	7.0	13.0	34.5
,,	14′	−10.0	8	6.0	7.0	4.0	6.0	17.0
15.30	15	−10.0	48	5.5	13.0	8.0	10.5	31.5
III 16, 10.30	16	+2.0	32	—	4.0	4.5	4.0	12.5
,,	20	+2.0	48	—	4.0	4.0	4.0	12.0
,,	21	+2.0	64	—	4.5	4.0	6.5	15.0
13.30	24	−1.0	48	5.6	5.0	—	—	—
14	25	−1.0	48	4.5	8.5	5.5	9.0	23.0
14.30	26	−4.0	8	8.0	1.5	3.5	5.5	10.5
15	28	−4.0	16	8.1	1.5	4.0	5.0	10.5
16.30	29	−6.5	64	7.0	9.5	6.5	12.5	28.5
III 17, 14	35	−8.0	32	9.2	6.5	6.5	10.5	23.5

a) The relation between the temperature and the thickness of the compressed layer

In this experiment the temperature means that of the air. The temperature of the snow was unfortunately not measured. It is well known that snow becomes wet and consequently viscous when the temperature rises, and the viscous nature depends on the accumulated effect of the temperature together with other meteorological elements. In this investigation we dealt only with the temperature of the air at the time of observation, and we admit that this result should be reconsidered in future experiments by taking the integral effect of the temperature.

Taking the eleven data that are available for this purpose from Table II, the relation between the temperature and the thickness of the compressed layer is plotted in Fig. 9, with the loaded weight as the parameter. It is seen, though roughly, that the thickness increases in proportion with the weight, and for a given weight it decreases as the temperature increases; that is, qualitatively, it decreases as the viscous nature of snow is intensified. The decrease in the thickness of the compressed layer with the increase of the temperature is very nicely shown in Photos. 8*a* and *b*. In both cases the weight was 48 kg and the same sled was used. The reader can see how the compression depth reaches far lower in the case of *a* when the temperature was −10°C, than in the case of *b* when it was +2°C.

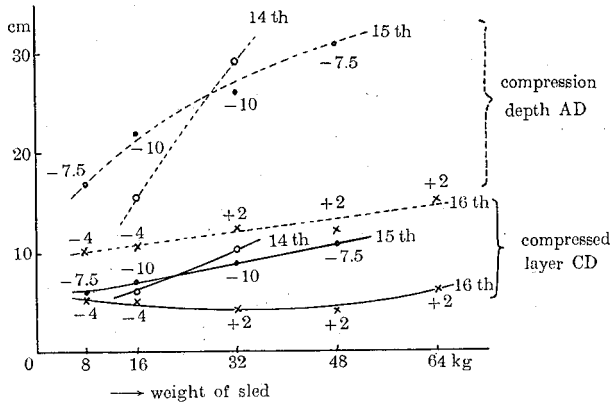
Fig. 9



b) The relation between the weight and the thickness of the compressed layer

The relation between the weight of the sled and the thickness of the compressed layer or the compression depth is plotted in Fig. 10. In this case it is found that no simple relation is observed when we take the temperature as the parameter. Some regular rule, however, seems to be obtainable if the date on which the experiment was carried out is taken as the parameter. The small figures noted near the marks in Fig. 10 show the temperature at the time of observation. It can be seen that the data

Fig. 10

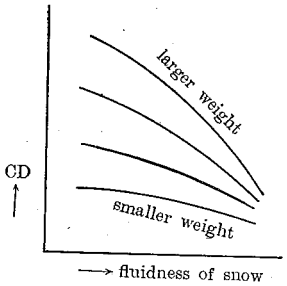


taken on the same day are represented by a smooth curve, regardless of the difference of the temperature. This result shows the well known fact that the physical nature of snow is determined by the integral effect of temperature together with other meteorological elements, and the temperature at the time of observation is not an essential factor. For example, each of the two curves of the 16th in Fig. 10 contains the data obtained at +2°C and −4°C on a smooth line. The values at +2°C were obtained in the morning and those at −4°C in the afternoon. The snow was wet and viscous this day, and the effect of the warm weather in the morning upon the nature of the snow in the colder afternoon is nicely shown by those curves. On the 14th and the 15th the snow was dry and in a good powderly condition. It will be seen from the curves in Fig. 10 that both the compression depth and the thickness of the compressed layer are smaller for wet snow and the rate of increase with respect to the weight loaded is also smaller for wet snow than for good powdery snow. "Fluidity" is an important feature of the snow for ski-running, not only from the standpoint of the enjoyment of ski-technics but also from that of the problem of winter transport. No method, however, seems to have been proposed for measuring the degree of this fluidity in a physical sense, and the authors consider that this important characteristic of snow will be to some extent represented by the amount of the compression depth or the thickness of the compressed layer, which could be measured by our blazing fire method.

We shall reconsider the physical meaning of the curves in Fig. 9, by replacing the temperature of the air, which was taken as the abscissa in

the former case, with the fluidity of the snow. If we take the fluidity as the abscissa, the points A and B in Fig. 9, that were obtained in the afternoon of the 16th when the snow was wet, must be displaced to the right. Then the trend of the system of curves in Fig. 9 will be transformed to that shown in Fig. 11, in which the relation between the compressed layer and the fluidity of snow is shown in a qualitative manner, taking the weight loaded as the parameter.

Fig. 11



c) The influence of the velocity of the sled

As shown in Fig. 8 the depressed block of snow under the track of the sled is composed of two layers, the disturbed layer and the compressed one. It was found by a later experiment to be described in Part III, that the boundary of these two layers is the plane in which the under-side of the sled made its way through the snow. The snow in the disturbed layer is brought about by the eddies left behind the sled, and consequently the thickness of this layer increases as the velocity of the sled becomes greater, if the other conditions are kept constant. In other words the depressed amount AB decreases when the velocity increases. Comparing the data No. 24 to No. 25 and No. 14 to No. 15 respectively in Table II, one will see the examples of the phenomenon above described. It suggests that the thickness of the disturbed layer will give a measure for the fluidity of snow as the function of the velocity, but the data are at present not sufficient for this point to be discussed.

d) Instability of the motion of the ski in powder snow

Hydrodynamics tells us that the motion of a plate in fluid is unstable if the plate is made to move in its plane. A somewhat similar phenomenon is observed in the case of the motion of a ski or sled in powder snow. A slight heterogeneity in the snow tends to make the skier deviate from a straight path. In the case of a straight run on skis this instability is regulated unconsciously by the skier. When a sled is allowed to run straight down a slope, it is often observed that the path of the sled deviates midway from the line of the greatest slope. If we examine the distribution of the pressure in the snow in such a case, we always find that the sled runs slantingly. Photo. 9, Pl. IV shows one example, in which one sees clearly how the strata N and T are lying slantwise.

8. Further experiments on the flow of snow, using a sled

Similar experiments to those described in section 6 were carried out at Mt. Tokati in March 1935, using a sled. The flow of snow was studied as before, and in this case soot was used as an indicator. The results obtained were qualitatively the same as in the case of a ski. In the former case the authors did not touch the physical meaning of the flow of soot on the sliding surface; that is, the line CS in Fig. 7. In this series of experiments this flow of soot was found to be more liable to take place the greater the velocity of the sled, as long as the other conditions and the nature of snow remained constant. A good example was observed in the experiment on the 16th March, when the snow was fairly wet and viscous. Two photographs showing this point are reproduced in Photos. 10 *a* & *b*, Pl. IV. These photographs show two experiments carried out in succession under the same conditions. In the case of *a* the sheet of soot extended five metres from the starting point, and the velocity of sled at this point was less than in the case of *b*, when the soot was 23 metres distant from the starting point. Unfortunately the velocity was not measured in these experiments. In *a* the parabolic drift of the snow can be observed but no flow of soot takes place ,whereas a remarkable flow is observed in the case of *b*. It will be very interesting to study the nature of this flow, which plays an important rôle in the problem of the friction between ski and snow, but at present the experiments are not circumstantial enough to elucidate this important phenomenon.

Part III. SUPPLEMENTARY EXPERIMENTS ON THE MECHANISM OF SKI-RUNNING

The experiments described in this Part were carried out at Mt. Tokati, the same place as before, at the beginning of February 1936. The temperature was between $-8.5°C$ and $-23°C$ during the period of the experiments which lasted six days. The snow was softer and more powdery than before and sometimes it was "wild"[1].

9. The general displacement of snow and the sliding plane of the ski

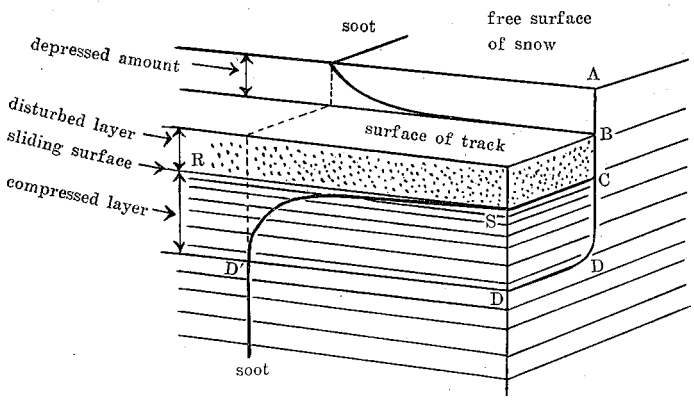
In the preceding experiments, the transverse and the longitudinal sections of the track were studied independently. For the former the

1) After SELIGMAN we shall call the newly fallen snow, that is very soft and extremely unstable, "wild snow".

blazing fire method was used and for the latter the soot method. In this series of experiments the simultaneous application of these two methods was undertaken in order to see the general displacement of snow. The relative position of the plane, in which the flow of soot takes place in the longitudinal section, to the compressed layer in the transverse section was examined. A sheet of soot is inserted vertically in the snow as before and straight run is made; then a transverse section is made at some distance, say, 1 metre, downhill from the original position of the soot. The soot appears as a horizontal line in this transverse section at some distance from the surface. Then the mode of the compression of the snow is examined by a blazing fire with respect to the same section. It was always found that the flow of soot coincides with the boundary surface between the disturbed and compressed layers. Photos. 11 *a* & *b*, Pl. IV, show the examples. In this case the velocity of the ski was 5.6 m/sec and the temperature was $-8.0°$C. *a* and *b* were taken before and after making the fire respectively. In *a* the section of the flow of soot S is seen under the track and in *b* one will see that this line S coinsides with the boundary surface between the disturbed and compressed layers.

The next point is to determine the plane in which the under-side of the ski slides. We shall call it the sliding plane of the ski. In a former experiment we tried in vain to find this sliding plane by the following method. A thin thread coated with wet paint was stretched horizontally over the snow surface at a height of several centimetres. When this thread was cut by the sliding sled, which was provided with a pole erected, it left a mark of paint on the pole. From this mark the sliding plane was measured and found to be somewhere near the boundary surface between the disturbed and compressed layers, but this method was not accurate enough to decide whether the sliding plane coincided exactly with the boundary surface or not. No such accuracy could be expected from an open field experiment. In the course of the present experiment it was found that a mass of red ochre pasted to the under-side of the ski leaves a trace of reddish colour in the snow so that the sliding plane can be determined easily and accurately. After some trials it was found that the best method was to paste a mass of red ochre with alcohol to the tail end of the ski. The flow of snow was examined as before. As a matter of fact the track reproduced in Photos. 11 *a* & *b* was made with this ski, and we found that the line marked by traces of red ochre just coincided with the flow of soot S. A longitudinal section of the same track, a photograph of which is reproduced in Photo. 12, Pl. V, will show the

Fig. 12



mechanism more clearly. The thin nearly horizontal line R is formed by traces of red ochre and it shows the surface on which the under-side of the ski made its way in the snow. This line is seen to coincide exactly with the flow of soot S.

Further the authors examined the general displacement of snow caused by the motion of the ski by the simultaneous application of a blazing fire, soot and red ochre. The result is summarized in a schematical diagram shown in Fig. 12. The general displacement of snow will be understood from the Figure at a glance. The starting point D′ of the parabolic deflection of the sheet of soot usually agrees with the depth D of the compressed layer, but sometimes it does not coincide with D. This point will be discussed later. For one example, the photograph of the longitudinal section of Fig. 12 is reproduced in Photo. 13*a* and the transverse section in Photo. 13*b*. In this case the sled weighed 32 kg, the velocity was 4.7 m/sec, the temperature was −8.5°C.

10. The snow structure and the mode of compression

The relation between the compression depth and the weight of the sled was discussed in the section 7*b*). The results are given in Fig. 10, which show that the curves representing this relation are quite different for different sorts of snow. Similar experiments were repeated more systematically during this expedition. The process of the experiments was the same as before. The structure of the snow, that had not been examined before, was made out by measuring the temperature and the density of the snow at various depths. The meteorological conditions during the stay of the expedition are shown in Table III.

Table III.

Date		Temperature max. °C	Temperature min. °C	New snowfall in mm (as water)	Interval of experiment
I	31	−12.5	−23.0	0.2	11^h–13^h
II	1	− 8.0	−14.5	12.1	9 –13
II	2	− 8.0	−13.5	3.6	9 –13
II	3	− 7.5	−15.5	2.8	9 –12
II	4	− 7.6	−14.0	0	8 –11

One series of experiments was carried out in succession during a period of about three hours, and was repeated once every day for five days. The results are given in Fig. 13 *a-e*. The thick lines show the compression depth and the sliding plane of the sled; the thin lines and the dotted lines give the density and the temperature of the snow respectivley at various depths from the free surface of the snow. The general tendency of the curve of the compression depth AD and the sliding plane AC is more or less similar to that observed in the previous investigation, shown in Fig. 10; that is, both AD and AC increase with the weight of the sled and each shows a trend like a saturation curve. Besides, in the present case we see a new fact in that each of the curves AD or AC sometimes shows a sudden increase when the weight of the sled reaches a certain point. The physical meaning of this sudden increase in the amount of AD or AC could be understood by comparing these curves with those of the density and the temperature of the snow. In the case of Fig. 13*a*, we see that the density shows a maximum at a depth of nearly 15 cm from the free surface and the temperature a minimum at the same point. We had a severe frost in the early morning of this day[1], and the point of minimum temperature was displaced to a depth of 15 cm by the heat conduction of the snow layer. It is well known that snow is hardened by frost even when the temperature is kept always below freezing point. In this case this hardening action cannot be due to freezing of thawed water and it is explained by a sublimation of the ice. We can, therefore, expect that a hardened snow layer or a semi-crust[2] of snow exists in this case in a layer approximately 5 cm to 25 cm from the surface. The curve of ρ also supports the existence of this broad semi-crust. Returning to the curves AD and AC, we

1) C.f. Table III, the minimum temperature was −23°C at nearly 4 h a.m.

2) This semi-crust may be a "breakable crust" or a "slab". In this paper we do not touch the differences between crust and slab.

see that the amount AC is nearly constant, being about 5 cm, when the weight of the sled is less than 32 kg. This shows that the sled slides on the broad crust layer when the weight is less than about 40 kg and it breaks the upper layer of the crust and sinks deeper when the weight exceeds this critical value. The curve AD shows the depth to which the compression or yielding of snow reaches, and it

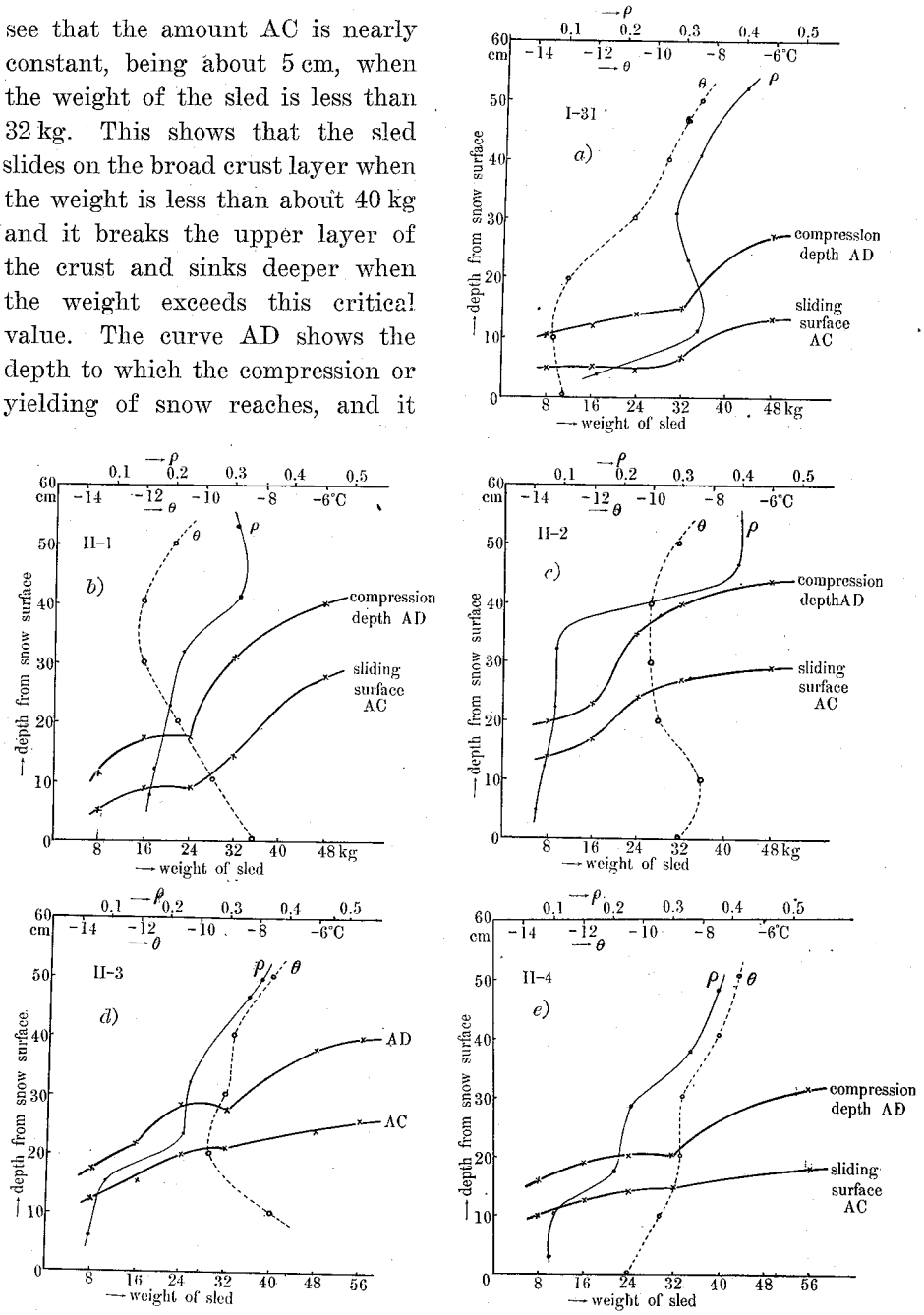


Fig. 13 *a, b, c, d, e.*

will be seen that the broad crust is completely broken when the weight exceeds the critical value mentioned above.

In the case of Fig. 13*b*, the curve of ρ shows that the semi-crust is situated deeper, being between the depths of 40 cm and 50 cm. In this case the compression depth is seen to reach 40 cm when the weight is 48 kg. The nature of the snow shown in Fig. 13*c* was quite different from the two cases above mentioned. It had snowed heavily the previous day and the newly fallen snow had not yet settled, the snow on the surface having the characteristics of wild snow. The curve of ρ shows that the snow is soft and feathery to a depth of nearly 30 cm and a marked crust is seen beneath a depth of 45 cm. Both the compression depth and the sliding plane are much deeper than in the other cases and in this case no marked jump in the value of AD or AC is observed. The yielding of the snow reaches a depth of 45 cm, that is, just above the broad crust, when the weight is 48 kg. In *d* and *e* the nature of the snow is the same. A not so remarkable crust is seen at depths between 20 cm and 30 cm in the former case and between 10 cm and 20 cm in the latter. In both cases the sled slides on the crust layer and this layer is broken when the weight of the sled exceeds 40 kg.

Summarizing the results described above, we can say that the structure of snow, especially the position and strength of the invisible semi-crust layer that is situated in the snow extending over a fairly wide region, can be examined from the curves of AD and AC together with those of ρ and θ. Our knowledge of the nature of snow-compression caused by the motion of a sled or ski, (described in § 7*b*), is thus advanced one step further.

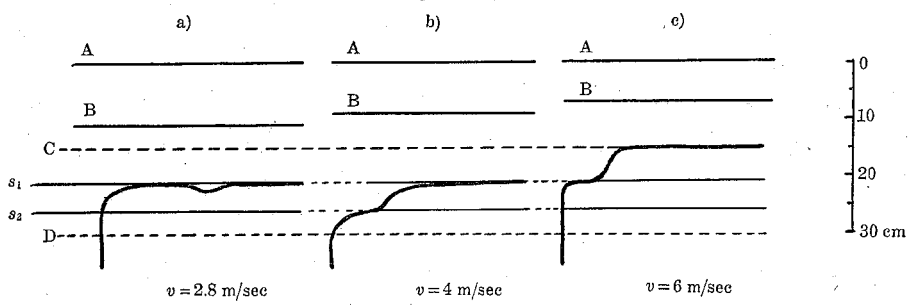
11. The snow structure and the flow of snow

In the former experiments the flow of snow that takes place under the sliding plane of the ski or sled was observed to have shown a parabolic distribution as shown in Photos. 5 and 10*b*. In that case the snow was more or less homogeneous in its mechanical properties, so that the displacement was similar to that which occurs in a viscous fluid. When the snow is comparatively new and the stratified structure is more marked, we can expect some discontinuous displacement in the region of this parabolic distribution. As pointed out by Seligman, the anchorage of snow particles becomes weaker as the sharp branches of snow crystals are blunted by sublimation, and if one layer is placed on another with an intermediate layer that is composed of particles with weak anchorage,

the upper layer is exposed to a danger of avalanche. A similar phenomenon is expected in our case also, only on a very small scale. If there exists such a mobile layer in the region of the parabolic distribution of the flow, slipping of an upper layer can take place when the snow is made to flow by the motion of a ski or sled. Such a phenomenon was sometimes observed in the present experiment. The sheet of soot inserted in the snow as an indicator showed the existence of such a mobile layer very nicely. One example is shown in Photo. 14, Pl. V, which was taken on II 1 when the temperature was $-9°C$, and the weight of the sled was 32 kg. In this case the flow took place in two steps, and a flow in three steps was also sometimes observed, showing that two such layers existed in the region of the compression depth.

The slipping of snow in the mobile layer may or may not occur. It is determined by the dragging force exerted on the snow by the motion of the ski. For a given sort of snow and ski, the dragging force is chiefly determined by the velocity of the ski. The experiment on II 2 showed an interesting example. The flow of soot for three cases of different velocity is schematically shown in Figs. 14 *a-c*, in which A is the free surface of

Fig. 14 *a–c*.



the snow and B is the surface of the track. In this case two mobile layers are observed; that is, the strata S_1 and S_2. In the case of *a*, when the velocity of the sled is 2.8 m/sec, the sliding plane of the sled coincides with the stratum S_1 and the compression depth reaches as far as S_2. When the velocity is 4 m/sec, *b*, the sliding plane is in the same plane as before and the compression reaches stratum D, a slipping of snow being clearly observed in the stratum S_2. In the case of *c* when the velocity of the sled is greatest 6 m/sec, the sled slides in the plane C and in this case a slipping is observed in the bottom surface of the compressed layer, which just coincides with the stratum S_1. From these results it is clearly seen

that in this case there exist two mobile layers in the range of the compression, and the slipping of the snow in these layers is caused only under favourable circumstances.

Summary

Part I. The physical nature of ground snow is discussed. The transformation of snow crystals into ice grains by sublimation is studied under a microscope and microphotographs showing the process of transformation are reproduced. It is found that the stratigraphic structure of ground snow can be made visible by a blazing fire. This phenomenon is due to the varying ability to absorb thawed water found in the different strata of snow.

Part II. The mode of snow-compression caused by ski-running is studied by the blazing fire method which makes the stratigraphic structure of snow visible. This blazing fire method is found to be very convenient for studying the distribution of stress in snow. The flow of snow accompanied by the motion of the ski is examined, using soot as an indicator. It is found that Prof. TERADA's theory of the mechanical properties of powder hold good in the case of powder snow. Similar experiments are repeated using a sled loaded with variable weights in place of a ski. The mode of snow-compression is studied, varying the temperature, the weight of the sled and its velocity. The instability of the motion of the ski in powder snow is discussed.

Part III. Supplementary experiments on the mechanism of ski-running are described. The position of the sliding plane of the ski is made visible by using red ochre pasted with alcohol to the tail end of the ski. The general displacement of the snow and the position of the sliding plane are studied by the simultaneous application of a blazing fire, soot and red ochre. The results are summarized and shown in a schematical diagram. The mode of compression and the flow of snow are studied systematically with reference to the snow structure. The position and strength of the invisible semi-crust in the snow are studied from the curve of the compression depth expressed as the function of weight. The existence of a mobile layer in the snow is found by using the soot method.

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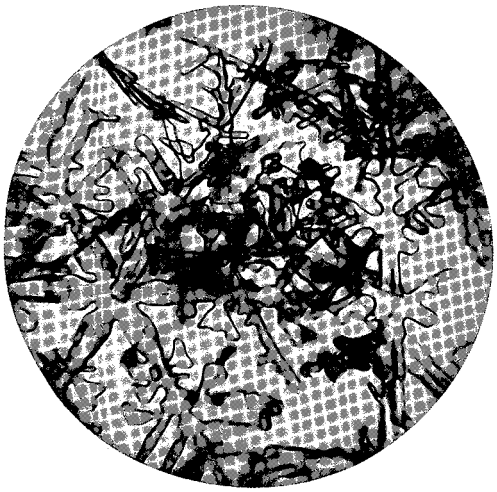

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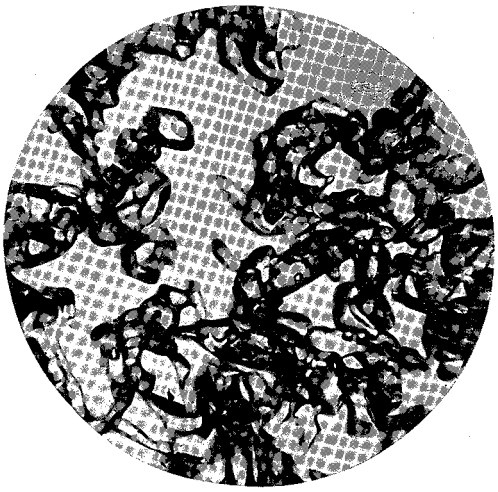

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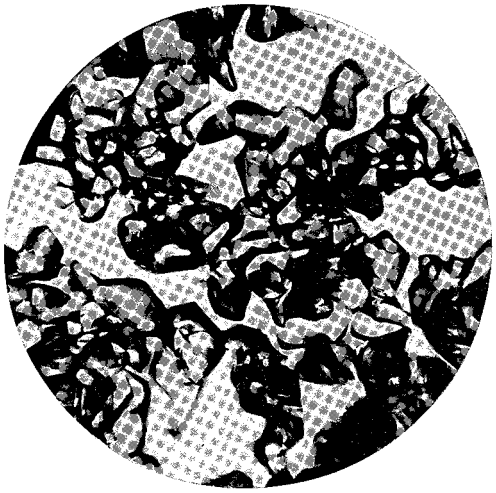

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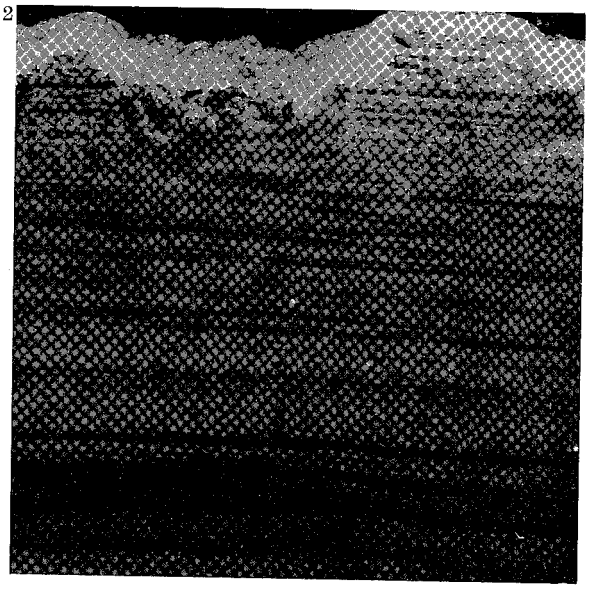

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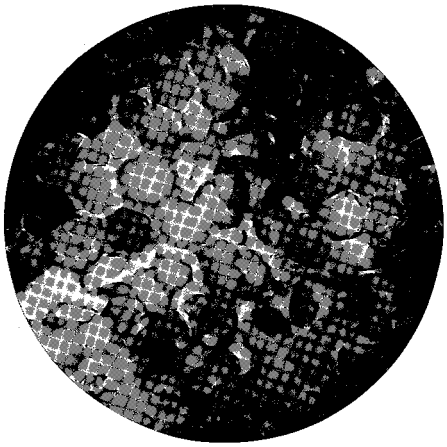

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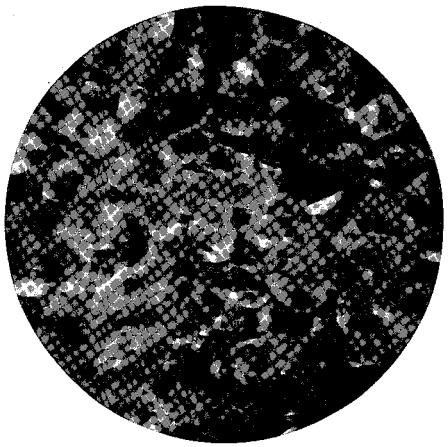

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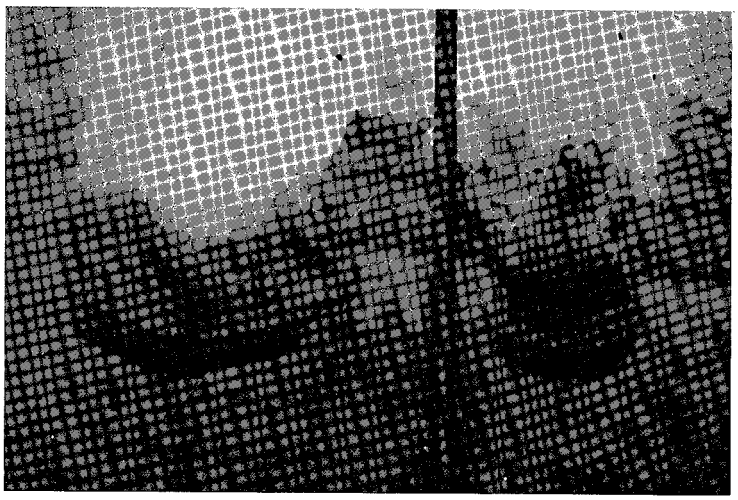

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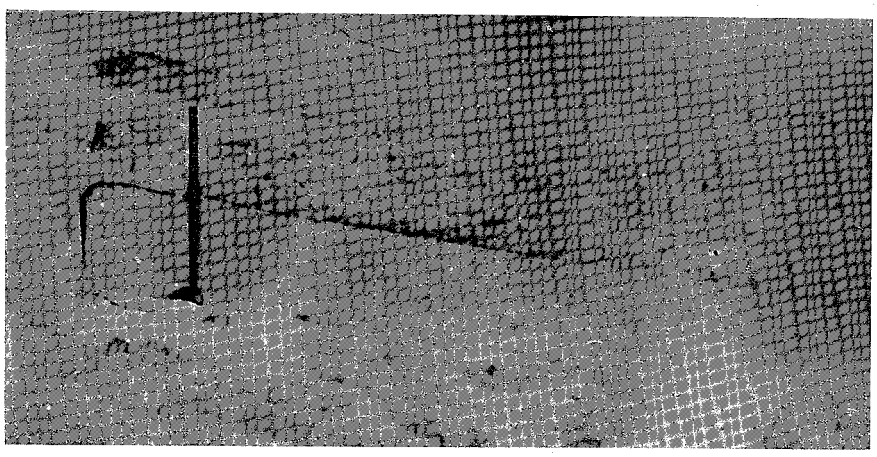

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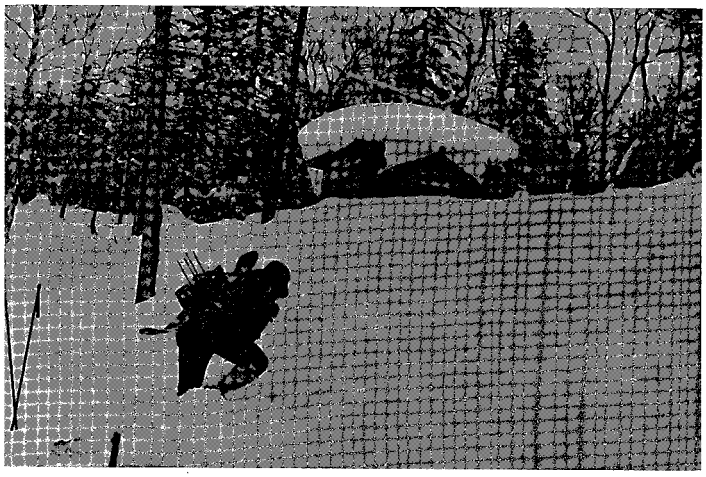

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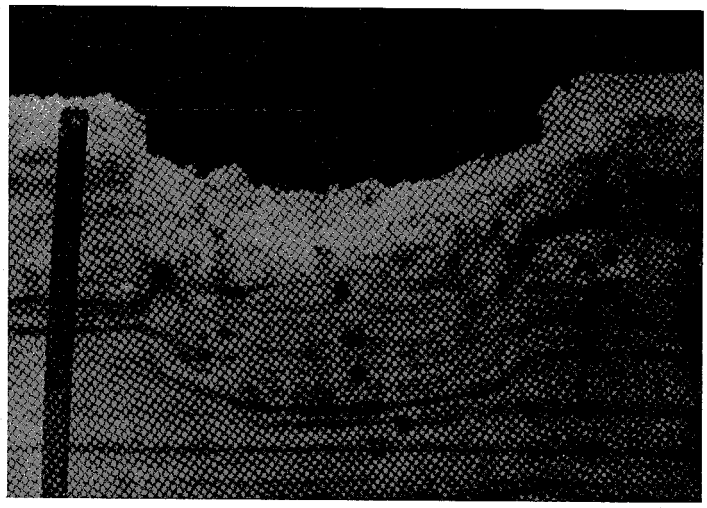

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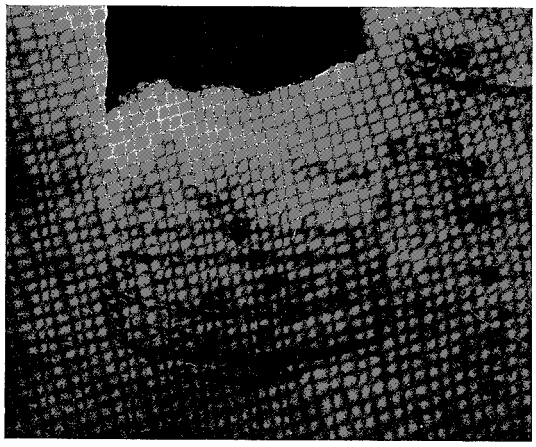

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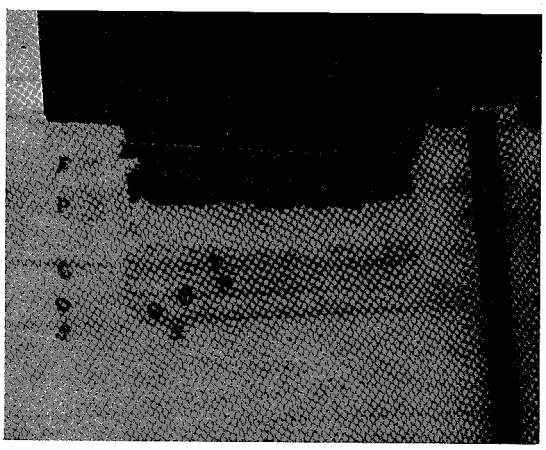

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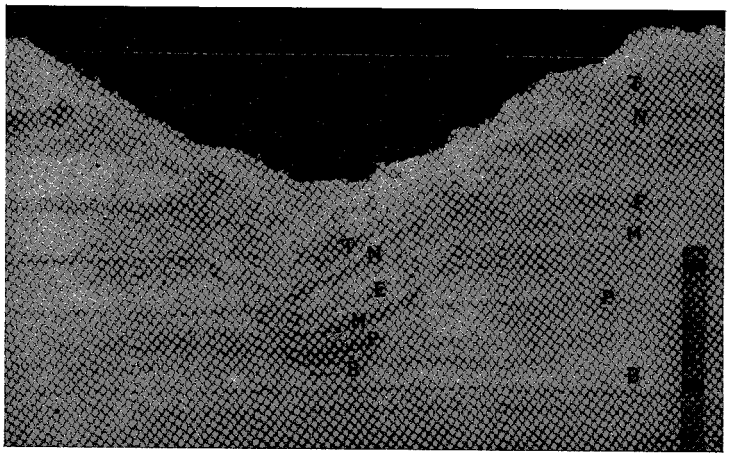

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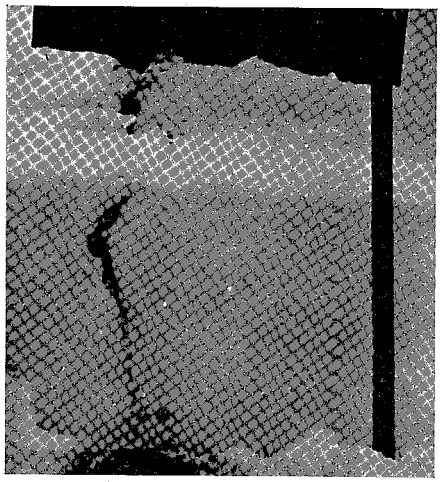

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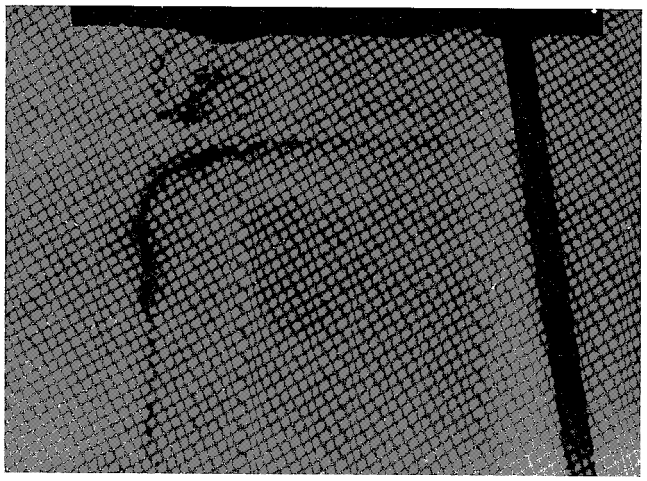

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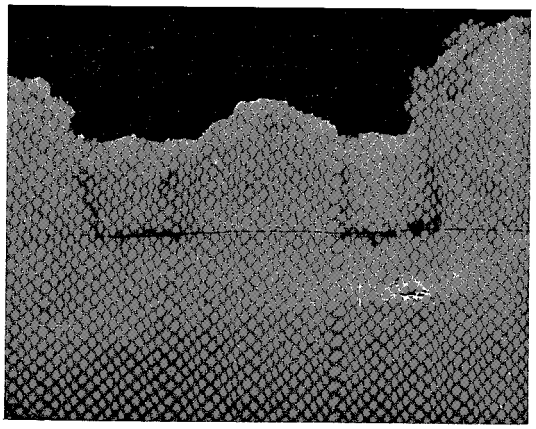

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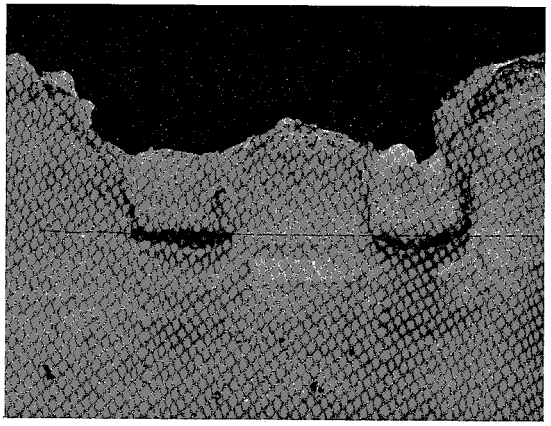

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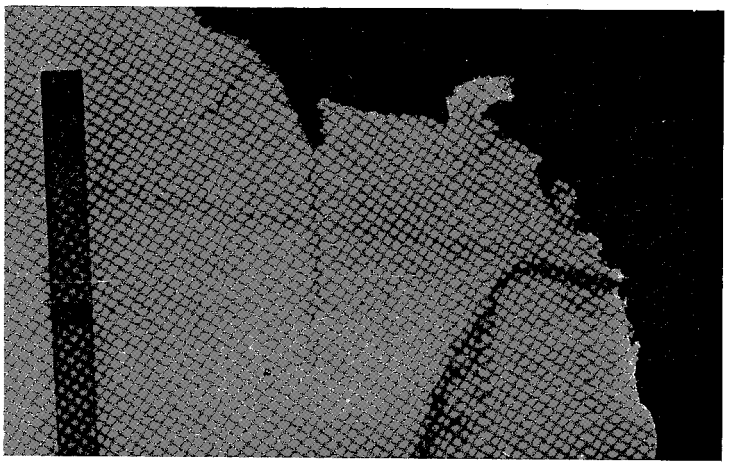

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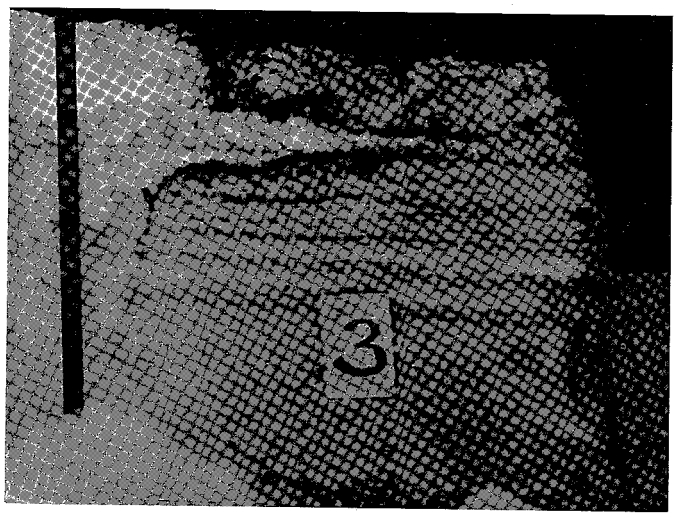

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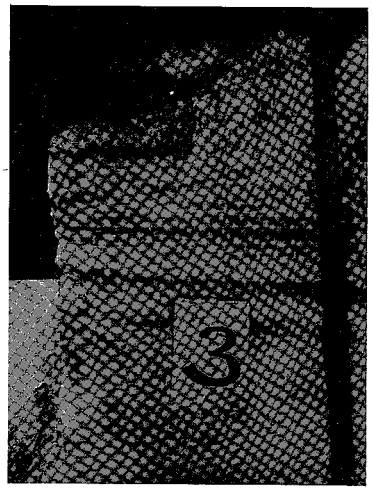

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