THE STRUCTURE OF WORDIE ICE SHELF, ANTARCTIC PENINSULA

J. M. Reynolds

Department of Geological Sciences, Plymouth Polytechnic, Drake Circus, Plymouth PL4 8AA, UK

Abstract. The structure of Wordie Ice Shelf has been interpreted from a multispectral Landsat satellite image obtained in February 1979 in conjunction with radio-echo sounding data. The ice-shelf structure is dominated by six major glacier units in which the principal structure is that of longitudinal foliation, which is formed as the glaciers drain from the Palmer Land ice sheet. Although this structure persists to the western ice front, a set of crevasse traces and crevasses is superimposed. The structure is affected further by the presence of 20 ice rises and ice rumples. This combined structure dictates the shapes and sizes of icebergs which calve from the ice shelf. A triangular-shaped zone of chaotic ice with an area of about 52 km² divides the ice shelf into two parts. Should the ice front recede east of Napier Ice Rise in response to the current climatic warming, the southern part of the ice shelf may deteriorate rapidly.

Introduction

Wordie Ice Shelf (Fig. 1) has had three airborne radio-echo sounding surveys undertaken over it in 1966/67, 1969/70 and February 1975 (Swithinbank, 1968; Smith, 1972; Crabtree, 1983). In January 1974 a Landsat multispectral Scanner (MSS) image of the ice shelf was obtained (E-1532-12325-7; 6 January 1974) which was used subsequently to provide the basis of a map of the area at a scale of 1:250000 (Marguerite Bay, Graham Land; BAS 250P, sheet SR 19-20/2, edition 1-DOS 1978). In February 1979 another Landsat MSS image (30335-12253-7) was obtained of the same area, part of which is reproduced as Fig. 2. The later image has provided considerably more detail of the ice shelf than the earlier one, due principally to improvements in the routine image processing of Landsat 3 data compared with that the Landsats 1 and 2.

This paper describes an interpretation of the 1979 satellite image undertaken in conjunction with ice-shelf isopleths determined from the radio-echo sounding. The analytical method follows that employed by Crabtree and Doake (1980) for the Ronne and Filchner ice shelves and, more particularly, that of Reynolds and Hambrey (1988) for George VI Ice Shelf, in which ice structures were inferred from features seen on satellite imagery. It will be demonstrated that not only does the satellite image provide information about the ice shelf itself, but also about the calving of icebergs into Marguerite Bay.

Glacier Flow Units and Structures

The ice shelf had an area of 1060 ± 20 km² in 1979, with an average length of 53 km north–south and width of 20 km east–west. The 81-km long ice front appears to be pinned by Buffer, Napier and Linchpin* ice rises. The ice shelf receives an ice input from local glaciers from Palmer Land across 130 km of the 148 km landward edge of the ice shelf, with some 16 km adjacent to Mount Balfour which does not contribute actively to sustain the ice shelf. Between February 1972 and January 1974,

* Linchpin Ice Rise: suggested by Dr G. Hattersley-Smith, Antarctic Place Names Committee.

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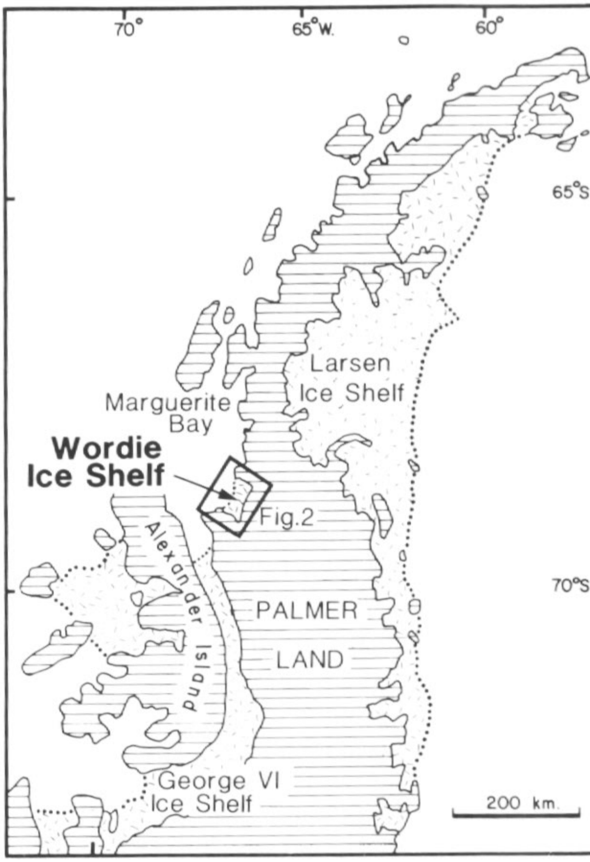

Fig. 1. Location map of Wordie Ice Shelf.

585 ± 30 km^2 of ice shelf had broken away, of which 90% had come from the southern part of the bay (Colvill, 1977). Miller Ice Rise continued to pin the ice front despite the massive break-out. A further 265 ± 20 km^2 of ice shelf broke away between 1974 and 1979 from across the length of the ice front (Doake, 1982). It is not known whether this break-up was due to a reduction in the influx of glacier ice from the local glaciers on Palmer Land or was a result of increased basal melting with a corresponding increase in the net surface ablation (Doake, 1982). In addition, with the amelioration of the climate in the Antarctic Peninsula over the last 30 years or so, the break-up of the ice shelf could be due to enhanced tidal action as a consequence of relaxed sea-ice conditions in Marguerite Bay. There is insufficient information available about Wordie Ice Shelf to investigate this in any detail.

It has been estimated that the mean annual temperature over the area is between −6 and −7°C (Reynolds, 1981*a*). Reynolds (1981*b*) has shown that melt lakes form in areas where the mean annual air temperature lies in the range of −6 to −10°C, the net surface mass balance is close to zero, and the surface drainage of the water is restricted. It may be inferred that on Wordie Ice Shelf comparable conditions prevail under which melt-water lakes form where Hariot Glacier flows into the ice shelf. These lakes can be seen on both the 1974 and the 1979 satellite images. It may be that this part of Wordie Ice Shelf lies in an accumulation shadow of Cape Berteaux

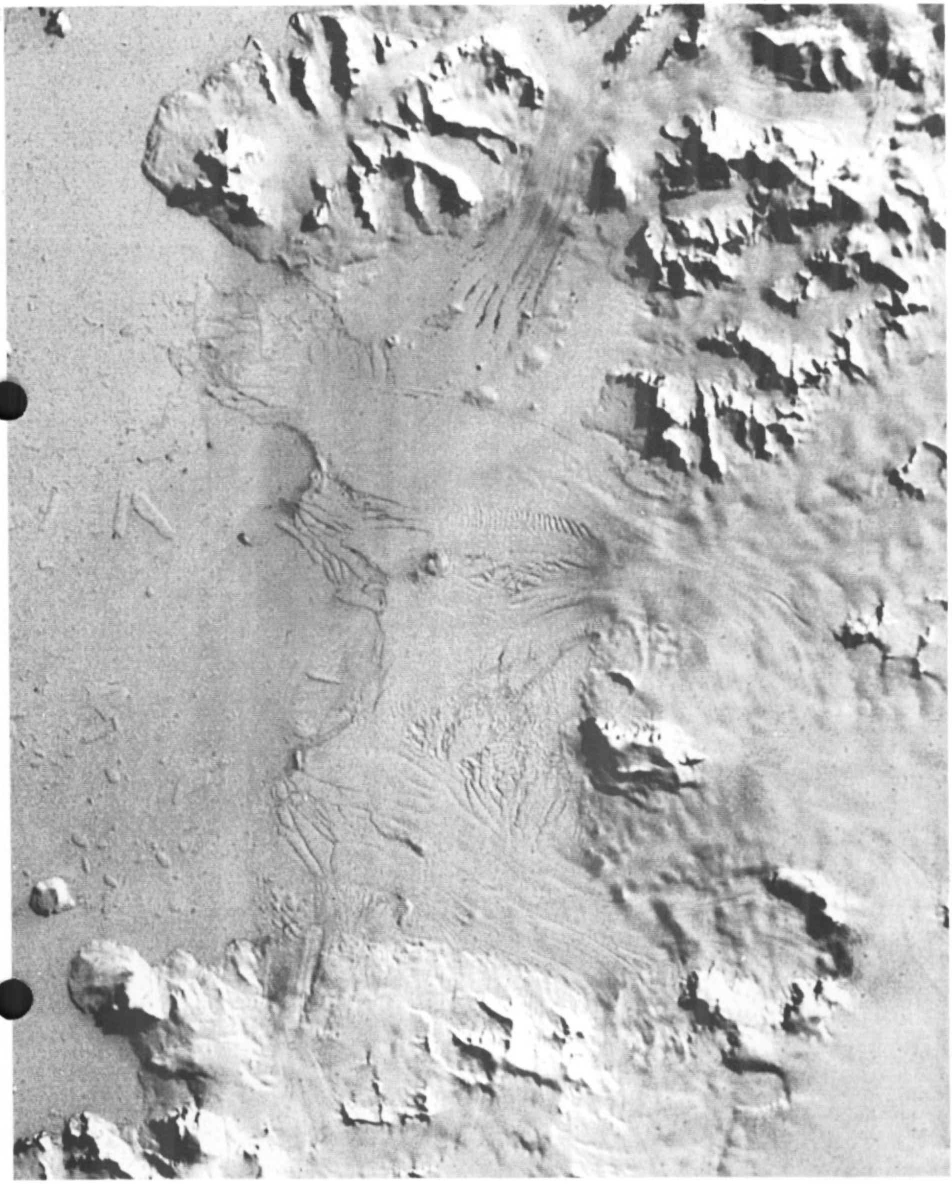

Fig. 2. Portion of 1979 Landsat MSS image (30335-12253-7) of Wordie Ice Shelf.

peninsula. This high ground may block the relatively warmer depressions which track in from the north-west from the South Pacific thus reducing the accumulation significantly, as happens on George VI Ice Shelf to the south-west (Reynolds, 1981*a*). Whatever their origin, these melt lakes at the southern end of Hariot Glacier help to delineate some of the ice structures in the area, a technique used previously for George VI Ice Shelf by Reynolds (1981*b*, 1983) and by Reynolds and Hambrey (1988).

Major flow lines within the glaciers feeding Wordie Ice Shelf have been interpreted from Fig. 2 and used to define individual glacier flow units (Fig. 3). As no ice velocity has been measured in the area the association of features which appear to be longitudinal foliation with flow lines remains conjectural. The justification of this approach is by analogy with similar work done on George VI Ice Shelf, where ice velocities have been measured (Reynolds and Hambrey, 1988). The volumes of each unit have been compared in order to determine the importance of each flow-unit's contribution to the ice shelf, and this is indicated in Fig. 3 by various sizes of arrow, with the heaviest arrow indicating a major input to the ice shelf. Six flow units have been identified: Hariot, Seller, Fleming and Prospect glaciers, and the glacier south of Mount Balfour and also a unit comprising the smaller glaciers which originate in the Kinnear Mountains. Fig. 2 shows that Hariot Glacier is less extensive than indicated on the 1:250000 map BAS 250P sheet SR 19-20/2 (1978), which was based on the 1974 satellite image on which cloud has been misidentified by the map compilers as being an extension of Hariot Glacier. Fig. 2 reveals 15 more small ice rises than had been known previously, principally around the southern portion of Hariot Glacier where it joins the ice shelf. It is possible that some of the smaller features may be ice rumples rather than ice rises, but the resolution of the image is insufficient to differentiate between them. The presence of these ice rises has probably allowed the glacier to flow as far west as it has without being affected by glaciers flowing westward from north of Triune Peaks. Similarly, Prospect Glacier and the smaller glaciers to the west of it are affected by three small ice rumples. One major feature of the ice shelf is a triangle-shaped region west of Mount Balfour with a chaotic surface and which covers an area of about 52 km^2. This feature is also associated with ice thicknesses of less than 175 m, although it should be noted that very few radio-echo soundings were taken over this area.

Radio-echo sounding isopleths have been recontoured in Fig. 3 using data from Smith (1972) in conjunction with information given by Crabtree (1983). The isopleth contours in Fig. 3 are shown as indicators of variations in ice thickness rather than as absolute values, because there are so few data values for such a structurally complex area. The radio-echo sounding data do reveal that ice thicknesses vary from about 100 to 125 m at the western ice front and increase towards the grounding line where they reach values of over 400 m. Ice thicknesses in excess of 700 m have been measured east of the grounding line. Smith (1972) reported that no bottom echos had been identified west of longitude 67° 50′ W as a consequence of brine infiltration into the ice shelf at sea level via rifts. It is this same area which broke out between 1970 and 1979.

Longitudinal foliation tends to develop parallel to flow lines in a constrained glacier (Hambrey and Müller, 1978). Flow lines and hence longitudinal foliation in Wordie Ice Shelf have been interpreted from the 1979 satellite image and are shown in Fig. 4. In addition the presence of melt water lakes at the southern end of Hariot Glacier also highlights flow lines, with the water ponding in the troughs of corrugations associated with flow lines. Longitudinal foliation is well developed on Hariot, Seller and Fleming glaciers and also on the glacier flowing west from Mount Leo. In each of these cases the foliation is still evident at the western ice front despite very heavy transverse crevassing as the glaciers approach the grounding line from Palmer Land. Seller and Fleming glaciers are particularly affected by crevassing between Triune Peaks and Mount Balfour.

Ice rises are seen to affect the flow regime of the glacier units. Wade Ice Rise, to the south-west of Hariot Glacier, causes the ice tongue to bifurcate, leaving a lens-shaped area of disturbed ice in its lee (Fig. 4). The ice tongues merge at the western side of

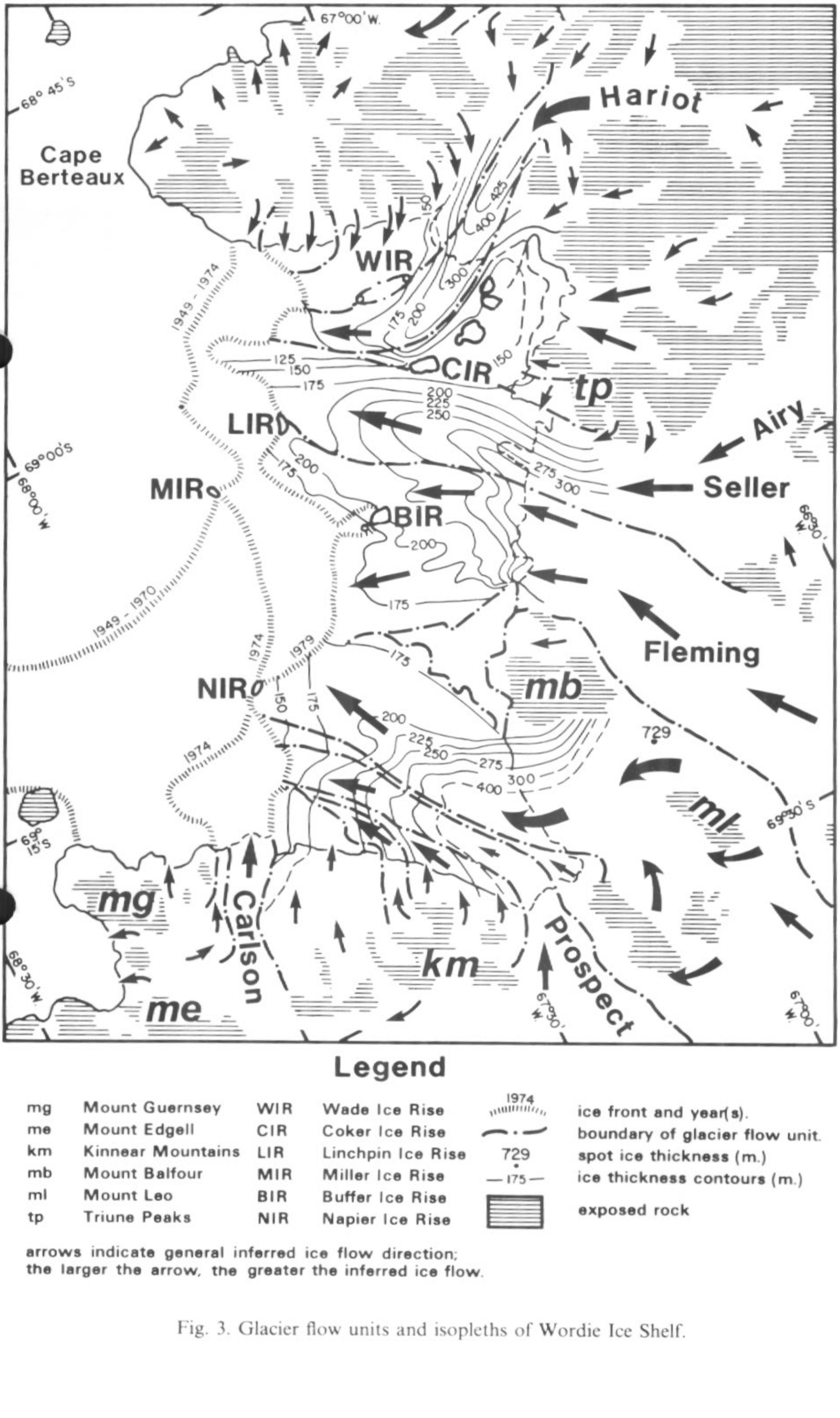

Fig. 3. Glacier flow units and isopleths of Wordie Ice Shelf.

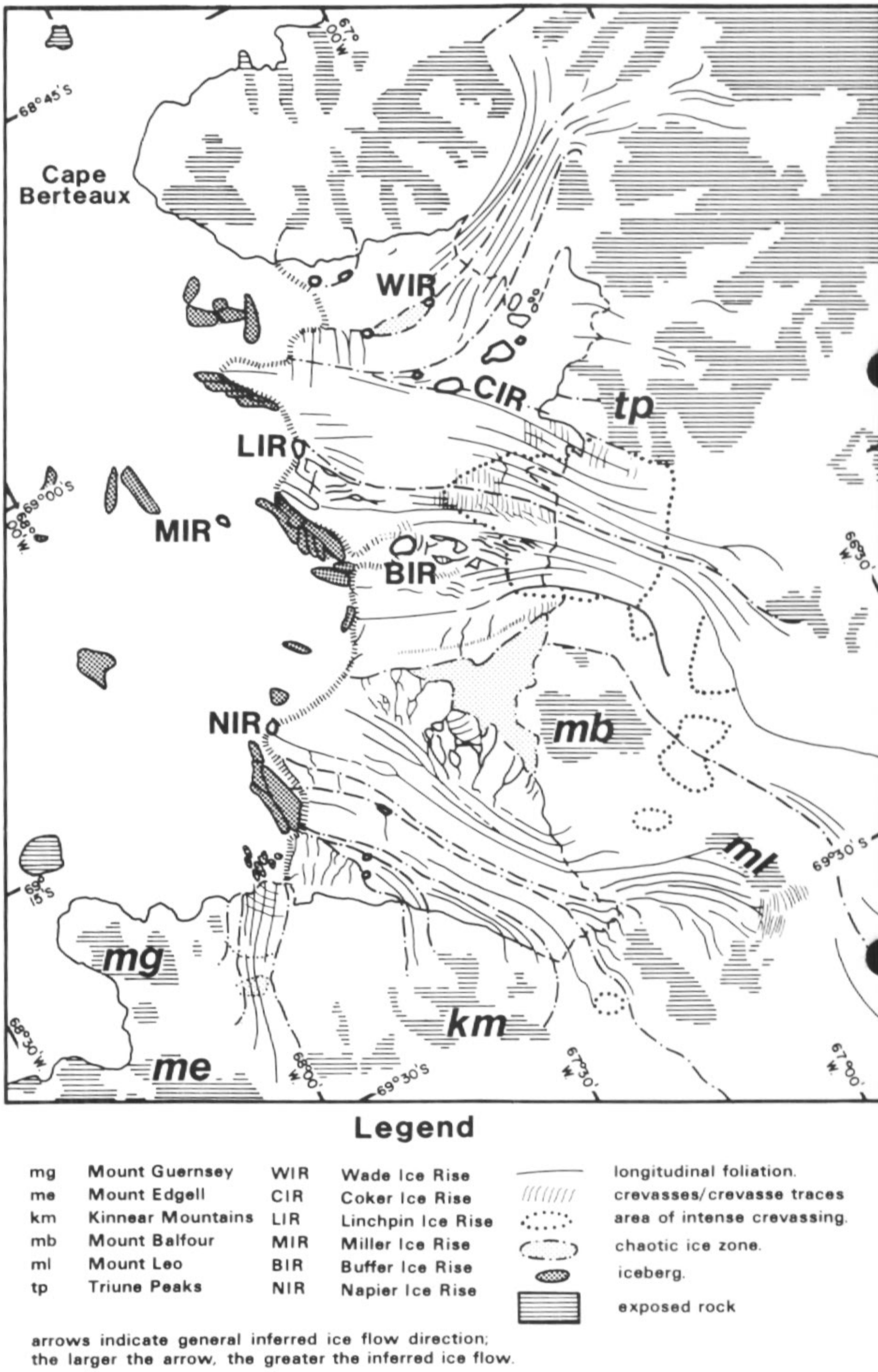

Fig. 4. Map of Wordie Ice Shelf depicting structural features interpreted from the 1979 Landsat image.

a second, unnamed ice rise, at which point the southern branch of Hariot Glacier becomes rifted leading to the formation of icebergs. Fleming Glacier is affected similarly by Buffer Ice Rise. The area of the ice shelf immediately to the east of this ice rise shows signs of considerable disturbance and possible rifting, some of which is parallel to the longitudinal foliation. Substantial rifting is also evident on the northern flank of the glacier unit to the west of Mount Balfour at the edge of the triangular chaotic zone already mentioned. The cracks in the ice shelf closest to the grounding line appear to be parallel to transverse crevasses, but further west they seem to align themselves more with flow lines. One block 5 km west of Mount Balfour shows crevasse traces quite clearly, and these indicate that the block has rotated through almost 45°. The combination of the chaotic triangle and the chasms to the south of it could lead to the rapid deterioration of this part of the ice shelf, should the ice front retreat from Napier Ice Rise. The region to the south of this area has rifts whose orientations are transverse to ice flow rather than parallel to it as occurs further north. The several small glacier units which originate in the Kinnear Mountains are constrained on their seaward side by two small ice rises. Subsequently, ice flowing northwards from 10 km west of the Kinnear Mountains is unaffected by the westward-flowing glaciers which approach from the east. The rifts in this ice unit are parallel to the glacier flow lines and also parallel to the ice front, which leads to icebergs breaking off along the rifts.

Crevasses and crevasse traces can be seen clearly where Fleming and Seller glaciers flow into the ice shelf. They are particularly well developed at the boundary between the two glaciers. Indeed, the form of the crevasse pattern here suggests that a second set of crevasses has formed and is superimposed over those which originate east of the grounding line. This second set has the appearance of being *en échelon* and may indicate that Seller Glacier is moving more quickly than Fleming Glacier, thereby causing shear. This is also consistent with Seller Glacier being thicker than Fleming Glacier at greater distances from the grounding line (Fig. 3).

Adjacent to the ice front, 17 large icebergs can be seen (Figs 2, 4), with an average area of 2.25 ± 1.2 km^2 and an average length:width ratio of 4.27 ± 1.71. The shape of the icebergs indicates that the ice structures dictate what form the bergs will take on calving. It has been mentioned already that some icebergs form from rifts which develop parallel to transverse crevasses (Prospect Glacier) or parallel to longitudinal foliation (Fleming and especially Seller glaciers). It is also likely that the icebergs from Seller and Fleming glaciers will deteriorate rapidly, as they contain transverse crevasse traces which could act as planes of weakness. From Fig. 3, the average thickness of freshly calved icebergs is roughly 130 ± 30 m. Icebergs originating from Carlson Glacier are considerably smaller than their northern counterparts, with areas of approximately 0.27 ± 0.13 km^2, and are also more equidimensional, with an average length:width radio of 1.83 ± 0.73. The difference in shape and size can be attributed to the structure of the source glacier – it has well-developed longitudinal foliation intersected orthogonally by major transverse crevasses producing blocks with surface areas comparable to those of the derived icebergs.

Conclusions

A multispectral Landsat satellite image obtained in February 1979 has provided an unparalleled opportunity to investigate the structure of Wordie Ice Shelf. Six major glacier flow units have been identified and have ice thicknesses varying from over 400 m near the grounding line to less than 125 m at the ice front. Between 1972 and 1979 about 850 ± 30 km^2 of ice broke off from the ice shelf, 585 ± 30 km^2 between

February 1972 and January 1974, and a further 265 ± 20 km^2 between 1974 and 1979. Three ice rises at or near the 1979 ice front pin the ice shelf and another 20 previously unmapped ice rises and ice rumples pin or restrict the flow of ice within the ice shelf. The dominant structure of the ice shelf is that of longitudinal foliation formed as the glaciers drain from the Palmer Land ice sheet, and this structure is maintained across the shelf to the ice front. Superimposed upon this are transverse crevasses and crevasse traces which are formed in icefalls as the source glaciers descend to and cross the grounding line. A superimposed set of crevasses is observed at the boundary between Seller and Fleming glaciers, and is thought to have formed as a consequence of differential movement between the two glaciers. A triangular-shaped zone of chaotic ice with an area of approximately 52 km^2 exists west of Mount Balfour. The southern boundary of this area is heavily rifted, and if the 1979 ice front recedes eastwards from Napier Ice Rise it could lead to a rapid deterioration of the southern part of the ice shelf. The shapes and sizes of icebergs derived from Wordie Ice Sh[illegible] are dictated by the structures of their source glaciers; the average area of iceberg produced is 2.25 ± 1.2 km^2 with an average thickness of about 130 ± 30 m.

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