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Relict flow stripes on the Ross Ice Shelf

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ABSTRACT. Analysis of AVHRR data collected during the summer and winter over the Ross Ice Shelf reveals complex patterns of curvilinear stripes. In particular, a large, looping pattern of stripes is observed west of Crary Ice Rise in an area where conventional glaciological data collected with surface and airborne methods have been interpreted to suggest uncomplicated flow. On the basis of previous work using radar data to study ice flow downstream of Crary Ice Rise, we conclude that the stripes represent relict flowlines. The mechanism that produces these stripes is unclear, but we hypothesize that they are associated with subtle topography. Based solely on the patterns of stripes and their location in the outflow of major ice streams, we propose that they are related to an ice raft torn from the grounded ice sheet about 400 km upstream from its present position.

INTRODUCTION

Long, curvilinear stripes appear on visible, near-infrared and thermal-infrared satellite imagery of polar ice. Depending in part on the wavelength band, the location of the stripes on the ice sheet and the persistence of the stripes over time, authors have associated some of the stripes with either glacial flow (Crabtree and Doake, 1980; Dowdeswell and McIntyre, 1987; Swithinbank and others, 1988), surface temperature and wind fields (Bromwich, in press) or some combination of both. Associating these stripes with glacial dynamic effects has proved particularly problematic, because, although they seem to form at the confluence of tributary glaciers and agree on a coarse scale with modern surface ice velocity fields, they persist for hundreds of kilometers through net accumulation areas. The stripes may be associated with surface topography and, indeed, only small changes in surface slope (less than 5%) are required to register a detectable change in pixel intensity on visible, near-infrared and thermal-infrared Advanced Very High Resolution Radiometer (AVHRR) data. But current theories on ice-sheet and especially ice-shelf flow suggest topographic stripes would suffer monotonically decreasing peak amplitude (relative to adjacent ice), as well as simple burial, in the accumulation region — each mechanism erasing the signature of the stripes. Variable snow textures associated with laterally varying brightness across a flow stripe would also seem to be muted rapidly as the ice traversed through net accumulation zones.

Recent analysis of AVHRR channel 2 and channel 4 data shows that these stripes are present over large portions of the Ross Ice Shelf. Whether or not a satisfying physical explanation of their presence on the imagery is available, we believe that useful glaciologic inferences can be gleaned from the satellite imagery by comparison with ancillary data sets. Specifically, the results derived from conventional glaciological research, starting with the International Geophysical Year, continuing on through the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS; Bentley, 1984) and finally with elements of the Siple Coast Project (Siple Coast Project Steering Committee, 1988), provide one of the more complete pictures of present ice-shelf flow dynamics. We use that information base to discuss temporally persistent curvilinear stripes recorded on AVHRR imagery west of Crary Ice Rise.

DESCRIPTION OF THE DATA

Satellite imagery provides an excellent opportunity to study the large-scale features of ice sheets and ice shelves. High-resolution visible imagery such as Landsat TM (28.5 m resolution) or SPOT HRV (10 m resolution) is extremely useful for identifying patterns of crevassing and

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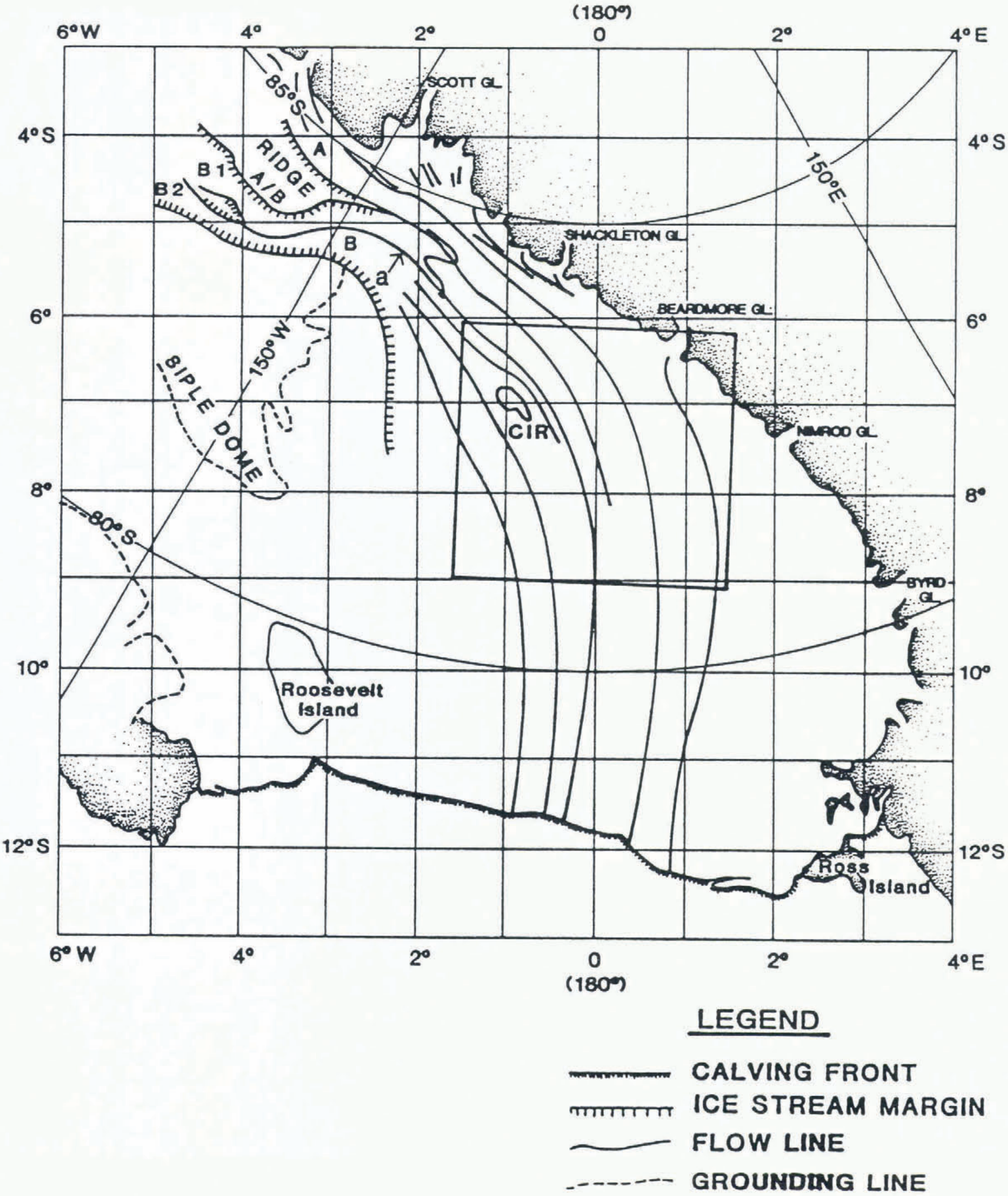

Fig. 1. Map of the Ross Embayment showing the position of Crary Ice Rise, several flowlines derived from ancillary data and the location of the two AVHRR images. Ice raft a is indicated by "a".

the orientation of individual crevasses. These data are limited by the 85 degree poleward extent, individual scene dimensions (185 km for Landsat; 60 km for SPOT) and high cost. AVHRR data collected from instruments on National Oceanic and Atmospheric Administration (NOAA) weather satellites complement these other sensors with wide swath (2400 km) but much coarser resolution (1.1 km maximum). AVHRR has ten-bit radiometric resolution ($\sim$0.1 K), which means that even subtle variations in topography or emissivity can be detected.

Channel 2 and Channel 4 (0.72 – 1.10 μm and 10.5 – 11.5 μm) AVHRR acquired in December 1987 (summer) and July 1988 (winter) over Crary Ice Rise (Fig. 1) are shown in Figure 2. Crary Ice Rise is located in the southeastern portion of the Ross Ice Shelf. The ice rise is known to be part of a peninsula of mostly grounded ice jutting into the freely floating ice portion of the shelf (Bindschadler and others, 1988). Ice rises are believed important because of the stabilizing effect they are presumed to have on the interior ice sheet (Thomas, 1979).

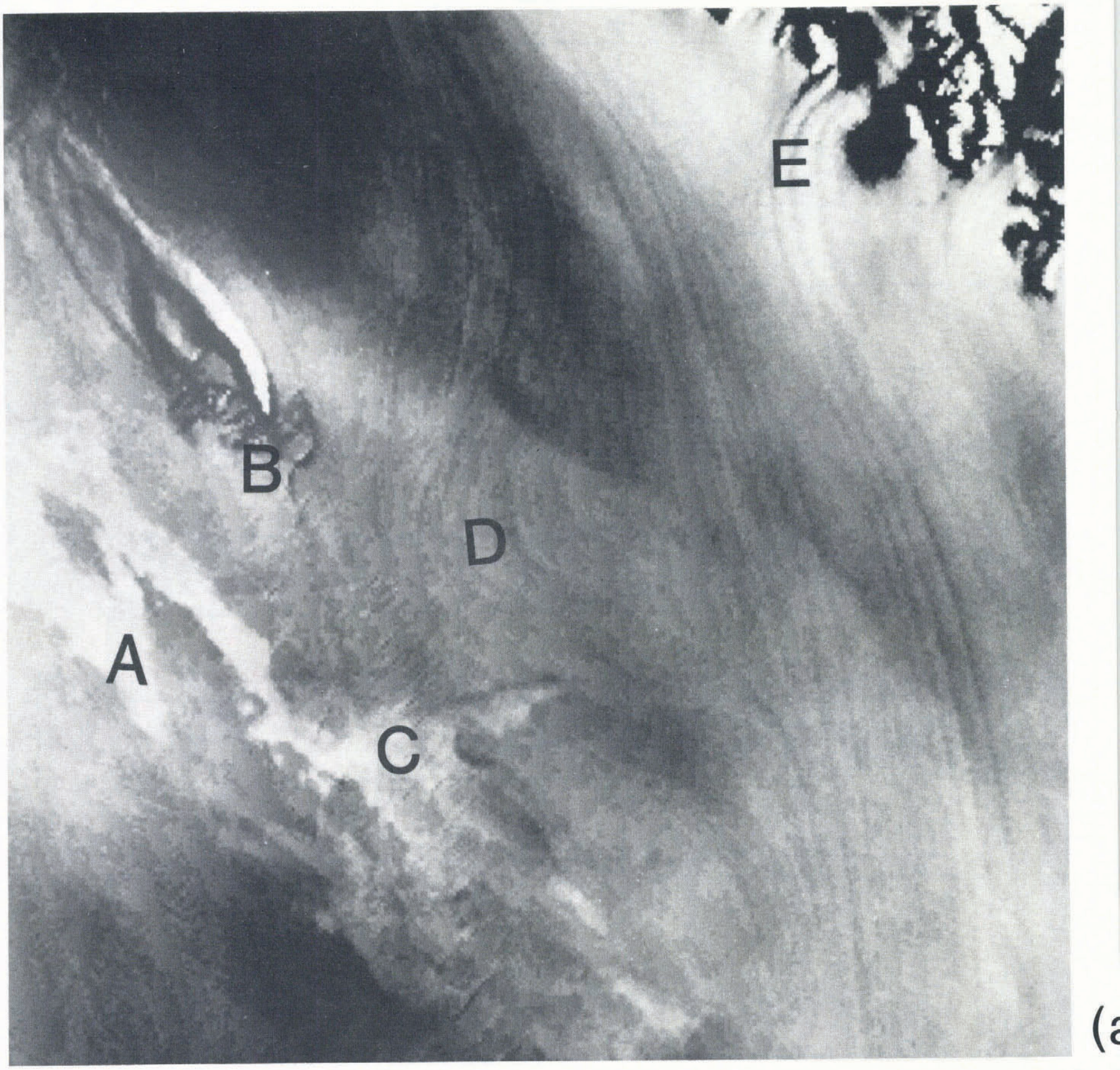

Fig. 2. AVHRR images of the location shown in Figure 1. North is toward the bottom. Fig. 2a: Band 2, near-infrared, summer; Fig. 2b: Band 4, thermal-infrared, winter. Warmer areas appear dark in the thermal-infrared image. Area A: irregular brightness pattern which may be due to snow type; B: rifts; C: en échelon pattern of linear segments; D: relict flow stripes; E: flow stripes originating from Beardmore Glacier; F: thermal plume. The jagged bands of varying brightness in Fig. 2a are due to image enhancement.

The image reveals different snow types as well as ice rifts. The snow types are evident as irregular brightness patterns over much of the image (area A, Fig. 2a) (Orheim and Lucchitta, 1988). Large rifts are located just down-glacier of the ice rise (area B, Fig. 2a) and penetrate the entire thickness of the ice shelf (Neal, 1979; Jezek, 1984).

An *en échelon* pattern of linear segments first appears about 60 km downstream of the ice rise (area C, Fig. 2a). It is well known that rifts form at the margin of Crary Ice Rise and the *en échelon* segments may be a sequence of rifts carried downstream with the flow of the ice shelf. However, the 60 km gap between the last detectable linear segment and the margin of the ice rise would, in this model, suggest that the rifting process terminated about 200 years ago. A second explanation of these linear segments is that they are not necessarily associated with the rifts at Crary Ice Rise, but are sags or dolines in the ice shelf, associated with active bottom crevasses (Jezek, 1980). According to this model, the crevasses form near the ice rise, but there is a lag between ice fracture and the development of a surface topographic distortion suffi-

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(b)

Fig. 2. (continued).

ciently large to be detected on AVHRR imagery. Either model can account for the *en échelon* pattern being generally parallel to the ice flow (measured by Thomas and others, 1984).

A series of strongly curved stripes appears west of the ice rise (area D, Fig. 2a). Continuous stripes also originate at the mouths of the major East Antarctic outlet glaciers seen in the image (area E, Fig. 2a). Stripes near Crary Ice Rise and those originating at the mouths of outlet glaciers are persistent on both the summer and winter images. This suggests that they are related to long-term glaciologic rather than short-term meteorologic processes.

Thermal-infrared imagery of the outlet glaciers (Fig. 2b) shows strong evidence for katabatic air flow down-glacier. These katabatic signatures are known as thermal plumes because of their larger brightness temperature (recorded as dark pixels on the image) compared to the surrounding ice. They were first discovered by Swithinbank (1973) and have been extensively studied by Bromwich (1989). Note that the thermal plumes (area F, Fig. 2b) cut across the stripes. This further supports a glaciologic interpretation for the origin of the stripes.

Curved stripes disappear on the AVHRR images upstream of Crary Ice Rise, but they have been observed on SPOT imagery of the area (personal communication from R.A. Bindschadler). It thus seems that there are more stripes than can be observed with the AVHRR sensor.

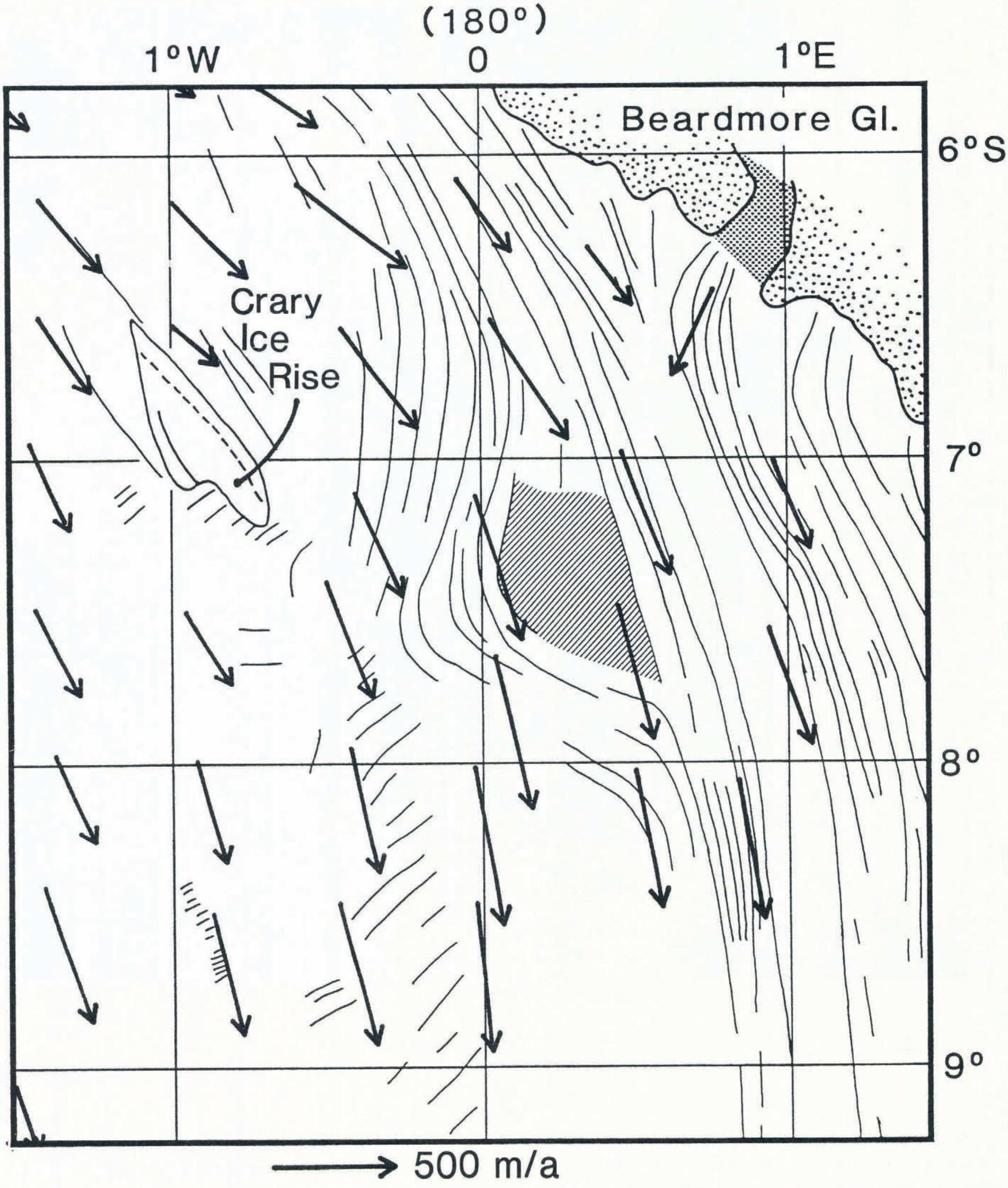

Fig. 3. Sketch map of the features identified in Figure 2. The hatched area bounded by curvilinear flow stripes is interpreted to be an ice raft. Arrows indicate ice velocity measured by RIGGS (Thomas and others, 1984).

DISCUSSION

We refer to the curved stripes as flow stripes because they seem to be flow features. They are not necessarily flowlines or streamlines. Indeed, flow stripes west of Crary Ice Rise do not correspond to present flowlines based on RIGGS velocities. The boundaries of the *en échelon* pattern follow the general ice-shelf flow direction (Fig. 3). Interpreting the stripes to the west of Crary Ice Rise as additional flowlines leads to unreasonable balance velocities and shear stresses. The lack of surface crevasses or rifts near the curved stripes also argues against strong shear stresses in the area of the stripes. Instead, we propose that these curved stripes are relict flow features. The features were formed in or near grounded ice.

One possibility is that the curved stripes correspond to an ice raft, a concept introduced by Whillans and others (1987). Ice rafts are ice bodies torn from an inland region during the activation phase of an ice stream. The extent of the proposed ice raft is indicated with a diagonally hatched pattern in Figure 3. As with ice rafts formed similarly but on the flanks of Crary Ice Rise (Jezek, 1984; Bindschadler and others, 1988), the grounded ice decoupled from the bed and was carried downstream. Such an interpretation is qualitatively supported by the flow patterns around the feature called ice rise "a" (Fig. 1), which is in fact an ice raft now moving down the flow field at velocities nearly the same as the surrounding ice (Bindschadler and others, 1987).

Another possibility is that the curved stripes were formed by differential variations in ice-stream discharge. If a tributary increases its flow, then the seam or suture line between both ice bodies is displaced. MacAyeal (1989) has modelled such events for the Ross Ice Shelf. Similar folded moraines have been frequently observed on valley glaciers, where they are linked to glacial surges (Post and LaChapelle, 1971; Voigt, 1965). However, the region shown hatched in Figure 3 lacks flow stripes. This points to an origin not in an ice stream or outlet glacier, but on an inter-stream ridge. This lack of flow stripes within the feature favors its interpretation as a raft, rather than as folding due to changes in ice-stream discharge.

Accepting the ice-raft hypothesis, we can infer the approximate point of origin of the strongly curved stripes by tracing back along a flowline deduced from measured velocity vectors. This leads to Ridge A/B (Fig. 1) as being the likely source for the raft. Integrating the reciprocal of the velocity field along the flowline, we find that the ice raft was entrained into the fast-flowing parts of the glacier about 800 years ago. Flow may have been different in the recent past, so this is a crude estimate.

The stripes seem to be surface-topographic features. We can offer two hypotheses for their genesis. Firstly, we note that flow stripes seem to originate where two ice tributaries converge. They may be formed of highly crevassed ice associated with shear margins. With time, the crevassed ice is buried and filled with snow which makes that ice less dense than otherwise. By isostasy, the originally crevassed ice stands topographically higher. An alternative suggestion is that ice composing the stripes is mechanically weaker than adjacent ice. Under lateral compression at the convergence of tributary glaciers, the weaker ice is preferentially squeezed into narrower and thicker segments. The laterally compressive regime of the Ross Ice Shelf (Thomas and others, 1984) maintains the features. The data are not adequate to discriminate between these two hypotheses.

SUMMARY

Satellite imagery is proving extremely valuable to ice-sheet glaciology. Even the sensor discussed here, which is designed for coarse-resolution meteorological purposes, has great glaciological utility. It is used here to map flow stripes on the Ross Ice Shelf. It appears that these flow stripes are not flowlines, but record a change in ice flow that occurred about 800 years ago. This ice-flow change was probably the break-off of a raft of inland ice. Previous authors have recognized related features and some were shown not to be flowlines (Bentley and others, 1979; Jezek, 1984). Analysis of these features can reveal a rich history of flow variations. That history can help in understanding how the ice-shelf–ice-stream system changed in the recent past.

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