Textural and Crystal-Fabric Anisotropies and the Flow of Ice Masses

Abstract. *Accurate modeling and prediction of glacier response requires a better understanding of the influence of physical anisotropies on creep. To investigate the effects of variations in the degree of preferred crystallographic orientation and ice crystal size on creep, 19 samples of anisotropic glacier ice were deformed in simple shear. Results indicate that the time required for ice samples to reach the minimum strain rate decreases as crystal size increases; an increase in crystal-fabric development from an isotropic fabric to one with a strong single maximum results in an enhancement of the minimum strain rate by a factor of 4; and a doubling of the crystal size results in about a ninefold increase in the minimum strain rate.*

Attempts to model present or past ice sheets are severely inhibited by lack of understanding of the influence of physical anisotropies on glacier flow. The flow law for ice (*1*), which is the starting point for most calculations of glacier flow, can be described by an Arrhenius-type equation

$$\dot{\gamma} = A\tau^n \exp(-Q/RT) \qquad (1)$$

In this equation $\dot{\gamma}$ is the octahedral shear-strain rate, A is a constant, τ is the octahedral-shear stress, $n = 3$ (*2*), Q is the activation energy for creep, R is the gas constant, and T is the absolute temperature. It is generally accepted that the parameter A in Eq. 1 is a function of crystal fabric and possibly crystal size as well.

The influence of variations in crystal fabric on A has been investigated with both laboratory-prepared and glacier ice samples (*3, 4*). Through uniaxial compression experiments at low octahedral stresses (0.05 to 0.4 bar), Lile (*3*) found that samples with girdle and moderate single-maximum fabrics deformed about 1.5 and 2.8 times faster, respectively, than those with a random fabric. Similarly, Russell-Head and Budd (*4*) observed, through tests in simple shear at octahedral stresses of 0.2 to 1.0 bar, that ice with a strong single-maximum fabric deformed about four times faster than did isotropic ice.

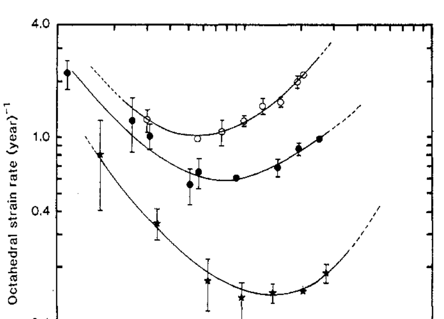

Fig. 1. Creep curves of log octahedral strain rate against log time for different values of the crystal size, d, and fabric intensity, f. Tests were done at a stress of 1.5 bars and a temperature of −9.1°C. Error bars represent 99 percent confidence limits for strain-rate calculations. Where error bars are not shown, they were smaller than the symbol representing the data point.

The possibility that the flow of ice is influenced by crystal size variations has been suggested by a number of results. Gold's (*5*) laboratory tests on columnar-grained ice showed that the smaller the average crystal diameter, the smaller the value of Young's modulus at constant temperature. Butkovitch and Landauer (*6, 7*) found that for polycrystalline samples with random fabrics, the samples with large crystals tended to deform more rapidly than those with smaller crystals. Their studies at low stresses (*7*) showed that the deformation rate of ice with an average crystal size of 1 to 2 cm was about four to five times as great as that of ice with an average grain size of about 3 mm. Bromer and Kingery (*8*) found that for columnar-grained polycrystalline samples, with average crystal sizes of about 2 to 5 mm, the viscosity was proportional to the square of the grain size. Baker (*9*) performed uniaxial-compression tests on laboratory-prepared samples with isotropic crystal fabrics and found that, for grain sizes larger than about 1 mm, a doubling of the average crystal size results in approximately a factor of 4 increase in creep rate. However, recent uniaxial-compression studies of laboratory-prepared samples by Duval and LeGac (*10*) and Jacka (*11*) suggest that crystal size has little or no effect on creep rate.

The work reported here was initiated (before I learned of these conflicting results) in order to determine whether the grain size effect found in uniaxial compression (*9*) could be extended to simple shear and to investigate the combined effects of crystal fabric and textural anisotropies on creep. Samples were obtained by collecting oriented blocks of glacier ice, averaging 0.5 m in mean dimension, from various locations in the margin of the Barnes Ice Cap, Baffin Island, Northwest Territories, Canada. Samples were transported to a cold laboratory at the University of Wisconsin at River Falls, where rectangular specimens, approximately 90 by 75 by 25 mm, were carefully cut from portions of the blocks with uniform physical properties. These smaller samples were then mounted in a creep apparatus and tested in simple shear at a constant stress of 1.5 bars and a constant temperature of −9.1°C. Specimens were deformed parallel to the direction of bubble elongation, which closely approximates the direction of maximum shear strain in the glacier (*12*). The apparatus used was similar to that described by Butkovitch and Landauer (*6*) except for minor modifications (*13*).

Tests were performed in a small chamber placed in the cold laboratory, which was kept at about −35°C. During experi-

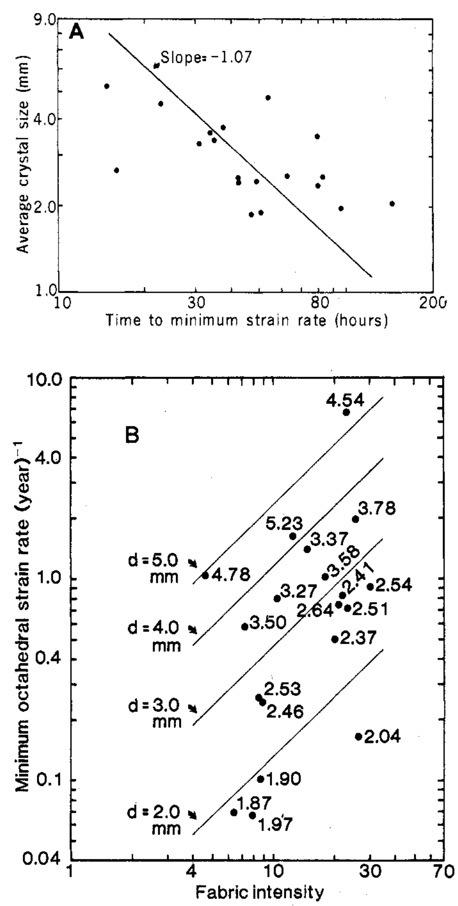

Fig. 2. Experimental results. (A) Plot of log crystal size against log time to minimum octahedral strain rate. The line with slope −1.07 was fitted to the data by least-squares methods. All data are from tests at a stress of 1.5 bars and a temperature of −9.1°C. (B) Plot of log minimum octahedral strain rate against log fabric intensity. Numerical values adjacent to data points indicate the crystal size of the samples in millimeters. Solid lines are plots of Eq. 2 for the crystal sizes indicated to the left of the lines.

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ments the temperature inside this chamber was controlled to within 0.1°C by a Lauda-Brinkmann K-4/R temperature bath and a Second Nature "Whisper 800" air circulator. Sublimation was minimized by placing crushed ice in the test chamber and thus saturating the air surrounding the apparatus.

Deformation was measured with a dial micrometer accurate to 2.54 μm and temperature was measured with a mercury thermometer, which could be read to ±0.02°C. During a test, the dial micrometer and thermometer were read at 0.5- to 2-hour intervals during the day. There was generally a gap of 6 to 7 hours in readings between about midnight and 7:00 a.m. Least-squares methods were used to calculate the creep rate over intervals of 4 to 12 hours. All tests were of sufficient duration that the creep rate decreased through a minimum value and then began to increase (Fig. 1). Total strain for the tests ranged from 0.7 to 10.7 percent.

Thin sections were cut from samples both before and after testing. Average crystal size was measured from enlarged thin-section photographs by the maximum chord-intercept method of Krumbein (*14*), a highly efficient technique for estimating the mean and standard deviation of grain sizes from thin sections when the texture is isotropic (*15*). Orientations of the *c* axis were measured on a Rigsby universal stage by standard techniques (*16, 17*), and data were plotted in equal-area stereographic projection. Fabric strength or intensity was determined by the method of Kamb (*18*), where the intensity, *f*, is a measure of the deviation of the fabric data from a random distribution. The higher the value of *f*, the greater the degree of fabric development.

Results of these experiments indicate that the time necessary for samples to reach the minimum strain rate is a weak inverse function of crystal size (Fig. 2A). The slope of the least-squares line through the data in Fig. 2A is −1.07 (correlation coefficient, .56). Hence, doubling the average crystal size will approximately halve the time required to achieve the minimum strain rate. Jacka (*11*) found a similar relation in uniaxial-compression tests on laboratory-prepared ice; however, in Jacka's experiments the time required to achieve the minimum strain rate was almost four times longer than that required for comparable samples tested at similar temperatures and stresses in simple shear. Results also indicate that the creep of polycrystalline ice, at a relatively low stress and high homologous temperature, is sensitive to variations in both crystal size and crystal fabric (Fig. 2B). If the data presented in Fig. 2B are subjected to a multiple-regression analysis, the results can be described by the empirical relation

$$\dot{\gamma}_{\min} = Bd^{l}f^{m}\tau^{n} \exp(-Q/RT) \qquad (2)$$

where $\dot{\gamma}_{\min}$ is the minimum octahedral shear-strain rate, B is a new constant, d is the average crystal size, and the other terms are as defined previously. The analysis yields $l = 3.14$, $m = 0.98$, and $B = 3.178 \times 10^{12}$ mm^{-l} bar^{-n} year^{-1} for $n = 3.0$ and $Q = 18.8$ kcal mole^{-1} with a correlation coefficient of .95. Equation 2 is plotted in Fig. 2B for an octahedral shear stress of 1.22 bars, an absolute temperature of 263.06 K, and grain sizes of 2.0, 3.0, 4.0, and 5.0 mm. The dependence of minimum strain rate on crystal size and fabric intensity is apparent from Fig. 2B. For instance, at a constant crystal size, a change in the degree of fabric development from an isotropic fabric (f = 5 to 7) to a strong single-maximum fabric (f = 28 to 30) results in about a factor of 4 increase in the minimum strain rate, in close agreement with the experimental results of Russell-Head and Budd (*4*). In addition, as crystal fabric remains unchanged, a doubling of the average crystal size results in about a factor of 9 increase in minimum strain rate. This is somewhat higher ($d^{3.14}$ versus $d^{2.50}$) than the grain size dependence observed in compression tests on laboratory-prepared isotropic samples (*9*).

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References and Notes

1. J. W. Glen, *Proc. R. Soc. London Ser. A* **228**, 519 (1955).
2. R. L. Hooke, in preparation.
3. R. C. Lile, *J. Glaciol.* **21**, 475 (1978).
4. D. S. Russell-Head and W. F. Budd, *ibid.* **24**, 117 (1979).
5. L. W. Gold, *Can. J. Phys.* **36**, 1265 (1958).
6. T. R. Butkovitch and J. K. Landauer, in *Symposium on the Physics of the Movement of Ice* (Publ. 47, International Association of Hydrological Sciences, Chamonix, 1958), p. 318.
7. ——, *U.S. Snow Ice Permafrost Res. Establ. Res. Rep. 72* (1960).
8. D. J. Bromer and W. D. Kingery, *J. Appl. Phys.* **39**, 1688 (1968).
9. R. W. Baker, *J. Glaciol.* **21**, 485 (1978).
10. P. Duval and H. LeGac, *ibid.* **25**, 151 (1980).
11. T. J. Jacka, in preparation.
12. R. L. Hooke and P. J. Hudleston, *J. Glaciol.* **20**, 285 (1978).
13. R. W. Baker, in preparation.
14. W. C. Krumbein, *J. Glaciol.* **43**, 482 (1935).
15. R. Kellerhals *et al.*, *J. Geol.* **83**, 79 (1975).
16. C. C. Langway, Jr., *U.S. Snow Ice Permafrost Res. Establ. Tech. Rep. 62* (1958).
17. B. Kamb, *Am. Mineral.* **47**, 227 (1962).
18. ——, *J. Geophys. Res.* **64**, 1891 (1959).
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Ruminant Methane $\delta(^{13}C/^{12}C)$ Values: Relation to Atmospheric Methane

Abstract. *The* $\delta(^{13}C/^{12}C)$ *− values of methane produced by fistulated steers, dairy cattle, and wethers, and dairy and beef cattle herds show a bimodal distribution that appears to be correlated with the plant type* (C_3 *or* C_4, *that is, producing either a three- or a four-carbon acid in the first step of photosynthesis) consumed by the animals. These results indicate that cattle and sheep, on a global basis, release methane with an average* $\delta(^{13}C/^{12}C)$ *value of −60 and −63 per mil, respectively. Together they are a source of atmospheric methane whose* $\delta(^{13}C/^{12}C)$ *is similar to published values for marsh gas and cannot explain the 20 per mil higher values for atmospheric methane.*

I have measured the $\delta(^{13}C/^{12}C)$ (*1*) of methane in gas samples taken from the rumens of five steers, two wethers, two dairy cattle, and from barns housing either beef or dairy cattle. The results show that differences in the carbon isotope ratios of the feed plants are reflected in the carbon isotope ratios of both the rumen CH_4 and the eructed CH_4. Furthermore, conclusions may be drawn about global sources of tropospheric CH_4 by comparing the data of this study with published information about both the relative magnitudes of, and carbon isotope ratios in, other known sources of atmospheric CH_4.

Rumen gas samples were collected from fistulated animals by two different methods. In the first method, a No. 18 hypodermic needle connected by a rubber hose to an evacuated 2-liter glass flask was pushed through the rubber diaphragm of the fistula in the animal's side and the flask's stopcock was opened. The flask was allowed to fill until the hissing stopped or until the animal objected and moved away. Some rumen fluid was also inadvertently collected. It

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