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Deformation and dynamic recrystallization of ice in polar ice sheets

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Abstract: The preferred c-axis orientation in ice from polar ice sheets develops essentially as a result of dislocation slip on basal planes. But grain growth and recrystallization are fundamental processes which interact with slip and can alter the texture of ice. The purpose of this work is to clarify the deformation modes of polar ice at low stresses and to assess the role of grain boundary migration as an accommodation process of intracrystalline slip. We have made an attempt to show that a Newtonian viscosity will be obtained if the normal grain growth occurs. The deformation of ice at low stresses is produced by intracrystalline slip, itself accommodated by grain boundary migration. A stress exponent between 2 and 3 is involved when rotation recrystallization is dominant.

1. Introduction

The deformation of polycrystalline ice is a topic of growing interest, studied increasingly in relation to the dynamics of glaciers and polar ice sheets. Models of ice sheets represent an essential part of investigations into the role played by ice masses in climate dynamics. Knowledge of the rheology of ice is necessary for dating ice cores and interpreting them in terms of paleoclimate. The analysis of recrystallization processes which widely occur in ice sheets is of the highest importance for the interpretation of fabrics and the modelling of the deformation of polycrystalline ice. This research work is also interesting for the understanding of the mechanical behavior of rocks and metallic materials at low stresses.

The constitutive law for the flow of polycrystalline ice for ice sheet modelling is that of an incompressible, non linear viscous fluid. Owing to the very large anisotropy of ice crystals and the pre-ponderance of intracrystalline dislocation glide, initially isotropic ice becomes anisotropic when texture forms [Pimienta et al., 1987]. A large strain rate variation with the direction of the applied stress has been observed in both laboratory and in situ measurements [Duval and Le Gac, 1982; Gundestrup and Hansen, 1984; Budd and Jacka, 1989]. This behavior renders the isotropic Norton-Hoff constitutive relation inadequate for modelling large-scale flow of ice sheets [Liboutry and Duval, 1985].

The preferred c-axes orientation of ice from polar ice sheets develops basically as the result of lattice rotation by intra-

crystalline slip [Azuma and Higashi, 1985; Lipenkov et al., 1989; Alley, 1992]. Abrupt changes in texture however are observed along deep ice cores [Gow and Williamson, 1976; Herron and Langway, 1982; Thorsteinsson et al., 1995]. These changes are associated with the occurrence of several recrystallization regimes [Duval and Castelnau, 1995; de La Chapelle et al., 1998].

The last ten years have seen increasing interest in the study of deep ice cores in order to reconstruct past climatic changes. Three deep ice cores to a depth of about 3000 m were recently retrieved near the summit of the Greenland ice sheet (the GRIP and GISP2 ice cores) and in East Antarctica, where drilling at the Vostok Station reached a depth of 3623 m in 1998. The Greenland ice cores have provided more than 100 kyr of climatic record. The Vostok ice core covers the past four climatic cycles and the age of Vostok ice at 3350 m is estimated to be 400 kyr [Petit et al., 1997]. A 2503 m ice core was drilled at Dome Fuji (East Antarctica) in 1996 where the ice thickness is expected to be about 3100 m and the mean annual temperature is -57.3 °C [Kameda et al., 1997]. At these core sites, the surface slope is very low ($< 1 \times 10^{-3}$) and strain rates throughout the depth of these cores are very low ($< 10^{-11} \text{ s}^{-1}$).

This paper is focused on processes which control the deformation and the development of fabrics in polar ice. Special emphasis is placed on the analysis of recrystallization mechanisms which occur in polar ice sheets.

2. Grain growth and recrystallization processes

The evolution of ice texture in polar ice is achieved via the normal grain growth, rotation recrystallization and migration recrystallization [Pimienta and Duval, 1989; Alley, 1992].

In the upper layers of ice sheets (several hundred meters), the mean grain size increases with depth. The driving force for the *normal grain growth* results from the decrease in free energy that accompanies reduction in grain boundary area. Compared with metals, the driving force $3\gamma_{gb}/D$ is low; it is less than $100 \text{ J}\cdot\text{m}^{-3}$ since the grain size D is generally larger than 1 mm and the grain boundary free energy $\gamma_{gb} = 0.065 \text{ J}\cdot\text{m}^{-2}$. This energy is equivalent to a dislocation density of $3 \times 10^{11} \text{ m}^{-2}$. A parabolic growth law was verified in several sites in Antarctica and Greenland [Gow, 1969]. However, grain growth seems to be inhibited by impurities and particles [Alley, 1986; Thorsteinsson et al., 1995]. The negative correlation between grain-growth rates and impurity concentrations obtained in the upper part of the GISP2 ice core strengthens the argument that impurities affect grain growth [Alley and Woods, 1996]. But the high correlation between the crystal growth rate and impurities does not demonstrate causality. The hypothesis of Petit et al. [1987] of a diagenic-temperature memory effect on the grain growth rate cannot be definitively ruled out. Information on the structure of grain boundaries and physical mechanisms for grain boundary migration in ice should significantly contribute to the determination of the role of impurities in grain growth.

The grain size profiles obtained from deep drillings give a clear indication of the

occurrence of the normal grain growth. At Byrd, grain growth stops at a depth close to 400 m [Gow and Williamson, 1976]. At GRIP, the normal grain growth occurs down to 650 m [Thorsteinsson et al., 1997]. At Vostok, due the increase in temperature just below the surface, the transition between grain growth and rotation recrystallization is difficult to define from the grain size profile. From Lipenkov [personal communication], first sub-boundaries are observed from 700 m. The normal grain growth should therefore cease at about this depth.

Sub-boundaries are observed below the zone where normal grain growth occurs. Due to heterogeneous deformation within grains, the misorientation of sub-boundaries increases and high angle boundaries develop. This mechanism is termed *rotation recrystallization* by the geological community and is also referred to as "*continuous recrystallization*" or "*recrystallization in situ*". The formation of new grains associated with this recrystallization mechanism appears to slow down texture development resulting from lattice rotation by slip when ice is loaded in uniaxial compression [Castelnau et al., 1996a]. According to Alley et al. [1995], the polygonization process counteracts further grain size increase due to grain growth below 400 m depth in the Byrd ice core (Antarctica). The same explanation was given by Castelnau et al. [1996a] for the stop in grain growth below 650 m in the GRIP ice core. In this recrystallization regime, grain boundaries migrate in the same low-velocity regime as that associated with grain growth, and which is characteristic of impurity-loaded boundaries (Figure 1).

In the deepest hundreds of meters of the central parts of ice sheets, the temperature

can be higher than $-10\text{ }^{\circ}\text{C}$, reaching the melting point at the interface between ice and rock. In this zone, rapid migration of grain boundaries can occur between dislocation-free nuclei and deformed grains. This recrystallization regime is generally referred to as *migration recrystallization* by geologists and *discontinuous recrystallization* in materials science. It obviously occurs in temperate glaciers. However, it is not observed along the 3623 m Vostok ice core where the temperature is about $-4\text{ }^{\circ}\text{C}$ at 3600 m. From de La Chapelle et al. [1998], the dislocation density is expected to be too low to initiate recrystallization. The grain boundary migration rate corresponding to this re-crystallization regime ranges from 10^{-12} to $10^{-8}\text{ m}^2\cdot\text{s}^{-1}$ near the melting point [Duval et al., 1983] (Figure 1). Migration recrystallization gives coarse and interlocking grains.

Fabrics associated with migration recrystallization are very different from those associated with rotation recrystallization. While rotation recrystallization retains the fabric pattern induced by slip [Castelnau et al., 1996a], migration recrystallization leads to fabrics that always promote basal slip [Duval, 1981]. Numerous studies on the development of fabrics associated with the fast boundary migration regime have been carried out on ice from temperate glaciers. It was shown by Duval [1981] that multimaxima fabrics reflect the state of stress. The nucleation of grains that are the less stressed (the best oriented for basal slip) would be favored by the size advantage of subgrains [de La Chapelle et al., 1998]. With generally low strain rates in ice sheets, new grains form in the vicinity of grain boundaries as a consequence of the very high plastic anisotropy of ice crystals. The selection of

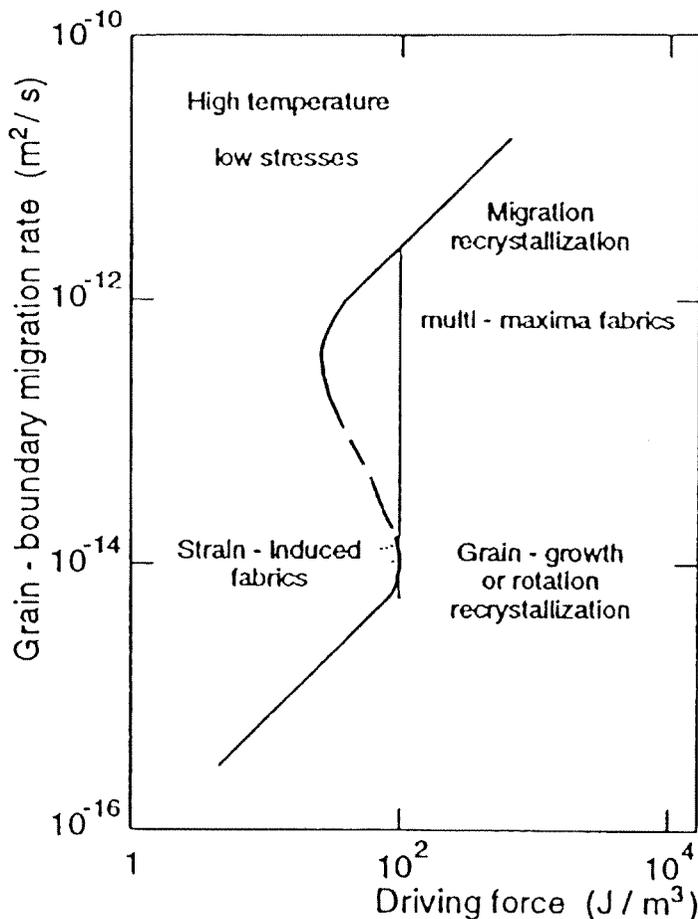


Figure 1: The grain boundary migration rate as a function of driving force in the temperature range, -10 to -15 °C. The grain boundary migration rate associated with grain growth at the surface of the ice sheet at Vostok ($\theta_s = -55$ °C) is about 10^{-17} m^2s^{-1} .

grains during growth might explain the so-called diamond-shaped fabric pattern described initially by Rigsby [1951].

During creep tests, stable fabrics are formed at a strain of about 10 % [Jacka and Maccagnan, 1984]. This is in accordance with the high grain boundary migration rate associated with migration recrystallization. On the other hand, the tertiary creep which is initiated after a strain of about 1 % during creep tests in the laboratory [Jacka, 1984] and associated with strain rates higher than that corresponding to the "secondary creep"

will not be invoked if migration recrystallization is not occurring. The increase of strain rate results from the softening processes associated with recrystallization and the development of fabrics [Duval, 1981]. The pattern of creep curves with primary, secondary (with a minimum creep rate) and tertiary creep will not be observed when rotation recrystallization is the predominant recrystallization process. From Jacka and Li (this volume), creep tests performed at -21 °C at a stress of 0.2 MPa. show no strain rate increase between 1 and

7 % strain, i.e. the tertiary creep was not initiated. On the other hand, grains were always randomly oriented at the completion of the test. These results indicate that dynamic migration recrystallization was not occurring.

3. Deformation mechanisms in polar ice sheets

The main feature of the plasticity of ice crystals is its outstanding anisotropy. For shear stresses of the order of 0.1 MPa., such as those found in active glaciers, ice deforms by basal glide. The resistance to shear on nonbasal planes is large and can be 60 times higher than resistance on the basal plane [Duval et al., 1983]. Basal slip is caused by the glide motion of basal dislocations with the $\langle 11\bar{2}0 \rangle$ Burgers vector. But, the rapid glide of short edge dislocations on $(1\bar{1}00)$ prismatic planes with this Burgers vector was observed by X-ray topography [Higashi et al., 1985; Ahmad and Whitworth, 1988]. The fact that basal slip is dominant in spite of faster movement of dislocations on non-basal planes is attributed by Higashi et al. and Ahmad and Whitworth to the large difference in the dislocation density. From Hondoh et al. [1990], long basal screw dislocations are dissociated on the basal plane and, therefore, cannot not move on prismatic planes.

Creep data for single crystals are shown in figure 2. Almost all authors report a stress exponent for basal glide of about 2 and an activation energy close to 60 kJ·mol⁻¹ [Duval et al., 1983]. This value of the stress exponent may be explained by the linear variation of both the number of dislocation sources and the velocity of dislocations with stress.

Creep data for isotropic polycrystalline ice are also given in figure 2. They concern the creep rate reached after a strain of about 1 %. At *high deviatoric stresses* (higher than 0.2 MPa), the stress exponent for the polycrystal is close to 3. During primary creep, strain rate decreases by more than 3 orders of magnitude [Jacka, 1984]. On first loading, the stress state within polycrystalline ice is almost uniform. However, owing to the very large plastic anisotropy of ice crystals, the resolved stress on the basal plane on each grain relaxes, and the load is transferred to the harder slip systems [Castelnau et al., 1996b]. As a result, an increasingly nonuniform state of internal stress develops. Extensive plasticity of polycrystalline ice is possible with only four independent slip systems [Hutchinson, 1977]. The anisotropic viscoplastic self-consistent (VPSC) model used by Castelnau et al. [1997] for predicting the mechanical behavior of polycrystalline ice and fabric development reproduces very well the macroscopic behavior of isotropic and anisotropic ice by assuming ice crystals deform by dislocation glide on basal, prismatic and pyramidal planes. The resistance of these slip systems was determined by an inverse approach, based on the comparison between model results and results of several mechanical tests. It was shown that the VPSC estimation of the rheology of *in situ* grains well matches that obtained experimentally on isolated crystals. The static model (uniform stress within the polycrystal) can reproduce the macroscopic behavior of anisotropic polycrystalline ice, but only by imposing a resistance to the basal slip systems much higher than that deduced from the behavior of isolated monocrystals [Castelnau et al., 1997].

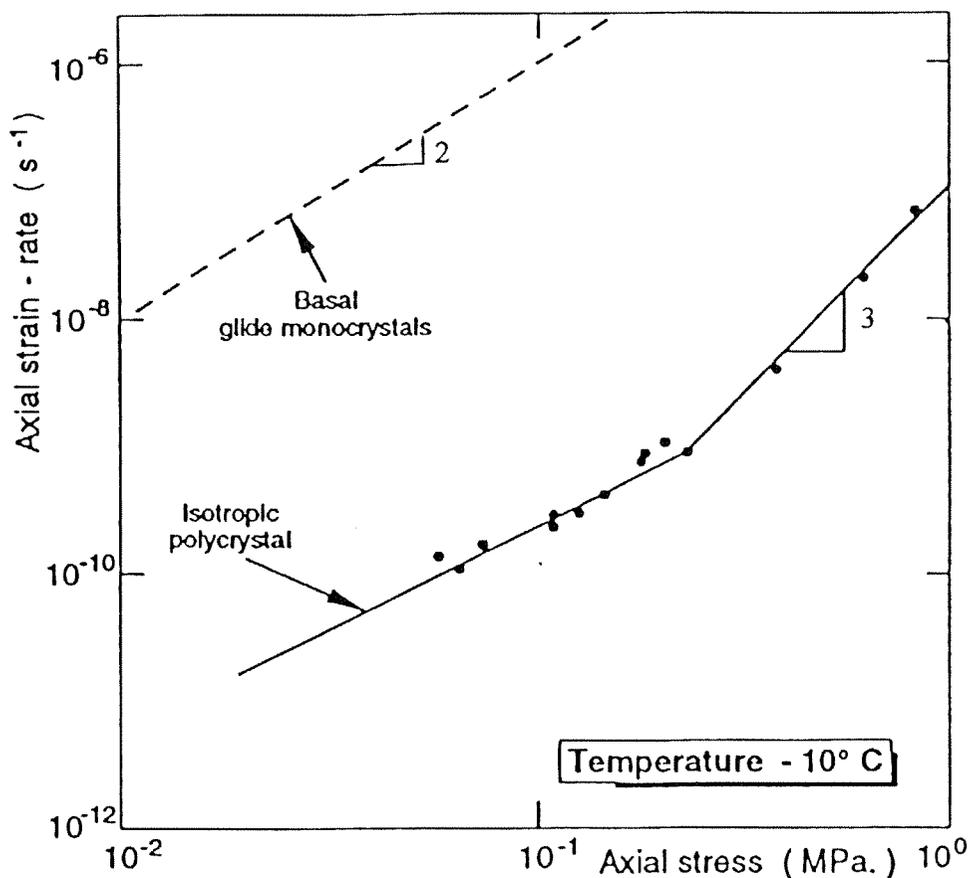


Figure 2: Data for basal glide in single crystals and for creep of isotropic polycrystals at -10°C . The strain rate for polycrystalline ice was determined after a strain of about 1 % [data are from Duval and Castelnaud, 1995].

At low deviatoric stresses (lower than 0.2 MPa), figure 2 shows that the stress exponent is lower than 2. This result is supported by field measurements [Doake and Wolff, 1985; Lliboutry and Duval, 1985; Dahl-Jensen and Gundestrup, 1987]. A linear flow law was obtained at low stresses by Lipenkov et al. [1997] from the densification of bubbly ice. Creep experiments were recently carried out on fine-grained ice (grain size ranging from 8 to 89 μm) samples by Goldsby and Kohlstedt [1997] in order to obtain accurate data on the flow law at low stresses. A regime with

$n=1.8$ was found at low stresses with a grain size dependence, $\dot{\epsilon} = d^{-p}$ and $p=1.4$. These authors found that grain boundary sliding is the dominant creep mechanism and the rate-limiting deformation mechanism in the $n=1.8$ regime. Extrapolation of this flow law to grain sizes of 1 mm or larger i.e. for conditions prevailing in ice sheets indicates that grain boundary sliding would often be a dominant mechanism of deformation in large ice sheets [Goldsby and Kohlstedt, 1998]. This conclusion is not in accordance with the development of fabrics induced by the rotation of the lattice by dislocation slip

[Azuma and Higashi, 1985; Castelnau et al., 1996b]. We suggest that the deformation of polar ice at low stresses is produced by intracrystalline slip accommodated by grain boundary migration linked to grain growth or rotation recrystallization [Duval and Castelnau, 1995]. Basic equations are given below to assess the stress/strain rate dependence and the coherence of these assumptions for describing the deformation of polar ice. The increment of dislocation density during deformation is considered to be due to workhardening and recovery. The increase in dislocation density during deformation arises from the generation of new dislocations. By assuming that the mean slip distance of the dislocations is the grain size D , the increase of the dislocation density due to workhardening is :

$$d\rho^+ / dt = \dot{\epsilon} / bD \quad (1)$$

where $\dot{\epsilon}$ is strain rate, and b is the magnitude of the Burgers' vector.

From de La Chapelle et al. [1998], the main process for the reduction of the dislocation density is grain boundary migration (gbm) associated with grain growth or rotation recrystallization. If we neglect other recovery processes (i.e. dislocation climb...), the reduction in the dislocation density by gbm is given by:

$$d\rho^- / dt = \alpha \rho K / D^2 \quad (2)$$

where K is the grain boundary migration rate ($K=2D \, dD/dt$). α is a coefficient higher than 1, which makes it possible to take into account a higher dislocation density near grain boundaries.

For steady state conditions,

$$\dot{\epsilon} = \alpha \rho b K / D \quad (3)$$

In the upper parts of ice sheets where the normal grain growth occurs, only the dislocation density depends on stress. *At high stresses*, the relationship between ρ and the stress σ is given by $\sigma = \beta G b \rho^{1/2}$, where G is the shear modulus and β a constant close to 0.4 [Friedel, 1964]. *At low stresses*, the dislocation density is related to stress via an inverse relationship with the distance between slip lines which is of the order of $bG/2\pi\sigma$. A linear relationship between ρ and σ is therefore found. As a consequence and as suggested by Pimienta and Duval [1987] and Alley [1992], a newtonian viscosity is expected at low stresses if the normal grain growth is occurring.

Equation (3) can be applied to estimate the dislocation density when the normal grain growth is occurring. At Vostok (East Antarctica), with a strain rate of $2.3 \times 10^{-13} \text{ s}^{-1}$ and $\alpha = 1$, the dislocation density ρ is about $1.5 \times 10^{11} \text{ m}^{-2}$ at 800 m. It is about $7 \times 10^{10} \text{ m}^{-2}$ at 500 m depth at GRIP. These values are compatible with the occurrence of grain growth [de La Chapelle et al., 1998].

If *rotation recrystallization* is the dominant recrystallization mechanism, grain boundaries migrate as for grain growth under the low-velocity regime (figure 1) [Duval and Castelnau, 1995]. The driving force however is provided by both the energy associated with dislocations and the curvature of grain boundaries. The velocity of grain boundary migration dD/dt ($K/2D$) depends on stress via the dislocation density. By assuming, as above, that ρ is proportional to stress, a non-linear flow law with a stress exponent close to 2 is expected. At high stresses, the assumption of a linear relationship between the dislocation density

and the stress is not tenable. A flow law with a stress exponent close to 3 is obtained.

In conclusion, there is a strong argument in favour of a flow law for ice sheets with a stress exponent equal to one when the normal grain growth occurs and between 2 and 3 when rotation recrystallization occurs. This discussion is based on the existence of a steady state with $d\rho = 0$, an exceptional situation in ice sheets when grain growth occurs since there is no direct relationship between grain size, stress or temperature. This is not the case for rotation recrystallization because grain size is dependent only on stress.

An important point not discussed in this work is the development of fabrics with strain. The simulation of fabric development by different micro-macro approaches reproduces very well the observed fabrics as long as dynamic recrystallization is not occurring [Azuma, 1994; Castelnau et al. 1996a and 1996b]. These models are also applied to characterize the relation between fabrics and the instantaneous anisotropic mechanical behavior. Recrystallization models should now be constructed and included within the polycrystal deformation models in order to simulate the development of fabrics when dynamic recrystallization is occurring.

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