definition of a surge. I regard a surge as involving some dynamic instability leading to excessive surface lowering, followed by gradual recovery as the surface builds up to levels associated with the prevailing climate, rather than a relatively uniform, though considerable, change in surface level from that appropriate to one climatic regime to that associated with another.

W. F. BUDD: Since the paper by Allison (1979) on the Lambert Glacier basin is not being presented I would like to comment that the interior of the Lambert basin appears to be one large region which has a quite definite positive balance. The region of Lambert Glacier which has apparently had substantial ice lowering of the order of 800 m or more seems to be rising at a high rate (*c*. 0.2 m/a) which, if continued, would reach the previous thickness in the order of 4 000 a.

My second point is that there seems to be a problem in matching the large, relatively rapid changes observed in isotope and gas-content profiles, without substantial increases in velocity, which are difficult to explain in terms of steady state or direct reaction to climate change.

REFERENCE

Allison, I. 1979. The mass budget of the Lambert Glacier drainage basin, Antarctica. *Journal of Glaciology*, Vol. 22, No. 87, p. 223–35.

MECHANICAL PROPERTIES OF ANTARCTIC DEEP-CORE ICE

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ABSTRACT. Tensile tests were carried out with core-ice samples obtained from various depths at Byrd Station, Antarctica in 1968. Specimens for the tests were so prepared as to have their long axes parallel (L specimen), perpendicular (T specimen), and inclined at 45° (I specimen) with respect to the axis of the core, or to the vertical direction of the ice sheet. Stress–strain relations for many specimens were obtained from tensile tests with different strain-rates and also at different temperatures between −10 and −20°C.

The stress–strain curves generally exhibited a type of stress saturation. This is different from that for either basal or non-basal glide of single crystals of ice, with which a large yield drop or strain-hardening effect were observed respectively. The saturated value of the stress on the curves was considered as the maximum stress or the yield value. The relationship between the strain-rate $\dot{\epsilon}$ and the maximum stress σ was expressed as

$$\dot{\epsilon} = A\sigma^n.$$

This relationship can be drawn as a straight line with inclination n on a log–log plot and the softness or the degree of deformability is expressed by the value of A or by the level of strain-rate on the line at the same stress level. Although there was not much difference between L and T specimens as regards the softness for a sample from relatively shallow depth, which exhibited no strong preferred orientation of *c*-axes, there appear significant differences among T and L specimens with a sample of moderately oriented *c*-axes from deeper depth: the L specimens are easier to deform than the T specimens. And for samples of very strong preferred

orientation (a single maximum in the fabric diagram), the I specimen deforms much easier than the L and T by one or two orders of magnitude of $\dot{\epsilon}$ at the same stress level, in addition to the same tendency between the L and T as stated above. These results are well interpreted by the feasibility of basal glide in polycrystalline aggregates with respect to the preferred orientations in ice specimens.

Our recent experiments on the deformation behaviour under hydrostatic pressure (up to 300 atmospheres) with Antarctic deep-core ice revealed that the strain-rate decreases with increasing pressure while the fracture stress increases. This tendency must be caused by the reduction of mobile dislocations in ice crystals due to closure of cracks. It is already known that a high density of dislocations around the cracks should give rise to the production of efficient sources of mobile dislocations. This explains the softening effect in ice which contains many cracks.

The mechanical properties of the core ice with strong preferred orientation obtained above were applied to gain an understanding of the results of measurements of bore-hole tilting at Byrd Station obtained by Garfield and Ueda (1976). The velocity profile was calculated on the assumption of laminar flow, with estimated shear stresses under Byrd Station and an activation energy 66 kJ/mol for considering the temperature effect. For the upper half of ice sheet ($<$1 200 m), our predicted velocity agreed well with the relative velocity component in the direction S. 40° W. obtained by Whillans (1977). However, for the lower part of ice sheet, the velocity predicted without considering the effect of hydrostatic pressure on the strain-rate is much higher than that found by Whillans. If we use results in which the effect of hydrostatic pressure is considered, then the predicted velocity is lower than that by Whillans at middle depths (1 200–1 500 m). To explain the large difference between the value of the velocity at the bottom extrapolated from our estimated profile of velocities and the real bottom velocity estimated from the surface velocity at Byrd Station measured by repeated Doppler satellite fixes, it seems necessary to consider the possibility of basal sliding. This may be not unreasonable, because the existence of water layer at the bed is proved by water flooding into the hole to a height of approximately 50 m above the bed when the bore hole was drilled.

REFERENCES

Garfield, D. E., *and* Ueda, H. T. 1976. Resurvey of the "Byrd" Station, Antarctica, drill hole. *Journal of Glaciology*, Vol. 17, No. 75, p. 29–34.

Whillans, I. M. 1977. The equation of continuity and its application to the ice sheet near "Byrd" Station, Antarctica. *Journal of Glaciology*, Vol. 18, No. 80, p. 359–71.

DISCUSSION

W. F. Budd: Your experiments were in uniaxial compression whereas the *in situ* ice seems to have been in horizontal shear. Do you think your tests can simulate the *in situ* deformation adequately?

H. Shoji: The specimens were so prepared as to have their long axes inclined 45° against the axis of the core. Then the horizontal plane of the core has maximum shear stress in the specimen. So, I think our tests can simulate the *in situ* deformation adequately.

D. R. Homer: What were the dimensions of your specimens? Weertman (1973) has suggested that specimens should be ten grain diameters across for mechanical testing. Are your results really representative of the core ice's mechanical properties?

Shoji: The dimensions of the specimens are $2 \times 2 \times 8$ cm^3. The grain size is about 5 mm. With specimens which have random orientation fabrics, size effect of the specimen cannot be neglected, but with specimens which have strong preferred orientation fabrics, the size effect is not so sensitive. So, I think our results can be representative of the ice core.

T. J. Hughes: Did you have rigid or free sliding conditions at the compression heads of the ice specimens you deformed in uniaxial compression? This is important for compressing ice with *c*-axes of crystals mostly at 45° to the compression axis. Shear stresses will be created across the heads for rigid conditions. For free conditions, non-homogeneous slip in the possible slip zone may increase the shear stress resolved along the 45° planes of easy glide.

Shoji: We had the rigid condition on one compression head and the free condition on the other, so there were no shear stresses across the heads. Some specimens did have non-homogeneous slip along the 45° planes, but we used data only for specimens having homogeneous slip.

J. W. Glen: Did you observe any anisotropy of transverse strain? With a 45° orientation of a strong *c*-axis fabric one might expect transverse strain to be zero in the direction where basal planes intersect the normal to the compression axis.

Shoji: I did not observe this precisely, but some specimens showed such an anisotropy after large total deformation (e.g. 30% strain).

REFERENCE

Weertman, J. 1973. Creep of ice. (*In* Whalley, E., *and others, ed. Physics and chemistry of ice: papers presented at the Symposium on the Physics and Chemistry of Ice, held in Ottawa, Canada, 14–18 August 1972. Edited by E. Whalley, S. J. Jones, L. W. Gold.* Ottawa, Royal Society of Canada, p. 320–27.)

FINITE-ELEMENT SIMULATION OF THE BARNES ICE CAP

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Abstract. The finite-element method is being used to simulate glacier flow problems, with particular emphasis on the surge behaviour of the Barnes Ice Cap, Baffin Island. Following an advanced feasibility study to determine the influence of major factors such as bed topography and flow relationships, a refined simulation model is being developed to incorporate realistically: the thermal regime of the ice mass; large deformations during flow and sliding; basal sliding zones; a temperature and stress dependent ice flow relationship; mass balance; and three-dimensional influences. The findings of the advanced feasibility study on isothermal, steady-state flow of the Barnes Ice Cap are presented in the paper before turning to a detailed discussion of the refined simulation model and its application to surging. It is clear that the finite-element method allows necessary refinements not available to analytical approaches.

https://doi.org/10.3189/S0022143000015021 Published online by Cambridge University Press