

The role of the water content on the creep rate of polycrystalline ice

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Abstract. Experiments on the creep of natural polycrystalline ice samples were performed in conditions similar to those found in temperate glaciers. The water content of the ice samples studied was measured directly for the experiments carried out closest to 0°C. The value of the constant B of Glen's law ($\dot{\gamma} = B\tau^n$) passes from 0.15 to 0.50 b⁻³ year⁻¹ when one passes from a temperature of $(-0.20 \pm 0.01)^\circ\text{C}$ and a negligible water content to a temperature of $0 \pm 0.005^\circ\text{C}$ and a water content equal to 0.8 per cent. For a given temperature, the variations in creep rate of the samples are due to variations in the salt content which cause variations in the water content. The role of water on the creep rate of polycrystalline ice is analysed in relation to the various mechanisms that control the deformation of ice.

Le rôle de la teneur en eau dans la vitesse du fluage de la glace polycristalline

Résumé. Des expériences de fluage de glaces polycristallines naturelles ont été réalisées sous des conditions semblables à celles trouvées dans les glaciers tempérés. La teneur en eau des glaces étudiées était mesurée directement pour les expériences réalisées le plus près de 0°C. La valeur de la constante B de la loi de Glen ($\dot{\gamma} = B\tau^n$) passe de 0.15 à 0.50 b⁻³ an⁻¹ lorsqu'on passe d'une température de $(-0.20 \pm 0.01)^\circ\text{C}$ et une teneur en eau négligeable à une température de $0 \pm 0.005^\circ\text{C}$ et une teneur en eau égale à 0.8 pour cent. Pour une température donnée, les variations de la vitesse de fluage entre les échantillons sont dues à des variations de la teneur en impuretés solubles, provoquant des variations de la teneur en eau. Le rôle de l'eau dans la vitesse du fluage de la glace polycristalline est analysé en fonction des différents mécanismes qui contrôlent la déformation de la glace.

INTRODUCTION

The flow law for polycrystalline ice has been established, particularly at temperatures below the melting point. Only Glen (1955) and Colbeck and Evans (1973) have studied the behaviour of ice at the melting point itself. The strain rates calculated by Colbeck and Evans are more than an order of magnitude higher than those deduced by Glen. According to Colbeck these differences are due to the fact that Glen's experiments were carried out below the melting point, at -0.02°C , for the pressure considered.

Temperate ice is ice which contains and is in local equilibrium with a liquid phase (Harrison, 1972; Lliboutry, 1971, 1975). The main feature of temperate ice is its water content. The temperature, when corrected for the effects of pressure and of interfacial solid-liquid tensions, may fluctuate within a few hundredths of a degree in relation to the water content and to the quantity of salts dissolved in the liquid phase. Measurements of the water content in ice from the Vallée Blanche made by Vallon *et al.* (1976) vary from 0.1 to 2 per cent according to the depth.

The aim of the present study was to measure the viscosity of natural polycrystalline ice in relation to water content.

EXPERIMENTAL METHODS

Apparatus

The viscosimeter used for these experiments allows one to exert simultaneously an axial torsion torque and a compression stress on a core of ice hollowed out along the axis (external diameter: 90–120 mm; internal diameter: about 45 mm; height: about 13 mm). The two cylindrical faces are subjected to the same

pressure by means of a fluid. The axial strain and the torsion strain are measured by two differential transformer transducers (Duval, 1976).

This apparatus was built specifically for the study of the creep of ice at its melting point. In order to do this, the whole apparatus is placed in a cold-room maintained at $(0 \pm 0.5)^\circ\text{C}$. A system of regulation inherent in the apparatus allows one to reach the melting point with precision. The temperature of the core is measured at its extremities and at different points along the internal and external faces of the cylinder by previously calibrated thermistors. The maximum variation of temperature measured in the course of an experiment is 0.01°C .

Procedure

The ice is first of all strained at a temperature in the vicinity of -0.2°C until tertiary creep, which occurs after recrystallization, takes place. Thanks to the system of regulation, the strain rates for temperatures closer and closer to 0°C can then be measured. For temperatures corresponding to water contents smaller than 0.1 per cent the strain rates are measured when the temperature of the centre of the core is the same as that at the extremities. For water contents greater than 0.1 per cent equal temperatures do not indicate the stability of the water content; indeed, large variations in the water content correspond to variations of temperature which cannot be measured with the apparatus ($\Delta\theta < 0.01^\circ\text{C}$). Thus the strain rates were measured only 12 or 24 h after the temperatures had stabilized. The water content was then measured without stopping the experiment.

Measurement of the water content

In order to measure the water content of the ice being studied, one of the extremities is cooled by frigistors to a temperature θ_1 of about -0.20°C . Since the ice is initially at a temperature θ_0 in the vicinity of 0°C , a cold wave sets in, beginning at the cold extremity. One then records the evolution of the temperatures θ_2 and θ_3 at two points x_2 and x_3 situated on the same generating line of the core. The water content is determined by measuring the times t_2 and t_3 that the cold front takes to reach the points x_2 and x_3 (Duval, 1976).

Samples

The samples studied came from a drilling carried out in July 1971 on the whole thickness of the glacier of the Vallée Blanche (French Alps). They are identified by VB and the depth from which they were taken. The petrographic study was carried out by Vallon *et al.* (1976).

RESULTS

Figure 1 shows the variation in the effective shear strain rate of the tertiary creep $\dot{\gamma}$ with the water content for three ice samples; $\dot{\gamma}$ is defined by

$$(\dot{\gamma}/2)^2 = \frac{1}{2} \sum_{i,j} (\dot{\epsilon}_{ij})^2$$

where $\dot{\epsilon}_{ij}$ are the strain rates. The effective shear stress τ , defined by

$$\tau^2 = \frac{1}{2} \sum_{i,j} (\tau'_{ij})^2$$

where τ'_{ij} are the components of the deviatoric stress tensor, was equal to 2.90 b. The points corresponding to water contents lower than 0.05 per cent were

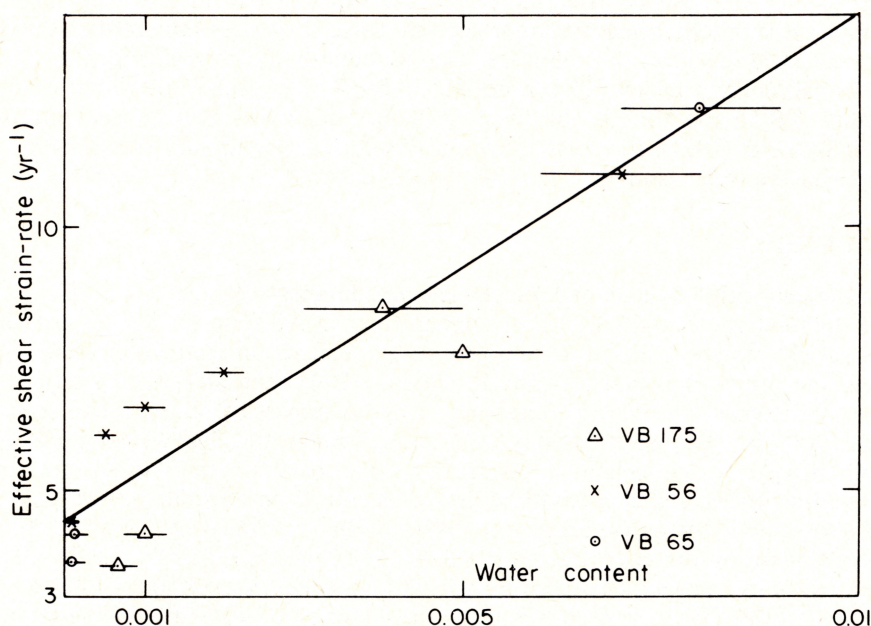


FIGURE 1. Tertiary effective shear strain rate *versus* water content. Effective shear stress $\tau = 2.90$ b.

calculated from the measurement of the temperature according to the equation

$$\theta = \frac{-55S}{W} \quad (1)$$

where S is the fraction of salt contained in the ice, θ the temperature and W the water content. The results are shown in Table 1. We adopted Glen's law

$$\dot{\gamma} = B\tau^n \quad (2)$$

with $n = 3$; B is a constant expressed in $\text{b}^{-3} \text{year}^{-1}$. The salt concentrations of the ice cores were calculated from equation (1) when both the temperature and the water content had been measured (Table 1).

TABLE 1. Variation of the effective shear strain rate *versus* temperature and water content at the melting point. Effective shear stress $\tau = 2.90$ b

Sample	Measured temperature ($\Delta\theta < 0.01$) [°C]	Effective shear strain rate [year ⁻¹]	Measured water content [%]	B [b ⁻³ year ⁻¹]	Calculated salinity [10 ⁻⁶ g/g]
VB 56	-0.20	4.36	—	0.18	—
	-0.015	6.05	0.05 ± 0.01	0.25	0.14 ± 0.08
	-0.007	6.65	0.1 ± 0.02	0.27	—
	-0.004	7.25	0.2 ± 0.02	0.30	—
	0	10.95	0.7 ± 0.1	0.45	—
VB 65	-0.20	3.65	—	0.15	—
	-0.08	4.36	—	0.18	—
	0	12.20	0.8 ± 0.1	0.50	—
VB 175	-0.10	3.66	—	0.15	—
	-0.07	4.20	0.1 ± 0.02	0.17	1.3 ± 0.3
	-0.025	7.60	0.5 ± 0.1	0.31	—
	-0.025	8.45	0.4 ± 0.1	0.35	—

These results show the rapid increase in the strain rate relative to the water content: it is tripled when the water content passes from less than 0.01 to 0.8 per cent. The variation of B with the water content is more or less linear.

The salt content of VB 175 is approximately 10 times greater than that of samples VB 56 and VB 65. This result is in agreement with the chemical analysis made by Briat (1974). But as is shown in Fig. 1, B seems to vary in the same way with the water content, whatever the salt content.

DISCUSSION

Comparison with field data and the glaciological implications

The different values of B found for temperatures in the vicinity of 0°C are to be compared with those deduced from field measurements on temperate glaciers. Thus, the values of B calculated by Raymond (1973) from measurements of internal deformation made in boreholes on the Athabasca Glacier, are of the order of $0.15 \text{ b}^{-3.5} \text{ year}^{-1}$. By way of contrast, Shreve and Sharp (1970) found, while using the same technique, far greater values of B for the Blue Glacier. These different values of B could be due to variations in the water content.

Llibouty (1975) analysed a process of instability provoked by the effect of the water content on the viscosity of the ice, which could appear in the glaciers. If there exists in a glacier a layer of ice with a high water content and if the stresses on this layer are fixed, the rate of production of water by the dissipation of energy, inversely proportional to the viscosity of the ice, will be very high. The viscosity of this layer of ice will then diminish very rapidly; hence there appears an accelerated process of water production and thus there is instability. The layers of ice made up of small crystals, which are observed in temperate glaciers, may be examples of this. Indeed, there would appear to be a correlation between the size of the crystals and the water content (Vallon *et al.*, 1976).

The role of the water content on the creep of polycrystalline ice

The increase in the strain rate for small temperature variations cannot be attributed to the thermal activation processes according to Arrhenius's relation. Barnes *et al.* (1971) think that the grain boundary sliding and the liquid at the junctions of three or four grains play complementary roles in facilitating the deformation of ice close to the melting point. However, the grain boundary sliding and the melting and refreezing processes do not control the deformation of temperate ice; indeed, the index of Glen's law remains equal to 3 (Duval, 1976).

In the absence of deformation, the water is situated mainly at the intersections of the three or four grains (Nye and Frank, 1973); but when the ice is subjected to nonhydrostatic stresses, the stresses are concentrated at different points in the sample, thus causing a lowering of the melting point. The water initially present at the intersections of the three or four grains will partially refreeze and will appear at the points at which the stresses have concentrated, i.e. in particular at the grain boundaries (Nye and Mae, 1972) and also perhaps at the points where dislocations pile up. The water should thus attenuate the effects of the strainhardening. The processes of recrystallization also attenuate the strainhardening effects. The role of the water could be to facilitate the migration of portions of grain boundaries in contact with it, i.e. to facilitate the syntectonic recrystallization.

Further, the number of point defects increases very rapidly near the melting point. The velocity of dislocations which increases with the number of rotational defects (Perez *et al.*, 1975) should thus be affected by the presence of water.

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