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Some Results of the International Glaciological Expedition to Greenland 1957–1960

Concerning the Rheological Behaviour of Snow and Ice

R. HAEFELI

Swiss Glacier Commission, Zürich, Switzerland

I. Introduction

The purpose of this paper is to give a very brief résumé of some results obtained by the rheological section of the International Glaciological Expedition to Greenland 1957–1960 (EGIG I). Most of the tests mentioned in this note under points 1–12 deal with the plastic deformation of firn and ice under its own weight and external forces. They have been executed on the station Jarl-Joset during the wintering 1959–1960 by F. Brandenberger.

The full publication of the rheological investigation of EGIG I will be issued in Meddlelser om Grønland. A glaciological synthesis of the whole enterprise can only be expected after evaluation of the results of the second International Glaciological Expedition to Greenland (EGIG II) which is planned for 1967 and 1968.

II. Summary of Some Rheological Results

1. The use of the Driving Rod System VAWE (Haefeli, 1951) allows to take ramm profiles of 10 to 20 m depth in the névé region of the Greenland inland ice. Of special interest is on the one hand the mean ramm hardness in function of the depth and on the other hand the question of what conditions and down to what depth the oscillations of the driving resistance (Ramm hardness) permit the distinction of summer and winter snow. Some relations between the ramm profile and the climatic conditions are evident (Fig. 1).

2. Apart from the driving resistance the shear strength of the polar névé measured with a vane apparatus was specially illuminating as to the great differences of the shear strength between summer and winter layers. The equipment based on a suitable combination of driving and vane apparatus has proved to be of good use (Fig. 1).

3. By inclination (Klinometer) measurements on tubes of different lengths drived perpendicularly into the névé it has been proved that there existe local creep movements in the surface layer. Near the station Milcent *e.g.* a change of inclination of 17‰ a year was measured on a tube of 3.75 m. These creep movements, influenced by the local morphology of the site might be the cause of the fact that at the deformation circle ϕ 100 m of the station Jarl Joset, where a strain rate of only 0.2‰ a year were to be expected, no definite results could be obtained. On the other hand the deformation quadrangles, the diagonals of which have a length of 1 km, have given some representative results to which we come back later.

4. The deformation measurements of spherical hollows ($\phi = 3$ m) at a depth of 20

resp. 40 m were made on the one hand to control the flow law of the polar firn, resp. the calculation of the corresponding parameter k_1 and n, and on the other hand to control a solution for the approximate calculation of the closing velocity of spherical hollows in firn and ice. Thereby the specific closing velocity showed to be, as expected, increasing continuously in a horizontal direction with the depth, whereas in a vertical direction it reaches a pronounced minimum at a certain depth (50–70 m) (Fig. 2).

5. Between 0 and 20 m depth the vertical strain rates were measured in the laboratory of the station Jarl Joset with special apparatuses (viscositumeter) and compared with those of "Eismitte" which had been watched by Sorge in 1931 and later evaluated by Bader (1954). On June 3, 1960, moreover, there was a rare opportunity of watching the effects of a "Firnstoss" on the settling of the surface névé layer.

6. The loading test with a circular plate is specially suited for a quick definition of the viscosity conditions of the névé in relation to practical questions (foundation problems). The viscosity values obtained by this method correspond well to those which were found later based on the density curve. On the other hand tests with the socalled viscositumeter might specially applied when the viscosity conditions of the

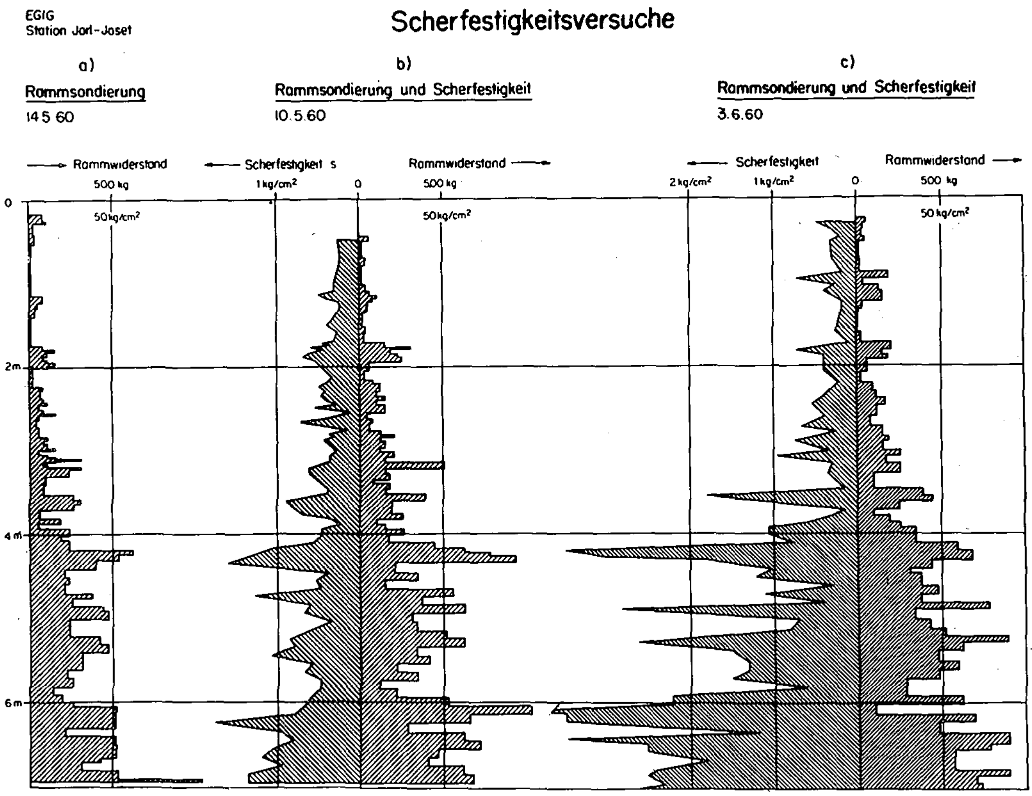

Fig. 1. Driving Resistance and shear strength at Station Jarl-Joset

a) Driving Resistance
b) On the right, driving resistance; left, shear strength with modified vane
c) On the right, driving resistance; left, shear strength with modified vane

névé are to be touched down to a certain depth under the névé surface (5–20 m).

7. Among the tests carried out in the firn laboratory of the station Jarl Joset during the wintering of 1959/60 unconfined compression tests are to be mentioned. Thereby the parameter k_1 of the flow law:

$$D = \frac{d\alpha}{dt} = k_1 \left(\frac{\tau}{\tau_1}\right)^n ; \quad \tau_1 = 1 \text{ kg/cm}^2 ,$$

for $n=3$ was determined on 69 firn samples originating from the pit Dumont at a depth of 0–40 m. The plotting k_1 in the logarithmic scale in function of the density turns approximately out to be a straight line over 4 magnitudes (Fig. 3). The dependence of the creep velocity of the firn on its density set by Bader (1962) was in general confirmed.

$$\text{for } n = 1: \quad D = k_{11} \left(\frac{\tau}{\tau_1}\right) .$$

8. The relative constancy of the firn characteristics makes its evaluation specially rewarding. To derive the viscosity curve (viscosity in function of the depth) from the density curve the stress condition of the firn must be known, that is to say, not only the perpendicular main principal stress, but also the horizontal minor principal stress must be determinable. Therefore the problem of the pressure at rest had to be solved at least approximately. After this the k_{11} value of the névé resp. its viscosity can be calculated for every depth based on the density curve. The corresponding Fig. 4

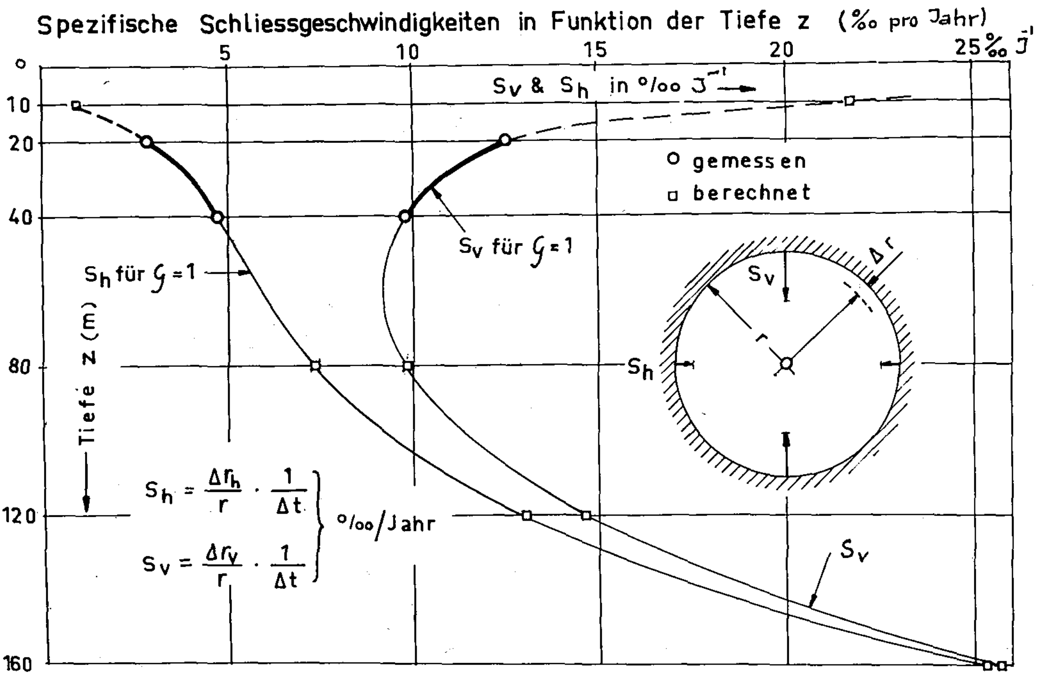

Fig. 2. Closing velocities of a spherical hole versus depth

s_h : Closing velocity in horizontal direction in ‰/year

s_v : Closing velocity in vertical direction in ‰/year

○: Measured, □: Calculated

shows distinctly by the great variation of the viscosity that the ice socle of the inland-ice is covered by the relatively fluid layer, the viscosity of which is at the surface about 10 000 times smaller than the one of the ice. This fact must be specially taken into consideration when critically examining the horizontal velocities measured at the névé surface (Yosida and others, 1956).

9. A rheological interpretation of the west-east profile as it resulted from the levelling on the Greenland inland-ice (Mälzer, 1964) was tried. As a working hypothesis an earlier study (Haefeli, 1961) was used, based on Glen's law, and presupposing among other things that within the névé region the ice does not slip on the ground. The

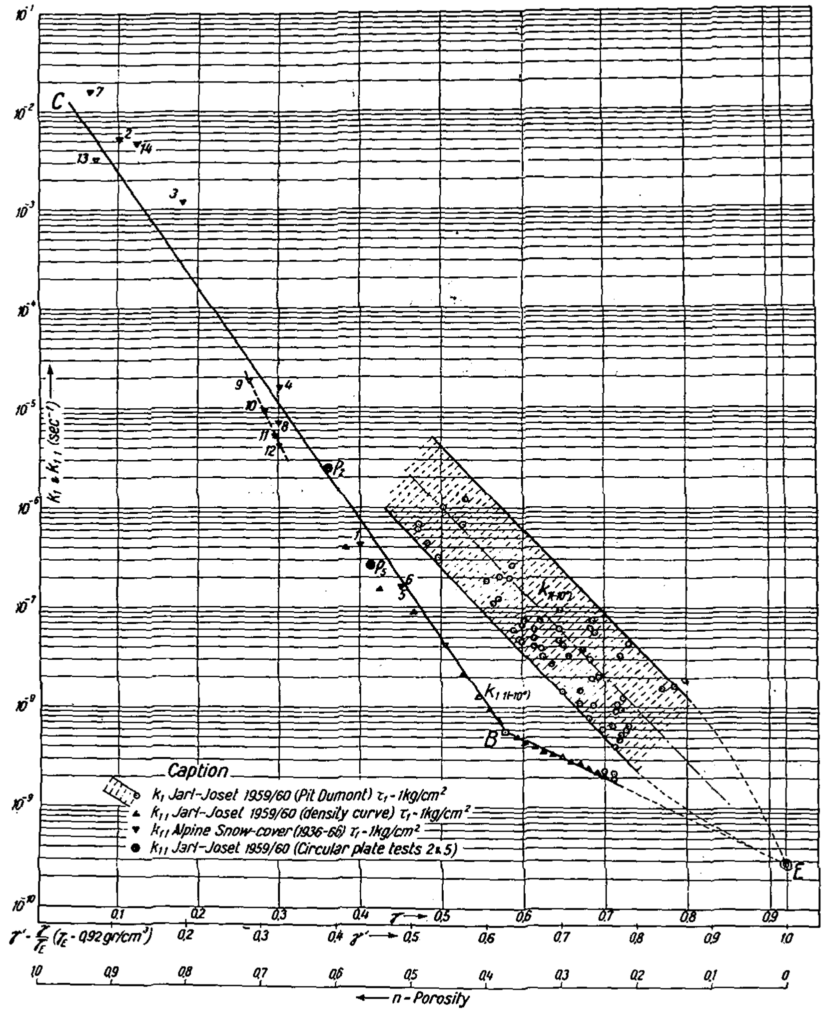

Fig. 3. Parameter k of the flow law of firn and snow versus density γ (reduced to -10°C)

on the right: k_1 for unconfined compression tests with firn and $n=3$

on the left: k_{11} for firn and snow of different origin and $n=1$

parameters k_1 and n of the flow law stay open at first and are fitted in on the base of two measured points of the névé surface. For $n=3.5$ the calculated curve corresponds so well to the measured one (after equalizing the waves) that the 2 curves in Fig. 5 can hardly be distinguished from one another. How far this fact can be taken as an indirect proof, that the suppositions made do not deviate too much from the real conditions, remains open. Specially must be discussed the relatively high value of the

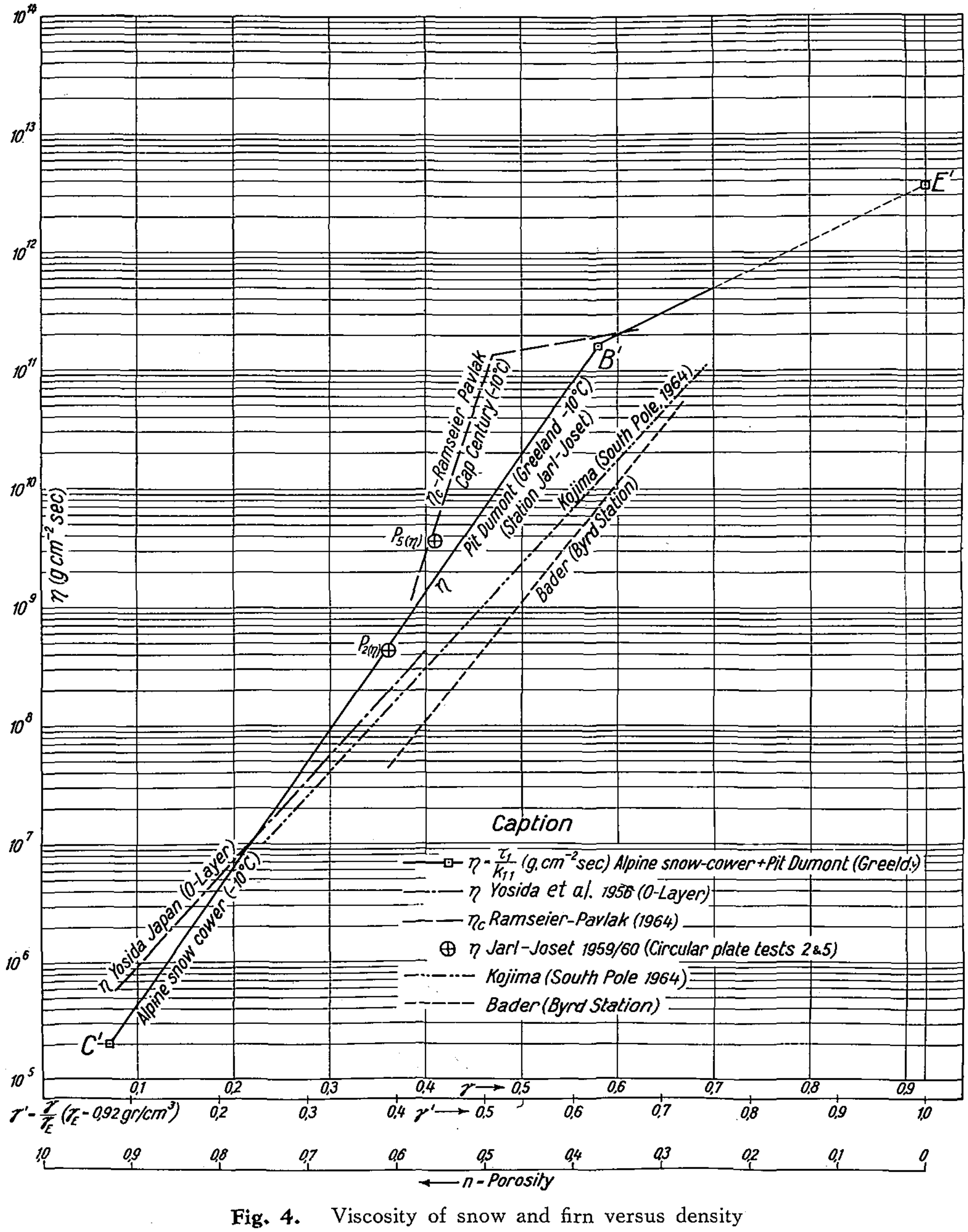

Fig. 4. Viscosity of snow and firn versus density (partly reduces to $-10°C$)

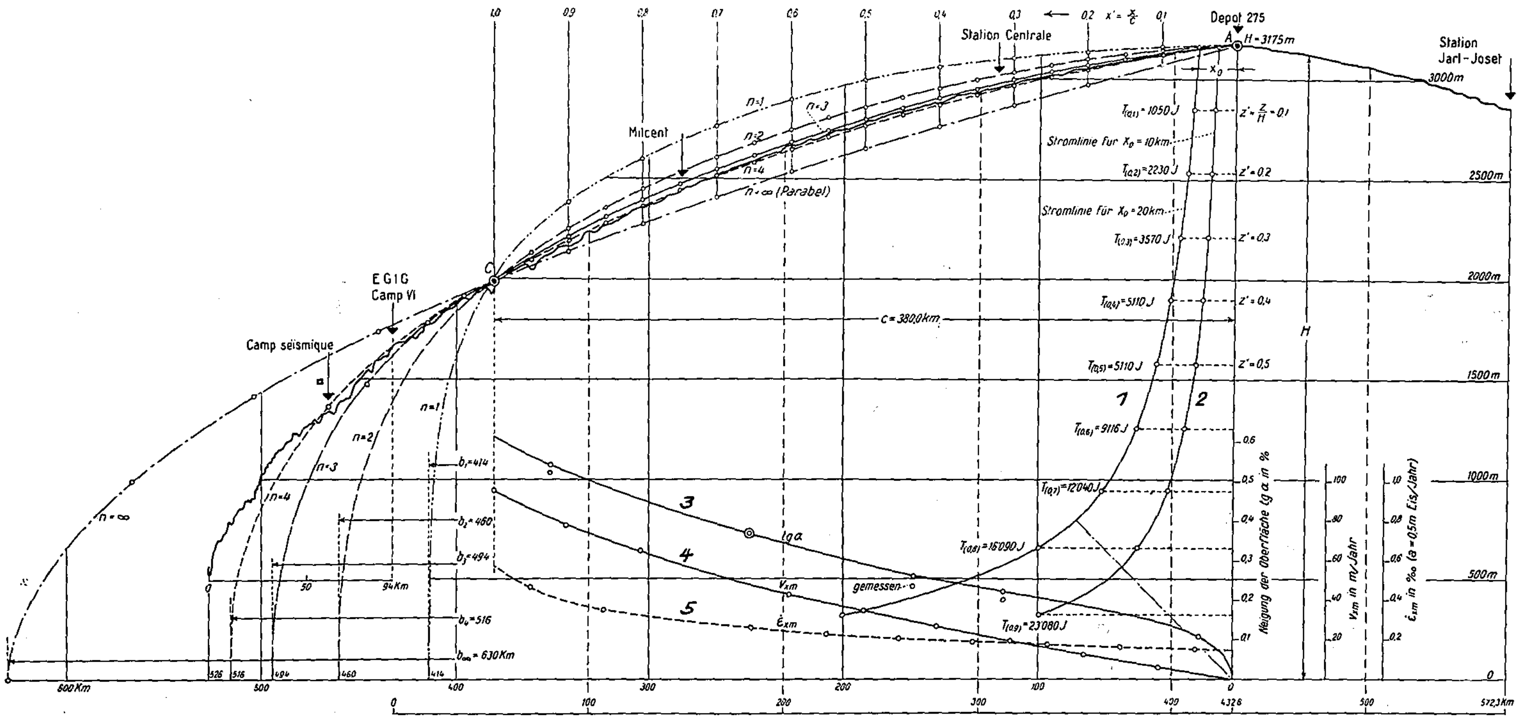

Fig. 5. W-E profile through Central Greenland (EGIG) Comparison between measured (Mälzer, 1959) and calculated surface. n = exponent of the flow law.

Curves 1 and 2, stream lines; 3, surface slope; 4, mean value of horizontal velocity; 5, horizontal strain rate mean temperature parameter k_1 which lies only a little below the one for temperate ice. Also the formation of surface waves stated uniquivocally by the levelling raises questions which cannot be answered before the repetition of the measurement (intended 1967/68).

10. It was tried to set an approximate calculation of the age of the ice on a rheological basis for the west-east profile and two dimensional flow. In Fig. 6 a curve 2 was drawn which indicates for any point P_0 of the névé surface how many thousand years a snow crystal deposited at this point will take at least to reach the coast.

11. Along the W-E profile 4 stretches of a total length of 35.4 km have been measured not only in 1959 but also in 1960. The strain rate of the single stretches of which each one is shorter than the length of the surface waves (*ca.* 10 km) shows

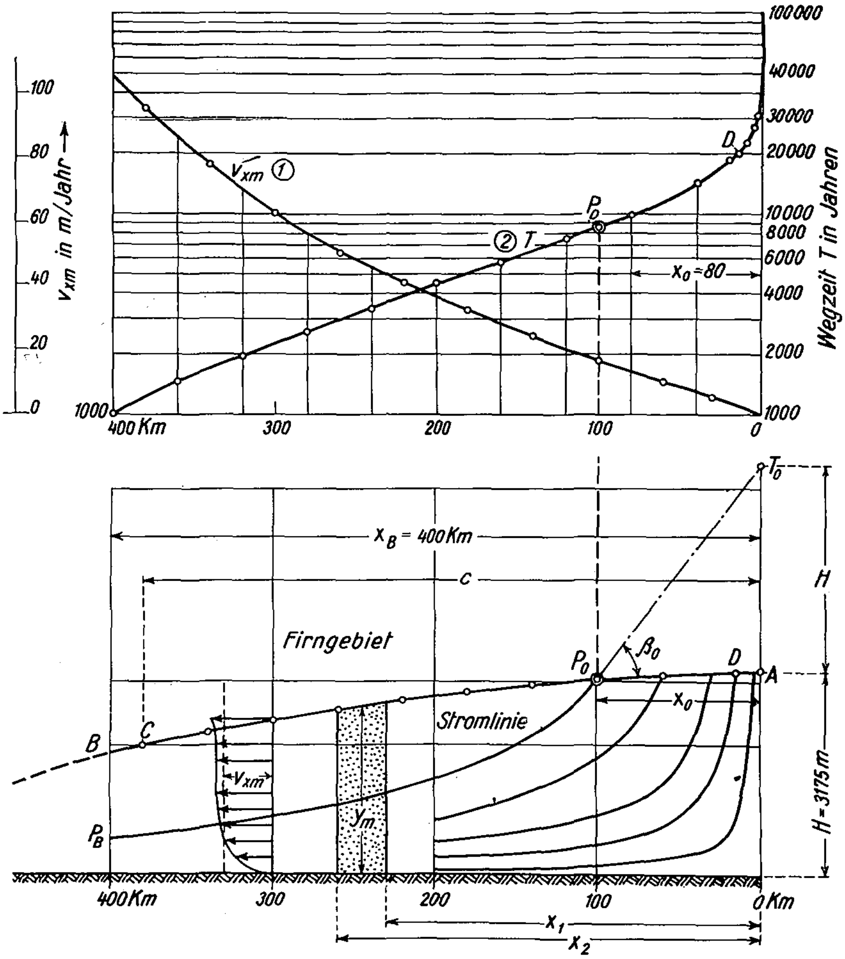

Fig. 6. Approximate determination of the age of the ice

Firngebiet = Firn region. Wegzeit in Jahren = travel time in years. Stromlinie = stream line

Curve ①: Mean velocity in m per year, Curve ②: Travel time between a surface point x_0 and the coast (approximately)

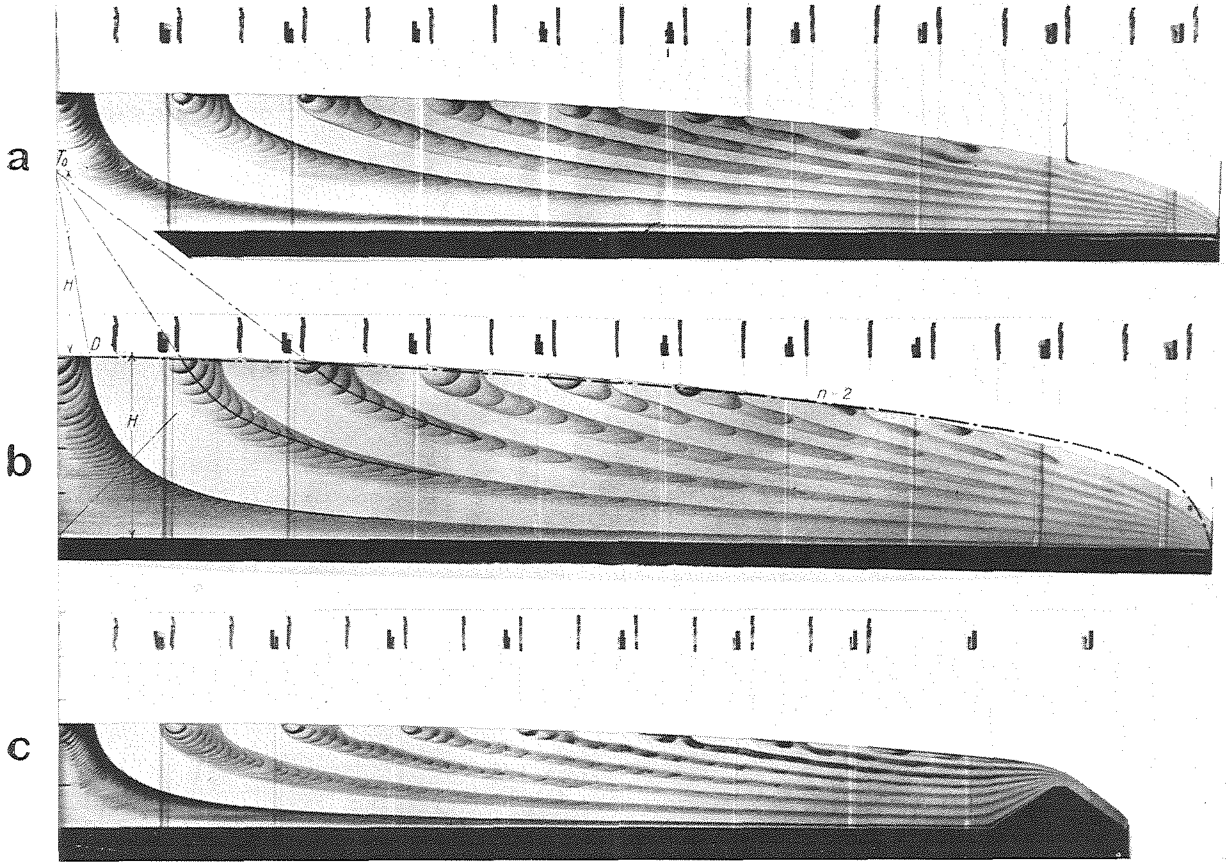

Fig. 7. Model Hele-Shaw for the firn region. Viscous flow of oil between two glass plates.
a) Constant accumulation. Distortion in height 27 times. Colour impulses every 40 sec
b) Constant accumulation. Distortion in height 20 times. Colour impulses every 50 sec
c) Without accumulation near the coast. Influence of a coastal mountain range. Colour impulses every 60 sec

a very big scattering, ranging between 0.23–2.72‰/year. Nevertheless, the strain rate of the total distance of 35.4 km differs only little from the theoretical value (*ca.* 1.0‰/year). Concerning the strain rates resulting of the deformation measurements of the quadrangles, only that of the station Milcent gave conclusive results, being in good agreement with the theoretical value.

12. As last point some result of a model test based on the method invented by Hele-Shaw may be mentioned (Fig. 7). The two-dimensional flow of a viscous liquid between two parallel glass plates with a distance between them of 4 mm was used to demonstrate not only the elliptical shape of the surface but also the stream lines and the velocity distribution. At the bottom of Fig. 7 the influence of a coastal mountain range is shown. Moreover, this model of which the random conditions can easily be changed permits also to study problems of two-dimensional non-stationary flow. For the execution of the test we are obliged to J. Zeller, VAWE, ETH.

Acknowledgments

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