

A CONTRIBUTION TO THE STUDY OF THE GLACIER GRAIN

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ABSTRACT. The melting of glacier ice always begins at the surface of the glacier grains. A mass of glacier ice at a temperature near its melting point is therefore an aggregate of crystals separated by a film of liquid. The electrical conductivity of ice subjected to differential melting differs considerably according to whether the fractions come from the grain surfaces or from the crystal centres, being much the higher in the former case. It is concluded therefore that the glacier grain consists of a crystal of pure ice with a surrounding film of brine, thus verifying the hypotheses of Buchanan and of Quincke on the formation of natural and artificial ice.

The growth of the grain is facilitated by the elimination of the saline skin between neighbouring crystals, the resulting coalescence having the character of autogenous welding. On the other hand, the intergranular film of liquid may act as a lubricant in the as yet inadequately explained mechanism of glacier flow.

RÉSUMÉ. La fusion de la glace de glacier commence toujours à la surface des "grains." Aussi, la masse d'un glacier dont la température est au voisinage du point de fusion n'est-elle qu'un agrégat de cristaux séparés par un film liquide.

Dans cette étude, l'auteur montre que la glace soumise à une fusion fractionnée livre des tranches d'eau d'une conductivité électrique globale très différente, celle issue de la surface des grains étant beaucoup plus élevée que la conductivité de l'eau provenant du centre des cristaux. Il en conclut que le grain de glacier est l'association d'un cristal de glace pure et d'une saumure adhérente, vérifiant ainsi les hypothèses de Buchanan et de Quincke sur la formation de la glace naturelle et artificielle.

Selon l'auteur, la croissance des grains est facilitée par l'élimination de la pellicule saline entre les cristaux voisins, et la coalescence qui en résulte a le caractère d'une soudure autogène. D'autre part, le film liquide intergranulaire intervient probablement comme lubrifiant dans le mécanisme encore mal expliqué de l'écoulement de la masse glaciaire.

I. INTRODUCTION

Glacier ice results from the slow metamorphosis of snow accumulated in the *névé* regions. The structure of this ice is well known; it is composed of "grains" of ice, each of which is a crystal of the hexagonal system but of very irregular surface. These crystals are embedded in one another and, so far as alpine glaciers are concerned, the principal axes of these crystals are generally without preferred orientation. At temperatures lower than their melting point they form a mass which is so compact that a blow produces a conchoidal fracture which does not conform with the surfaces of the grains.

The melting of glacier ice has been described in detail by many authors from Hugi (1843) onwards and I shall only mention the process very briefly. A block of ice exposed to the sun's rays or any other heat radiation does not melt in a homogeneous manner. The melting takes place first at the surface of contact, and the crystals thus freed resemble the mixed-up pieces of a jig-saw puzzle. Later, the grains separate more completely, and show new phases of melting which cause the striations of Forel and the figures of Tyndall to appear. Forel's striations show up the laminae of ice on the crystal surface perpendicular to the main axis. Tyndall's figures are melt phenomena inside these laminae and often contain a little air.

Thus, when the temperature of the glacier approaches the melting point, the ice loses its compactness and becomes an aggregate of crystals separated by a liquid film. When this film can no longer adhere to the surface of the grains, it drains away through the capillary fissures observed by the old naturalists. These fissures are in reality the intergranular canals resulting from an advanced state of melting.

These facts are classic and allow us to presume the existence of the heterogeneous composition of the glacier grain to account for which various physical-chemical hypotheses have been suggested (see section 3). These hypotheses prompted me to make an experimental study of which the main results are set out below.

2. EXPERIMENTS IN CONNEXION WITH THE STRUCTURE OF THE ICE GRAIN

From 1932 to 1947 I examined some fifty specimens of ice from the following glaciers: Fee, Gorner, Great Aletsch, Ried, Rhône and Saleinaz, all situated in the Valais (Switzerland). All samples were taken with the greatest care from sound, compact ice, but through lack of proper means I had to confine my investigations to surface ice and to that of some grottoes dug to satisfy the curiosity of tourists (Fee, Rhône). However, near the Jungfrauoch Scientific Research Station (Hochalpine Forschungsstation Jungfrauoch) I found a veritable ice laboratory made by Dr. R. U. Winterhalter, where I was able to study *névé* ice taken from a depth of about 20 m. in ideal conditions. Facilities for doing part of the work at the Research Station itself were also placed at my disposal.

In the specimens examined, I found grains of very varied dimensions, from those of 1 cm. at the Jungfrauoch to those of 10–15 cm. on the lower tongue of the Great Aletsch Glacier, between Riederalp and Aletschalp.

Each specimen of ice was melted on the spot or nearby either by means of the sun's rays, or by the rays of an electric arc from the Jungfrauoch laboratory. I usually melted 300 grammes of ice, gathering separately the ten samples of water successively yielded by the fractionated melting of the grains. It makes no difference whether the specimen is composed of a single block of ice or of several pieces. The rays, penetrating to the interior of the transparent ice, start the melting process on the surface of each grain, so that the first sample of water, having seeped through the numerous capillary fissures, unquestionably originates from the first layer, that is the surface, of the grains. The subsequent samples are produced by the progressive melting of the grains in the direction of their centre. The process is therefore one of fractionated melting of which the last sample yields water from the central portion of the grains.

When the specimen of ice is taken from the frozen glacier, as for example from the Jungfrauoch where the ice temperature is about -4°C ., the first layer of melting only appears after exposure of the ice to radiation, and the water that it yields can be collected without difficulty. But in the case of ice from the glacier tongue, the temperature of which is at about freezing point even in a grotto, the surface of the crystals is already in process of melting, which necessitates special operational precautions to avoid the loss of some or all of the first layer of melting.

It must be noted, too, that the complete and rapid separation of the successive samples of water is far from perfect. Moreover, as it is necessary to work at a temperature above 0°C ., it is not easy to avoid the melting of the ice on contact with the air or with the vessel containing the ice. Finally, the water contained in the Tyndall figures drains off simultaneously with that of the melting of the grains, and mixes with the various samples collected.

It is therefore probable that the chemical composition of the successive samples of water which are collected differs somewhat from the real chemical composition of the various layers. However, although these considerations are not negligible, they in no way modify the general results and the theoretical conclusions.

Although the masses of the ten samples of water collected are equal, they correspond to very unequal fractions of the diameter of the grains. The first only represents a thickness of 0.035 of the diameter of the grains, that is an outer skin equal to only one-thirtieth of the thickness of the grains. The last, on the other hand, represents 0.465 or nearly half the diameter.

The various melt water samples were analysed immediately, or at the very most a few hours after collection, in order to avoid the inevitable changes which would have resulted from keeping them. It became clear at once that the low content of dissolved substances excluded any possibility of gravimetric analysis. On the other hand, taking into consideration the object of this research and wishing to make use of a simple method which could be applied on the spot, my choice fell on the measuring of the total conductivity of the solutions by the usual method for determining

the conductivity of electrolytes. This method is too well known to need description here. I merely recall that the conductivity, or specific conductance, is the inverse of the resistivity or specific resistance. The practical unit of conductance is the Mho/cm., or reciprocal of the practical unit of resistivity, the ohm-cm. Ordinary double distilled water, from which the CO_2 has been removed by boiling, has a conductivity of 1×10^{-6} Mho/cm. The conductivities measured during the course of this research are very low, being between 1×10^{-6} Mho/cm. and 1×10^{-4} Mho/cm., rarely more. It follows therefore that the concentration of substances dissolved in the water is also very small, and that this concentration is roughly in proportion to the conductivity.

My research has not yet been directed towards the actual nature of the substances contained in glacier ice. It is, however, very probable that this is a question of the salts brought down by atmospheric precipitation, and in which may be recognized—according to various authors—ammoniacal nitrogen, nitrous and nitric acids, chlorides and sulphates, sodium salts and dissolved gases. According to my own observations, the concentration of these salts in glacier ice occurs to the same extent as that which I have measured in atmospheric precipitations in upper mountain areas.

3. PRINCIPAL RESULTS

(a) *Whatever its origin the glacier grain is always composed of a crystal of pure ice surrounded by a saline skin.*

By way of example, the following are the results of analysis No. 17 of a specimen of ice taken on 14 August 1936, from the grotto of the Fee Glacier (Saas-Fee).

COMPUTATION OF THICKNESS OF WATER LAYER MELTED FOR SUCCESSIVE CHANGES IN VOLUME OF ONE-TENTH OF THE ORIGINAL VOLUME OF THE GRAIN, THE ORIGINAL LINEAR DIMENSION BEING TAKEN AS UNITY

(1) Sample No. (each 30 cm. ³)	(2) Linear dimension at beginning of each successive melting process	(3) Linear dimension at end of the correspond- ing melting process	(4) Thickness of water layer removed, i.e. (2)-(3)	(5) Conductivity (in Mho/cm. at 20° C.)
1	1.000	0.965	0.035	37.5×10^{-6}
2	0.965	0.928	0.037	1.5×10^{-6}
3	0.928	0.887	0.041	1.5×10^{-6}
4	0.887	0.842	0.045	1.3×10^{-6}
5	0.842	0.794	0.048	1.1×10^{-6}
6	0.794	0.737	0.057	1.1×10^{-6}
7	0.737	0.670	0.067	1.0×10^{-6}
8	0.670	0.585	0.085	1.0×10^{-6}
9	0.585	0.465	0.120	1.0×10^{-6}
10	0.465	0.000	0.465	2.1×10^{-6} *

* The conductivity at the centre of the grain is in general less than that of the layer surrounding it; but I have often observed, as in this example, evidence to the contrary. This is perhaps due to the water of the Tyndall figures, perhaps also to a slight solution of the mineral residue always left by the melting of the ice.

This example shows very clearly that the presence of salts is practically limited to the peripheral layer of the grain. This is confirmed by the following observation, made the same day with another specimen of the same ice. From this I collected a first sample of water equal to one-thirtieth of the total mass, thus representing an even smaller fraction (0.988) of the ice melted at the surface of each grain. This water showed a conductivity of 63.4×10^{-6} Mho/cm. justifying the term "saline skin" which I propose to give to the outer layer of grain.

(b) *The salinity of the skin is greater in the ice of the névé than in that of the glacier proper.*

At the Jungfrauoch (altitude 3450 m.) I studied cold ice (at a mean annual temperature of -6° to -4° C.) formed of small grains (maximum 1.5 to 2 cm.). The conductivity of the water from the skin of this cold ice was on the average 30×10^{-6} Mho/cm. (maximum 120×10^{-6} Mho/cm.).

In the lower region of the Great Aletsch Glacier, at an altitude of about 1800 m. I examined ice composed of grains of much larger size and at a much higher temperature since it reaches melting point during the greater part of the year. The conductivity of the water from the saline skin of this ice was not more, on the average, than 4×10^{-6} Mho/cm. (maximum 12×10^{-6} Mho/cm.).

(c) *The purity of the ice constituting the nucleus of the crystal is greater in the ice of the terminal region than in that of the névé.*

In the example of the Great Aletsch Glacier (cf. (b) above) I found the average conductivity of the water from the centre of the grains to be 3×10^{-6} Mho/cm. at the Jungfrauoch (minimum 1.5×10^{-6} Mho/cm.) against 1×10^{-6} Mho/cm. (minimum 0.85×10^{-6} Mho/cm.) for the ice of the glacier tongue.

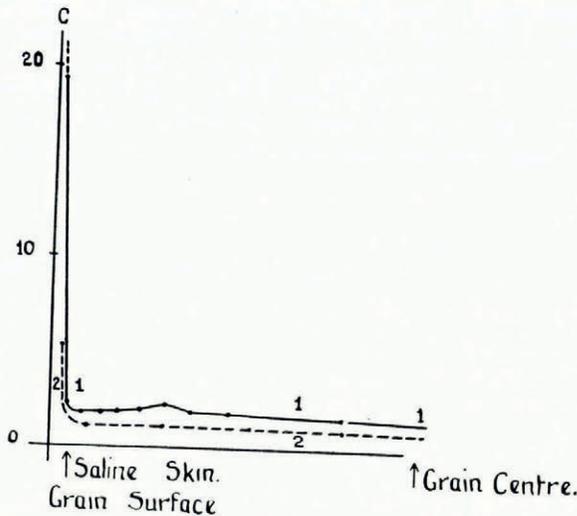


Fig. 1. Conductivity of melt water from the ice of the Great Aletsch Glacier
 1. Sample No. 40, from the firn at the Jungfrauoch, 11.4.47
 2. Sample No. 18, from the tongue of the glacier, 23.8.41
 C. = Conductivity in 10^{-6} Mho/cm.

The water provided by the centre of the glacier grains therefore often has a purity comparable to that of the purest distilled water that can be prepared and kept in the laboratory.

Fig. 1 above illustrates the results given under (b) and (c) above.

(d) The observations made in connexion with the blue ice and the white ice on the Ried Glacier have shown no systematic difference in the structure of the grains of the two kinds of ice, of which the white simply contains more air.

4. CONCLUSIONS

The above results furnish proof of the heterogeneity of ice grains. They constitute, at least as far as my knowledge goes, the first experimental verification of Buchanan's theory, according to

which natural ice is the association of a pure ice crystal and of an adhering saline solution. It is known that Buchanan had justified this hypothesis by a very profound study of the freezing temperature of saline solutions of varied concentration, and by the study of the coefficient of thermal expansion of the ice obtained in these conditions and at different temperatures. The results of this work equally confirm an analogous hypothesis formulated by Quincke. On the other hand, they permit us to discard the amorphous cement theory applied to ice.

A closer examination of the results given above (cf. 3 (c) and (d)) shows that in course of their growth and when they reach the warm upper layers of the glaciers where they melt, the grains eliminate a large part of their brine, and do so more rapidly from the skin than from the centre of the crystals.

5. SOME THEORETICAL RESULTS

Although my researches are not finished and do not yet authorize me to formulate new hypotheses about glacier mechanism, it nevertheless seems useful to set out some personal views on the questions raised.

First, it seems to me that the problem of the growth of the grains cannot be solved without observations of the temperatures of the different parts of a glacier. On the other hand, laboratory research on the formation of glacier ice will be necessary. I presume to think that this will enable us to reach the conclusion that growth depends essentially on temperature. When this approaches the melting point the elimination of the saline skin between neighbouring crystals must facilitate their coalescence. Pressure and the orientation of the crystals perhaps also play a part in this process, which has the character of autogenous welding, without the thermal equilibrium being modified.

Finally, the probable existence of a liquid film coating the crystals in the greater part of a temperate glacier must act as a lubricant in the displacement of the grains, and thus at last permit an explanation of that "semi-fluidity" in glaciers already suspected by Agassiz: "The glacier . . . is an agglomeration of fragments of rigid ice, juxtaposed and rendered mobile by the introduction of a foreign body into their interstices." The fact that the temperature plays an essential part had already been observed by this same authority who added that: "The movement of the glacier . . . depends in the highest degree on the climate, since its progression varies according to the seasons."

Every new hypothesis on the "plasticity" or "viscosity" of glaciers will have to take into account the part played by the liquid film produced by the melting of the saline skin which the grains possess.

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