Journal of Glaciology, Vol. 12, No. 64, 1973

CORRESPONDENCE

The Editor,

Journal of Glaciology

SIR, *Barnes Ice Cap and englacial debris in glaciers*

An exchange of letters between Drs Andrews and Boulton (Andrews, 1971, 1972; Boulton, 1971, 1972) on the subject of englacial debris in glaciers requires further clarification and the addition of presently held data which applies specifically to the Barnes Ice Cap. The data are of three types: temperature, debris content and flow rate.

1. *Temperature.* With reference to Boulton's (1972, p. 156) suggestion that the difference in thermal regimes is responsible for the contrast in discharge of subglacial debris of cold and temperate glacier ice, recently collected temperature data for the Barnes Ice Cap indicate that it very likely has the thermal characteristics proposed by Weertman (1961, p. 976). On the south shoulder at an elevation of about 890 m a.s.l. a 22 m deep SIPRE core hole was used in 1971 to measure a temperature profile. At a depth of 20 m below the top of the last superimposed ice surface, the temperature was $-8° \pm 0.1°$ C which is considerably higher than the mean annual surface temperature (approximately $-15°$ C). This large temperature difference is caused by the formation of superimposed ice on the crown of the ice cap. The extent to which this effect occurs on the South Dome area is estimated to be 7 km at least either side of the divide.

Radio echo sounding measurements at the bore-hole location (personal communication from S. J. Jones) gave an ice depth of 420 ± 20 m. According to a Robin-type analysis (Robin, 1955) which is appropriate here, the basal temperature is likely to be at or near the pressure melting point. In the marginal ice (elevation 500 m a.s.l.) temperature measurements by Professor R. LeB. Hooke (personal communication) indicate that the base is well below the pressure melting point. With the exception of the marginal sections that are breached by pro-glacial lakes, the ice-cap margin has a cold base.

On some marginal sections of the ice cap, debris is emerging on the surface at a distance of about 100 m from the toe. Because of the dip angle of the dirt layers and the expected curvature of the subsurface dirt trajectories, the debris was probably carried from a distance of *at least* several hundred meters from the present margin (cf. Andrews, 1972, p. 155). Therefore it might be expected that a mechanism like Weertman's gets material into the ice, *or*, beginning where the vertical strain-rate is stretching (ablation area), a diffusion mechanism (Weertman, 1968) gets debris into the ice. These observations seem to be in accordance with Boulton (1971, p. 411; 1972, p. 156).

2. *Debris content.* With regard to the dirt content in the marginal ice of the Barnes Ice Cap, I present the following data: in an ice cliff 25 m high near the edge of Generator Lake, a large recumbent flow fold may be observed. The exposed parts of the limbs are separated by about 10–12 m and are outlined by wide (0.1–2 m) dirt bands which have been sampled. The content of debris in the ice is $8 \pm 3\%$ by volume for the ice that is visibly dirty, which for the fold, is about 15 m of the basal ice. A pre-fold thickness of basal dirt would be about 8 m. The dirt content was determined by measuring the percentage of debris by weight in several ice samples. Since the largest particle occurring in the actual samples was about 2 cm, a "correction" was applied to account for inaccessible larger-sized particles many of which studded the cliff. To do this a "complete" grading curve for the local moraine was used. For the ice above the dirty zone the content of dirt (percentage by volume) is about two orders of magnitude less than the folded dirt bands (cf. Boulton, 1971, p. 410).

It is unclear whether Andrews and Boulton always refer to the same "system", and if they do so whether it is relevant to the issue being discussed. First, I understand that the ice-cored moraines (Goldthwait, 1951) are the ones effectively *detached* from the ice cap now. These are known to be covered by about 1 m of till. The ice core of these moraines is not deforming sufficiently to be detected by conventional means. If Andrews (1971, p. 410) is referring to the same type of moraine, then his (estimated) figure of 95% ice by volume (5% debris) is time dependent, and not related to the value given above, which is for presently deforming basal ice. However, under no circumstances can my figure be taken to apply to all sections of the Barnes Ice Cap margin. There are sections which contain little or no dirt.

Secondly, the physical character of the ice-cap margin varies considerably depending on the locality. It is not sufficient or acceptable to make a judgement for the whole ice cap based on observations at one locality. The existence of well-developed "ice-perched moraines" (Hooke, 1968) may correspond to the condition where the base of a vertical flow plane through the ice cap passes from an inner area of basal melting to the outer zone of basal freezing. The absence of an "ice-perched moraine" may simply correspond to the condition where the appropriate flow plane contains all cold ice. If a section of margin is modified by local advance and has incorporated snow, ice and moraine, it is possible that only a limited amount of debris is introduced into the ice over the last few hundred meters as Andrews (1972, p. 155) tends to believe.

3. *Flow-rate*. Embleton and King (1968, p. 43) described the movement on the Barnes Ice Cap as "very sluggish or negligible"; (p. 96) ". . . where the ice is barely moving". Andrews (1971) stated that the ice cap has ". . . general low velocities . . .".

Løken and others (1968, p. 97) provided data which show that surface ice-flow rates may exceed 25 m a^{-1} (ice thickness 300 m) between the South Dome summit and Generator Lake. The highest surface horizontal flow rate yet measured (1970–71) is about 28 m a^{-1}, where ice flows into Generator Lake.

Along a 10.5 km traverse from the divide of the south shoulder (bore-hole location) to the margin, the horizontal flow rate reaches a maximum of only about 6 m a^{-1} (ice depth 200 m) at a distance of 8 km from the divide; then it decreases to about 3.7 m a^{-1} (ice thickness 110 m) at a distance of 600 m from the margin in the direction of which the horizontal flow rate decreases towards zero. The surface longitudinal strain-rate only becomes compressive within the last 3 km from the margin.

The temperature data discussed in (1) may lend credance to the hypothesis of local surges (Løken, 1969).

As more data become available, it will be possible to determine more quantitatively the rates of debris production for more parts of the ice-cap margin.

Glaciology Division,
Inland Waters Directorate,
Department of the Environment,
No. 8 Temporary Building,
Carling Avenue,
Ottawa, Ontario, Canada

G. Holdsworth

12 May 1972

REFERENCES

Andrews, J. T. 1971. Englacial debris in glaciers. *Journal of Glaciology*, Vol. 10, No. 60, p. 410. [Letter.]

Andrews, J. T. 1972. Englacial debris in glaciers. *Journal of Glaciology*, Vol. 11, No. 61, p. 155. [Letter.]

Boulton, G. S. 1971. Englacial debris in glaciers: reply to the comments of Dr J. T. Andrews. *Journal of Glaciology*, Vol. 10, No. 60, p. 410–11. [Letter.]

Boulton, G. S. 1972. Englacial debris in glaciers: reply to the comments of Dr J. T. Andrews. *Journal of Glaciology*, Vol. 11, No. 61, p. 155–56. [Letter.]

Embleton, C., *and* King, C. A. M. 1968. *Glacial and periglacial geomorphology*. [London], Edward Arnold (Publishers) Ltd.

Goldthwait, R. P. 1951. Development of end moraines in east-central Baffin Island. *Journal of Geology*. Vol. 59, No. 6, p. 567–77.

Hooke, R. LeB. 1968. Comments on "The formation of shear moraines: an example from south Victoria Land, Antarctica". *Journal of Glaciology*, Vol. 7, No. 50, p. 351–52. [Letter.]

Løken, O. H. 1969. Evidence of surges on the Barnes Ice Cap, Baffin Island. *Canadian Journal of Earth Sciences*, Vol. 6, No. 4, Pt. 2, p. 899–901.

Løken, O. H., *and others*. 1968. North-central Baffin Island field report, 1967, by O. H. Løken, A. Geiger and P. Langlais. *Canada. Dept. of Energy, Mines and Resources. Inland Waters Branch, Report Series* No. 2.

Robin, G. de Q. 1955. Ice movement and temperature distribution in glaciers and ice sheets. *Journal of Glaciology*, Vol. 2, No. 18, p. 523–32.

Weertman, J. 1961. Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. *Journal of Glaciology*, Vol. 3, No. 30, p. 965–78.

Weertman, J. 1968. Diffusion law for the dispersion of hard particles in an ice matrix that undergoes simple shear deformation. *Journal of Glaciology*, Vol. 7, No. 50, p. 161–65.