

ICE-THICKNESS PATTERNS AND THE DYNAMICS OF THE ROSS ICE SHELF, ANTARCTICA*

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ABSTRACT. As part of the Ross Ice Shelf Geophysical and Glaciological Survey, a detailed map of ice thickness has been produced from airborne radar measurements closely tied to the network of survey stations on the ice-shelf surface. The map, drawn with a 20 m contour interval, reveals a highly complex pattern of thickness variations reflecting presumably, at least in part, complex ice-shelf dynamics. Many features of the thickness variation pattern appear to be associated with zones of grounded ice, but not all. Features of interest include many ice thickness minima, with closures up to 120 m; a narrow, greatly elongated ridge-trough system 450 km or more in length; a few ice thickness maxima; steep regional gradients of 10 m/km in freely floating ice; highly contorted contours suggesting a large-scale "turbulence"; and at least two remarkable step-like changes in ice thickness. The irregularity of many of these features suggests dynamic non-equilibrium, i.e. the existence of transients in the dynamic system, so that the ice shelf as a whole suggests a state of rather rapid change. Flow-bands constructed on the basis of the strengths of the echo from the ice-water interface clearly delineate the outflow from the main East Antarctic outlet glaciers in the grid eastern part of the shelf. A discontinuous flow band originating in a small mountain glacier (Robb Glacier) suggests a variable mesoclimate in the vicinity of the glacier within the last thousand years. Strong reflections near the ice front suggest bottom melting of saline ice previously frozen on to the underside of the ice. Several rifts or incipient rifts in the ice shelf characteristically show two lateral bands of strong reflections with a non-reflecting zone in between.

RÉSUMÉ. La répartition des épaisseurs de glace et la dynamique du Ross Ice Shelf, Antarctique. Comme une participation à Ross Ice Shelf Geophysical and Glaciological Survey, une carte détaillée de l'épaisseur de la glace a été établie par mesures aériennes au radar, en liaison étroite avec le réseau des stations d'observations sur la couverture de glace elle-même. Dessinée avec des courbes de niveau équidistantes de 20 m, la carte révèle un dessin très compliqué des variations d'épaisseur de la glace, qui reflète probablement au moins en partie, la complexité de la dynamique de la couverture de glace. Beaucoup de caractéristiques du dessin des variations d'épaisseur de glace paraissent associées avec des zones de glaces de terre mais pas toutes. Les caractéristiques intéressantes comportent beaucoup de minimum d'épaisseur de glace qui vont jusqu'à 120 m; un système étroit et très allongé de rides et de creux de 450 km et plus de longueur; un petit nombre de maximum d'épaisseur de glace; un gradient régional élevé de 10 m/km dans la glace flottant librement; des lignes de niveau très sinucuses suggérant une "turbulence" à grande échelle; et au moins deux remarquables changements en marche d'escalier de l'épaisseur de la glace. L'irrégularité de beaucoup de ces traits suggèrent un déséquilibre dynamique, si bien que la couverture de glace dans son ensemble fait penser à un stade de changement assez rapide. Les zones de courant construites d'après la vigueur des échos reçus de l'interface glace-eau délimitent clairement l'écoulement à partir des principaux glaciers débouchant sur l'Est Antarctique vers la grille de la partie orientale de la couverture de glace. Un courant discontinu originaire d'un petit glacier de montagne (Robb Glacier) fait penser à un climat interne variable dans le voisinage de ce glacier au cours du dernier millier d'années. De fortes réflexions près du front de glace font supposer une fusion au fond de la glace saline autrefois gelée dessous la glace. Plusieurs crevasses ou débuts de crevasses dans la couverture de glace se caractérisent par deux bandes latérales à forte réflexion entourant une zone non réfléchissante.

ZUSAMMENFASSUNG. *Eisdickenverteilung und Dynamik des Ross Ice Shelf, Antarktika.* Als Teil des Ross Ice Shelf, Geophysical and Glaciological Survey wurde aus Radarmessungen aus der Luft, die eng mit dem Netz der Vermessungsstationen auf der Schelfeisoberfläche verbunden wurden, eine detaillierte Karte der Eisdicken hergestellt. Die Karte, die mit 20 m-Höhenlinien versehen ist, enthüllt ein höchst komplexes Muster von Dicken Schwankungen, die zumindest teilweise eine komplexe Schelfeisdynamik widerspiegeln. Viele Erscheinungen des Dickenmusters, jedoch nicht alle, scheinen mit Zonen aufsitzenenden Eises verbunden zu

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sein. Interessante Erscheinungen sind unter anderem: Dickenminima mit Grenzen bis zu 120 m; ein enges, weitgehend verlängertes Rücken- und Trogsystem von 450 oder mehr km Länge, einige wenige Dickenmaxima; steile regionale Neigungen von 10 m/km in frei schwimmendem Eis; höchst gewundene Höhenlinien, die auf eine grossflächige "Turbulenz" hindeuten; letztlich zwei bemerkenswerte sprunghafte Wechsel in der Eisdicke. Die Unregelmässigkeit vieler dieser Erscheinungen lassen ein dynamisches Ungleichgewicht vermuten, d.h. das Vorhandensein von Übergangsstadien im dynamischen System, die das gesamte Schelfeis in einem Zustand sehr raschen Wechsels erscheinen lassen. Strombänder, konstruiert auf der Basis der Echostärke von der Grenzfläche zwischen Eis und Wasser, zeichnen klar den Zustrom über die Ausflussgletscher aus der Ostantarktis in der Osthälfte des Schelfeises nach. Die diskontinuierliches Stromband, das von einem kleinen Gebirgsgletscher (Robb Glacier) ausgeht, lässt ein veränderliches Mesoklima in der Umgebung des Gletschers während der letzten 1 000 Jahre vermuten. Starke Reflexionen nahe der Eisfront deuten auf das Abschmelzen salzhaltigen Eises an der Unterseite, das vorher dort aufgefroren war. Einige Risse oder beginnende Risse im Schelfeis zeigen sich charakteristisch als zwei benachbarte Bänder mit starker Reflexion, getrennt durch eine reflexionslose Zone.

INTRODUCTION

During the years 1973–78, an extensive geophysical and glaciological survey was carried out over the Ross Ice Shelf in Antarctica. This survey, known as RIGGS (Ross Ice Shelf Geophysical and Glaciological Survey) included: ice thickness, water depth, gravity, seismic, electrical, and electromagnetic measurements by the University of Wisconsin; strain measurements and, in conjunction with the U.S. Geological Survey, measurements of absolute motion of the ice shelf by the University of Maine; and, near-surface snow sampling by SUNY–Buffalo, the Desert Research Institute of the University of Nevada, and the University of Copenhagen. We report here the ice-thickness measurements.

INSTRUMENTATION

The measurement of ice thickness was carried out by radar sounding partly on the snow surface but primarily from a Twin Otter aircraft. The radar system used for all the airborne work was a 35 MHz SPRI system very kindly lent to us by S. J. Jones of Environment Canada. Echograms were produced by recording, on "Polaroid" photographic film, an intensity-modulated display of the signal received on an oscilloscope. The horizontal trace was gradually moved vertically across the oscilloscope face, thus providing a continuous record of reflections from both the surface and the base of the ice shelf. The antennae were folded dipoles fixed under, and parallel to, the wings of the Twin Otter, with the transmitting antenna on one wing and the receiving antenna on the other. This arrangement was designed and installed during the first season of the RIGGS survey by one of the authors (J.W.C.) in cooperation with the crew of the Twin Otter aircraft operated by Bradley Air Services, Ltd. The flights were carried out at a height of about 1 500 m above the surface.

DATA REDUCTION

The ice-thickness map (Fig. 1) was drawn primarily on the basis of the RIGGS data. Some use was made, for the clarification of ambiguities and an extension of the contours, of the maps presented by Robin (1975) and Crary and others (1962), the latter being based on seismic data. Those measurements were not integrated generally into the map presented here, in the case of Robin (1975) because the navigational quality of the flights was relatively poor (no inertial navigation system was available at that time), and, in the case of Crary and others (1962) because of the scattered correlation, with differences up to 50 m, between seismic and radar thickness values (Robertson, unpublished). Since we believe that the erratic correlation is largely attributable to uncertainties in seismic reflection times and wave velocities, rather than to uncertainties in the radar technique, we do not believe that errors using radar data alone approach 50 m. No attempt has yet been made to combine these data with those collected as part of the National Science Foundation–Scott Polar Research Institute–Technical University of Denmark program of radio echo-sounding from C-130 aircraft; this will be done in the future.

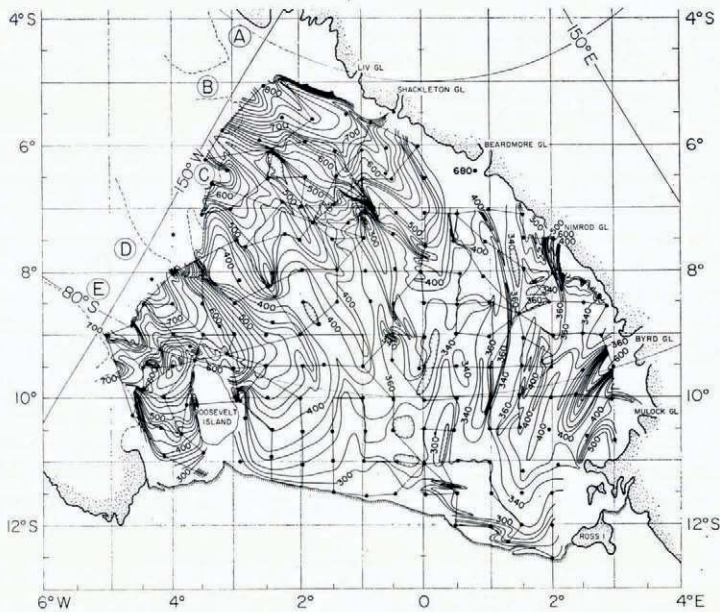


Fig. 1. Map of the Ross Ice Shelf thickness. Dots denote surface stations; thin straight line segments indicate flight paths. Marginal numbers are grid coordinates, with the Greenwich meridian as grid long. 0° , and the South Pole at grid lat. 0° . The contour interval is 20 m. Even 100 m contour lines are marked; also the 340 m and 360 m contour lines in the grid eastern portion of the ice shelf.

Since radar-sounding flights were frequently tied to previously occupied surface stations, and were repeatedly closed to RIGGS base stations, we believe the navigational control on our data is sufficiently tight to permit the detailed correlation of relatively small changes in ice thickness between flight lines. The positional accuracies are generally better than five kilometers (about the width of a station dot in Fig. 1). The error in ice-thickness determination depends upon the travel-time resolution ($\pm 0.05 \mu\text{s}$) and the accuracy of the wave velocity assumed. Although wave velocities may vary across the ice shelf (Jezek and others, 1978) a constant velocity of $173 \text{ m } \mu\text{s}^{-1}$ was chosen to reduce the data. The combination of travel-time and wave-velocity uncertainties results in an estimated error in ice thickness of $\pm 10 \text{ m}$ for relative measurements and $\pm 20 \text{ m}$ for absolute values. This means that virtually all of the features shown on the map (Fig. 1) are probably real, particularly where they are represented by more than one contour line, although the details of the shapes of the features are often quite poorly determined where they lie between flight lines. The contour interval on the map is 20 m.

DISCUSSION

Ice-thickness map

The map is presented without detailed interpretation. More detailed consideration of various aspects of this map will be given by the authors (and, we hope, by others also) in the future; here we only point out some of the characteristics of interest.

The first thing that strikes the observer about the ice-thickness map is its general complexity. The Ross Ice Shelf is anything but a flat sheet of ice. This fact, of course, was already known in a general way from previously published maps (Bentley and others, 1974; Clough

and Robertson, 1975; Robin, 1975) but is shown much more dramatically with the 20 m contour interval used here. We believe that this complicated pattern of ice thickness reflects complicated dynamics of the ice shelf. It is notable that the complications are not associated solely with points of grounding, such as Roosevelt Island and Crary Ice Rise (7° S., 1° W. grid), although the largest disturbances are found there.

The lobes of thicker ice associated with the glaciers and ice streams show very clearly. The largest ice-stream lobes are those at the top of the map and grid north and east of Roosevelt Island, coming from ice streams B and D, respectively. The most prominent glacier lobes shown are those associated with Nimrod and (especially) Byrd Glaciers; presumably lobes associated with Beardmore Glacier, and others, would also appear if our data coverage were better. These major lobes are already well known from the earlier maps cited above.

Many closed ice-thickness minima appear on the map. The one with the greatest amplitude is grid south of Crary Ice Rise and shows a closure of 120 m. This is clearly the result of the ice flow around the obstacle provided by the ice rise. The next largest minimum (closure, 80 m), however, is up-stream of Roosevelt Island, centered at about $9^{\circ} 18'$ S., 4° W. The map of the sea-floor topography in this area (Clough and Robertson, 1975; Robertson and others, in press) shows clearly that the ice-thickness minimum lies over a trench and cannot be explained by any up-stream grounding. It is apparently produced in some way by the combination of the zone of thinner ice lying between ice streams D and E and the effect of Roosevelt Island.

Another minimum (closure, 50 m) occurs out in the middle of the ice shelf (9° S., $0^{\circ} 30'$ W.) with no apparent cause. The shape of this minimum is not well determined, but its existence is certain through correlation between two closely-spaced flight lines.

Smaller minima, generally rather elongated in shape, exist in numerous places, many of them, rather surprisingly, lying in the open regions of the central and grid eastern parts of the shelf. A series of minima is found along grid long. 0° , suggesting an association with the convergence of ice flow lines stemming from opposite sides of Crary Ice Rise.

A striking ridge-trough system follows a flow line for at least 450 km from near the grid western edge of the mouth of Beardmore Glacier, and probably for another 100 km to cross the flight line along 11° S., just grid west of 1° E. (the latter correlation was not recognized at the time the contours in Fig. 1 were drawn). Flow lines are discussed further below. This feature shows variations in cross-sectional shape that we believe are due to a combination of smoothing by spreading, melting and freezing at the ice-water interface, and real differences in the initial shape of the feature when it formed at or near the glacier mouth. The preservation of this feature with little change in amplitude across almost the entire ice shelf is remarkable.

There are also a few ice-thickness maxima and "ridges", although they are less numerous and less pronounced than the minima. Two such enclosed maxima can be seen at 10° S., 2° E., and 10° S., 1.5° E. Another lies just to the grid north of Roosevelt Island. (The maximum at 8° S., 2.5° W. corresponds to an actual grounding of the ice sheet just up-stream of the region known as "Steershead Crevasses".) A long ridge, or nose, extends grid north-westward from about 9° S., 1° W.—it may or may not show a small closure. Another feature of interest is the strong gradient in ice thickness over deep water at 5° S., 2° W.; here again the cause cannot be directly related to grounding of the ice.

At least two rather remarkable "steps" appear at 9.5° S., 0° , and 30 km to the grid north. The characteristic appearance of these features can be seen in the photograph of the continuous sounding record (Fig. 2) in places indicated by the arrows. The direction of flight corresponding to Figure 2 was grid southward from the left edge of the figure to the dotted vertical line ("T.P."), then grid eastward. The two "steps" lie close to the same flow line, and, indeed, are interpreted by us (Fig. 3) as probably lying on the same flow line. If this is so, however, then the grid east side of the common feature formed by these two steps is up in one

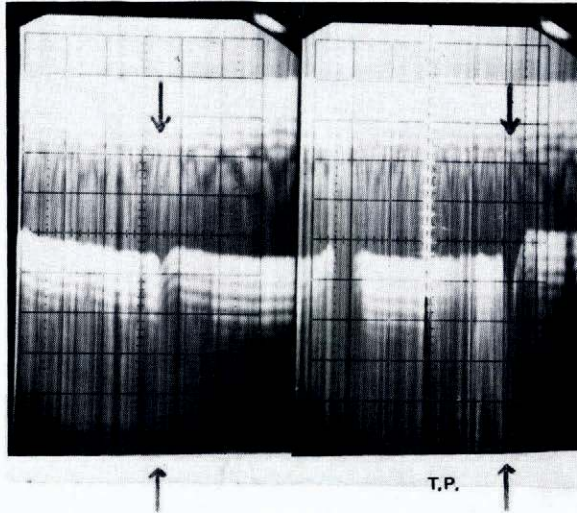


Fig. 2. Echogram along a flight segment running from about $9^{\circ} 6' S.$, 0° to the turning point at $9^{\circ} 36' S.$, $0^{\circ} 6' W.$ (T.P.) to $9^{\circ} 36' S.$, $0^{\circ} 12' E.$ The reflection from the bottom of the ice shelf is shown by the white band just below the center of the figure. The grid-line interval represents $1 \mu s$ of travel time vertically, and about 4 km horizontally. The "step-like" feature discussed in the text is indicated by arrows. A typical non-reflecting zone appears two grid intervals to the left of "T.P."

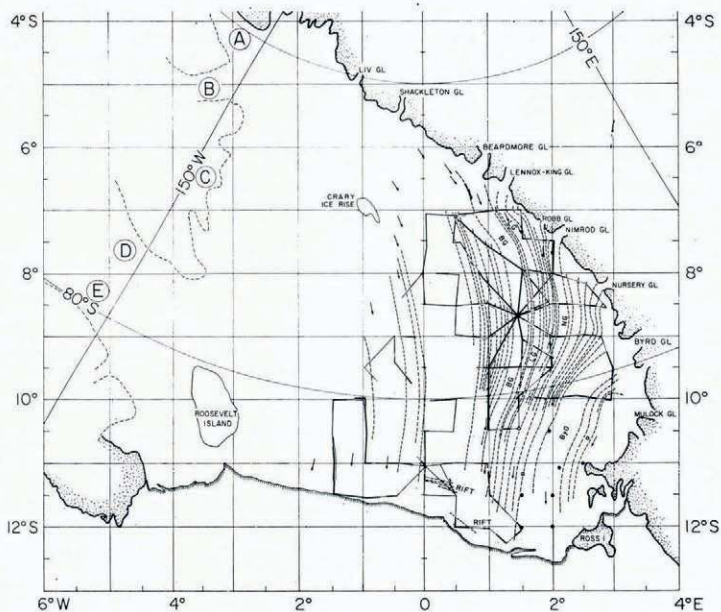


Fig. 3. Flow-line map. The strength of the echo along each flight track is indicated by the thickness of the corresponding line segment. There are actually four different line thicknesses, but the primary information is in the locational contrast between the thickest lines and all the others. Where the flight lines are absent (cf. Fig. 1) the data were too poor for echo-strength analysis. Short thick (thin) dashes next to the flight lines denote short, strongly reflecting (non-reflecting) zones within regions showing primarily the opposite characteristic. Black dots solid and open circles denote strong and weak echos, respectively, at surface stations. The ice bands from the major outlet glaciers are indicated by: BG (Beardmore Glacier), LG (Lennox-King Glacier), NG (Nimrod Glacier), and ByG (Byrd Glacier). Measured directions of ice movement are shown by arrows.

case and down in the other, giving a very peculiar "scissors" shape to the combined feature. If, on the other hand, they lie on separate but adjacent flow lines, as would be indicated by the map constructed by Neal (1979), then these "steps" represent a step-wise thinning in the ice shelf from grid west to east.

Abrupt changes in ice thickness appear in several places close to grounding lines. Troughs appear on both sides of Roosevelt Island (the separation of the trough on the grid east side from the grounding line may be attributable to a poor delineation of the island). Less well-defined troughs also appear on both sides of the grounding line nose around 8° S., $3^{\circ} 30'$ W. On the other hand, a very prominent ridge lies along the north-east side of Crary Ice Rise. The ridge is notable in that it is not centered over, or up-stream of, the grounded ice, but in the floating ice just alongside the ice rise.

Flow-line map

Following the suggestion of C. S. Neal, we have correlated regions of good, poor, and intermediate reflection strengths from the oscilloscope photographs and have associated these with flow lines grid east of a line approximately along longitude $0^{\circ} 30'$ E. (Fig. 3). To the west such correlation has not yet proven possible owing to the absence of clearly defined bands in the ice flowing from West Antarctica. The few flow lines shown in Figure 3, west of 0° grid longitude, are based on actual measurements of ice movement (Dorrer and others, 1969; Thomas, 1976) and the correlation of a few specific features (e.g. the "steps" discussed below).

It is very clear from the original data that strong reflectors are associated with ice flowing out of the main outlet glaciers in the grid eastern part of the ice shelf. Particularly prominent are the zones associated with Beardmore, Nimrod, and Byrd Glaciers. Lennox-King Glacier also produces a continuous strong reflector. The direction of the flow lines has been interpreted not only from the zonation in the ice but also from actual measurements (Swithinbank, 1963; Dorrer and others, 1969; Thomas, 1976; personal communication from G. de Q. Robin and C. W. M. Swithinbank).

The main features of this flow-line map agree closely with those of the map presented by Neal (1979). Neal (1979) has carried out a quantitative analysis of the reflection strengths and related them to models of ice-shelf structure. We find that our more qualitative observations fully support his conclusions.

Some additional features are shown in Figure 3. There are some strongly reflecting zones which apparently are associated with smaller glaciers along the Transantarctic Mountains that do not drain ice from the main interior plateau. We note in particular a very small "bright" band that appears on the flight track just to the grid west of the mouth of Nimrod Glacier and is clearly associated with Robb Glacier. The bright band can be traced quite well down to 9° S., although varying somewhat in width. From there southward it becomes weaker and narrower, disappearing completely at $9^{\circ} 30'$ S. At 10° S. it reappears, only to disappear again at the next flight crossing. We suggest that the alternate appearance and disappearance of this band of strongly reflecting ice corresponds to a past variation in the activity of Robb Glacier—variations in the mesoclimate could cause a reduction in the flow from Robb Glacier to the point where cracking through the ice and brine infiltration, as is believed to be characteristic of the glacially-inactive regions of the Transantarctic Mountain front (Neal, 1979), could take place. The time scale of these variations would be hundreds of years; the timing can be detailed more accurately when movement rates are available for this part of the ice shelf.

Very strong reflections appear along the track sections within 25 km or so of the ice front. This is particularly striking at 12° S., $0^{\circ} 30'$ E., we interpret this as due to the disappearance by melting of the saline ice frozen onto the underside of the shelf and causing poor reflections farther up-stream (Neal, 1979).

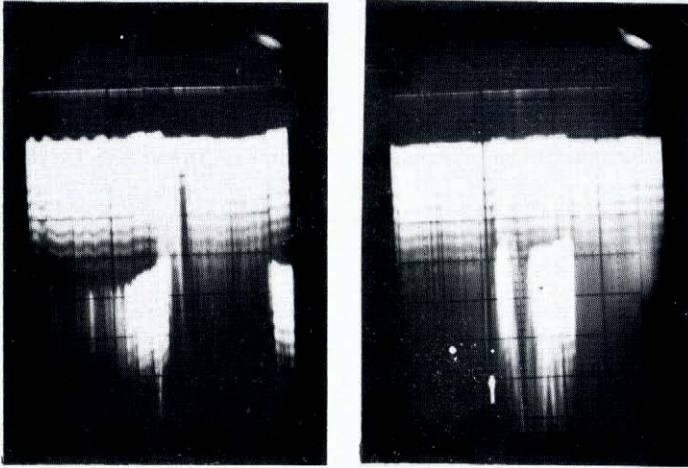


Fig. 4. Echogram across two rifts in the ice shelf. Rifts in the ice shelf, at

a (left). $9^{\circ} 18' S.$, $0^{\circ} 24' E.$

b (right). $12^{\circ} S.$, $1^{\circ} E.$

a runs from east to west (grid); b runs from south-east to north-west (grid).

Several rifts also appear clearly on the reflection records. The most striking is that at about $9^{\circ} 18' S.$, $0^{\circ} 24' E.$ (Fig. 4a), a feature that is clearly seen in the surface of the ice shelf, and has been mapped for a number of years. A smaller unmapped feature that is not visible at the surface appears at $12^{\circ} S.$, $1^{\circ} E.$ (Fig. 4b). These rifts characteristically show two lateral bands of very strong reflection with a non-reflecting zone between.

These results are presented here, even though they are not in the form of a final report, in the hope that they will prove stimulating to glaciologists interested in the Ross Ice Shelf and the surrounding areas.

ACKNOWLEDGEMENTS

Field work and data analysis were supported by National Science Foundation grants OPP72-05802 and DPP76-01415.

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DISCUSSION

C. W. M. SWITHINBANK: We have interpreted similar steps in radio-echo bottom profiles of ice shelves as representing the confluence of streams of ice from discrete sources. Are your steps oriented along a flow line and would you interpret them in the same way?

C. R. BENTLEY: I find that interpretation difficult in this case. The steps appear to lie within the margins of the outflow from ice stream B, although they might possibly occur at the boundary between that ice and the "turbulent" zone down-stream from Crary Ice Rise. Flow lines are not yet well defined in this region; the two steps do lie on a flow line in my interpretation, but in that case they represent opposite displacements: east side up in one case, and west side up in the other. In Neal's flow-line interpretation (Neal, 1979) they do not lie on the same flow line, in which case they represent a double step toward thinner ice from grid west to grid east.

J. G. PAREN: Your radio-echo depths have been calculated using a constant deep-ice velocity. You have suggested earlier that there may be a progressive change of velocity with position on the Ross Ice Shelf. Is there any correlation of velocity with the slight bumps you have found in an otherwise flat ice shelf? Is the velocity variation large enough to affect the map?

BENTLEY: The maximum deviation of our measured velocities from that used in the mapping was about 3%, corresponding to a thickness variation of 10 to 20 m over the ice shelf. That implies that some of the shallowest features could marginally be explained that way, but none defined by more than one contour line.