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## RATE CONTROLLING PROCESSES IN THE CREEP OF POLAR GLACIER ICE

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## Résumé

Des essais mécaniques en torsion ont été effectués sur de la glace artificielle et sur des échantillons provenant d'une carotte extraite à la station de Pôle Sud. Les résultats indiquent un exposant  $n$  inférieur à 2 pour des contraintes inférieures à 0,1 MPa. L'analyse des données d'inclinométrie de Dye 3 conduit au même résultat. Les mécanismes de déformation pour la glace polaire sont discutés. La migration des joints de grain associée au grossissement des grains peut accommoder le glissement intracristallin et conduire à une viscosité Newtonienne. Cependant, la rotation des grains résultant du glissement des dislocations et la migration des joints de grain induite par la déformation sont des mécanismes complémentaires et efficaces pour accommoder la déformation plastique entre les grains d'orientation différente. Ces mécanismes de déformation concernent une grande partie des glaces polaires.

## Abstract

Torsion tests have been carried out on artificial ice and on samples cut from an ice core obtained at South Pole Station. Results give a stress exponent smaller than 2 for stresses lower than 0.1 MPa. Analysis of the inclinometer survey of the Dye 3 borehole yields the same result. The deformation mechanisms of polar ice at low stresses are reviewed. A Newtonian viscosity may be expected with dislocation glide accommodated by grainboundary migration linked with graingrowth. However, rotation of crystals by dislocation glide and strain-induced boundary migration are complementary and efficient mechanisms to accommodate the incompatible plastic deformation between grains of different lattice orientation. These deformation mechanisms concern a great part of polar ice.

## 1. Introduction

Polar ice-sheet flow modelling is hindered by the limited knowledge of the rheological law for polycrystalline ice. Stresses are typically around 0.1 MPa or less. In the literature, field studies suggest a relationship between strain rate  $\dot{\epsilon}$  and stress  $\sigma$  of the form  $\dot{\epsilon} = A \sigma^n$  with  $n$  ranging from 1 to 3 [1-6]. At these low stresses laboratory data are questionable if the minimum creep rate  $\dot{\epsilon}_{\min}$  is not reached. However it appears that  $\dot{\epsilon}_{\min}$  is obtained over a total strain of less than 1% [7][8]. Several laboratory tests have yielded an exponent  $n$  smaller than 2 at low stresses [9 - 10].

Theoretical studies suggest that  $n$  may be 1 at low stresses where the rate-controlling processes are lattice and grainboundary diffusion [11]. However, this deformation mechanism does not seem to be an efficient process for polar ice [12]. A kind of superplastic behavior linked with grain growth has been suggested by Duval and Lliboutry [12], giving an exponent smaller than 3. The purpose of the paper is to clarify the deformation processes of polar ice at low stresses both by experimental techniques and theoretical analyses.

2. Laboratory creep tests

Torsion creep tests were performed on artificial and natural fined-grained polycrystalline ice with random c-axis orientation. Artificial ice was prepared using the technique described by Duval and Le Gac [13]. Natural ice comes from a 130 m deep drilling carried out at South Pole Station. The ice-transition occurs at a depth of about 115 m. The depth of the studied ice samples was approximately 120 m with a density of about 0.85 g/cm<sup>3</sup>.

Tests were conducted at -15°C with the torsion apparatus described by Duval [14]. Samples were cylindrical with diameter 70 mm and length 130 mm. Results on artificial and natural ice are presented in table 1. We have quoted the measured strain-rates at the end of experiments. For artificial ice the test was conducted on one sample by increasing the applied stress from 0.034 to 0.114 MPa. The total strain ranged from 2 to 9 X 10<sup>-4</sup> for each point. By analyzing creep curves it was shown that Andrade's law was verified (Pimienta, unpublished). The extrapolated creep rates are given in table 1. Figure 1 shows the measured strain rates versus shear stress for both artificial and South Pole ices. The deduced stress exponent is smaller than 2. A similar result is obtained with the extrapolated minimum strain rates.

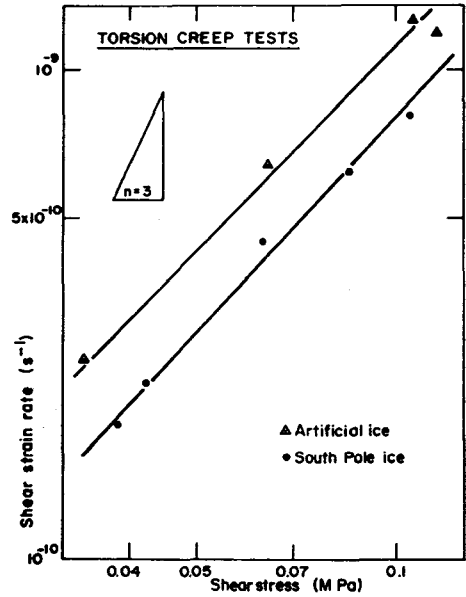


Fig.1 : Minimum measured shear strain rate as a function of shear stress. Temperature T = -15°C

	Maximum shear stress (MPa)	Grain size(mm <sup>2</sup> )		Duration of experiments (hours)	Total shear strain	Measured shear strain rate (s <sup>-1</sup> )	Extrapolated shear strain rate (s <sup>-1</sup> )
		before	after				
PS154a	0.038	2.7	2.5	200	2 x 10 <sup>-4</sup>	1.9x10 <sup>-10</sup>	1 x 10 <sup>-10</sup>
PS158b	0.042	1.6	2.4	650	8 x 10 <sup>-4</sup>	2.3x10 <sup>-10</sup>	2 x 10 <sup>-10</sup>
PS157b	0.063	1.8	2	150	4 x 10 <sup>-4</sup>	4.5x10 <sup>-10</sup>	2.1x10 <sup>-10</sup>
PS158a	0.084	1.5	1.8	200	8 x 10 <sup>-4</sup>	6.2x10 <sup>-10</sup>	3.9x10 <sup>-10</sup>
PS154a	0.105	2.5	2.5	120	4 x 10 <sup>-4</sup>	8.2x10 <sup>-10</sup>	6.9x10 <sup>-10</sup>
ARTIF1	0.034	1.6	-	190	3 x 10 <sup>-4</sup>	2.5x10 <sup>-10</sup>	1.4x10 <sup>-10</sup>
ARTIF1	0.064	-	-	145	6 x 10 <sup>-4</sup>	6.4x10 <sup>-10</sup>	3.2x10 <sup>-10</sup>
ARTIF1	0.106	-	-	120	8 x 10 <sup>-4</sup>	1.2x10 <sup>-9</sup>	8.8x10 <sup>-10</sup>
ARTIF1	0.114	-	1.6	170	8.5x10 <sup>-4</sup>	1.2x10 <sup>-9</sup>	1.1x10 <sup>-9</sup>

TABLE 1: Summary of laboratory results at -15 C

3. Inclinometer data at Dye 3

An inclinometer profile of the bore-hole at Dye 3 (Greenland) was obtained by Gundestrup and Hansen [15]. From the velocity profile estimated by the authors, we have calculated the horizontal shear strain rate. Figure 2 shows the adjusted

values of shear strain rate as a function of shear stress between 1000 and 1784 m. Data were referred to a temperature of  $-20^{\circ}\text{C}$  using an activation energy of 60 kJ/mol. Shear stress was calculated with a surface slope of  $3.3 \times 10^{-3}$  rad. [16]. Data for Wisconsin ice were not included in this analysis. Quasi-linearity of the flow law is observed while the strengthening of fabrics between 1000 and 1784 m [17] gives an apparent exponent  $n$  higher than expected for isotropic ice. This field investigation is therefore in a good agreement with that of Doake and Wolff [1] and that of Lliboutry and Duval [2].

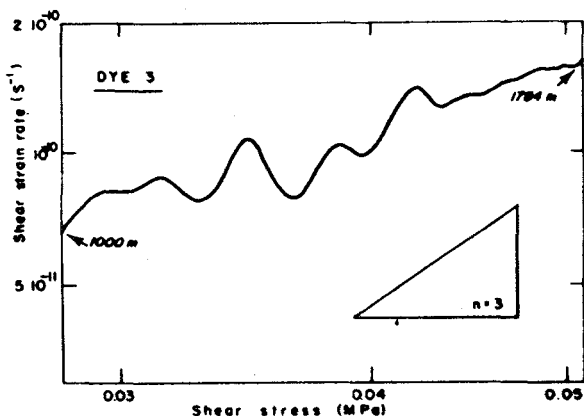


Figure 2 :  
Calculated shear strain rate (referred to a temperature of  $-20^{\circ}\text{C}$  using an activation energy of 60 KJ) versus shear stress (from inclinometry data of Gundestrup and Hansen [15]).

#### 4. Texture of polar ice

Changes in ice texture with increasing depth in polar ice sheets reveal striking similarities [18]. An excellent illustration of the texture of polar ice has been given by Gow and Williamson [19] with the 2164 m ice core at Byrd Station (Antarctica). In the upper 450 m crystal size increases linearly with depth, the driving force coming from the free energy at grain boundaries. No preferred orientation of c-axes is evident in this upper layer. Between 450 m and 1200 m, with a near constant crystal size ( $l^2 \approx 40 \text{ mm}^2$ ), the progressive growth of an oriented fabric is observed. A highly oriented fine-grained structure is found between 1200 and 1800 m in glacial ice. A rapid transformation from single to multiple maximum fabric occurs below 1800 m accompanied by the growth of large crystals. This transformation is an obvious effect of recrystallization. In Greenland, recrystallization does not seem to occur, probably because the temperature is below  $-10^{\circ}\text{C}$  near bedrock [20].

#### 5. Deformation processes associated with grain growth

##### 5.1. Incompatibility of diffusional creep and of non-linear dislocation creep with grain growth

At low stresses, deformation can occur by grain boundary sliding accompanied by a mechanism of diffusion of molecules from crystal boundaries that carry a compressive load to those under tension. The driving force for the diffusion process is about  $20\sigma b^3/l$  ( $b$  is Burgers' vector and  $l$  the grain size). For grain growth, a driving force of about  $4\gamma b^2/l$  ( $\gamma$  is the specific grain boundary energy) higher than the drag forces is required. In polar ice grain growth occurs with a driving force much higher than that for diffusional creep [12]. Grains therefore grow much faster than they deform by grainboundary sliding and molecule diffusion. On the other hand, Nabarro-Herring creep yields a viscosity much larger than that deduced by inclinometry [2].

Concerning the non-linear dislocation creep with  $n=3$ , it implies very high strain energy in comparison with the grainboundary energy which drives grain growth [21].

The stored energy increases with strain and can be higher than  $10^4 \text{ J/m}^3$  for a strain of 1%. Since the driving force for grain growth is typically around  $100 \text{ J/m}^3$  power law creep with  $n=3$  is not compatible with grain growth. Since grain growth does occur another deformation process must therefore be invoked to explain the quasi-Newtonian behavior of polar ice.

### 5.2. Newtonian dislocation creep

A linear relationship at low stresses can be accounted for by a dislocation mechanism if the dislocation density does not change with stress [2] [23]. This flow process is referred to as Harper-Dörn creep and has characteristics which are markedly different from those associated with diffusional creep. This deformation process leads to creep rates which are more than one order of magnitude faster than those predicted by the diffusional creep law.

Several dislocation models have been put forward to explain H.D. creep. For polar ice the absorption of lattice dislocations at grainboundaries can impede strain-hardening and makes strain energy small compared with the driving force for grain growth. This is possible as long as the grainboundary migration (gbm) associated with grain growth accommodates dislocation glide. In each grain the emission of  $n$  loops produces a shear strain of about  $nb/1$ . This strain is accommodated by a migration of boundaries  $\Delta l$  which must be at least equal to  $nb$ . With  $\dot{\epsilon} = nb/1$  and  $dl/dt = K/2l$  ( $K$  is the growth rate) this condition leads to :

$$K/2l \geq \dot{\epsilon} l$$

	Grain size $l^2$ ( $\text{mm}^2$ )	$K$ ( $\text{m}^2/\text{year}$ )	Vertical strain rate ( $\text{year}^{-1}$ )	$K/2l^2$ ( $\text{year}^{-1}$ )	Dislocation number absorbed by GB in each grain ( $\text{year}^{-1}$ )
Byrd surface	3	$1.2 \times 10^{-8}$	$7.8 \times 10^{-5}$	$2 \times 10^{-3}$	300
Dome C surf.	1	$4 \times 10^{-10}$	$1 \times 10^{-5}$	$2 \times 10^{-4}$	20
Dome C (900m)	4	$1.2 \times 10^{-10}$	$1 \times 10^{-5}$	$1.5 \times 10^{-5}$	45
Dye 3 surf.	3	$1.5 \times 10^{-8}$	$3 \times 10^{-4}$	$2.5 \times 10^{-3}$	1200

Table 2: Efficiency of grainboundary migration as an accommodation process of dislocation glide.

The condition  $K/2l^2 \geq \dot{\epsilon} l$  is verified if grain growth occurs.

It is important to observe that few dislocations ( $n = \dot{\epsilon} l/b$ ) are absorbed by GB during one year.

An upper bound for  $\dot{\epsilon}$  was calculated for the Byrd and Dome C ice cores and compared with the expected vertical strain rate (table 2). At Byrd this process must take place down to a depth of 450 m (grain growth stops at this depth). At Dome C it takes place down to at least 900 m since the surface slope is too low for the horizontal shear strain rate to be higher than  $10^{-5} \text{ a}^{-1}$ .

In conclusion, grainboundary migration associated with grain growth is an efficient accommodation process for dislocation glide in fine-grained ices. In consequence the usual transient creep cannot occur and strain energy is always small compared with the driving force for grain growth. If the number of dislocations emitted from sources does not change with stress, a Newtonian viscosity is expected.

## 6. Deformation processes in the transition zone

A transition zone can be defined as follows: the zone where grain growth does not occur as a result of an insufficient driving force and where dynamic recrystallization is not initiated because of insufficient differences in strain energy between grains. At Byrd station this zone is situated between 450 and 1800 m. In laboratory tests the critical strain for the initiation of recrystallization is less than 1%. With a strain rate of  $10^{-3} \text{ a}^{-1}$  and with an accumulation rate of  $16 \text{ g/cm}^3$  recrystallization should be initiated in the first meters of this transition zone. It seems therefore quite reasonable that grain boundaries absorb lattice dislocations produced by deformation to make possible the rotation of crystals. The idea that gbm can occur to accommodate the incompatible deformation that arises in neighboring grains has been put forward by Means and Jessell [23]. The occurrence of gbm in deforming ice is illustrated in figure 3 which shows the relationship between the migration rate and the driving force at three temperatures [21]. For the Byrd ice core we have plotted points corresponding to grain growth near the surface and to the beginning of recrystallization at 1800 m. A critical driving force of about  $10^4 \text{ J/m}^3$  was assumed for the initiation of recrystallization [21]. A linear relationship between boundary migration rate and driving force was assumed in polar ice since impurities do not generally exert a drag force on boundaries when grain growth occurs [24]. Fine-grained ices are however found in some ice cores which contain a high concentration of microparticles and soluble impurities, especially in Arctic ice sheets [25] [18]. In the transition zone, gbm occurs as a result of differences in strain energy between two grains. The occurrence of accommodation migration in polar ice is demonstrated in the Byrd ice core. The fabric pattern gradually changes from a random to a single maximum as a result of the rotation of basal planes by deformation [26]. The cumulative horizontal shear strain largely exceeds 0.5 at 1200 m where the single-vertical maximum is observed and recrystallization does not occur. The efficiency of gbm as an accommodation process decreases with depth and recrystallization is initiated as soon as the driving force exceeds  $10^4 \text{ J/m}^3$  (fig.3).

The apparent low value of the exponent  $n$  of the flow law (fig.2) between 450 and 1800 m [1-3] can be explained by grain boundary accommodation migration which impedes the reaching of secondary creep corresponding to the minimum creep rate at strain of about 1%.

At high stresses the development of Frank-Read Sources, requiring a stress of  $\tau = 2\mu b/l$  ( $\mu$  is the shear modulus), leads to the emission of a great number of dislocations. Areas of high dislocation density are found on both sides of grain boundaries. The migration of boundaries is therefore rapidly stopped. Nucleation and propagation of dynamic recrystallization nuclei occur as soon as strain energy exceeds  $10^4 \text{ J/m}^3$  (fig.3). The small strain (of about 1%) necessary to initiate recrystallization is caused by the pattern of internal stresses which develop with minima at grains which are favorably oriented for basal slip and maxima at the unfavorably oriented grains [21].

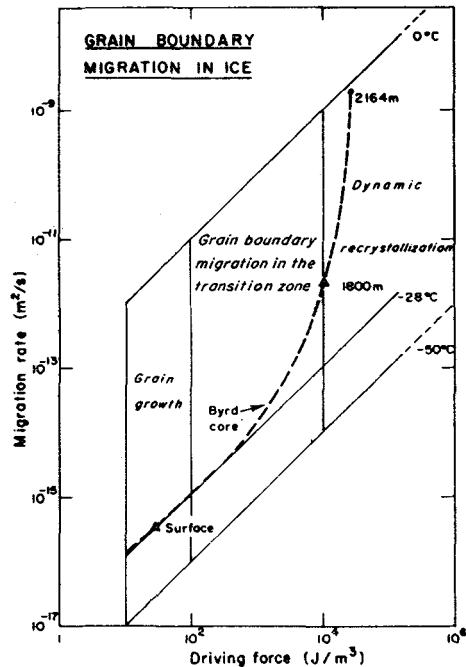


Fig.3 : Migration rate of grain boundaries as a function of driving force

## 7. Conclusion

Experimental laboratory tests conducted at low stresses and analysis of the inclinometer survey of the Dye 3 bore hole yield a relationship between strain rate and stress with an exponent  $< 2$ . Several deformation mechanisms must be involved for polar ice. Accommodation migration of grain boundaries associated with grain growth occurs in the first hundred meters of ice sheets. In this case a Newtonian viscosity is expected if the number of dislocation sources is constant. Below there is a transition zone where grain growth and recrystallization cannot occur. Rotation of crystals by dislocation glide and GBM can accommodate the incompatible plastic deformation between grains. The exponent of the flow law is always smaller than 3. In Greenland this zone is found down to bedrock whereas in Antarctica recrystallization is initiated in the last hundred meters.

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## COMMENTS

S.MURRELL

What is the driving force for grain-growth and grain boundary migration ?

Answer :

For grain growth , the driving force comes from the free energy at grain boundaries. It is about  $100 \text{ J/m}^3$  in polar ice.

Grain boundary migration (GBM) can occur if there are differences in strain energy between 2 grains. In polar ice, the driving force is higher than  $100 \text{ J/m}^3$ . Nucleation of new grains and GBM occur only if strain energy is higher than  $10^4 \text{ J/m}^3$ .