research nor the practical ice services can now forgo the combined use of synoptic weather maps and synoptic oceanographical charts in conjunction with the use of ice charts.

The difference between the older working methods and the new course followed by sea ice research now becomes clear. The causality of phenomena gradually gains in importance. In consequence of the new course new problems and new methods are appearing. Specific laws governing the formation of ice are established, and a specific terminology will necessarily follow. With greater knowledge of the internal relationship between ice formation and ice metamorphosis, a uniform terminology will be evolved and scientifically based ice forecasts will provide additional security for navigation. With the establishment of specific laws and concepts, sea ice research will attain equality of status with glacier research as a special branch of science.

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OBSERVATIONS IN A COLD ICE CAP

By R. HAEFELI *and* F. BRENTANI

(Continued from Vol. 2, No. 18, 1955, p. 571–81)

PART II

IV. RELATIONSHIPS OF STRESS AND TEMPERATURE

The stress, movement, temperature and viscosity conditions in cold ice affect each other very closely.

1. *Stress Relationships*

In the purely schematic illustration in Fig. 11 (p. 625) some of the prominent features of stress and temperature variations in the ice cap are indicated in general terms in connection with the progress of movement. On examining the normal vertical and horizontal stresses σ_y and σ_z, a distinction must be made between states of stress before and after the formation of longitudinal crevasses. Before the formation of cracks, the distribution of horizontal stresses σ_y along a vertical in the region of the division of movement should be qualitatively similar to Diagram 4 (Fig. 11). The horizontal tensile stresses in the centre of the cap are influenced both by the specific boundary conditions and by the variations of viscosity in a vertical direction.

The concentration of tensile stresses in the central zone of the cross-section leads to the observed formation of longitudinal crevasses, whereupon the picture of stress is radically altered; the horizontal tensile stress is in places reduced to zero, so that in certain zones a bi-axial state of compression arises (σ_x and σ_z) with σ_z as the overburden pressure and σ_x the compressive stress perpendicular to the plane of the figure. The gradual filling up of the cracks with water gives a lateral water pressure, which produces yet another radical alteration in the state of stress and deformation of the cold ice, and also gives periodic fluctuations, depending upon the height of the water level.

Technically the possibility now arises of draining the cracks, as was done during the construction of the cross-tunnels, and thus of influencing the state of stress and movement in the cap in a particular manner and of slowing down the horizontal movement to both north and south.

If no drainage takes place, the water gradually freezes in the cracks, giving rise to an additional horizontal moving pressure, which in the nineteenth century was often considered to be the main cause of glacier movement.

2. *Temperature Relationships*

The course of ice and rock temperatures is characterized by a three-dimensional heat flow, in which the partly ice-free north wall of the Jungfraujoch causes the lateral penetration of cold into the underlying rock (mean annual air temperature —8° C.). In Fig. 11, the estimated qualitative position of the 0° isotherm is drawn in. The rock temperature at the entrance of the tunnel into the ice remained continually below 0° C. (Permafrost), while in the ice tunnel itself, ice temperatures of from —1° to —3° C. were measured. Until completion of construction in 1954 no start can be made with exact temperature measurements, and in particular with the taking of vertical temperature profiles from the firn surface to the rock bed beneath[8].

The very slow freezing process of the water collected in the longitudinal crevasses during the melting period is to be explained primarily by the relatively low conductivity of the ice and the small temperature gradient between ice and water, as well as by the complete lack or inadequate amount of communication, especially in winter, between the crack and the outside air (snow covering). When the water level sank, dendrites of ice about 50 cm. in diameter were discovered.

The air circulation observed in the tunnels and crevasses had to be studied in connexion with the ice temperature and evaporation and condensation on the ice surface. For example, in the ice laboratory, in tunnels and cracks evaporation of ice occurred as a rule at the bottom, while heavy formations of hoar frost were deposited on the roof. By means of the air circulation, material was actually carried in the hollow spaces from the bottom to the top in the form of vapour. By artificially regulating the flow of air, the temperature in the ice tunnels was kept as low as possible, so as to delay the plastic deformation of the profile of the tunnels.

V. Viscosity Relationships in Cold Ice

The methods now described and their application to the determination of the rheological properties of cold glacier ice serve to supplement the investigations of the stress-strain rate curve by measurements on artificially grown ice which have recently been carried out in various laboratories[9, 10, 11, 24].

The creep of ice is not only dependent upon shear stress and temperature, but also upon numerous other factors, such as the average principal stress, crystallography, chemical composition, load at earlier times, etc. The influence of these factors is insufficiently known at present, and so it has been found advantageous for the solving of technical problems to simplify the relations, which in reality are very complicated, by the use of an easily understood approximation[12]. This purpose is achieved by the concept of the standard apparent viscosity μ which corresponds to a definite point P in the stress-strain curve, according to the equation (*cf.* Fig. 12, p. 625):

$$\omega=\frac{d\gamma}{dt}=\frac{\tau}{\mu}, \qquad \mu=\tan\mu^{*}=\frac{\tau}{\omega} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

By reason of this simplification, the calculation of creep movements within a certain area of stress can be worked out, in a similar way as for a Newtonian fluid: in every concrete case, the art lies in the correct estimation of the standard apparent viscosity μ, which cannot be regarded as a material constant in view of its dependence upon the state of stress, etc.

In our particular case, three different methods were employed to arrive at the apparent viscosity, namely:

(*a*) Measurement of length alterations of the cross-tunnels under approximately known overburden pressure.

(*b*) Deformation of a circular tunnel under a general stress. (Cross-tunnel Q_{100}.)

(*c*) Deformation of a circular tunnel under uni-axial compression. (Longitudinal tunnel.)

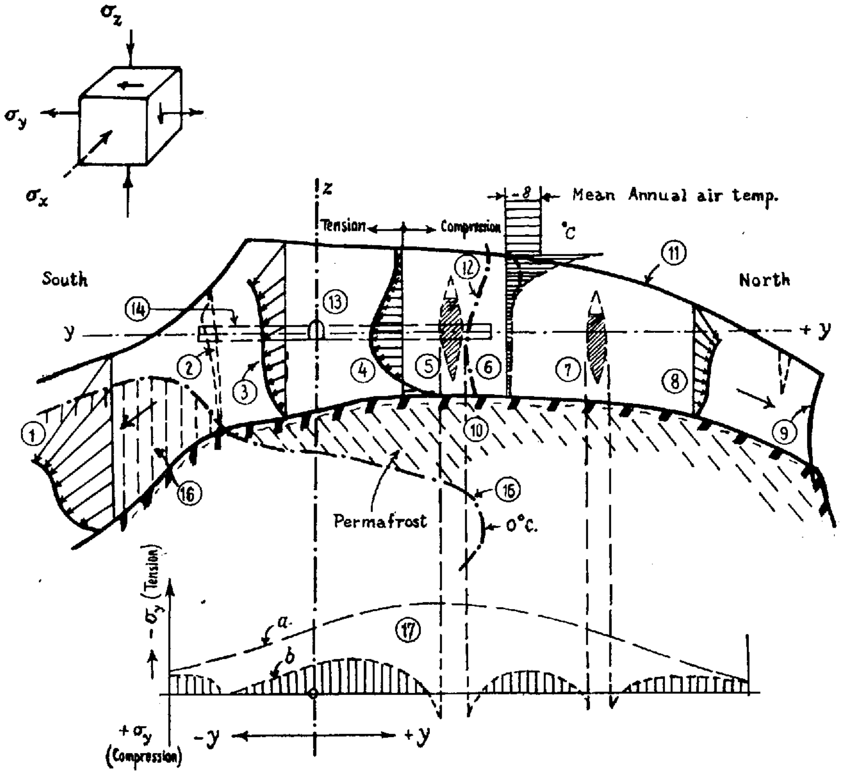

Fig. 11. Schematic representation of the temperature, stress and velocity relations in the cross-section of the cap

1. Velocity profile below the bergschrund	10. Rock bed
2. South bergschrund	11. Firn surface
3. Velocity profile above the south bergschrund	12. Division of movement
4. Horizontal stress distribution	13. Longitudinal tunnel (principal tunnel)
5. Water-filled crevasse (observed)	14. Cross tunnel
6. Temperature profile (mean annual temperature −8° C.)	15. 0° isotherm
7. Water-filled crevasse (conjectural)	16. Temperate ice
8. Velocity profile above break-away (north)	17. Horizontal stress variation along the axis of the cross tunnel, (a) before crevasse formation, (b) after crevasse formation
9. Break-away of the ice	

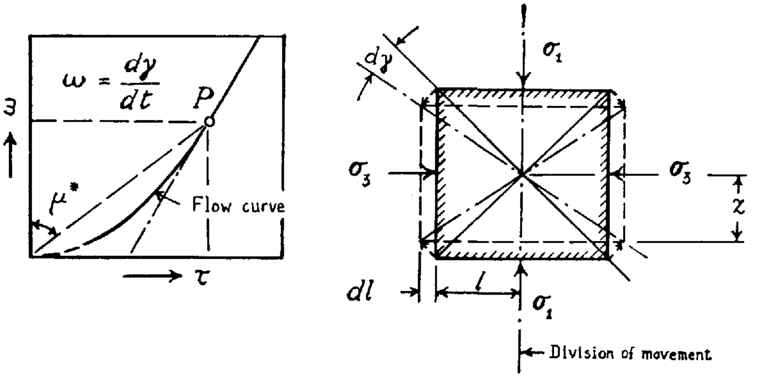

Fig. 12. Diagrams to illustrate the theory. Left, Flow curve of ice. Right, Deformation of an ice cube at the division of movement, i.e. *in the middle of the ice sheet*

$$\mu = \tau/\omega = \tan \mu^*; \quad \omega = \frac{d\gamma}{dt}$$

$$\tau = \mu \,.\, \frac{d\gamma}{dt} = \frac{1}{2}(\sigma_1 - \sigma_3) = \frac{1}{2}\Delta\sigma; \ \Delta\sigma = 2\mu \,.\, \omega; \ \omega = a/H$$

μ = *Mean value of the apparent viscosity*

a = *Mean ice accumulation per year between M and P on Fig. 13*

Except for a short section of method (*b*), we here limit ourselves to an explanation of methods (*a*) and (*c*), using the measurements of strain made in cross-tunnel Q_{120}.

(*a*) If one examines a prismatic ice lamella (Figs. 11 and 12) in the region of the division of movement,* bounded on both sides by longitudinal cracks, then the horizontal principal stress $\sigma_3 = \sigma_y$ in the plane of the picture can be approximately put equal to zero, so that in this plane $(y-z)$, the vertical pressure from above alone acts as principal stress $\sigma_1 = \sigma_z$. If one ignores the insufficiently well known, yet relatively small alterations in length perpendicular to the plane of the picture, this corresponds to the supposition that the so-called rest pressure is effective in the x-direction (neutral zone).

With these assumptions, the apparent viscosity of the ice can be calculated as follows (Fig. 12):

$$\sigma_3 \sim 0; \quad \mu_m = \frac{\tau}{\omega} = \frac{\sigma_1}{2\omega}; \quad \omega = \frac{\mathrm{d}\gamma}{\mathrm{d}t} \sim \frac{\Delta l}{l} \cdot \frac{1}{\Delta t} = \epsilon_y \qquad (3)$$

The angular rate of change ω is thus identical with the rate of strain ϵ_y of the cross-tunnel. If we substitute the value of ϵ_y which was taken during the second period of measurement (see Part I, p. 578), while σ_1 is estimated as the overburden pressure of 28 m. of ice and firn at an estimated mean density of $\rho_i = 850$ kg./m.^{3}, then it follows that:

$$\sigma_1 = 850 \times 28 = 24 \times 10^3 \text{ kg./m.}^2$$

$$\epsilon_y = 0{\cdot}0087\% \text{per day} \sim 1{\cdot}0 \times 10^{-9} \text{ sec.}^{-1}$$

$$\mu_m = \frac{\sigma_1}{2\epsilon_y} = \frac{24 \times 10^3}{2 \times 10^{-9}} = 12 \times 10^{12} \text{ kg. sec./m.}^2$$

$$= 11{\cdot}8 \times 10^{14} \text{ poise} \qquad (4)$$

(*b*) The measurements in circular profile K2 ($\sim$2·6 m. diameter) do not cover a sufficiently long period of time to provide reliable results. An initial measurement period of 90 days showed that the deformed circular profile resembled an ellipse, from which it follows—contrary to our expectations—that the state of stress in the plane considered is not hydrostatic. The orientation of the two axes of the ellipse indicates the direction of the standard principal stresses, while the ratio of the principal stresses can be deduced from the change in length of these axes. A rough application of the relations given under (*c*) showed in the main that the apparent viscosity of the ice may here reach 6×10^{14} poise.

For the sake of comparison, it should be mentioned that in the circular profile of the Z'Mutt tunnel, *i.e.* in temperate ice, the following values for the apparent viscosity were discovered (see Ref. 1, Part I, p. 580):

Pressure from above $p = 39$ t./m.^{2}, $\mu = 2{\cdot}5 \times 10^{14}$ poise
" " " $p = 22$ t./m.^{2}, $\mu = 7{\cdot}2 \times 10^{14}$ poise.

The dependence of the μ value upon the pressure from above, or the shear stress, is conditioned by the exponential character of the stress-strain curve (*cf.* Fig. 12)[10, 11, 24].

(*c*) In the deformation of the circular profile K_1 (2·9 m. dia.) observed in the longitudinal tunnel, the horizontal measurement increased somewhat to begin with, but then shrank again approximately to its original value. From this, a certain time variation of horizontal side pressure is indicated (*cf.* Fig. 8, p. 579 of Part I).

The general calculation of deformation in a circular profile under the influence of a vertical pressure from above p_1 and a horizontal pressure p_2 gives the following radial alterations in length for an elastic material [13]:

Vertical: $$\Delta r_1 = \left[\frac{2}{3}p_1 - \frac{1}{6}p_2\right] \cdot \frac{r}{G}, \qquad (5)$$

where G is the shear modulus.

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* Absolute zero point of horizontal displacements.

Horizontal:
$$\Delta r_2=\left[\frac{2}{3}p_2-\frac{1}{6}p_1\right]\cdot\frac{r}{G}\,; \qquad (6)$$

for $p_1=p_2$:
$$\frac{\Delta r}{r}=\frac{p}{2G}\,.$$

For the horizontal measurement to remain constant ($\Delta r_2=0$), p_2 must be 25% of p_1. With this assumption it follows that the specific reduction of the vertical cross-section is:

$$\delta_1=\frac{\Delta r_1}{r}=\frac{15}{24}\cdot\frac{p_1}{G}=0{\cdot}625\frac{p_1}{G} \qquad (7)$$

To arrive at the viscous-fluid creep from the elastic deformation, we put:

$$\tau=G\,.\,\Delta\gamma\equiv\mu\,.\,\frac{\Delta\gamma}{\Delta t};\quad G\equiv\frac{\mu}{\Delta t} \qquad (8)$$

If this value of G is introduced into equation (7), and the states of stress of the elastic and plastic deformations identified, then the specific rate of contraction v_1 of the vertical diameter is calculated as follows:

$$v_1=\frac{\delta_1}{\Delta T}=0{\cdot}625\frac{p_1}{\mu};\quad \mu=0{\cdot}625\,\frac{p_1}{v_1} \qquad (9)$$

Measuring period 20/2/51 to 8/1/53; $v_1=0{\cdot}0333\%$ per day; $p_1=27$ t./m.^{2}; $\Delta T=687$ days.

$$\mu=0{\cdot}625\times\frac{27\times10^3}{0{\cdot}0333}\times10^3\times0{\cdot}864\times10^5=4{\cdot}4\times10^{12}\text{ kg. sec./m.}^2=4{\cdot}3\times10^{14}\text{ poise.}$$

This relatively low value of the apparent viscosity μ, which is not far from the approximate value obtained for the circular profile K_2 in (*b*) above, also lies within the range of the values for the Z'Mutt tunnel in temperate ice[20]. It should be noted that the latest laboratory experiments of S. Steinemann revealed no sudden alteration or increase of the ice plasticity on passing the point of pressure melting, *i.e.* on crossing from temperate to cold ice (oral communication). The recent measurements in the ice tunnel recorded up to the present time seem to confirm this point of view, in the sense of a continual increase of the apparent viscosity with lower temperatures as stated by Glen in the form of a "minimum creep rate" for polycrystalline ice[24].

VI. Comparison of Greenland and Alpine Relationships

Without embarking at this stage on the conclusions which can be drawn from the above examination for alpine glaciers in both scientific and technical aspects, we will now limit ourselves to a short discussion of some theoretical relations concerning the movement of ice caps with plane deformation, with special reference to the Greenland ice sheet above the firn line (central Greenland).

If the length of the cap in relation to its breadth is very great, the glacial movement may in the first approximation be assumed to be an even laminar flow with some discontinuities (slipping movement): in this case, the apparent viscosity of the medium varies from point to point. For the division of movement (M) on a horizontal rock base we arrive, by reason of the equation of continuity, at the following mean value for the stress deviator $\Delta\sigma=\sigma_1-\sigma_3$ in the stationary state of the cap:

$$\Delta\sigma=2\mu\,.\,\frac{\Delta\gamma}{\Delta p}=2\mu\,.\,\frac{a}{H} \qquad (10)$$

The definition of the individual symbols can be seen in Fig. 13 (p. 628). From this, it follows that the mean difference $\Delta\sigma$ between horizontal and vertical principal stress, upon which depends, among other things, the danger of longitudinal cracks forming, is directly proportional to the annual accumulation a and inversely proportional to the height H of the ice cap.

For example, if one calculates for Greenland with an ice thickness of 3200 m., an accumulation $a=0{\cdot}30$ m. of ice per year and a mean apparent viscosity of the ice of 10^{15} poise, there is a mean

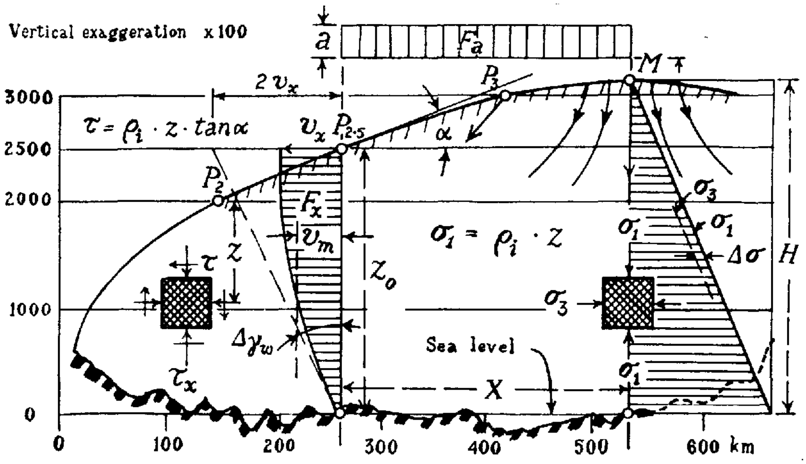

Fig. 13. Diagrammatic representation of the relations in the Greenland ice sheet. (Profile after Expeditions Polaires Françaises, Missions Paul-Emile Victor. Vertical exaggeration $\times 100$*).*

At the division of moment $\Delta\sigma \sim 2\mu a/H$; ρ_i *= Mean density of ice.*
The balance equation is, Area $F_x = F_a$; $v_m = a \,.\, x/z_0 = \alpha \,.\, v_x$.

For F_x *a parabola:* $v_x = 3/2 \,.\, \dfrac{ax}{z_0}$; $\mu_m = \tan\alpha \,.\, \rho_i \,.\, z_0^3/3a \,.\, x$

deviator of about 60 kg./m.², which has no great practical significance. *In the ice centre, therefore, there exists almost a hydrostatic state of stress.*

On the other hand, it follows that a very small deviator $\Delta\sigma$ suffices to make possible a stationary condition in the ice centre.

Whereas the horizontal shear stresses at the division of movement are $\tau_{xz} = 0$, this is not the case in any general vertical section (P) through the cap because of the tilting of the surface. Here τ_{xz} is the more decisive factor for the progress of movement, and with a horizontal rock base and a small angle of slope α of the firn surface, the following equation is valid [14]:

$$\tau_{xz} \cong \rho_i \, z \tan\alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

If one supposes the average firn accumulation a from M to P to be known, then from considering the balance it follows in terms of the quantities defined in Fig. 13 that:

$$F_x = F_a; \; v_m = \frac{a\,x}{z_0} = \lambda . v_x \; (v_x = \text{surface velocity}) \quad . \quad . \quad . \quad (12)$$

This equation for the average cross-section velocity v_m in the stationary state of the cap is generally valid, *i.e.* it is wholly independent of the particular form of the velocity profile or the question of whether or not slipping on the base takes place (pure condition of continuity).

For the simple assumption of a parabolic velocity profile, which would correspond to a constant viscosity of the medium without slipping on the base ($v_u = 0$), the following relationships are valid:

$$v_x = \frac{3}{2}\,\frac{a\,x}{z_0}; \; \mu_m \sim \tan\alpha \,.\, \rho_i \,.\, \frac{z_0^3}{3\,a\,x} \,\dagger \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Thanks to the Greenland expedition of Paul Victor we are to-day adequately informed about the contours of the rock base in Greenland (see Ref. 4, Pt. I, p. 580). The following numerical example is based on the profile contained in *Rapport Préliminaire* No. 15, *Série Scientifique* (*Campagne* 1950). For a hypothetically selected mean annual accumulation of $a = 0{\cdot}3$ m. of ice, the average values set out in Table II work out as follows (Equations 13 and 14):

† $\omega = \dfrac{\Delta\gamma}{\Delta t} \sim \dfrac{\tau_{xz0}}{\mu_m} = \dfrac{2v_x}{z_0}$; v_x from Eqn. (13), τ_{xz0} from Eqn. (11) $\mu_m \sim \dfrac{\tau_{xz0} \,.\, z_0}{2v_x} = \tan\alpha \,.\, \rho_i \,.\, \dfrac{z_0^3}{3ax}$ (14)

TABLE II. ICE SHEET MOVEMENT AND VISCOSITY RELATIONS
(for slipping velocity on the rock bed $v_u = 0$)

Point	a m./yr.	z_0 m.	x km.	tan α %	v_m m./yr.	$v_x = 1\cdot5 v_m$ m./yr.	τ_{xz0} t./m.^{2}	μ_m poise
								$\times 10^{14}$
1	0·3	2000	385	0·54	58	87	9·7	3·5
2	0·3	2500	270	0·33	33	50	7·5	6
3	0·3	3000	115	0·22	11·5	17	6·0	16

τ_{xz0}=shear stress on the bottom of the Ice Sheet. ρ_i=0·9 t./m.^{3} (1 t./m.^{2}∼0·1 bars)

With regard to magnitude, these apparent viscosities agree with the values reached for the cold ice cap on the Jungfraujoch. From this it follows that the movement in the firn area of inland ice can also be conceived as occurring without slipping on the base, *i.e.* only as a result of the plastic deformation (creep) of the cap.

We are fully aware that the comparison of the small ice cap on the Jungfraujoch with the enormous inland ice mass, whose greatest thickness is 60–70 times and breadth up to 3000 times larger, must be regarded at least as daring. But the following considerations may be borne in mind to assist such a comparison.

In the light of recent glaciological research, the plastic properties of polycrystalline glacier ice, or its apparent viscosity, seen from a crystallographical point of view, depends chiefly upon the following factors: on the one hand upon the significant shear stress and on the other upon the temperature of the ice. As far as the shear stresses are concerned, the difference between Greenland and the Jungfraujoch is of no consequence, for the greatest shear stress on the top of the ice tunnel, which, with no side pressure, corresponds to half the pressure from above, is of the same magnitude as the shear stress along the rock base of the inland ice (Table II).* On the other hand, the normal stresses, or hydrostatic pressures, differ widely; yet up to the present, no resulting influence of hydrostatic pressure upon the plastic behaviour of cold ice can, according to Steinemann, be confirmed.

With respect to ice temperature, we are in both cases concerned with cold ice, although the mean temperature of the ice on the Jungfraujoch is appreciably higher than in central Greenland. The relatively high value of viscosity for Point 3 of the inland ice (Table II) indicates a low mean ice temperature, together with small shear stresses.

Following the seismic examination of the ice sheet by the Expéditions Polaires Françaises (Missions Paul-Émile Victor) and the relatively high speed of seismic waves recorded thereby (*ca.* 3800 m./sec.), J.-J. Holtzscherer also comes to the conclusion that the central inland ice is probably cold down to the base: that is to say, its temperature throughout lies below the point of pressure melting and frost penetrates down to the bottom (see Ref. 4, Part I, p. 580). Robin reached a similar conclusion, proving theoretically by a study of heat flow that with an annual accumulation of 30 cm. of ice, the temperature of the rock base in the central zone of the Greenland ice sheet lies well below the point of pressure melting, which under a thickness of 3000 m. of ice is about −2° C.[15], while for a surface temperature of −29° C. the calculated bottom temperature according to Robin is about −12° C. From seismic shooting information Holtzscherer estimates the basal temperature near the centre of the ice sheet at around −10° C.

Quite independently of the above-mentioned seismic and thermodynamic examinations, the results gained from the ice cap on the Jungfraujoch offered the possibility of shedding light upon the Greenland problem from a third angle, namely on the basis of glacier movement. The attempted extrapolation of the small ice cap onto the Greenland ice sheet leads one to presume that in central Greenland there exists a core in which the ice does not slip on the base but is frozen hard to it, where the resultant shear stresses lie well below the shear strength. This would mean that the 0° isotherm in the core dips below the glacier bottom (Permafrost) corresponding to the above-mentioned hypotheses based on seismic and thermodynamic examination[4, 15].

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* The division of movement in central Greenland is an exception; here the shear stress (τ_{xz0}∼0) is very small.

The fact that three different methods lead to basically the same result should not allow one to overlook the provisional nature of the extrapolation of the results obtained from the Jungfraujoch. The deviation of the actual three-dimensional motion from the above, where a plane creep motion has been assumed, requires further clarification. The question of the influence of pressure from all sides upon the ability of the ice to deform is vital for the justification of such an extrapolation. In this connection, mention must be made of the latest experiments of S. Steinemann, where superposition on a shear stress of a hydrostatic pressure up to 90 kg./cm.^{2} reveals practically no influence of this pressure upon the plastic behaviour of the cold ice.* On the other hand we must remember that in central Greenland the overburden pressure of the ice reaches 300 kg./cm.^{2}.

The observation and measurement of smaller and more easily accessible natural objects, such as for example the ice cap of the Jungfraujoch, offers the possibility, among other things, of acting as a link between arctic exploration on the one hand and research in the ice laboratory on the other, so as to further our knowledge of nature by direct observation[16–23].

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The division of the work between the authors of this paper is as follows: the first-named technical adviser to the P.T.T. took over the leadership and valuation of the glaciological examinations, while the second carried out the geodetic measurements as local leader of the tunnel construction work.

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* Publication in preparation.

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