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# SURFACE FEATURES OF ICE STREAM B, MARIE BYRD LAND, WEST ANTARCTICA

by

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ABSTRACT

Aerial photographs have been obtained of Ice Stream B, one of the active ice streams draining the West Antarctic Ice Sheet. A sketch map made from these photographs shows two tributaries. The margin of the active ice is marked by curved crevasses and intense crevassing occurs just inward of them. Transverse crevasses dominate the center of the ice streams and diagonal types appear at the lower end. A "suture zone" originates at the tributary convergence and longitudinal surface ridges occur at the downglacier end. The causes of these surface features are discussed and the relative importance of four stresses in resisting the driving stress is assessed. We conclude that basal drag may be important, longitudinal compression is probably important at the lower end, and longitudinal tension is probably most important near the head of the ice stream. Side drag leads to shearing at the margins, but does not restrain much of the ice stream.

## INTRODUCTION

An ice stream is a portion of an ice sheet flowing rapidly between more nearly stagnant ice ridges. The ice streams in West Antarctica (Fig.1) were identified by radar detection of their crevassed margins (Rose 1979). Our measurement of surface velocity at the Up-B camp (Fig.2), is 450 ($1\sigma$ = 5) m $a^{-1}$, which is at least twice the calculated balance velocity (Budd and others 1984, Rose 1979). The discrepancy may be due to the difficulty of determining the boundary of the catchment area when doing the calculations. Balance velocities for the ridges are less than 10 m $a^{-1}$. The ice streams are almost certainly wet-based, and the ridge ice is probably frozen to its bed (Rose 1979).

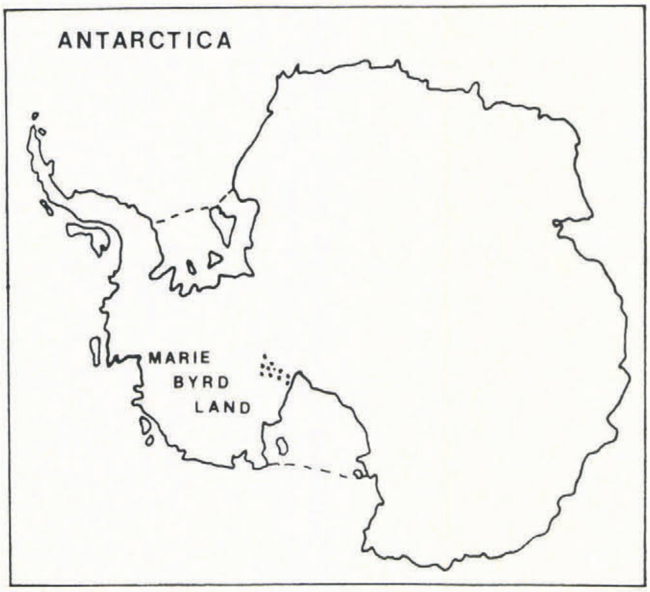


Fig.1. Location map, with Ice Stream B indicated by stippling

The flow dynamics of ice streams are not understood. Their beds are relatively flat, smooth, and only slightly lower in elevation than those under the ridge ice (Drewry 1983), so it is possible thast basal friction is very small. The resistance to ice flow may be by lateral shear at the margins, by tension from up-glacier, by compression from down-glacier, or by basal drag. As a step toward describing ice stream flow, we have prepared a sketch map of Ice Stream B, based on aerial photography, and an interpretation of the surface features.

## DATA ACQUISITION AND PROCESSING

Aerial photography of Ice Stream B was obtained in December 1983 by the United States Geological Survey from approximately 7000 m above the terrain. A mosaic (scale 1:40 000) was constructed from paper prints of these photographs. The photographs were neither rectified nor scaled. The resulting minor mismatches among adjacent photographs, resulting from tilt displacement, relief displacement, and scale changes, were distributed uniformly.

The photomosaic is 8.5 m long and 1.2 m wide and its resolution is about 15 µm, which corresponds to 0.7 m on the glacier. Surface features were identified stereoscopically, or by using shadows and the relative position of the sun. Selected features were traced from the mosaic onto drafting film, omitting sastrugi and at least every second drift mound and crevasse. The tracing was photographically reduced, then photocopied onto paper to produce the final map at 1:250 000 scale. Figure 2 is a reduced and simplified version of this map, in which a further two-thirds of the features have been omitted.

## FEATURES OBSERVED

### 1. Snowdrift features

Snowdrifts, ranging from sastrugi several meters long to drift mounds which are up to 200 m in length, appear on the photographs. These drifts dominate the surface texture in many areas, but in this contribution attention is directed toward crevasse patterns.

### 2. Crevasses

Surface crevasses occur over most of Ice Stream B. They are nearly all bridged. Presumably, a crevasse forms where the principal extensional stress and its associated strain rate exceed some critical value, which is about .01 $a^{-1}$ in some temperate glaciers (Holdsworth 1965, Meier 1957, Meier and others 1957) and .002 $a^{-1}$ in a polar glacier at $-28\,^{\circ}$C (Holdsworth 1969). In the southern tributary ice, crevasses occur predominantly in groups or bands. Each band consists of crevasses of similar orientation and is separated from adjacent bands by a narrow (tens to hundreds of meters) zone that appears crevasse-free. Bands are aligned approximately with the ice flow. They begin suddenly and continue down-flow. The cause of banding is not understood, but it may be that local obstructions to ice flow cause families of crevasses to originate either over them or just up-glacier. Ice flow then carries the crevasses down-glacier. The down-glacier limit of the band occurs where snow filling is able to keep up with crevasse opening.

Crevasse bands are greatest in number in the ice of

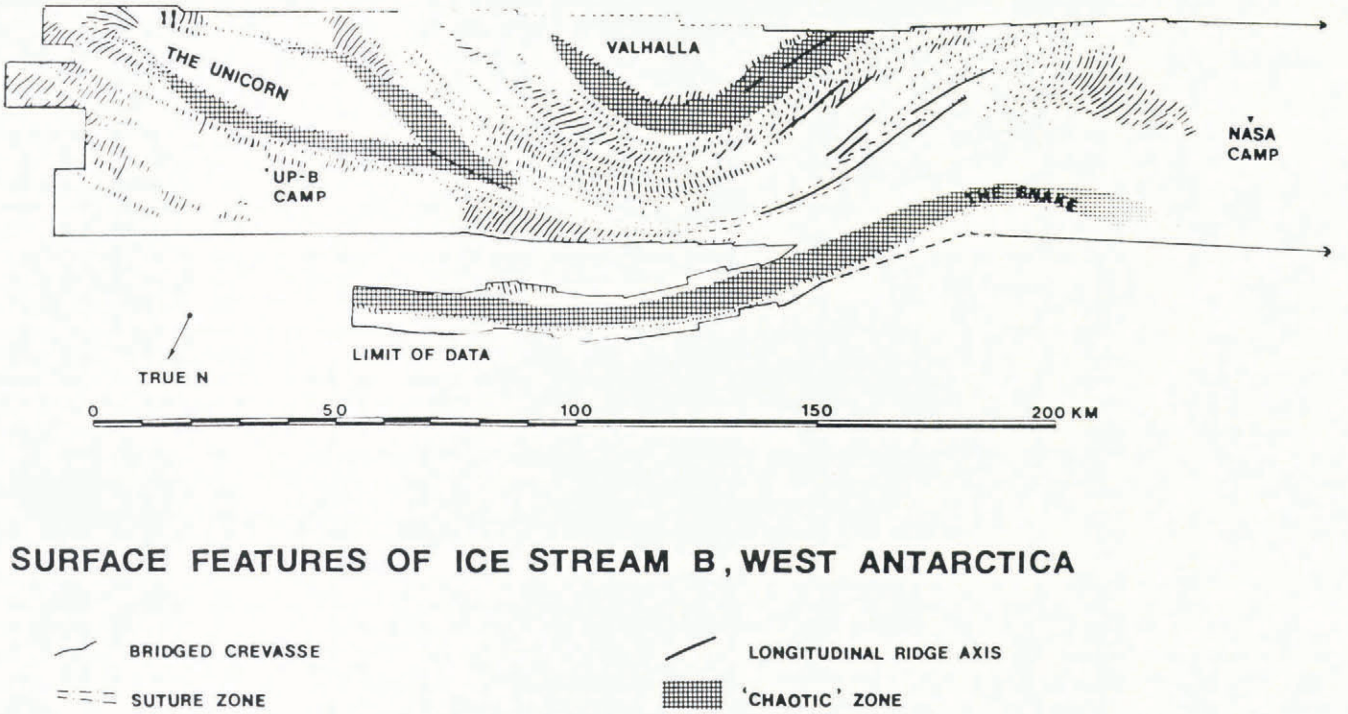


Fig.2. Reduced and simplified version of the original surface features map, based on aerial photography of Ice Stream B. Ice flow is from east to west (left to right).

the south tributary. The resolution of the bed topographic map (Drewry 1983) is not adequate to determine if there are basal features associated with the crevasse bands. The crevasse bands do not intersect.

Crevasses within a band are usually parallel to each other and are transverse to flow. The longitudinal strain rate in the south tributary, calculated from changes in crevasse spacing within a band, assuming ice velocity to be 450 m $a^{-1}$, ranges from .026 $a^{-1}$ to .038 $a^{-1}$ (with .002 $a^{-1}$ uncertainty). This is much larger than the value of principal strain rate causing crevassing (.01 $a^{-1}$ or less). Uncertainties in identifying the crevasse margins have not allowed us to determine how much of the strain is accomodated by stretching of the inter-crevasse blocks, leading to increasing crevasse spacing, or by crevasse widening.

The bend in Ice Stream B occurs at its narrowest part. The ice thickness there is also somewhat less than elsewhere. In order to satisfy conservation of mass, the ice speed at the bend must be higher than that up-glacier and the ice must accelerate. The correspondingly larger stretching stress may explain why this is an area of greater crevasse density.

The bands gradually disappear down-glacier, perhaps due to burial by snowdrift. As the ice flows past the constriction, the strain rate decreases and conditions become more conductive to snow bridge formation and maintenance. Eventually the crevasses are buried.

3. Ice-stream margins

The margins of Ice Stream B are prominent features in the aerial photographs. The outermost part of each margin is a simple set of curved crevasses. Immediately inward of this is the "chaotic zone", where intersecting crevasses dissect the surface and impart a block appearance. The northern chaotic zone varies in width from 1 km, near the Up-B camp, to 6 km, on the Ross Ice Shelf. The chaotic zones around the "unicorn" (Figure 2) is 1 to 3 km wide, up-glacier of their convergence.

The irregularity of the surface in the chaotic zones induces snowdrifts which complicate the surface appearance and we have not been able to detect a pattern in crevasse orientation. Presumably, the major shearing between ice stream and ridge occurs within the chaotic zones.

4. Suture zone

The "suture zone" is a prominent positive relief feature, originating at the convergence of the north and south ice tributaries. It continues down-glacier but decreases in amplitude. At the convergence, it consists of two parallel longitudinal ridges separated by a trough. This feature widens from .5 km at the convergence to 1 km at 60 km down-flow, where the ice stream narrows.

The suture zone may be the amalgamation of two chaotic zones. Its positive relief may exist because it is composed of low density material, seracs and partially snow-filled crevasses, in approximate isostatic balance with the ice around it. Order-of-magnitude calculations indicate that lateral flow off the topographic high can account for the measured spreading.

Down-glacier, the suture zone widens and flattens into several low-lying ridges, many of which exhibit crevasses on their crests. The direction of principal strain given by the orientation of these crevasses indicates that the ice on the southern side of the ridges has a higher velocity than the ice on the northern side. The suture zone may continue to be a zone of shear weakness in the ice stream.

5. Longitudinal ridges

A number of parallel longitudinal surface ridges occur in the lower one-third of Ice Stream B. Unlike those in the suture zone, these ridges begin and end gradually and are 10 to 15 km long. Those which are located near the center of the ice stream might be related to the suture zone. Most of the ridges, however, occur south of the suture zone and one even occurs in the southern chaotic zone. The area where longitudinal ridges occur coincides with the area on the bed topographic map (Drewry 1983) which contains several large scale bed undulations, so they may be related.

The longitudinal ridges die out where the ice stream widens; perhaps a regime of general lateral extension does not form ridges and ridges from up-glacier are buried or spread out.

STRESSES RESISTING ICE FLOW

Ice moves according to the driving stress (ice density x gravitational acceleration x ice thickness x surface slope), which describes the effect of gravity on the mass of ice.

The driving stress is opposed by resistive stresses, which could be longitudinal tension, longitudinal compression, side drag, or basal drag. The distribution of the surface features on Ice Stream B is used to discuss the relative importance of these resistive stresses.

Longitudinal extension results from the tension exerted on the ice stream by the inland ice. The surface expression of this is the transverse orientation of crevasses near the upper end of Ice Stream B. The length of crevasses (up to 10 km) is much greater than the ice thickness (1 km), and may indicate that the extension is transversely fairly uniform. Using the flow law for ice and a flow-law constant appropriate for $-25\,^{\circ}C$ (Paterson 1981), the deviatoric stretching stress implied by the observed strain rate is 2.2 bar, and the full longitudinal tension is 3.3. bar. This stress is sufficient to balance the driving stress (0.2 bar) over 16.5 km of the ice stream (assuming that the tension does not vary with depth and that no additional deviatoric stresses act on this section of the ice stream). This is a small fraction of the whole ice stream, but, locally, tension from the inland ice can be significant and may be an important restraint on ice stream flow.

Basal drag is another possible resistance to the driving stress. The bed surface under Ice Stream B is relatively flat and smooth (Drewry 1983) and the ice is probably moving mainly by basal sliding (Rose 1979). A mean basal drag of 0.2 bar would support the driving stress of the ice stream. The surface crevasses are long and straight, which may indicate that basal drag is fairly uniform across the ice stream's width and along its length. The crevasse bands and longitudinal ridges are the only indications that basal drag may be variable.

The ice stream margins are prominent features in the aerial photographs, so side stress must resist some of the driving stress. If the driving stress (about 0.2 bar) were entirely resisted by side drag, the side drag would be about 5 bar. Using Glen's flow law for ice at $-25\,^{\circ}C$, the shear strain rate resulting from this side drag would be $.005\ a^{-1}$. Shear and gradients in shear would cause crevasse rotation and bending, respectively, from an originally straight configuration. Long, straight, transverse crevasses are, however, found in most parts of the ice stream adjacent to the chaotic zones. Especially in the north tributary, they remain so for a considerable distance down-glacier. This suggests that the shearing and shear stress are confined to the chaotic zones. In the south tributary ice near the bend in the ice stream, however, some shear exists inward of the chaotic zone. Assuming that crevasse bands indicate flow lines, and measuring crevasse rotation relative to the edges of these bands, it can be seen that rotation varies across the ice stream at that bend. Rotation is zero near the suture zone and across most of the width. Within 6.25 km of the chaotic zone, it increases to approximate $1.5^{\circ}$ per km of travel, which corresponds to a shear strain rate of $.008\ a^{-1}$. No bending is observed. This suggests that in this special area there is an important side-shear stress, but it is restricted to ice close to the chaotic zone. In general, and in contrast to the conclusions of McIntyre (1985), it appears that side drag is not a dominant restraint on driving stress.

Longitudinal compression on Ice Stream B is due to the back pressure of the Ross Ice Shelf, because this ice shelf is confined by islands and by the margin of the Ross Sea embayment. Near the down-glacier end, the orientation of crevasses changes from transverse to diagonal, with respect to ice flow. If crevasses are oriented perpendicular to the direction of principal extension, then these crevasses indicate divergence of ice. This divergence could be due to lateral spreading as the ice stream begins to float and form the ice shelf and it is the approximate area in which the ice stream to ice shelf transition is expected to occur. Lateral divergence could also be caused by flow around an ice rise. The effects of the ice shelf are, however, restricted to the lower reaches of the ice stream, with longitudinal extensional flow dominating the remainder. Thus, back pressure from the ice shelf does not seem to be the major component of the overall stress balance of the ice stream.

## CONCLUSIONS

A map of the surface features of Ice Stream B in West Antarctica has been drawn, based on aerial photography. A number of different features can be identified. They are snowdrifts, crevasses, crevasse bands, a chaotic zone, the ice stream margins, the suture zone, and longitudinal ridges.

The surface features of Ice Stream B are used to assess qualitatively the importance of longitudinal tension, longitudinal compression, side drag, and basal drag in resisting the ice flow. Longitudinal tension is important, as indicated by the length and transverse orientation of most of the crevasses, and by stress calculated from measured changes in crevasse spacing. Longitudinal compression caused by the back pressure of the Ross Ice Shelf is probably important only near the down-glacier end of the ice stream. The absence of measurable crevasse rotation in most places indicates that side shear stress is not important, except within the chaotic zones. Finally, the relatively simple crevasse patterns suggest that basal drag may be uniform, except at the origin of crevasse bands and at longitudinal ridges. We plan to measure the velocity field on and near the ice stream and so test these inferences as to where the major resistances to flow are located.

## ACKNOWLEDGEMENTS

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