

showed an original backward tilt of the iceberg. Pauer and others (1958, p. 89) shows icebergs close to the front of Jakobshavns Isbræ which have tilted backward. Reeh does not deal with the question, but a backward tilt would probably have to be expected if the break was near the line at which the ice starts to float.

The author states himself in his Conclusion that his theory is not verified by the calving of the Antarctic ice shelves although one should expect them to be more likely to conform than the laterally confined ice streams of Greenland. We find indeed floating glacier tongues like those of the Mertz and Ninnis Glaciers and ice shelves like the Amery Ice Shelf which attain lengths of not once but 100 times their thickness before they calve.

Incidentally, although the author is right that storm waves can hardly explain the calving of big icebergs, this might be different with tsunamis which have wavelengths of many kilometres and influence the whole water body. They occur sometimes at Antarctic ice fronts (Barré, [1953], [Tom.] 2, p. 179).

One might wish that Mr Reeh could develop his learned and elaborate theory to a state in which the processes leading to and happening during calving are fully covered.

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SIR, *Calving from floating glaciers: reply to Professor F. Loewe's comments*

In his comments Professor Loewe claims the following things:

1. The manner of calving of Rink Gletscher and Jakobshavn Isbræ is not typical for the ice streams of western Greenland.
2. Rink Gletscher and Jakobshavn Isbræ are not floating glaciers and therefore cannot be used to prove the theory of calving proposed.
3. The front of a floating glacier is not always bent downwards as predicted by the theory.
4. The often observed backward tilting of the icebergs detached at the calvings should be in contradiction to the downward bending of the front predicted by the theory.

My attitude to these points is as follows:

1. I agree that the manner of calving of Rink Gletscher and Jakobshavn Isbræ is not typical for the ice streams of western Greenland, but I think that the reason is that these glaciers have floating fronts, in distinction to the main part of the ice streams terminating in Disko Bugt and the Umanak district in western Greenland.

2. My opinion is based on the following:

- (a) The slope of the surface of the two glaciers is very small.
- (b) The biggest icebergs from the two glaciers do not turn over at the calvings, but float away, the old glacier surface turning upwards (Carbannel and Bauer, 1968, p. 21; Sorge, 1933, p. 13).
- (c) According to figs. 12 and 13 in my article, the level of the southern part of the surface of Rink Gletscher is about 80 m above sea-level. According to Carbannel and Bauer (1968) p. 50, the height of the front is 70–75 m above sea-level. Putting the mean density of the ice as 0.9 Mg/m^3 (Sorge, 1933, p. 13) and the mean density of sea-water to 1.02 Mg/m^3 (Steenstrup, 1893, p. 84), we get

$$d_1 = 0.9/1.02 \approx 0.88.$$

Under the assumption of a floating front, the ratio of total ice thickness to front height above sea-level is thus determined to be

$$f = \frac{1}{0.12} < 8.5.$$

Due to the severe crevassing of the surface, the ratio is quite likely less. So, no reason exists for assuming the frontal thickness of Rink Gletscher to be more than 720 m, of which less than 650 m is below sea-level. According to Sorge (1933, p. 19), the depth of the fjord immediately in front of the glacier is 692 m. Consequently at least a part of the front must be floating, as is also stated by Sorge (1933, p. 16).

Moreover, only the outermost part of the glacier needs to be afloat in order to make possible the deformation procedure described in my paper. As seen from fig. 6 in the article, significant downward movements take place only in a region extending from the front of the glacier to less than the thickness of the glacier behind the front.

- 3. It is true that the theory at the state at which it was put forward in the article, will always lead to a downward movement of the front. This is due to the simplification of neglecting temperature variations and the resulting variation of the cross-sectional rigidity in the vertical direction. When dealing with deformations, the moment of the forces acting at the front must be calculated with respect to the centre of the transformed cross-section. If the rigidity of the cross-section is constant in the vertical direction, the centre is situated at the midpoint of the cross-section and the front is bent downwards. If a temperature gradient exists, the centre is situated above the midpoint, more and more the greater the temperature gradient, and at a certain gradient the moment changes its sign resulting in an upward bending of the front. Also the depth of the crevasses influences the sign and magnitude of the bending moment. An improved theory taking into account the influence of temperature and depth of crevasses is under elaboration.
- 4. The fact that the icebergs often tilt backwards has nothing to do with what causes a depression of the glacier into the sea. The question of whether an iceberg will tilt forward or backward depends on:
 - (a) Shape of front—and fracture cross-sections.
 - (b) Magnitude of depression.
 - (c) Slope and thickness of the frontal part.
 - (d) Distance from the front to the fracture cross-section.
 - (e) Relative density of the glacier ice.

Assuming front and fracture cross-sections perpendicular to the glacier surface, a rough calculation with reasonable values of density, depression and slope of the frontal part leads us to expect that backward tilt will occur if the distance from the front to the fracture cross-section is more than about half the thickness of the glacier, while forward tilt will occur if it is less. This is in agreement with observations made by Ole Olesen of Grønlands Geologiske Undersøgelse and the author at Daugård Jensen Gletscher during the Grønlands Geologiske Undersøgelse expedition to East Greenland, July–August 1968, where both ways of tilting of icebergs detached at calvings were observed and photographed. Further details will appear in a paper under elaboration.

Finally I should like to remark, that the theory at the state at which it was put forward in the article was a first approximation only, as was also pointed out. On the other hand, it is my opinion, that the

basic idea put forward in the article holds, viz. that the stresses induced by the moment at the front of the glacier play a major role in the calving procedure. At present a more correct theory is under elaboration.

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SIR,

Crystal shape in polar glaciers and the philosophy of ice-fabric diagrams

In his recent study, Rigsby (1968) found that single crystals in coarse-grained ice from a temperate glacier may branch and rejoin, and may twist about in a very irregular manner in three dimensions. In the process the *c*-axis of the crystal may be bent as much as 10°. In the last paragraph but one, Rigsby suggested that this complex shape of crystals may cast doubt on many fabric diagrams obtained from temperate glacier ice. He observed that it is not known whether crystals of finer-grained ice from polar glaciers are equally complex. Some work that I did in August 1967, at the Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, bears on these problems.

Two or more crystals in different parts of a thin section may appear to have nearly identical *c*-axis orientations, and Rigsby's study suggests that these "cells" may be part of the same crystal in three dimensions. This raises the possibility of two types of uncertainty in the preparation and interpretation of fabric diagrams.

First, if the *c*-axes of two cells are nearly parallel, should those two cells be counted as one crystal (1 point) or two crystals (2 points) in plotting a fabric diagram? If two cells from different crystals are incorrectly thought to be part of the same crystal and thus counted as one point, the fabric will be artificially weakened. This effect might become particularly serious in a fabric with a strong preferred orientation, as many cells might be incorrectly rejected. Furthermore, it is possible that a bent crystal will occur as two cells with different *c*-axis orientations and that both these cells will be counted.

Secondly, crystals may be granulated in regions of high shear strain (Rigsby, 1960, p. 605). A broken crystal would appear as two or more cells in a thin section and if slight rotation of the grains had occurred the *c*-axes of the cells would no longer be parallel. Should such cells be counted as one crystal, or as separate crystals?

Fabric analyses are useful because ice recrystallizes under stress and because crystals assume a preferred orientation during recrystallization such that glide planes are sub-parallel to one another, and to the direction of shear strain. It is necessary to decide whether the critical parameter in this process is the fact that a large number of individual crystals assume a certain orientation, or whether it is more important that in a large percentage of the ice volume, glide planes are sub-parallel to the direction of shear strain. The former case is intuitively more interesting as it treats the mechanics of crystal growth and glacier flow. However, to study this aspect of fabric diagrams it is essential to measure each crystal, including branched or broken crystals, only once. As discussed above this is generally impractical.

Thus in most cases we are forced to the second approach, that of considering the percentage of the volume in which glide planes are sub-parallel to the direction of shear strain. To employ this approach, one should measure the volume of each crystal and weight the points in the fabric diagram proportionally. In general, this is also impractical, but an approximate weighting according to the area of the crystal exposed in a thin section is possible (Kamb, 1959, p. 1900).