OBSERVATIONS ON THE QUASI-VISCOUS BEHAVIOUR OF ICE IN A TUNNEL IN THE Z'MUTT GLACIER

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ABSTRACT. It is suggested that both discontinuous shearing and continuous flow (creep) may coexist in one and the same glacier, provided the stress is high enough for the shear resistance to be reached. Experiments made in a tunnel in the Z'Mutt Glacier suggest that all the motion here observed was continuous, and also show that the viscosity is influenced by the stress conditions. A series of tests made by forcing a ball into the ice also enabled estimates of the viscosity and melting pressure to be made and emphasized the importance of melting in glacier flow.

ZUSAMMENFASSUNG. Diskontinuierliche Scherung und kontinuierliche Verformung (Kriechen) können in demselben Gletscher nebeneinander bestehen, vorausgesetzt, dass die Scherspannung gross genug ist, um die Scherfestigkeit zu erreichen. Experimentelle Messungen, die in einem Stollen im Z'Muttgletscher ausgeführt wurden, deuten darauf hin, dass die Verformung im untersuchten Bereich kontinuierlich ist und dass die Viskosität vom Spannungszustand abhängt. Die Viskosität und der Schmelzdruck wurden auch mit Hilfe eines Apparates gemessen, der eine Kugel in das Eis eindrückte. Es wird auf die Wichtigkeit der Druckschmelzung im fliessenden Gletscher hingewiesen.

IN discussions of the mechanism of glacier flow, two apparently contrary opinions are nowadays presented which seem, on closer consideration, better qualified to supplement one another. On the one hand we have the well-known classical approach which considers the motion as "viscous flow" in the sense of Newton, Stokes or Navier, and on the other hand, there are the more recent attempts [1, 2] to solve the problem by means of the theory of plasticity on the basis of a system of regular shear.

The co-existence of continuous and discontinuous deformation of ice—including "*Blockschollen*" movement—in one and the same glacier has been observed repeatedly and shows clearly that the movement of glaciers cannot, in general, be explained by a single system (*Gesetzmässigkeit*).[3] If the shear stress remains below the shear resistance the deformation of the ice is perfectly continuous as in viscous flow—in the new terminology it creeps. This type of motion, which has been detected by numerous velocity measurements, prevails in the class of flat alpine glaciers irrespective of whether slipping occurs on the bed.

In comparison with other materials, it may be mentioned that creep in its most general form (variable volume) can be accurately followed in all detail in the winter snow cover.[4, 5] The creep process also plays an essential part in the deformation of metals at high temperatures, which is closely related to the continuous deformation of snow and ice. In a saturated clay, too, creep takes place as soon as the shear stress exceeds about half the shear resistance.[6]

When the limiting equilibrium state is reached and the shear resistance is exceeded locally, shear surfaces are formed, which in stratified ice run predominantly along the natural surfaces of discontinuity, while in homogeneous isotropic ice they are determined by the laws of the theory of plasticity. An apparently continuous form of motion could only occur here if there were an indefinitely large number of shear surfaces. As, however, these shear surfaces usually appear singly or at a great distance one from another, as is characteristic for materials with a high cohesion, a composite motion takes place. Creep occurs between the individual shear surfaces as well as the shear movement, and this may form a greater or lesser part of the total movement. This creep is not covered by the theory of plasticity, whose principal application is therefore found in those cases in which creep is of minor importance in comparison with the shear movement.

In the region of creep which, apart from the slipping of the glacier on its bedrock, is the main form of movement in alpine glaciers, the works of Somigliana and Lagally, which are based on the assumption of a constant viscosity, have led to remarkable results. If the assumption of a constant viscosity, which made this first great step possible, is to-day no longer sufficient for a detailed picture, it is primarily because some of the numerous factors which influence the deformation of ice must be supposed to vary from point to point. Among these factors we must include not only the crystallographic characteristics of the ice but also the general conditions of stress.

Very valuable evidence of creep in a temperate glacier can be obtained by direct measurement of the distribution of velocity in a vertical profile, as has been done by Perutz and his collaborators on the Jungfraujoch.[7] The relation between the rate of flow and the shear stress which resulted from this test showed fundamentally an increasing fluidity with increasing shear stress (Fig. 1, p. 95). In a recent publication Perutz and Gerrard[8] propose the following tentative relation between shear stress and rate of flow:

$$\frac{d\gamma}{dt}=\frac{\tau^n}{k}$$

where n appears to be of the order of 2.

On the other hand the observations which were made in the Z'Mutt Glacier led to the assumption that the viscosity is inversely proportional to the depth, that is to say to the shear stress.[9] In this case the slope of the straight line AB which represents a Newtonian liquid, would increase proportionally with τ and the curve ABC should be replaced by a parabola. Our tentative proposition, which must only be considered as a possible special case of a general theory, which should contain the influence not only of the shear stress but also of the normal stresses, is therefore practically identical with that of Perutz and Gerrard with $n=2$. The surface velocity of a plane layer of ice with a constant thickness would, in this case, increase with the cube instead of the square of the thickness. It is further remarkable that the yield stress at which creep begins, which was proved to be zero for snow, may also be extremely small if not zero in temperate ice.

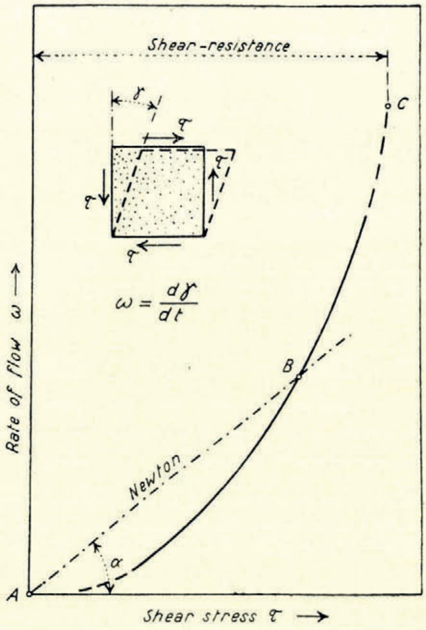

Fig. 1. Relation between rate of flow and shear stress

In the analysis of the creep described below, the usual Newtonian theory of viscosity is retained as being the simplest working hypothesis, but with the limitation that the viscosity is presumed constant only in a relatively small region. In order to determine the local variation, attempts have been made to develop methods of measuring the viscosity at different points inside the glacier.

The first of these methods was the examination of the creep of the walls of a circular pit or tunnel. This method was used in the upper tunnel of the Mont Collon Glacier [10] as well as in the Z'Mutt tunnel, and at lengths of about 200 m. and 1000 m. respectively only perfectly continuous and steady deformation was observed. As the shear resistance of the ice had nowhere been reached only pure creep motion was to be expected here. The location and movement of the Z'Mutt glacier are shown in Fig. 2 and 3 (p. 96 and 97).

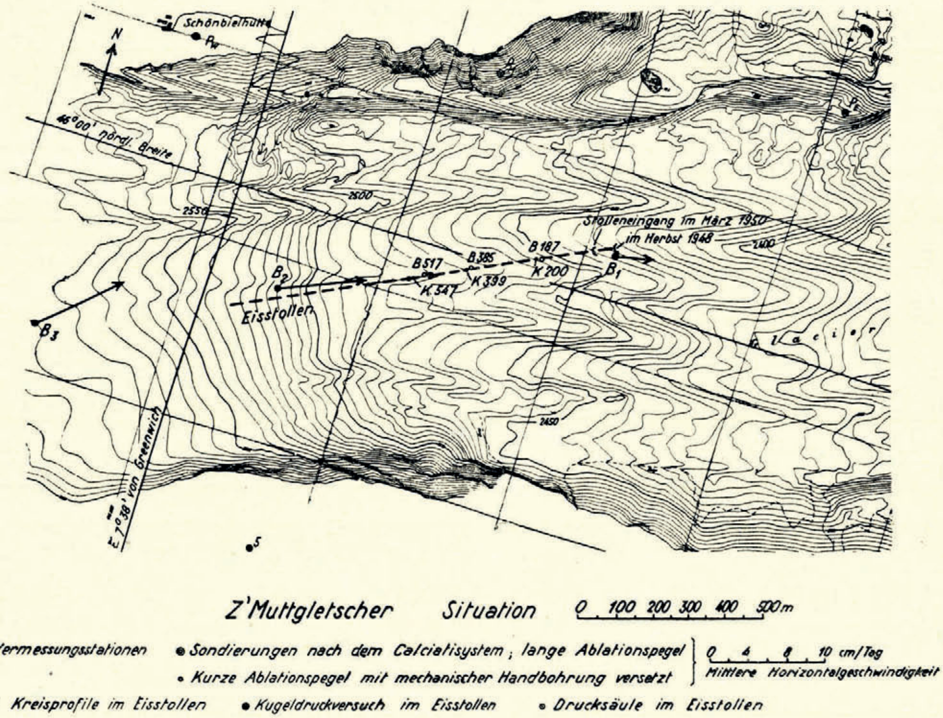

Fig. 2. Plan of the Z'Mutt Glacier showing mean surface velocity at various points (arrows) cf. scale in bottom right-hand corner, the tunnel (Eisstollen) and its mouths in autumn 1948 and March 1950 (Stolleneingang), also the positions in the tunnel at which creep profiles and ball pressure tests were made

1. Measurements of the Contraction Velocity by Creep of Circular Pits and Shafts

In the case of a semi-infinite body with a horizontal surface and constant viscosity, the following approximate relation is obtained between the relative velocity of contraction v_r of a circular pit, the hydrostatic pressure p of the overlying ice at the point considered, and the viscosity μ of the medium (see Fig. 4, p. 97):

$$v_r = \frac{v}{r} \sim \frac{p}{2\mu} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

Under certain conditions this relation can also be applied to a tunnel far below the surface, and the above-mentioned tunnel in the Z'Mutt Glacier, which had been dug by the E.O.S. (now Grande Dixence S.A.), provided an opportunity to check this. Three circular holes each of 6 m. length were excavated in the tunnel and their deformation was observed for about a year (Fig. 5, p. 98). On the whole the circular form was maintained, whence it follows that transverse to the axis of the tunnel there prevails an approximately hydrostatic state of stress, as assumed by the

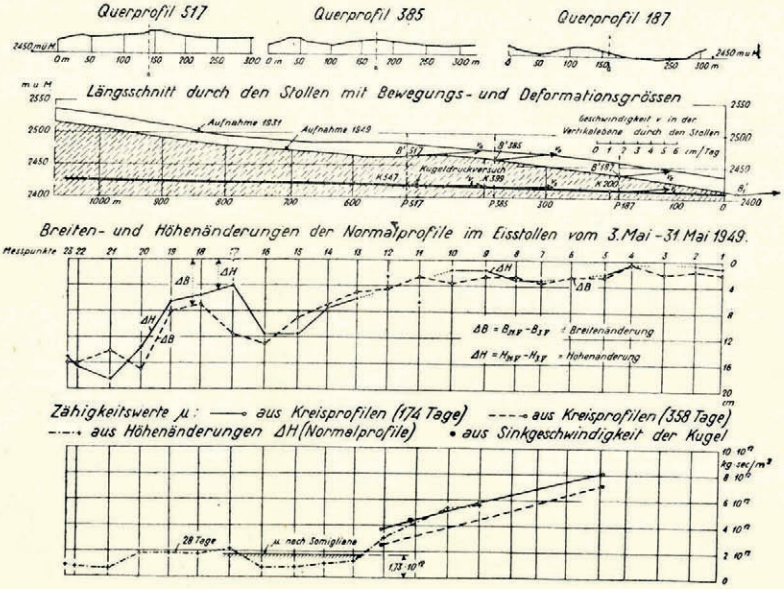

Fig. 3. From top to bottom: (1) *Cross sections of the glacier at the three measuring points in the tunnel.* (2) *Profile of the glacier surface parallel to the tunnel showing movement and deformation.* (3) *Variations of breadth ΔB and of height ΔH of the tunnel from 3–31 May 1949 plotted against position in the tunnel.* (4) *Viscosity μ as measured by* (a) *circular profile over 174 days* ———o, (b) *circular profile over 358 days* - - - o, (c) *height variation ΔH* –·–·+, (d) *velocity of sinking of the ball* •

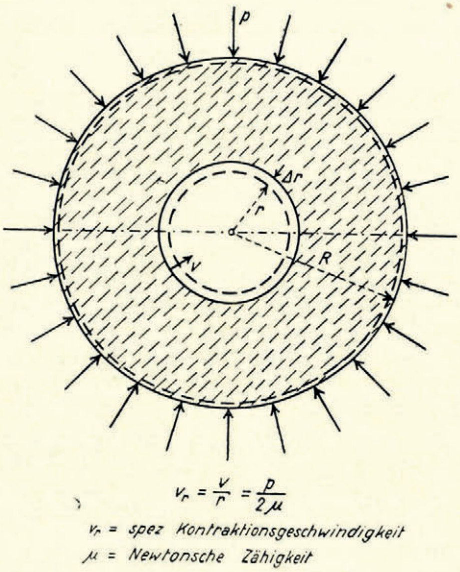

Fig. 4. Contraction of a circular shaft. v_r=*specific contraction rate,* μ=*Newtonian viscosity*

theory. The velocity of contraction increased more rapidly in the interior of the tunnel than was expected by reason of the pressure of the overlying ice, and showed considerable fluctuations during the year (Fig. 6, p. 98). Calculation using equation (1) of the mean annual contraction velocity for the three profiles examined showed a very marked decrease of viscosity from the outside to the interior, *i.e.* from about 8 to $3 \cdot 7 \times 10^{14}$ poise (see profiles 200 and 547 in Fig. 6). These values are higher than the average viscosity of the glacier obtained by Somigliana's formula.

2. MEASUREMENT OF THE SINKING VELOCITY OF A LOADED BALL

This method enables us to measure the "viscosity" of the ice at various points. As long as the contact stress between the loaded ball and ice remains below the melting pressure p_0, the sinking of the ball will occur without pressure melting, *i.e.* only because of the quasi-viscous behaviour of the medium. In this case Stokes's law gives an approximate velocity for the sinking of the ball,

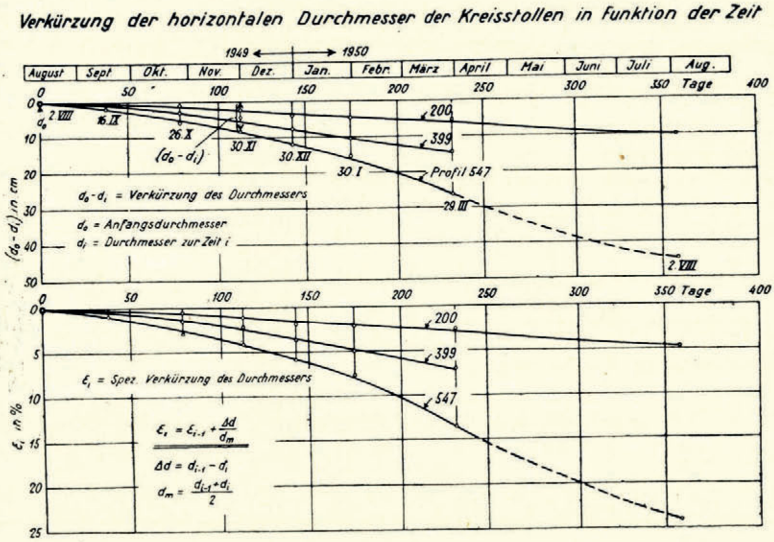

Fig. 5. Reduction of the horizontal diameter of circular shaft as a function of time, d_0=initial diameter, d_i=diameter at time i, ϵ_i= percentage reduction in diameter

$$v \sim \frac{\sigma}{12\mu} \cdot d, \quad \sigma < p_0$$

where σ is the mean stress calculated from the cross-section of the ball and *d* its diameter.

If σ is greater than p_0, pressure melting takes place and much greater velocities result. As the curve of velocity shows a sharp bend at the transition to pressure melting, not only the viscosity μ but also the melting pressure p_0 can be found in this way. The latter will be determined by the position of the bend and thus several tests with appropriate loads are necessary. Moreover the temperature of the ice can be deduced from the melting pressure.

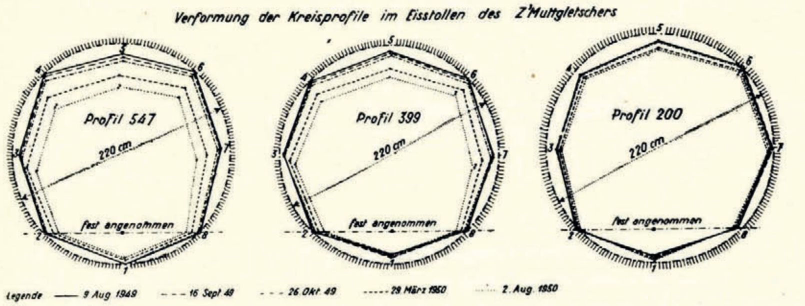

Fig. 6. Deformation of circular profiles in the ice tunnel of the Z'Mutt Glacier

The first tests were made in a small recess in the Z'Mutt Glacier tunnel at a point where the overlying ice reached a depth of about 48 m. The metal ball of 10 cm.^{2} cross-section was loaded with a vertical load to pressures ranging between 2·5 and 10 Kg./cm.^{2} (Fig. 7, p. 99). The higher pressures (10–5·0 Kg./cm.^{2}) produced a very large sinking velocity (0·07–0·58 cm./day). Only the lowest load of 2·5 Kg./cm.^{2} gave a normal value for the viscosity, and this agrees well with the values obtained by measuring the contraction velocity of the circular holes (Fig. 3). The melting pressure was about 4·3 Kg./cm.², a value which agrees more or less with the pressure of the overlying ice at the position of the test. This corresponds to an ice temperature of —0·032° C.

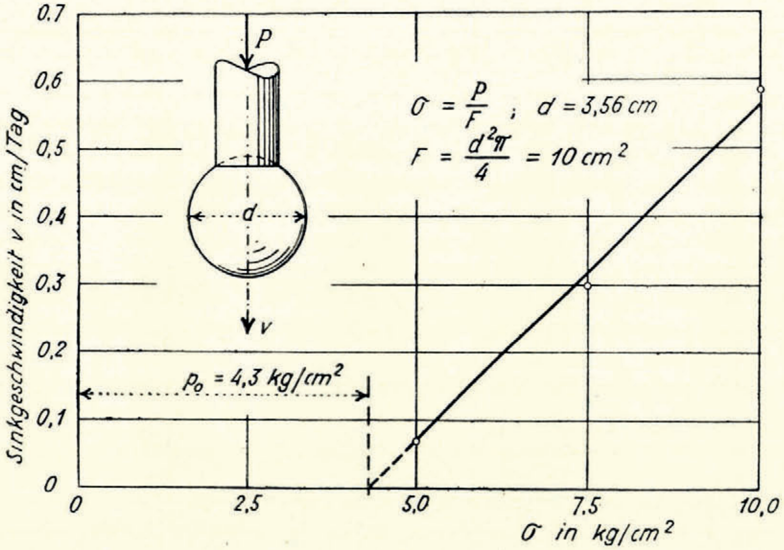

Fig. 7. Velocity of sinking of a loaded ball as a function of applied stress

The tests with the sinking ball confirm the importance of pressure melting in glacier flow. Owing to local pressure concentrations the fluidity and thus the deformation of the ice is locally increased. The importance of thermodynamical and hydrodynamical considerations is thus apparent.

A detailed description of the measurements and results obtained in the Z'Mutt tunnel, which can only be given summarily here, is contained in the report presented to the International Commission on Snow and Ice at Brussels in 1951.[9, 11] It may be mentioned here that according to Renaud the chemical properties of the water film between the ice crystals has a great influence on the plasticity of the ice.

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