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PHYSICAL INVESTIGATIONS ON SNOW. PART I, SNOW CRYSTALS OBSERVED IN 1933 AT SAPPORO AND SOME RELATIONS WITH METEOROLOGICAL CONDITIONS.

By

Ukitirô NAKAYA and Tuneo IIZIMA.

1. INTRODUCTION.

Sapporo is the prefectural seat of Hokkaido, the northern island of the Japanese archipelago, and is situated near the coast of the Japan Sea. During the winter it is severely cold and snow falls very frequently, the whole land being covered by snow drifts continually from the beginning of December to the end of March. The mean temperature is about -3.2°C in Dec., -6.3° in Jan., -5.4° in Feb. and -1.7° in March, and it is very seldom that the maximum temperature exceeds 0°C in January or February. As the climate is suitable for the study of the problems connected with snow crystals and snow drifts, one of the authors has decided to attack this subject during a period extending over successive winters, this report being the first of a series.

Last year we secured the famous collection of snow crystals by Bentley, published in one volume with a preface by Humphreys[(1)]. This is no doubt the most comprehensive work in this field, but unfortunately the reproduced photographs lack descriptions of magnification and dates of fall. Although his method of reproducing beautiful microphotographs of snow crystals,—cutting the film away on duplicate negatives along the rim of the image,—leaves their scientific value wholly unimpaired for ordinary purposes, it is more

(1) Bentley and Humphreys, Snow Crystals, New York, 1931.

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desirable to get the detailed structure without touching the film for special purposes like examining the crystal habit of fine fern-like crystals. This was done as shown in the accompanying photographs by using Tôyô Process plates and a careful method of developing. During the winter of 1933 we took microphotographs for 17 snow-falls and tried to discover relations with the weather conditions. Examining 140 photographs obtained, there were found 11 types of crystals among 17, into which Humphreys proposed in Bentley's book to classify all the snow crystals hitherto known to us(1). Besides we found one, and only one, crystal of new type probably not reported yet, which will be described later. This copious variety observed in only one season indicates that observations at a place like Sapporo, which is near to the sea-coast and is enriched with diversified weather conditions, can be very fruitful.

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(1) Humphreys proposes to classify snow crystals into the following types for descriptive purposes.

A. Hexagonal column.
* § 1. Plane and with ends normal to side faces.
* § 2. With ends terminating in thin plates normal to the sides and of greater diameter than the column.
§ 3. With end plates and also one or more intermediate plates.
* § 4. With one end pyramidal, and one plane.
5. With both ends pyramidal.

B. Hexagonal right pyramid.
6. Right pyramid complete.
7. Right pyramid truncated.
8. Double or abutting pyramids complete.
9. Double or abutting pyramids truncated.

C. Hexagonal plate.
* § 10. Relatively large and plane.
* § 11. Relatively large and with simple extentions at corners.
* § 12. Relatively large and with elaborate extentions.
* § 13. Relatively small, with long plane rays.
* § 14. Relatively small with fern, or plum-like, extentions.

D. Triangular plates.
* § 15. Plane.
* § 16. With extensions.

E. Twelve-sided plates.
* 17. With extensions, six of one kind and alternately six of a different kind.

* Reproduced in Bentley's book.
§ Observed at Sapporo in the winter of 1933.

2. EXPLANATION OF PHOTOGRAPHS.

The method of taking microphotographs is almost the same as Bentley's. Snow crystals are received on a glass plate which is previously kept dry and cold in a snow bath, and are examined with a magnifying glass in order to choose a perfect crysal. Under some weather conditions they fall as individual crystals, but usually these crystals are gathered together, from twenty or thirty to several hundred of them making a cluster. For future reference we shall call this cluster a "snow flake," and the component crystals "snow crystals." When snow falls in the state of flakes, we receive one flake on a glass plate and breathe upon it gently to detach a few component crystals from the cluster, or simply wait till a separated crystal comes on the plate, which, in our climate, is always more or less mixed with the flakes. When a suitable crystal has been obtained, it is brought under the microscope and photographed by transmitted light. As a source of illumination the light of the sky was found after several trials to be most suitable for the purpose.

a) Plates of hexagonal symmetry.

Photos. 1–5 and 7, 8 are the most common type of snow crystals, being plates of hexagonal symmetry with more or less dendritic extensions. According to Humphrey's classification they belong to types 11–14, and, as a group, are sometimes called the stellar plate form. The fern-like crystals as shown in Photos. 4, 7 and 8 are frequently observed at Sapporo. They are relatively large, being usually 3–4 mm. in diameter, and their structures can be well observed by the naked eye. In Bentley's observations at Jericho this type is reported to be relatively small in size. Photo. 9 is an example of the plane hexagonal plate. This type was relatively seldom observed at Sapporo last winter, and it was comparatively small in size, whereas Bentley, in his observation, reports that it belongs to a type of larger size. These inconsistencies will no doubt be due to the difference in climatic conditions.

b) Plate of digonal symmetry.

Photo. 6 shows an example of a crystal of digonal symmetry. This type is not infrequently reported by many observers, and is sometimes explained as the result of the uniting of two nuclei of crystals at an early stage of their development. This, however, cannot be so simply explained, because the digonal nature is not only noticeable in its form but also in its minute structure or design. For example, in Photo. 6, the designs of three plane rays in one side of the digonal symmetry are all unlike each other, "equal" marks being seen near the centre only in two opposite horizontal rays.

c) Plates of trigonal symmetry.

Photos. 10 and 11 are examples of the plates of trigonal symmetry. This type is classified by Humphreys as a triangular plate, but it will be better called a plate of trigonal symmetry. The former takes the form of regular hexagonal plate, but the design shows character of marked trigonal symmetry. The latter is an example showing the trigonal nature both in form and design. This type of crystal is not at all rare, being reported by many observers, as Dobrowolski, Mügge, Bentley, etc. This leads Wherry[1] to take the system of crystallisation of ice as trigonal.

d) Crystals with small water droplets.

It is well known that sometimes small water droplets attach to a snow crystal, scattering irregularly all over the surface, as shown in Photos. 12 and 13. In Bentley's book this type is not often reproduced, but in our observations at Sapporo last winter, five snowfalls out of seventeen observed consisted almost entirely of this type. The abundance of this type is, as will be described later, probably due to geographical position, our observations being made near to the sea-coast.

e) Columnar crystals.

Photos. 14–19 show examples of columnar crystals. During last winter this type was observed in three snowfalls in February. The

(1) E. T. Wherry. Monthly Weather Rev. 48 (1920) 29.

hexagonal cylinder as shown in Photo. 14 was most abundant, but the one with a pyramidal face at one end as reproduced in Photo. 15 was also not infrequently observed. Photos. 16a and b show the mode of melting of the hexagonal cylinder. The process of liquefaction proceeds from both ends, showing a marked nature of polarity. When Adams(1) obtained this columnar crystal of ice by mixing air saturated with water vapour with air vaporized from the surface of liquid air, he observed a mode of liquefaction exactly similar to that in Photo. 16a. Judging from this polar nature, he considered this hexagonal cylinder not as a crystal individual but as a twine. Though the column with a pyramidal face as shown in Photo. 15 has not yet been obtained in the laboratory, and, accordingly, its nature is still somewhat unknown, it is very probable that this crystal is a crystal individual of ice. Examination of the crystal structure of ice by the X-ray method has been tried by many workers without a conclusive result; the recent study of Barnes(2) has led to the supposition that it is possibly D_{3h}^4 (ditrigonal bipyramidal) or D_{6h}^4 (dihexagonal bipyramidal), the latter being more probable, although neither show any polar nature. There is, however, some objection(3) to his theory, and it will be better considered that the X-ray determination of the crystal structure of ice is not yet completed. Another illustration which seems to show the strong polar nature of the pyramidal terminations of crystals of the type of Photo. 15 is that they have a tendency to unite with each other at their heads. We observed in only one season of last winter three examples of two, three and four of these crystals uniting at their pyramidal ends as shown in Photos. 17–19.

3. RARE CRYSTALS.

It is generally accepted that all snow crystals are classified into two prominent types, the plate form and the columnar crystal. The former is believed to be due to the rapid development of the crystal

(1) J. M. Adams, Phys. Rev., 35, (1930) 113. Proc. Roy. Soc. A, 128 (1930) 588.
(2) W. H. Barnes, Proc. Roy. Soc. A, 125 (1929) 670.
(3) E. Brandenburger, ZS. f. Kristallographie, 73 (1930) 429.

in the basal plane of the hexagonal system, while the latter is obtained by the growth of crystals along the principal axis of the system of crystallisation. Sometimes those two types are combined, resulting in a columnar crystal with thin hexagonal plates at one or both ends attached normally to the sides. The hexagonal column with end plates and also one or more intermediate plates is seldom reported. A photograph of a crystal of this type with two intermediate plates was obtained last winter, and is shown together with its sketch in Photos. 20a and b. During microscopical observation of 17 snowfalls last winter, we noticed one crystal which takes the form of a hexagonal plate with the usual dendritic extensions but is remarkable in thickness, being opaque throughout when observed by transmitted light. A photograph of this thick plate of crystal is reproduced, Photo. 21a. This crystal looked to be an assemblege of columnar crystals standing side by side, as shown diagrammatically in Photo. 21b. This being the case, the crystal may be considered to disclose a complete combination of the two prominent modes of growth of snow crystal, that is, growing both in and perpendicular to the basal plane of the hexagonal system. This form is not described in Bentley's book, nor is it seen in the Atlas of V. Goldschmidt(1), and seems to be a new type not yet reported.

4. RELATIONS WITH METEOROLOGICAL CONDITIONS.

The relations between the type of snow crystal and the meteorological elements were studied by many workers. As for the relation with the temperature on the earth surface, Kalb(2) introduces the results of Heim's observations in the antarctic region, which state that when the air temperature was −27°C all crystals observed were of the columnar type, but, as the temperature rose higher, the plate type increased in number until plate crystals only were observed at

(1) Victor Goldschmidt, Atlas der Krystalformen, Heidelberg, 1916. This atlas illustrates about 550 crystals of ice and snow of various types.

(2) G. Kalb, Centralblatt für Mineralogie, A (1921) 129.

$-12°C$. More extensively, classifying snow crystals into seven types, Bentley studied statistically their relations with respect to the section of snowstorm, temperature and cloud source for 131 snowfalls. Referring to his result, Shedd(1) discusses the evolution of snow crystals relating to the surrounding conditions. The relation, however, with the meteorological elements observed on the earth surface is essentially of little importance. In consequence, these results obtained by many authors sometimes do not agree with each other. For example, in the case of Bentley's observation well developed stellar crystals were abundant when the air temperature was relatively lower, but according to the statistics by Hellman(2) the contrary was the case. As for the cloud source, here also, it seems that a direct relationship is not to be expected, as some form of snow crystal is probably grown near to the earth surface. As an example of an extreme case Hoffmann's observations(3) of snowfall in a large chamber may be cited, the snowfall being produced by an air current through an open window while no snow was falling outdoors.

Humphreys(4) succeeded in explaining the halos of unusual radii due to cloud at high altitude as being produced by hexagonal columns of ice acting as refracting prisms, and he concluded that such clouds are composed of columnar snow crystals. His view that the simple form of columnar crystal is produced by a slow process at a high altitude where humidity is less, while the plate with dendritic extensions is a product of rapid growth in a humid region near to the earth surface, is concordant with our present knowledge on crystal habits.

As for the relation with meteorological elements, not only the types of crystals but also the form of flakes is to be examined. The form of flakes is conveniently classified into two kinds: the "cotton snow flake" and the "powder snow." In the case of the former the

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(1) J. C. Shedd, Monthly Weather Rev., 47 (1916) 691.
(2) G. Hellmann, Schneekrystalle, Berlin, 1893.
(3) M. K. Hoffmann, Centralblatt für Mineralogie, A (1933) 177.
(4) Humphreys, Physics of the Air, 2nd Ed., 1929, pp. 483-518.

component crystals are usually of the stellar plate form and are uniting with each other at the ends of their branching rays, the macroscopic view appearing like a piece of cotton waste. These components usually keep their crystal forms individually in the cluster, as shown in Photos. 22 and 23. "Powder snow" is essentially a term for an assemblege of columnar crystals as shown in Photo. 24, but this is a rather rare case. The term "powder snow" that is used in daily life or by skiiers means a smaller snow flake in which the component crystals are deformed and entangled so that the form of the individual crystals is no more observed. Photo. 26 shows a part of this powder snow observed under the microscope. Of course there are many intermediate states between these two classifications: for example, trace of crystal structure is observed in some part of a powder snow flake. In some cases granular or small ball-like snow falls mixed with powder snow flakes. This type seems to be a product of the further development of ordinary powder snow. Under the microscope it looks like thin paper tapes crumpled round into a ball, as shown in Photo. 27.

It is sometimes believed that in Hokkaido cotton snow falls at the beginning and end of a winter season, and during midwinter, when the temperature is low, only powder snow visits the country, but actual observation shows that this is not the case, as will be seen in Table I. The temperature and humidity observed on the earth surface have no direct relation with the kind of snow flakes. Wind velocity, however, has a powerful influence, five examples in the Table showing that cotton snow is confined to occasions when wind velocity is 2 m/sec or less. When wind velocity increases to, say 6 m/sec, all snowfalls were of the powder type, but the contrary was, naturally, not the case. It is obvious that the wind velocity observed on the earth surface does not tell anything about the wind velocity at higher altitudes where the powder snow is formed. We can say only that calm weather is necessary for the formation of cotton snow and that great wind velocity has strong bearings on the origin of powder snow. Problems concerning the formation of snow flakes seem to be of

TABLE I.

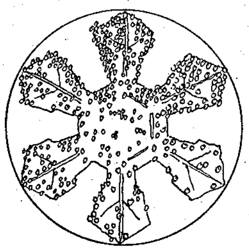
Date	Photo-graphed	Form of flake and crystal	Wind direction	Wind velocity	Humidity	Tempera-ture	State of Snowfall
I 26	15–16h	Cotton flake, regular crystal	SE	2m/sec	83%	–7°C	Whole day
29	15–16	Powder snow, crystal deformed	N	1	75	–6	5 hours
II 5	15–16	Cotton flake, with droplets	NNW	1.5	95	–3	Few hours
9	10–11	Powder snow, with droplets	NW	2	70	–3	,,
10	15	Powder snow, crystal deformed	SW	2	62	–4	,,
	18–20	Columnar crystal mixed	NW	10	100	–8	Continuous
13	16	,, ,, ,,	W	1.5	85	–7	Few hours
15	15–16	Powder snow, granular mixed	N	9	90	–6	Intermittent
	19–20	Relatively regular crystal	SE	2	100	–8	,,
17	16	Powder snow, with droplets	NW	6	95	–7	Few hours
	20–21	Cotton flake, regular large	E	1	95	–9	,,
20	10	Powder snow, with droplets	NW	6	90	–5	,,
22	10–11	Cotton flake, regular large	SE	1	85	–4	Continuous
23	11	Cotton flake, regular	E	2	75	-6	Intermittent, heavy
	13–15	Powder snow, with droplets	NE–WNW	1.5–8	90–60	–4	Intermittent
24	11–13	Columnar crystals only	ES	3.5	85	–3	Continuous
	15–17	Columns and plane plates	E	3	95	–6	,,

interest specially from the practical point of view, but our present data are not sufficient enough to discuss the matter further. We are compelled to confine ourselves in future descriptions to the crystal type only.

We examined meteorological elements and weather charts on each day in which photographs of snow crystals were obtained, and tried to see whether we could draw some conclusion from these data observed on earth surface. Paying attention to the fact that Sapporo is situated near to the sea-coast and the sea-winds blow directly from the Japan Sea without any intervening obstacle, we first examined the wind direction and noticed that snow crystals with water droplets as Photo. 12 are observed chiefly when the wind comes from the direction of the sea-coast, that is, when the wind direction is NW. As is seen in the Table, four snowfalls out of five of this kind occurred when the wind was NW. In one case it changed from NE to WNW, still from the direction of the sea-coast. A typical example is the case of Feb. 5th. As the weather charts (Fig. 1c and d) show, the weather was calm and no line of discontinuity was seen on the charts. While the wind was SE or S during the morning, that is, from the direction of the mountainous district, it suddenly changed to NW at about 13h. At the same time the humidity increased from about 50% to 90%, the temperature began to fall, and it began to snow. When the wind direction changed back to SE again at about 17h the snowfall ceased. These circumstances are clearly seen in Fig. 1b. In this case almost all snow crystals were of the type attached with innumerable water droplets, as shown in Photo. 12, and they came down in the state of cotton snow flakes. In the four other cases, also, a similar relation was observed, though not so clear as in this example. In those cases the wind velocity was 6 m/sec or more, except in one case, and the kind of flakes was powder type. An example of powder snow flake with water droplets is reproduced in Photo. 25. As the abundant existence of minute water droplets of which the nuclei are ultra-microscopic spray of sea-water is made clear by the studies of Aitken and others, it will be of interest to perform a chemical analysis of this kind of snow.

Fig. 1. a, b, c and d.

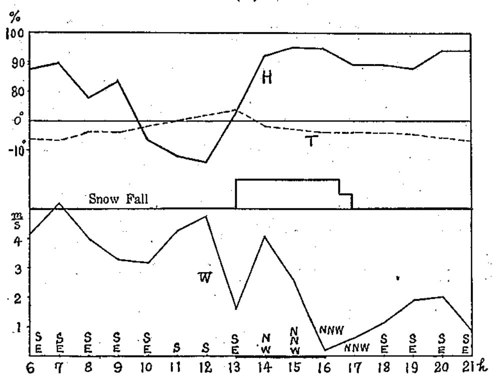
(a)



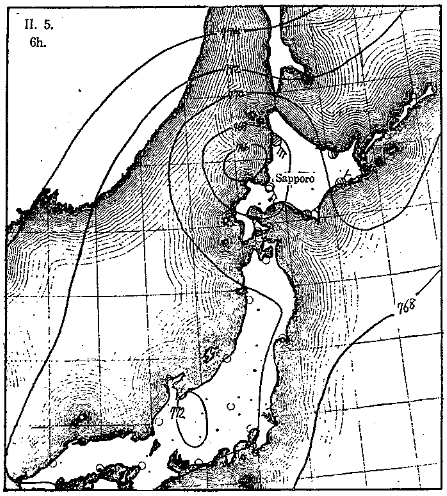
×29

Photo. 12.

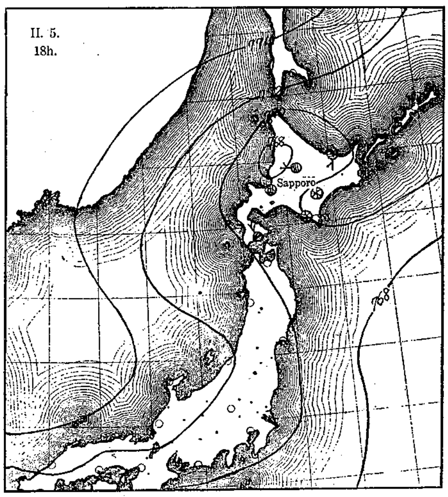
(b)



(c)



(d)



Columnar crystals were observed in three snowfalls: of Feb. 10th, 13th and 24th. From Feb. 10th till 13th a line of discontinuity was persistent on the Pacific along the Japan Arc and a cold spell visited the whole country. The mean temperature of the three days, Feb. 11th 12th and 13th, was −12°C, being about 5°C below those of the preceding and following days. The columnar crystals observed on Feb. 10th and 13th(1) are no doubt an accompaniment of the cold spell.

(1) Observations on Feb. 11th and 12th are lacking, but it snowed also on these days and it seems that columnar crystals were mixed with plate types in those cases.

This case is concordant with the records of various observers, which say that columnar crystals fall when the temperature is low. The temperature observed on the earth surface, however, seems to have no direct bearing in this case either. This will be recongnized from the observations on Feb. 24th. Almost all the crystals which fell on this day from 11h to 15h were of the columnar type, as shown in Photo. 24, and after 15h plane hexagonal plates began to mix with the columns. The temperature on the earth surface was, as shown in Fig. 2b, about -5°C during the snowfall, it being a rather warmer day than the others.

Fig. 2. a, b, c and d.

(a)

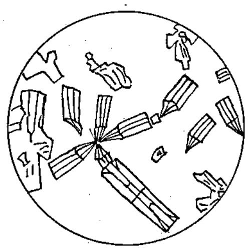


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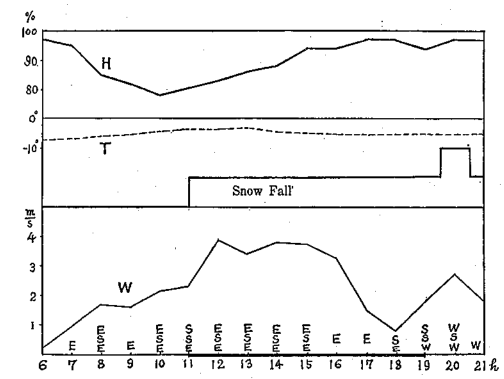
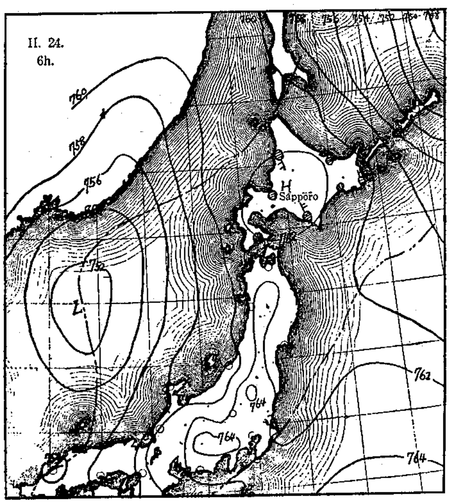
Photo. 24.

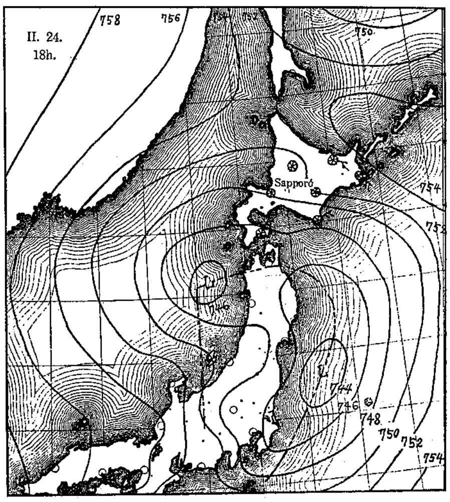
(b)



(c)



(d)



The weather charts are shown in Figs. 2. c and d. We see that conspicuous lines of discontinuity were falling on the Japan Sea and the Pacific, and changed their positions abruptly during the time interval between 6h and 18h. The gradient of atmospheric pressure was also very steep. All these characteristics show the violent disturbance of weather conditions, which, according to Humphreys, will be favourable for bringing down to the earth surface the snow crystals at high altitudes.

5. CONCLUDING REMARKS.

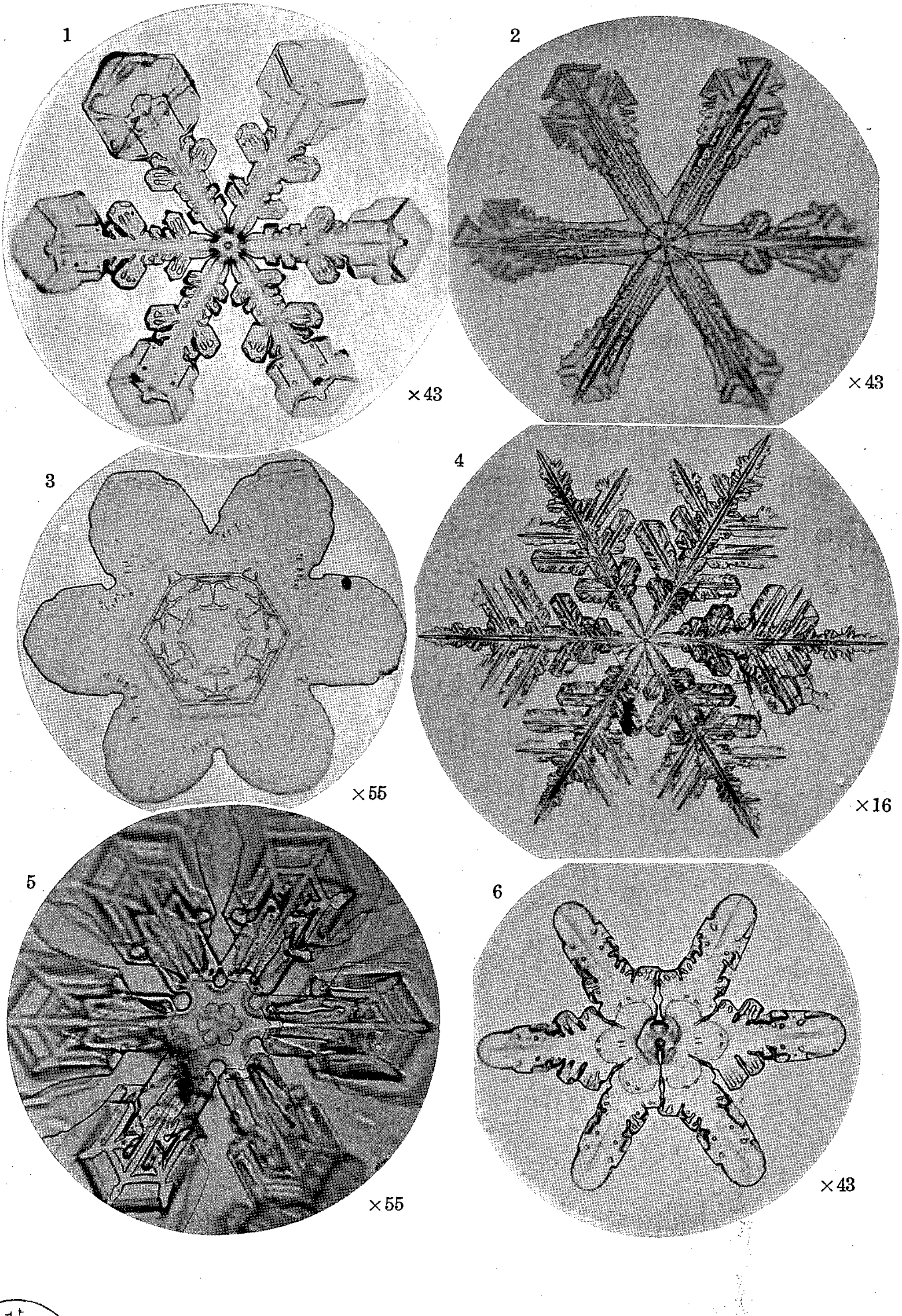
Concerning the evolution of snow crystals, it is now generally accepted that simple forms are obtained by a slow process and dendritic forms occur when developed rapidly from a supersaturated atmosphere, as the tendency of the mode of crystal growth in general. Difficulties, however, arise from the facts that snow-crystals are developed by direct condensation from vapour phase and the molecular nature of water is so complicated that even the crystal lattice of ordinary ice is not yet determined. Accordingly the mechanisms of the development of various types of snow as described here and elsewhere are, in the present state of our knowledge, far from being clarified. The best way for attacking this problem is, of course, to make them in laboratory, but few attempts seem to have been made in this line. So far as our literature at hand is concerned, the experiment of Adams(1) is the only one. He succeeded in making columnar crystals in the laboratory, but the conditions under which they were produced are not clearly known. Attempts at producing snow not in atmospheric air but by suspension in other liquids have been tried by many workers. Czermak(2) made hails in a mixture of toluol and chloroform, Hoffmann(3) produced powder snow by cooling water mixed with a small quantity of saponin, and Kuroda(4) reports

(1) Adams, loc. cit.
(2) Paul Czermak, Sitz. Ber. Wien, II, a, (1900) 185.
(3) M. K. Hoffmann, Cetralblatt f. Mieralogie, A, (1933) 177.
(4) M. Kuroda, Kwagaku, 3 (1933) 276, (in Japanese).

that he obtained crystals of the hexagonal plate form by cooling a mixture of water and alcohol. When the artificial production of snow crystals is developed further our knowledge on this subject will be greatly improved.

EXPLANATION OF PHOTOGRAPHS.

1. Regular crystal of hexagonal symmetry, I. 26. 15h., ×43.
2. ,, ,, , ,, , ,,
3. ,, ,, , II. 24. 15. 5h., ×55.
4. Larger crystal, I. 26. 16h., ×16. (dia. 3. 8mm.)
5. Regular crystal, II. 10. 18h., ×55.
6. Crystal of digonal symmetry, I. 26. 15h., ×43.
7. Larger crystal, II. 22. 11h., ×20. (dia. 3. 1mm.)
8. ,, , ,, , ×25.
9. Hexagonal plate, II. 24. 15. 5h., ×73.
10. ,, of trigonal symmetry, II. 24. 17h., ×55.
11. ,, ,, , ,, , ×120.
12. Snow crystal with water droplets, II. 5. 16h., ×43.
13. ,, ,, , I. 26. 16h., ×43.
14. Columnar crystal, II. 24. 11h., ×55.
15. Crystal individual of snow, II. 24. 11h., ×55.
16. Mode of melting of a columnar crystal, (a) II. 24. 12. 5h., (b) 13h., ×55.
17. Two crystal individuals uniting together, II. 10. 19h., ×55.
18. Three ,, ,, , II. 10. 18h., ×55.
19. Four ,, ,, , II. 24. 12h., ×50.
20. Combination of a columnar crystal and plates, II. 24. 16h., ×55.
21. New type of snow crystal, II. 23. 14h., ×20.
22. Part of a Cotten snow flake, II. 23. 11h., ×12.
23. ,, ,, , II. 22. 10h., ×14.
24. Assemblage of columnar snow crystals, II. 24. 13. 5h., ×20.
25. Powder snow with water droplets, II. 23. 13h., ×20.
26. Part of powder snow, I. 29. 15h., ×43.
27. Granular or Ball-like snow, II. 15. 15h., ×50.


1
×43
2
×43
3
×55
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×16
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×55
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×43

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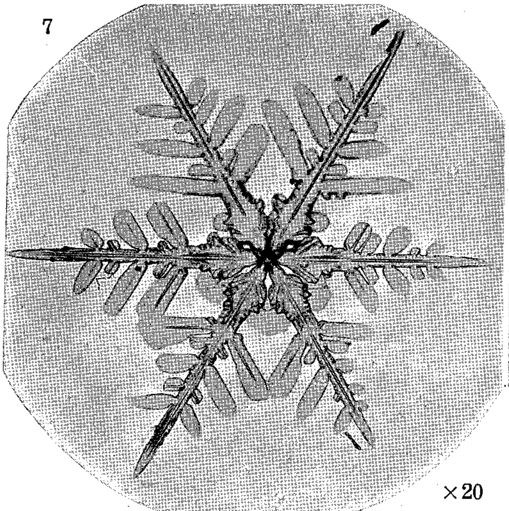

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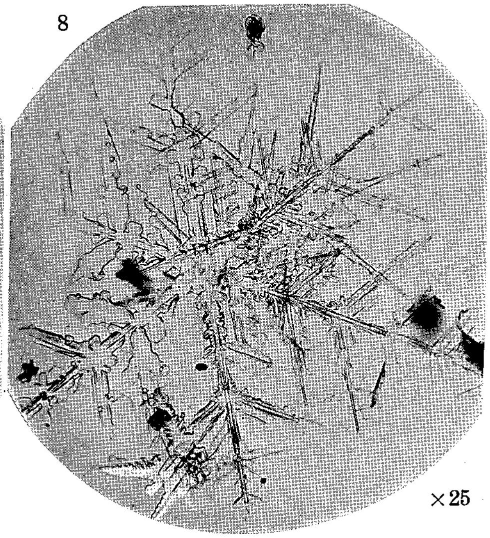

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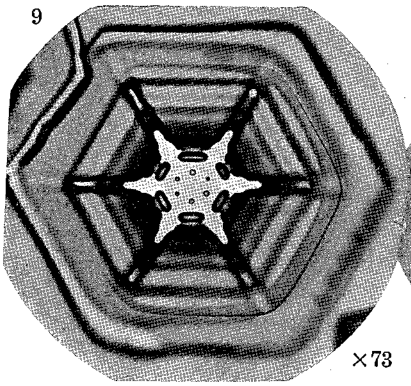

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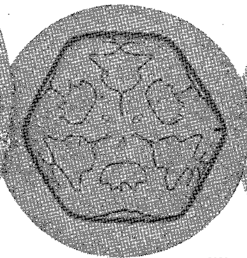

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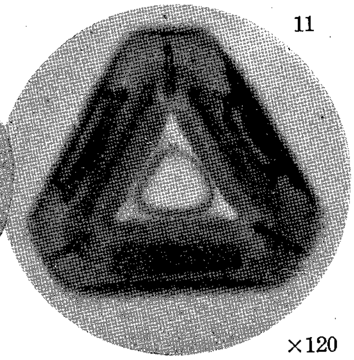

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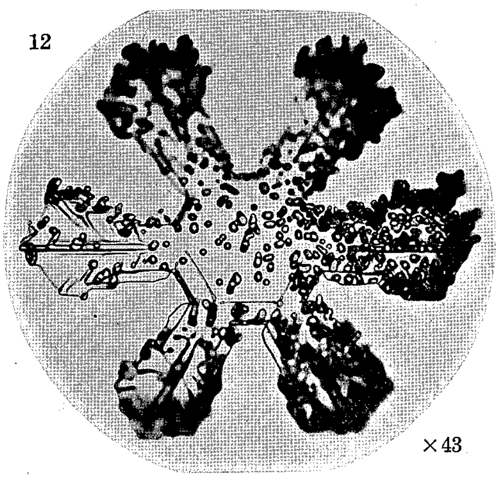

×43

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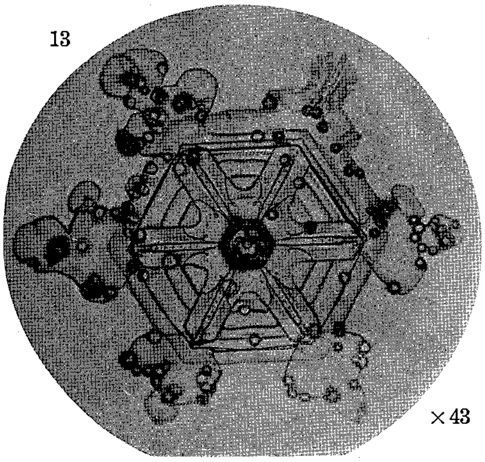
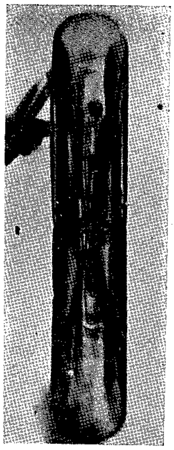


×43

14

×55



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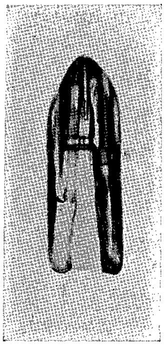

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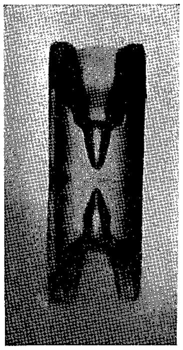

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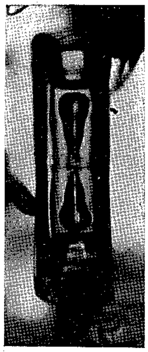

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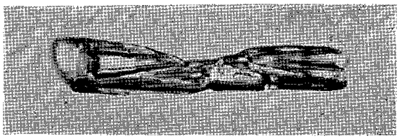

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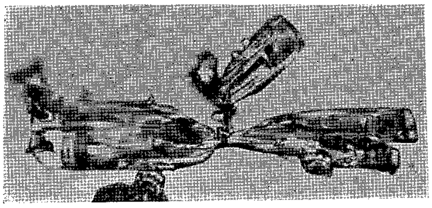

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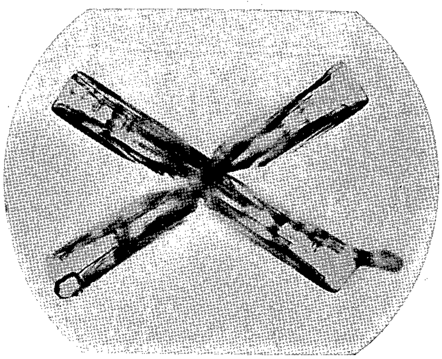

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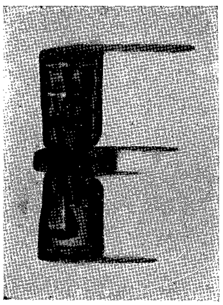

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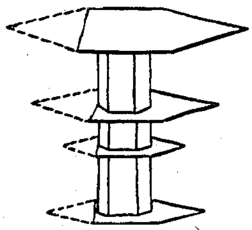

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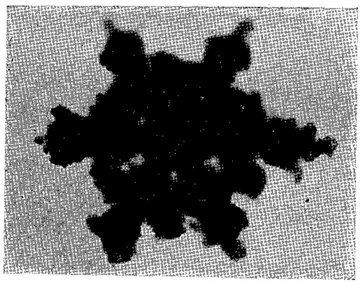

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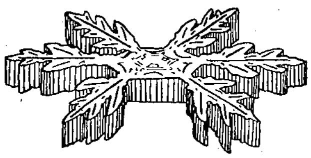

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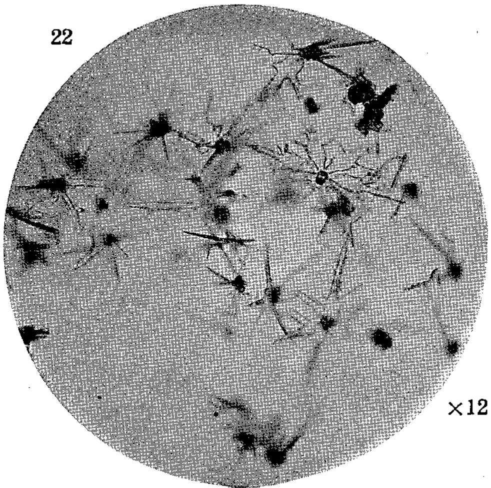

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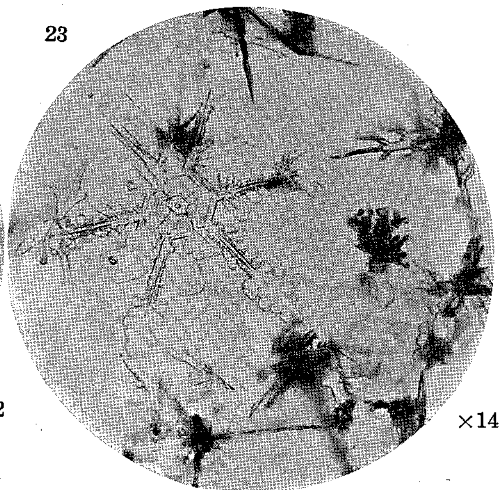

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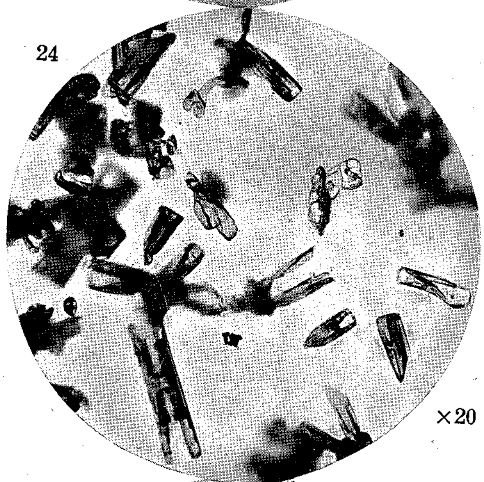

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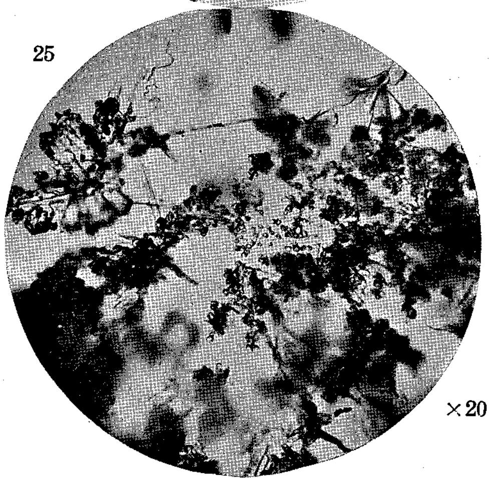

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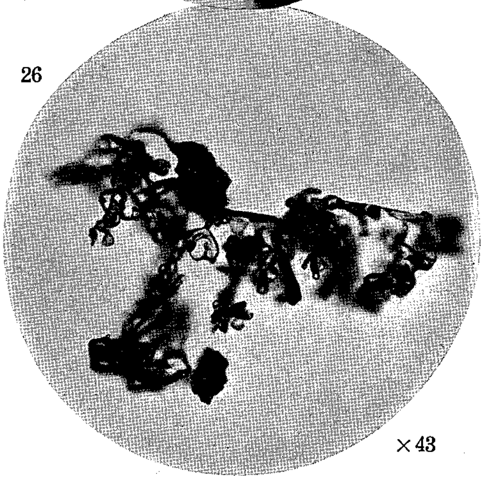

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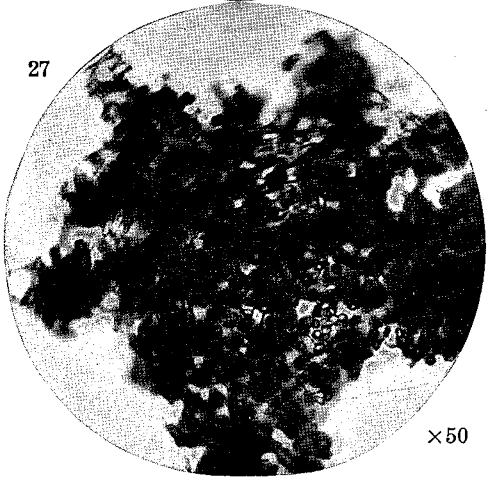

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