JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. B4, 2082, 10.1029/2001JB000946, 2002

# Comment on "Superplastic deformation of ice: Experimental observations" by D. L. Goldsby and D. L. Kohlstedt

P. Duval and M. Montagnat

Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, Saint Martin d'Hères, France

Received 11 October 2001; revised 24 October 2001; accepted 29 October 2001; published 30 April 2002.

*INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3902 Mineral Physics: Creep and deformation; 5120 Physical Properties of Rocks: Plasticity, diffusion, and creep

## 1. Introduction

[1] Knowledge of the rheological properties of ice at deviatoric stresses lower than 0.1 MPa is of great interest when modeling the flow of glaciers and ice sheets. In spite of the difficulty of obtaining convincing results in the laboratory, there is now agreement on a flow law with a stress exponent lower than 2 [*Mellor and Testa*, 1969; *Duval*, 1973; *Alley*, 1992; *Duval and Castelnau*, 1995]. This result is also supported by borehole deformation measurements [*Dahl-Jensen and Gundestrup*, 1987] and bubbly ice densification modeling [*Lipenkov et al.*, 1997].

[2] Creep experiments on fine-grained ice (grain size lower than 200 μm) performed by *Goldsby and Kohlstedt* [1997] have made it possible to identify a grain size dependent creep regime with a stress exponent of ~1.8 and an activation energy of 49 kJ mol$^{-1}$ for $215 \leq T \leq 236$ K. According to *Goldsby and Kohlstedt* [1997, 1998, 2001], grain boundary sliding (GBS) significantly contributes to deformation in this creep regime. Microstructures data obtained from scanning electron microscope measurements also support a deformation mode dominated by GBS similar to the deformation mode of superplastic materials. Extrapolation to grain sizes and temperatures found in glaciers and ice sheets gives results that are consistent with laboratory creep measurements more or less obtained in the in situ conditions [*Goldsby and Kohlstedt*, 2001], although some of these measurements were made before reaching steady state [*Budd and Jacka*, 1989]. *Goldsby and Kohlstedt* [2001] conclude that superplastic flow dominates the flow of glaciers and ice sheets.

[3] The purpose of our comments is to show that GBS as a significant creep mechanism is not compatible with observations on the development of fabrics (distribution of the orientation of the c-axes) and microstructures in ice sheets. Special emphasis is placed on the role of grain boundary migration as a recovery process in glacier ice.

## 2. Role of Grain Boundary Sliding in the Rheology of Glacier Ice at Low Stresses

[4] As indicated by *Goldsby and Kohlstedt* [2001], the creep regime of glacier ice with a stress exponent of 1.8 is found at deviatoric stresses lower than 0.1 MPa. As at high stresses, strain rates are significantly lower than those of single crystals oriented for basal slip and deformed in the same conditions. This is consistent with the results of *Duval and Castelnau* [1995]. Basal slip would therefore be the dominant deformation mechanism and could be accommodated by GBS [*Goldsby and Kohlstedt*, 2001] or by grain boundary migration [*Pimienta and Duval*, 1987].

[5] GBS is generally considered to be the dominant deformation mechanism for superplastic metals in region II with a stress exponent of ~2 [*Arieli and Mukherjee*, 1980; *Langdon*, 1994a, 1994b]. This deformation mode is obviously not compatible with the development of fabrics [*Perez-Prado et al.*, 1998]. The effect of GBS on fabric development was numerically modeled by *Zhang et al.* [1994]. Intracrystalline slip was allowed with only one slip system. By reducing grain interaction the introduction of a small amount of GBS slightly enhances fabric development. However, as expected, more GBS weakens fabric development, and an absence of preferred orientation is found when deformation is dominated by GBS. The effect of GBS on fabric development in ice is analyzed here using the visco-plastic self-consistent (VPSC) model as described by *Tomé* [1999] and by comparison with measured fabrics in the Greenland Ice Core Project (GRIP) ice core [*Thorsteinsson et al.*, 1997]. Fabrics were calculated by assuming that grain rotation was induced by intracrystalline slip and was not affected by GBS. Figures 1a and 1b show both the observed fabric at a depth of 1549 m for the GRIP ice core and that simulated by the VPSC model for an equivalent strain of 0.75 corresponding to the estimated equivalent strain at this depth. The fabric obtained by the VPSC model assuming that GBS represents 70% of the total strain is shown in Figure 1c. As indicated by *Duval et al.* [2000], GBS as a dominant deformation mode is clearly not compatible with the development of fabrics in ice sheets. This conclusion is supported by results on the relationship between grain flattening and strain along the Vostok [*Lipenkov et al.*, 1989] and Dome Concordia [*Arnaud et al.*, 2000] ice cores. It has been shown that the strain rate deduced from the flattening of crystals roughly corresponds to the estimated strain rate near the surface of these two sites in Antarctica. In conclusion, GBS could accommodate basal slip, but its contribution to strain should not be significant.

## 3. Rate-Controlling Processes in the Creep of Polar Ice

[6] As discussed above, the deformation of polar ice is essentially produced by intracrystalline slip. Grain boundary migration (GBM) associated with normal grain growth and recrystallization occurs throughout the whole thickness of ice sheets [*Alley*, 1992; *De La Chapelle et al.*, 1998]. By reducing the rate of dislocations accumulation at grain boundaries, GBM can be an efficient accommodation mechanism of basal slip [*Pimienta and Duval*, 1987; *Alley*, 1992].

[7] A physical deformation model based on the equilibrium between hardening and recovery has been developed by *Montagnat and Duval* [2000]. The increase of the dislocation density is related to the Orowan equation by assuming that the dislocation

0148-0227/02/2001JB000946$09.00

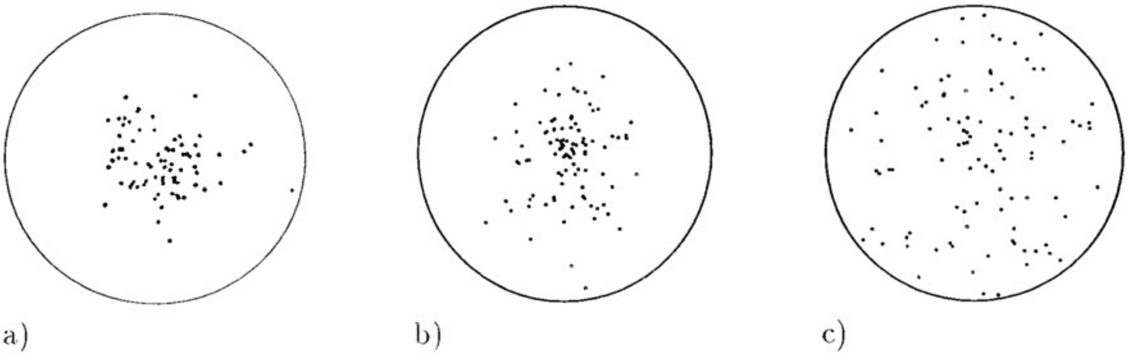

**Figure 1.** (a) Fabric pattern of the GRIP ice core at the depth of 1549 m compared with fabrics calculated using the VPSC model [*Tomé*, 1999] (b) for an equivalent strain of 0.75 (expected strain at this depth) and (c) for an equivalent strain of 0.225 (30% of the total strain).

free path corresponds to grain size in the absence of subboundaries. The reduction in dislocation density is related to the annihilation of dislocations by moving grain boundaries and to the formation of grain boundaries by the progressive misorientation of subboundaries. Application to ice sheets shows that GBM associated with grain growth or rotation recrystallization is an efficient recovery process and can be considered as the main accommodation mechanism of basal slip [*De La Chapelle et al.*, 1998; *Montagnat and Duval*, 2000].

[8] In conclusion, GBS does not appear the dominant deformation mechanism in ice sheets. As a consequence, results obtained by *Goldsby and Kohlstedt* [2001] for fine-grained ice samples exhibiting a superplastic behavior with GBS as a dominant deformation mechanism cannot be straight extrapolated to ice sheets. However, grain boundary migration is an ''incontournable'' recovery process and can accommodate basal slip. The flow law with a stress exponent of ~2 could be related to the efficiency of GBM in relieving the internal stress field resulting from the high plastic anisotropy of the ice crystal [*Duval et al.*, 1983].

[9] **Acknowledgments.** This work was supported by the Commission of European Communities (CEC) (EPICA project) and by CNRS (SDU and SPI departments). The authors would like to acknowledge Jean-Jacques Blandin for helpful discussions.

## References

Alley, R. B., Flow-law hypotheses for ice-sheet modeling, *J. Glaciol.*, *38*, 245–256, 1992.

Arieli, A., and A. K. Mukherjee, A model for the rate-controlling mechanism in superplasticity, *Mater. Sci. Eng.*, *45*, 61–70, 1980.

Arnaud, L., J. Weiss, M. Gay, and P. Duval, Shallow-ice microstructure at Dome Concordia, Antarctica, *Ann. Glaciol.*, *30*, 8–12, 2000.

Budd, W. F., and T. H. Jacka, A review of ice rheology for ice sheet modeling, *Cold Reg. Sci. Technol.*, *16*, 107–144, 1989.

Dahl-Jensen, D., and N. S. Gundestrup, Constitutive properties of ice at Dye 3, Greenland, *IAHS Publ.*, *170*, 31–43, 1987.

De La Chapelle, S., O. Castelnau, V. Y. Lipenkov, and P. Duval, Dynamic recrystallization and texture development in ice as revealed by the study of deep ice cores in Antarctica and Greenland, *J. Geophys. Res.*, *103*, 5091–5105, 1998.

Duval, P., Fluage de la glace polycristalline pour les faibles contraintes, *C. R. Acad. Sci.*, *277*, 703–706, 1973.

Duval, P., and O. Castelnau, Dynamic recrystallization of ice in polar ice sheets, *J. Phys. IV*, *5*, 197–205, 1995.

Duval, P., M. F. Ashby, and I. Anderman, Rate-controlling processes in the creep of polycrystalline ice, *J. Phys. Chem.*, *87*, 4066–4074, 1983.

Duval, P., L. Arnaud, O. Brissaud, M. Montagnat, and S. De la Chapelle, Deformation and recrystallization processes of ice from polar ice sheets, *Ann. Glaciol.*, *30*, 83–87, 2000.

Goldsby, D. L., and D. L. Kohlstedt, Grain boundary sliding in fine-grained ice, *Scr. Mater.*, *37*, 1399–1406, 1997.

Goldsby, D. L., and D. L. Kohlstedt, Are glaciers and ice sheets superplastic? [Abstract], *Eos Trans. AGU*, *79*(45), Fall Meet. Suppl., F310–F311, 1998.

Goldsby, D. L., and D. L. Kohlstedt, Superplastic deformation of ice: Experimental observations, *J. Geophys. Res.*, *106*, 11,017–11,030, 2001.

Langdon, T. G., A unified approach to grain boundary sliding in creep and superplasticity, *Acta Metall. Mater.*, *42*, 2437–2443, 1994a.

Langdon, T. G., An evaluation of the strain contributed by grain boundary sliding in superplasticity, *Mater. Sci. Eng. A*, *174*, 225–230, 1994b.

Lipenkov, V. Y., N. I. Barkov, P. Duval, and P. Pimienta, Crystalline texture of the 2083 m ice core at Vostok Station, Antarctica, *J. Glaciol.*, *35*, 392–398, 1989.

Lipenkov, V. Y., A .N. Salamatin, and P. Duval, Bubbly ice densification in ice sheets, II, Applications, *J. Glaciol.*, *43*, 397–407, 1997.

Mellor, M., and R. Testa, Creep of ice under low stress, *J. Glaciol.*, *8*, 147–152, 1969.

Montagnat, M., and P. Duval, Rate controlling processes in the creep of polar ice, influence of grain boundary migration associated with recrystallization, *Earth Planet. Sci. Lett.*, *183*, 179–186, 2000.

Perez-Prado, M. T., M. C. Cristina, O. A. Ruano, and G. Gonzalez-Doncel, Grain boundary sliding and crystallographic slip during superplasticity of Al-5%Ca-5%Zn as studied by texture analysis, *Mater. Sci. Eng. A*, *244*, 216–223, 1998.

Pimienta, P., and P. Duval, Rate-controlling processes in the creep of polar glacier ice, *J. Phys. Colloq.*, *C1*, 243–248, 1987.

Thorsteinsson, T., J. Kipfstuhl, and H. Miller, Textures and fabrics in the GRIP ice core, *J. Geophys. Res.*, *102*, 26,583–26,600, 1997.

Tomé, C. N., Self-consistent polycrystal models: A directional compliance criterion to describe grain interactions, *Modell. Simul. Mater. Eng.*, *7*, 723–738, 1999.

Zhang, Y., B. E. Hobbs, and M. W. Jessel, The effect of grain boundary sliding on fabric development in polycrystalline aggregates, *J. Struct. Geol.*, *16*, 1315–1325, 1994.

---

P. Duval and M. Montagnat, Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, B.P. 96, Saint Martin d'Hères Cedex, F-38402 France. (duval@glaciog.ujf-grenoble.fr)