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SHORT NOTE

SUPERPLASTICITY OWING TO GRAIN GROWTH IN POLAR ICES

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Abstract. Deep coring in polar ice sheets has only located the well-known recrystallized ice with a fabric peculiar to tertiary dislocation creep in bottom layers. At lesser depths, anisotropic ice with steady grain-sizes is found; secondary dislocation creep is the dominant process and an anisotropic third-power relation viscosity should ensue. In this paper, ices from the surface down to several hundred metres in depth are considered. Their grain-size increases with time owing to free energy at grain boundaries. This continuous boundary migration appears to be a much more efficient process for relative displacements of the grains than boundary sliding accommodated by diffusional processes between grains of constant size. Locally heterogeneous superplastic deformation leading to moderate viscosities is therefore expected. This deformation mechanism can explain the field data which seem to show a viscosity more than one order of magnitude lower than would result from Nabarro–Herring creep or secondary dislocation creep.

Résumé. *Superplasticité de la glace polaire résultant du grossissement des grains.* Les carottages profonds dans les calottes polaires ont montré que la glace, avec une fabrique induite par la recristallisation dynamique typique du fluage tertiaire, n'était trouvée que dans les couches situées près du lit rocheux. Au-dessus, on trouve une glace anisotrope avec une taille de grains plus ou moins stationnaire; le fluage dislocation est le processus dominant avec une loi puissance anisotrope. Dans ce papier, on considére les glaces depuis la surface jusqu'à plusieurs centaines de mètres de profondeur. L'augmentation de la taille des grains avec leur âge est due à l'énergie libre des joints de grains. Cette migration continue des joints de grains semble être un processus d'accommodation beaucoup plus efficace que les processus de diffusion pour le glissement aux joints de grains. De faibles viscosités devraient résulter de cette déformation superplastique localement hétérogène. Ce mécanisme de déformation peut expliquer les données de terrain qui semblent montrer une viscosité au moins 10 fois plus faible que celle qui résulterait du fluage Nabarro–Herring ou du fluage–dislocation secondaire.

Zusammenfassung. *Überplastizität infolge Kornwachstums in polaren Eismassen.* Tiefbohrungen in polaren Eisschilden lokalisierten nur das wohlbekannte rekristallisierte Eis mit einem Gefüge, das durch tertiärer Versetzung-Kriechen in tieferen Schichten gekennzeichnet ist. In geringerer Tiefe tritt anisotropes Eis von gleichmässiger Korngrösse auf; sekundärer Kriechen infolge Versetzungen ist dort der ausschlaggebende Vorgang und eine anisotrope Viskositätsbeziehung 3. Grades sollte sich ergeben. In dieser Arbeit werden Eisproben von der Oberfläche bis hinab zu einigen hundert Meter Tiefe betrachtet. Ihre Korngrössen nehmen mit der Zeit infolge der freien Energie an den Korngrenzen zu. Diese ständige Verlagerung der Grenzen scheint sich auf die relative Versetzung der Körner viel stärker auszuwirken als das Gleiten an den Grenzen, das sich infolge von Diffusionsvorgängen zwischen Körnern konstanter Grösse vollzieht. Es ist daher lokal eine heterogene überplastische Deformation zu erwarten, die zu mässigen Viskositäten führt. Dieser Verformunsmechanismus kann Felddaten erklären, die eine Viskosität aufzuweisen scheinen, welche mehr als eine Grössenordnung niedriger ist als jene, die aus einem Kriechen nach Nabarro–Herring oder aus einem solchen infolge sekundärer Versetzung-Kriechen hervorgehen würde.

GRAIN GROWTH IN POLAR ICE

Crystal size in polar ice caps, as measured by the mean grain area on thin slides (S), increases with age from the surface down to several hundred metres in depth. Nevertheless growth rates are smaller for glacial-age ices, which must be considered separately (Duval and Lorius, 1980). At Byrd Station, with an ice temperature of T = -28°C, S increases to 40 mm² at 400 m in depth and then remains constant (Wisconsinan ice is found only at 1200 m in depth (Gow and Williamson, 1976). At Vostok station (T = -56°C), S increases to 3 mm² at 300 m in depth (Korotkevitch and others, 1978) and at Dome C to 5 mm² at 400 m in depth (T = -54°C to -51.6°C) (Duval and Lorius, 1980). In all three cases grains remain equal-sized and no fabric is present.

Next, after a transition zone, glacial-age ices are found. At Dome C, S increases from 2.3 mm² at 500 m in depth to 7 mm² at the bottom of the bore hole (900 m in depth) while a faint fabric gradually appears with c-axes clustering near the vertical. At Vostok station, S increases from 1.3 mm² at 400 m to 6 mm² at 900 m (Korotkevitch and others, 1978). Below 550 m grains are elongated in the flow direction and the c-axes are concentrated in the vicinity of the vertical plane perpendicular to this flow direction (Barkov and others, unpublished). These fabrics, which we consider to be stress-induced, will be examined elsewhere.

Grain growth in firn, as in ice, follows the relationship

$$S = S_0 + Kt \tag{1}$$

where t is time and K is temperature dependent: $K = K_0 \exp(-Q/RT)$. For Holocene ice, at Byrd Station $K = 1.2 \times 10^{-8}$ m² a⁻¹ and at Dome C. $K = 4 \times 10^{-10}$ m² a⁻¹ while $Q \approx 45$ kJ/mol (Gow, [1975]). This apparent activation energy is significantly smaller than the value for lattice diffusion (59.4 kJ per mol). The driving force for grain growth is provided by the free energy at grain boundaries, which on average is $\gamma = 0.065$ J m⁻² (Higashi, 1978). When a grain of size ℓ is in contact with a grain of size ℓ_i, the pressure difference between them is $\Delta p_i = 4\gamma(1/\ell - 1/\ell_i)$. The driving force F_i on a unit cell is about $b^2 \Delta p_i$ ($b = 4.52 \times 10^{-10}$ If unit cells change lattice independently, the corresponding flux of matter (in volume) would be $F_i D^*/kT$ from the Einstein relation, where D^* denotes the diffusion coefficient for the migration process and k is Boltzmann's constant. With $\Sigma(1 - \ell/\ell_i) = \alpha$, where the sum is extended to all the neighbours of the crystal of size ℓ, the grain growth rate is:

$$k = 2\ell \frac{d\ell}{dt} = \frac{8\alpha b^2 \gamma D^*}{kT}. \tag{2}$$

In this paper, the deformation mechanisms of polar ice are discussed in relation to grain-boundary migration associated with grain growth.

DEFORMATION MECHANISMS OF POLAR ICE

Diffusional flow and power-law creep

At low stresses, it is commonly considered that ice may deform by homogeneous Nabarro-Herring diffusional creep (Coble creep may be neglected without changing the results significantly). This mechanism leads to a rate equation of the form:

$$\dot{\varepsilon}_{ij} = \frac{Ab^3 D}{kT\ell^2} \sigma'_{ij} \tag{3}$$

where σ'_{ij} is the deviatoric stress, D is the volume diffusion coefficient, and A is a dimensionless factor equal to 20 at small strains (Goodman and others, 1981).

But the familiar deformation mechanism in polycrystalline ice is power-law creep. Strain-rates are given by the relation:

$$\dot{\varepsilon}_{ij} = \frac{B}{2}\tau^2\sigma'_{ij} \qquad (4)$$

where τ is the effective shear stress and B is a material constant.

Deformation mechanism maps constructed by Goodman and others (1981), Frost and Ashby (1982), and Duval and others (1983) show the regime of dominance of each flow mechanism. To obtain more information about flow mechanisms in the top hundred metres of polar ice sheets, we have calculated the deviatoric stresses corresponding to the vertical strain-rates $\dot{\varepsilon}_{zz}$ from Equation (3) with

$$\dot{\varepsilon}_{zz} = -b/H \qquad (5)$$

where b is the accumulation rate and H the ice thickness (steady state is assumed). Results obtained in several locations in Antarctica and Greenland are summarized in Table I (crystal size at snow-ice transition was used in calculations).

Using data from the Byrd Station strain network given by Whillans and Johnsen (1983), surface strain-rates give an effective shear strain-rate $[2(\dot{\varepsilon}_{xx}^2 + \dot{\varepsilon}_{yy}^2 + \dot{\varepsilon}_{zz}^2)]^{\frac{1}{2}} = 1.3\times10^{-4}\ a^{-1}$ (by ignoring any horizontal shear rate). According to Equation (4) with B = 0.0015 $bar^{-3}\ a^{-1}$ at -28°C (Duval and Le Gac, 1982), the deviatoric stress σ'_{zz} would be 0.053 MPa instead of 0.088 MPa for diffusional creep (Table I). Dislocation creep would therefore be the dominant flow mechanism for the Byrd ice core from the surface. The same conclusion is attained for "Camp Century" and South Pole owing to high deviatoric stresses deduced from the diffusional creep equation (Table I).

But, whatever the flow mechanism which is occurring in polar ice, it must be modelled with grain-growth in the top hundred metres. Equation (1) implies that strain energy is small in comparison with the grain-boundary energy which drives grain-growth. The stored energy for dislocation creep increases with strain and can be higher than $10^4\ J/m^3$ after a strain of 1% (Duval and others, 1983). Since the grain-boundary energy $(3\gamma/\ell)$ is typically of order 100 J/m^3, the power-law creep Equation (4) is not compatible with grain growth.

On the other hand, the driving force for grain growth is around $4(\gamma b^2)/\ell$ while that for diffusional creep is $A\sigma b^3/\ell$. With $\sigma = 5\times10^4$ Pa, $A\sigma b$ is at most of the order of $5\times10^{-4}\ J/m^2$ i.e. more than two orders of magnitude lower than 4γ. By assuming that impurities do not influence the grain-boundary mobility, the lower bound for the diffusion coefficient D* is the lattice diffusion coefficient. Grains therefore grow much faster than they deform by vacancy diffusion. Crystal growth rates found in several sites in Antarctica or Greenland (Table I) support this conclusion.

Sliding with boundary migration accommodation: a type of superplasticity

Polycrystalline ice as a whole can deform without a general strain of the individual crystals owing to sliding on grain boundaries. This superplastic behaviour has been analysed by Ashby and Verrall (1973) for the case with no change in grain volume. The main dissipation of energy does not come from boundary sliding, but from minute changes in the shape of the crystals (by diffusion of vacancies) to allow their displacements, and from some temporary increases in the boundary area. With a two-dimensional model, these investigators found Equation (3) with A = 98.

In the case of continual grain growth, stress concentrations generated by grain-boundary sliding (or by dislocation glide) may be efficiently relieved by grain-boundary migration. The dissipation of free energy at boundaries (about $d(3\gamma/\ell)/dt$ per unit volume and unit time) should allow much more work for the applied stress. With elastic accommodation, sliding stops when internal stresses balance the applied stress. Since the stored elastic energy per unit volume induced by grain-boundary sliding, of the order of $\frac{1}{2}\tau^2/G$ (G is the shear modulus), is very small compared with the grain-boundary energy, grain growth is not influenced by stress as long as only the elastic strain is concerned. The major part of this elastic energy is concentrated along grain boundaries and especially near the triple point. A boundary migration distance of the same order of magnitude as the sliding displacement $(\approx\sigma'_{ij}\ell/2G)$ is necessary for the accomodation of grain-boundary sliding.

As concerns the Byrd bore hole, the boundary-sliding displacement induced by $\sigma'_{zz} = 5\times10^4$ Pa is about 1.7×10^{-8} m corresponding to an elastic strain $\varepsilon_e = 8.3\times10^{-6}$. This strain must be accommodated in a time $t = \varepsilon_e/\dot{\varepsilon}_{zz}$ = 0.1a. The boundary migration distance during this time is about 2.5×10^{-7} m i.e. more than one order of magnitude larger than the sliding displacement. Boundary migration associated with grain-growth is therefore a very efficient mechanism to accommodate boundary sliding and stresses σ'_{zz} given in Table I are probably too high. On the other hand, data from the inclinometrer survey of the Byrd bore

TABLE I. VERTICAL STRAIN-RATES AND CORRESPONDING DEVIATORIC STRESSES AT SHALLOW DEPTH AT SEVERAL LOCATIONS IN ANTARCTICA AND GREENLAND

Location	*Snow temperature* °C	$\dot{\varepsilon}_{zz}$ a^{-1}	K $m^2 a^{-1}$	σ'_{zz} from Equation (3) MPa	σ'_{zz} from Equation (4) MPa	References
"Camp Century"	-24	2.76×10^{-4}	1.6×10^{-8}	0.12	-	Gow ([1975])
Byrd Station	-28	7.85×10^{-5}	1.2×10^{-8}	0.088	0.053	Gow ([1975])
Mizuho	-33	3.68×10^{-5}	3×10^{-9}	0.074	-	Narita and Maeno (1979)
South Pole	-51	3.19×10^{-5}	6×10^{-10}	0.14	-	Gow ([1975])
Dome C	-54	1×10^{-5}	4×10^{-10}	0.065	-	Duval and Lorius (1980)
Vostok	-56	7×10^{-6}	2×10^{-10}	0.059	-	Korotkevitch and others (1978)

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hole (Garfield and Ueda, 1976) analysed by Lliboutry and Duval (in press) indicate that the viscosity is about 500 times lower than that given by Equations (3) and (4). Paterson (1983), analysing data from the inclinometer surveys of the bore holes at Byrd Station and "Camp Century", Greenland, arrived at this conclusion: "the Holocene ice is soft: the reason for this unexpected result is unclear". Only grain-boundary migration can be the origin of such a low viscosity.

CONCLUSION

Diffusional creep does not appear to be a rate-controlling deformation mechanism in polar ice. With regard to dislocation creep, it must be modelled with grain growth. Since grain-boundary migration impedes strain-hardening, a true steady state should be established for a strain much smaller than 1%. But grain-boundary sliding accommodated by boundary migration is probably the principal deformation mechanism of polar ice at shallow depth.

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