

# An evaluation of the rate-controlling flow process in Newtonian creep of polycrystalline ice

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## Abstract

Using experimental data and theoretical calculation for Newtonian creep in polycrystalline ice, it is demonstrated that unlike most other materials, in which the rate-controlling flow process is edge dislocation climb under saturated condition, the rate-controlling flow process of polycrystalline ice is dislocation glide along the basal plane under a constant dislocation density. The dislocation density during Newtonian creep of ice is determined by the initial state instead of the magnitude of the Peierls stress. The transition stress (threshold) from power-law creep to Newtonian creep is controlled by the dislocation density instead of the Peierls stress. The activation energy of the Newtonian creep is similar to that of the self-diffusion due to the requirements of the diffusion of protons during dislocation glide.

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## 1. Introduction

Experimental studies of the creep processes in polycrystalline ice (including both freshwater ice and sea ice) have shown the occurrence of a transition from power-law dislocation creep (stress exponent equals 3) at high stresses to a Newtonian creep (stress exponent equals 1, see Table 1). Generally, this fall-off has been observed at stresses lower than 0.2 MPa. It should be noted that most low-stress exponents with values higher than 1 are obtained from experiments performed in the transition regime between power-law behavior and Newtonian creep, and the value of the exponent tends to approach 1 as the stress continues to decrease (see, for example, data summarized by Langdon [14]). Additionally, Cole [12], and Cole and Durell [11] demonstrated, with experiments on both polycrystalline sea ice and freshwater ice, that the stress level associated with the fall-off from  $n = 3$  behavior increases with the specimen's dislocation density.

Weertman [15] indicated that a decreased stress exponent might be caused by the diffusion-based (Nabarro–Herring creep) creep mechanism. However, Duval et al. [16] indicated that since ice has very low diffusion coefficients and the activation energy for lattice diffusion normalized by the product of the melting

temperature and the gas constant has a larger value for ice than for most materials, diffusion alone will not generate observable strain rates in Newtonian deformation stage, at least for the grain sizes that are typically found in nature. Song et al. [17] have shown quantitatively that the strain rates predicted by diffusional mechanism are at least an order of magnitude lower than the experimental counterparts. Thus, the low-stress exponent is expected to be due to a creep mechanism other than the Nabarro–Herring mechanism.

Another possible mechanism for creep at low stresses of materials is grain boundary sliding (GBS) accommodated by other mechanisms. Wang [18] has shown that for most materials, grain size-sensitive Newtonian behavior at low stresses can be explained by GBS accommodated by either diffusion or GBS itself. In diffusional creep, the diffusion of matter from one grain boundary to the other causes the straining of the sample and GBS is only a supplementary process. But in GBS creep, GBS leads to grain rearrangement and thus contributes to strain while diffusion occurs as an accommodation process to maintain the coherency of the grains. In the studies of Goldsby and Kohlstedt [19,20], GBS significantly contributes to deformation in the range that the stress exponent lower than 2. However, Duval and Montagnat [21] have shown that GBS as a significant creep mechanism is not compatible with the observations on the development of fabrics (distribution of the orientation of the  $c$ -axes) and microstructures in ice sheet.

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Table 1  
Low-stress creep data for coarse-grained ice

Stress exponent	Grain size (mm)	Temperature (K)	References
~1	1–2	258–268	[1]
0.86–1.15	3–20	254–272	[2]
~1	0.8	238–273	[3]
~1	1–10	260–270	[4]
~1.8	1	271	[5]
1.3	2	273	[6]
~1.5	1–2	258	[7]
1.8	1–2	260	[8]
1.85	0.5–5	268	[9]
~1.5	–	260–273	[10]
~1	3–5	263	[11]
~1	3–5	253–268	[12]
1.06–1.15	5	263	[13]

The third possible mechanism for the Newtonian behavior of ice is viscous dislocation creep, named Harper–Dorn (H–D) creep. Previous studies [22–26] have indicated that the rate-controlling flow process in Harper–Dorn creep is the climb of edge dislocations for all materials (including ice) under saturated conditions and under a constant dislocation density. The transition from power-law creep to H–D creep probably occurs at or in the vicinity of the Peierls stress. The dislocation density is independent of the applied stress but determined by the Peierls stress. If this is the case, the transition stress from power-law creep to Newtonian creep should be independent of the initial dislocation density. However, Cole [12], Cole and Durell [11], and Song et al. [17] demonstrated, with experiments on both polycrystalline sea ice and freshwater ice, that the transition stress increases with the specimen's dislocation density. Pimienta and Duval [7], and Song et al. [17] have suggested that the rate-controlling flow process in this viscous behavior might be dislocation glide along the basal planes with a constant dislocation density. Concerning the controversies of the rate controlling mechanism (whether it is edge dislocation climb or basal dislocation glide) in this linear viscous dislocation creep of polycrystalline ice, the purpose of this study is to re-examine the rate-controlling mechanism using extensive data base now available.

## 2. Possible rate-controlling mechanisms

### 2.1. Climb of edge dislocations

H–D creep has a linear dependence of strain rate on stress and activation energy equals to that for lattice self-diffusion. The general rate equation for H–D creep is of the form [22,23]:

$$\dot{\epsilon} = A_{\text{HD}} \frac{D_{\text{L}} G b}{kT} \left( \frac{\sigma}{G} \right) \quad (1)$$

where  $\dot{\epsilon}$  is the uniaxial strain rate,  $\sigma$  the stress,  $G$  the shear modulus,  $b = 4.52 \times 10^{-10}$  m the Burgers vector,  $k$  the Boltzmann's constant,  $T$  the absolute temperature,  $A_{\text{HD}}$  the dimensionless constant ( $A_{\text{HD}} = 1.4(\tau_{\text{p}}/G)^2$ , where  $\tau_{\text{p}}$  is the Peierls stress) and  $D_{\text{L}}$  is the lattice diffusion coefficient of the rate controlling species ( $D_{\text{L}} = D_{\text{ov}} \exp(-Q_{\text{L}}/RT)$ , where  $D_{\text{ov}} = 9.1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$  is the frequency factor and

$Q_{\text{L}} = 59.4 \text{ kJ mol}^{-1}$  is activation energy for self-diffusion for ice). Wang pointed out that this Harper–Dorn model is different in two aspects from the climb model proposed by Nabarro [27] for Al and suggested also for other materials [23]. First, the strain is contributed by dislocation glide but by dislocation climb in the Nabarro's model. Thus, the Wang's model is capable of accounting for the large strains produced by H–D creep. Second, according to Wang's model, if the initial dislocation density is lower than the steady state dislocation density, the creep rate decreases as the strain increases during transient creep. If the initial dislocation density is higher than the steady state density, H–D creep may not take place until barriers to dislocation glide have been sufficiently reduced by recovery processes.

It should be noted that the diffusion activation energy ( $Q_{\text{L}}$ ) cannot be used as proof that the rate-controlling flow process is dislocation climb (which in turn is controlled by self-diffusion) for ice because glide mechanisms can also involve the motion of hydrogen (proton) in the lattice. To determine the constant  $A_{\text{HD}}$ , it is necessary to know the magnitude of the Peierls stress ( $\tau_{\text{p}}$ ), which is of the form [28]:

$$\tau_{\text{p}} = \frac{G}{1-v} \exp\left(\frac{2\pi d}{(1-v)b}\right) \quad (2)$$

where  $d$  is the interspacing between slip planes and  $v$  is the Poisson's ratio. Eq. (2) is for an edge dislocation, while for a screw dislocation, the term  $1-v$  should be replaced by unity. Since the thermal vibrations of atoms can serve to lower the misfit energy of a dislocation, the Peierls stress should be decreased as the temperature increases. The temperature-dependent Peierls stress can be expressed as [29]:

$$\frac{\tau_{\text{p}}(T)}{G} = \left(\frac{1}{1-v}\right)^{-T/10T_{\text{m}}} \left(\frac{\tau_{\text{p}}}{G}\right) \exp(T/10T_{\text{m}}) \quad (3)$$

In Wang's model, the steady state dislocation density ( $\rho_{\text{HD}}$ , under saturated condition) in H–D creep is related to the Peierls stress ( $\tau_{\text{p}}$ ) by [29,30]:

$$b\rho_{\text{HD}}^{1/2} = \frac{\tau_{\text{p}}}{G} \quad (4)$$

Thus, based on Eqs. (1)–(4), the strain rate of the Newtonian creep in polycrystalline ice can be determined if we know the Peierls stress of ice crystals.

### 2.2. Basal glide of dislocations

It is widely accepted that plastic deformation in ice crystals is dislocations glide along the basal planes (0001). The Burgers vectors for glide on the basal planes are the three lattice vectors, which can be written in the form  $(a/3)(2\bar{1}\bar{1}0)$  [31]. In principle, dislocation glide takes place along the glide set instead of the shuffle set to lower its energy by dissociating into two Shockley partial dislocations separated by a stacking fault. The glide-controlled theory indicates that if the applied stress is sufficiently low, dislocations do not multiply, and linear flow process should be observed with the activation energy of basal glide. A transition to power law behavior begins when the stress is high enough to cause dislocation multiplication. Based on dislocation

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