Correspondence

The Editor,
Journal of Glaciology

Sir,

Ice-blister observations on glaciers, sea ice and rivers

The paper "Surficial glaciology of Jakobshavns Isbræ, West Greenland: Part I. Surface morphology", by K. Echelmeyer and others appeared in the *Journal of Glaciology*, Vol. 31, No. 127. In this paper, the authors made reference to ice-blister formations which they believed had not previously been reported in the literature. These ice features were estimated to be 3–8 m high and 7–20 m long. Two types of blister were noted, hollow and solid. All were found in the ablation zone where summer surface melt forms pools in glacial depressions and crevasses or surface streams.

I saw similar ice blisters on Koettlitz Glacier Ice Tongue, Antarctica, in 1977. During the ablation season, significant surface melting occurs on this ice tongue. In some years, the melting is so severe that "rivers" of rapidly flowing water develop and erode deep channels in the ice surface (Fig. 1). The steep ice walls of the channels were up to 6 m above the water in the areas of study. A truly unique aspect of this flow is that it ran along the spine of the ice tongue back toward the area where the glacier ice becomes free-floating rather than toward the front of the ice tongue and into McMurdo Sound. The ice blisters observed were either cone-shaped (Fig. 2) or sinuous mounds. All were of the solid type in that they
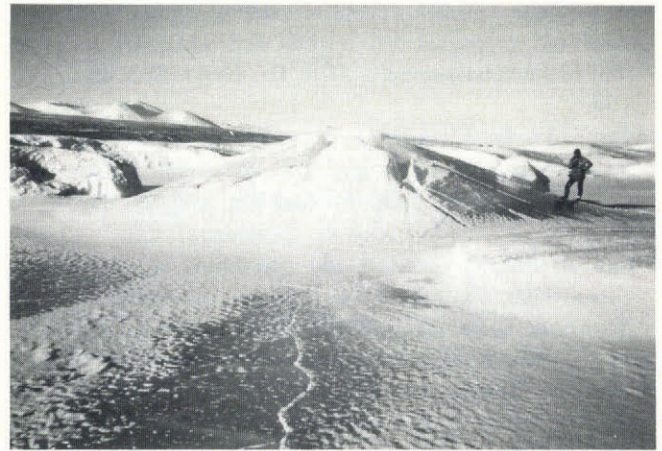
Fig. 2. Conical (by person) and low-elevation linear (foreground) ice blisters in a refrozen "river" on Koettlitz Glacier Ice Tongue.

were not filled with water or air. The ice blisters appeared to occur where deep depressions had formed in the river and stream channels or in deep melt pools. Since the new ice was "transparent", one could see through it and in places observe fine sand grains and small pebbles. This material marked the boundary between the new ice and the glacier ice. Some of this granular material can be seen on the river bed in Figure 1.

Two ice blisters can be seen in Figure 2. The prominent one, beside the person, was 3 m high and conical in form. The second was $\frac{1}{2}$ m high. The apex of this feature ran along the crack in the foreground and under the feet of the photographer. The conical ice blister is seen to be highly fractured. There were six major wedges or pie-shaped pieces, which in turn were also laced with a number of surface fractures. Beside the person in Figure 2 is a block of ice about 1 m thick that had popped off the tip of one wedge when it was deflected upward.

Another observation of the ice blisters in Antarctica was made by Van Autenboer (1962). He described three ice mounds, up to 2 m high and 15 m in diameter, located near the terminus of Gunnestadbreen. His figure 2 (p. 351) shows a feature that is very similar to the one shown in Figure 2 of this letter.

The conical ice blister shown in Figure 2 bears a resemblance to the sketch presented by Wright and Priestley (1922, p. 343). They stated that "On several occasions peculiar structures were observed in sea ice which resembled in appearance nothing so much as the skin of a blister, which had broken ...". Their explanation for sea-ice blister formation was a sudden discharge of gas from beneath the sea-ice sheet. This explanation certainly does not apply to the solid ice blisters observed on

Fig. 1. River of meltwater on Koettlitz Glacier Ice Tongue. The dark blotches in the river are granular material resting on the ice bottom. A small 1 m high tracked vehicle is at the tip of the arrow. Dark bands in channel wall are related to ice-fabric variations.

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Fig. 3. A small conical (upper right) and several sinuous ice blisters observed in the Katakturuk River delta, Camden Bay, Beaufort Sea coast, Alaska, in 1980.

Koettlitz Glacier Ice Tongue nor on the Jakobshavns Isbræ ice field.

The solid ice blisters probably grew following the general theory described by Sumgin (1941), Liverovskii and Morozov (1941), Lewis (1962) and other early investigators as applying to frost mounds in general and river-ice blisters, ice domes and mounds in particular. Once the run-off season ended and the shallower surface waters froze to the glacial ice, water in the deeper pools became fully confined by ice. With time, the expansive forces in the water, associated with continued freezing, either gradually, intermittently or in sudden rapid events, forced the ice cover upward. During this process, the ice blister cracked at its apex and secondary ones formed until all the water in the blister had frozen and expansive uplift stopped. No icings were observed beside the Koettlitz Glacier ice blisters, therefore none of the confined water had escaped during their uplift and fracturing. The hollow ice blisters observed on the Jakobshavns Isbræ ice field by Echelmeyer and others (1991) had apparently drained.

As mentioned above, ice blisters (mounds) also occur on rivers where the bed is impervious, such as in permafrost areas (Fig. 3). Many Russian and North American papers can be found describing such features (Leffingwell, 1919; Smith and Mertie, 1930; Muller, 1947; Carey, 1970, 1973; Chacho and others, 1990; Crory, 1991). On the North Slope of Alaska these numerous and conspicuous features are easily seen from the ground or an aircraft.

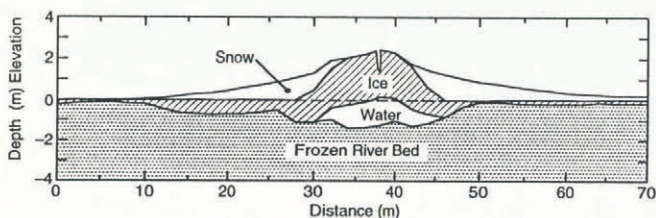Between 1978 and 1984, I made helicopter reconnais-

Fig. 4. Representative cross-section of a sinuous ice blister studied in the Katakturuk River delta, Alaska. The in situ salinity of the ice-blister water was 0.6‰.

sance flights along the Chukchi and Beaufort Sea coasts of Alaska each spring. During these years, conical or long sinuous ice blisters were seen on most of the rivers entering the sea. No river on the Alaska North Slope flows during the winter but massive spring-fed icings do occur, and some remain after the summer melt season. A number of the ice blisters were drilled at their apexes. Many blisters were found to contain a core of water (Fig. 4). The water would rise in the 5 cm diameter borehole but only at one location did a very small quantity of the water flow out at the top of the blister. The confined water pressure is not known but it probably was much lower than the several tens of atmospheres determined by Petrov (1930) for confined ground water below seasonal frost in areas of spring-fed icings. Pressure on the order of 25–100 kPa seems more realistic based on measurements of the water pressure in frost mounds by Pollard and French (1984). The drillhole-flow observations indicated that the blisters were not spring-fed and that the ice uplift is analogous to cream being forced upward from a freezing bottle of milk, or to the crown on the top or bottom of a frozen bucket of water.

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19 March 1992

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The accuracy of references in the text and in this list is the responsibility of the author, to whom queries should be addressed.

ERRATUM

The author has drawn attention to the incorrect order of text in col. 2, p. 187 and col. 1, p. 188.
The correct order of text should be

Finally, having noted that water levels in boreholes fluctuate widely over a range of time-scales, it is important to recognize that in the model results presented here it is assumed that the piezometric surface is effectively steady-state. The simulations do not include the effects of temporal variations in basal water pressures. However, field observations have shown that sliding velocities respond quickly to variations in basal water pressures over time-scales ranging from hours to seasons (e.g. Boulton and Vivian, 1973; Hodge, 1976), and this lends support to the model assumption that sliding velocities reflect current water-pressure conditions, rather than some complex, integrated response to conditions over a longer time-scale. Thus, it seems reasonable to assume that the piezometric surface is steady-state for this initial sensitivity analysis.

SENSITIVITY TO VARIATIONS IN BASAL FRICTION

Another major assumption of the simulations presented so far is that k, the friction factor in the sliding law, inversely related to bed roughness and debris concentration, is uniform across the glacier section. However, there may be important cross-sectional variations in the friction factor: one might expect effective roughness at the margins of many glaciers to be anomalously high because of relatively high concentrations of basal and englacial debris from subglacial and subaerial sources (Kamb and

others, 1976; Engelhardt and others, 1978; Hallet, 1981). Although it is not clear exactly how to treat this problem quantitatively (Hallet, 1981), it is mathematically convenient to let k scale with N^p towards the edge of the glacier (above the piezometric surface) so that spatial variations in the product of k and N^{-p} vanish (equivalent to using a Weertman-type sliding law in the marginal zone (Weertman, 1964)). As k is inversely proportional to effective roughness, and decreases in the marginal zone, this adjustment accords with the expectation that the effective roughness at the margins of glaciers is relatively high. Simulations with this assumption will be referred to here as simulations which use an adjusted sliding law.

The tests of possible combinations of m and p were repeated with the adjusted sliding law and showed again that high values of m do not result in low marginal sliding velocities (Fig. 6). However, with $m = 1$ and $p = 1$, marginal velocities are low, and with increasing p the basal-velocity distribution becomes more peaked towards the center of the glacier and includes negligible velocities towards the glacier margin. It is important to note that with the adjusted sliding-law velocity reversals no longer occur close to the glacier margin, and the complete flow field looks similar to the empirical data (cf. Figs 1 and 7). With variable piezometric heights (Fig. 8), the model again predicts that relative marginal velocities increase as the piezometric surface is lowered relative to the glacier surface, and only in a case where the piezometric surface is nearly high enough to float the center of the glacier does the model predict low relative marginal velocities.