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Implications of the break-up of Wordie Ice Shelf, Antarctica for sea level

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Abstract: Temperature records in the Antarctic Peninsula have shown a climatic warming of 1.5°C over the past 30 years and a number of ice shelves have retreated. The most dramatic retreat has been that of Wordie Ice Shelf which has undergone a catastrophic disintegration since the 1960s. Understanding the cause and mechanism of the break-up may provide important clues to the fate of ice shelves farther south which, it has been suggested, help to stabilize the West Antarctic Ice Sheet. The break-up of Wordie Ice Shelf has been analysed using Landsat and SPOT imagery. These observations show that the relative contribution of the various input glaciers to the grounding line flux has not altered during the break-up. This means that the effect of the rapid and almost complete removal of the ice shelf has not been transmitted upstream and is not causing a rapid increase in velocities on the input glaciers. The volume of grounded ice in the catchment of Wordie Ice Shelf will thus, be largely unaffected by the break-up and there will be no significant contribution to sea level change. Since other ice shelves around the Antarctic Peninsula are also fed by relatively steep mountain glaciers the effect of the loss of the ice shelves on sea level would be likely to be similarly small.

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Introduction

Ice shelves are the floating extremities of ice sheets. They are largely composed of ice that accumulated as a grounded ice sheet and entered the ice shelf through glaciers, although *in situ* surface accumulation (e.g. Wilkins Ice Shelf; Vaughan *et al.* in press) and basal marine ice (e.g. Filchner-Ronne Ice Shelf; Thyssen 1988) may form a significant fraction of ice shelf volume. Ice shelves can be important components in the dynamic balance of the whole ice sheet. Ronne/Filchner and Ross ice shelves especially, probably play a significant role in influencing the evolution of the West Antarctic Ice Sheet (WAIS) whose base is mostly below sea level and so may be vulnerable to small changes in thickness around its margin (e.g. Hughes 1973, Mercer 1978, Thomas *et al.* 1979). The Antarctic Peninsula Ice Sheet is somewhat different from the rest of WAIS, in that it covers a mountainous terrain with the bedrock mostly well above sea level. This ice sheet is thus not sensitive to the same mechanism of rapid collapse that would be associated with a loss of the surrounding ice shelves around the rest of WAIS.

Current estimates indicate that the Antarctic Peninsula receives around 25% of the snowfall of the whole continent despite having only 6.8% of its area (Drewry & Morris 1992) and that ice sheet response times to changes in amount of accumulation will be between 60 and 250 years. Drewry & Morris suggested that a conservative estimate of the contribution from changes in the Antarctic Peninsula Ice Sheet to eustatic sea level change would be a rise of 0.5 mm over the next 40 years assuming a 2°C increase in mean annual air temperature. Under the same warming scenario the IPCC predicts a fall in eustatic sea level of 24 ± 24 mm, which includes a contribution from the Antarctic Peninsula of a fall of 1.6 mm. Neither estimate, however, includes any change in the volume of grounded ice resulting from the loss of ice shelves; this effect has not previously been discussed.

It is thus important to study the rapid retreat of the ice shelves of the Antarctic Peninsula and the implications for the Antarctic Peninsula Ice Sheet:

a) to measure the direct contribution to eustatic sea level rise

b) to assess ice shelves as indicators of climate warming

c) as a possible indicator of the behaviour of the larger ice shelves farther south.

Wordie Ice Shelf

Morrison (1990) presented temperature records for Faraday Base (1957–1989) and Marguerite Bay (1962–1989) and showed an increase of 0.064°C year^{-1} in mean annual air temperature since records began, a total of around 1.5°C. Contemporary with this temperature rise have been considerable changes in the extent of ice shelves around the Antarctic Peninsula (Fig. 1). Larsen Ice Shelf (Skvarca in press), George VI Ice Shelf (Doake 1982), and most dramatically, Wordie Ice Shelf (Doake & Vaughan 1991) have all shown continued progressive ice front retreat. This behaviour is clearly distinct from the more usual stable cycle of slow ice front advance punctuated by calving events.

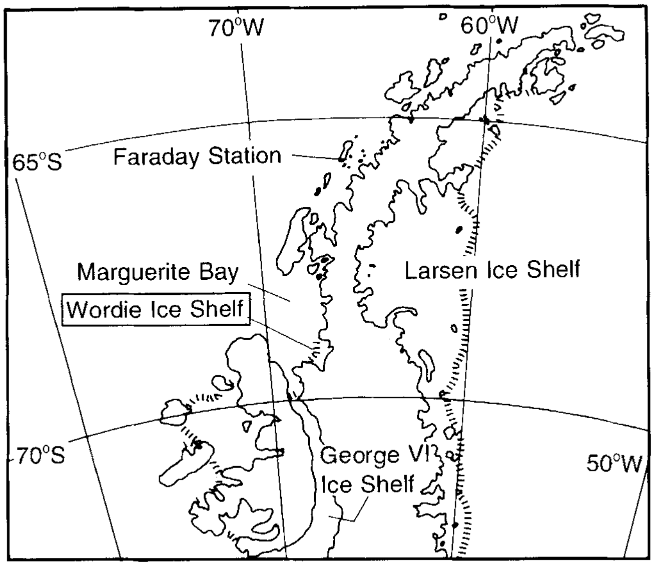

Fig. 1. Location map of the Antarctic Peninsula.

Wordie Ice Shelf lies off the west coast of the Antarctic Peninsula and drains a grounded catchment area of *c.* 15 000 km². In the 1940s and 1950s it was crossed by sledging parties, and around 10 ice rises and ice rumples were identified. It is fed by seven glacier units (Reynolds 1988). In the last few decades Wordie Ice Shelf has rapidly disintegrated to its current state; little more than a few disconnected and retreating glacier tongues (Doake & Vaughan 1991). In this study I concentrate on the effects of the break-up on the inland ice but first describe some of the main features of the disintegration process.

Break-up of Wordie Ice Shelf

Doake & Vaughan (1991) analysed Landsat images of the Wordie Ice Shelf acquired in 1974, 1979 and 1989 (Fig. 2) and images covering only the ice front portion taken in 1986 (Landsat) and 1988 (SPOT). The 1989 image was registered to surveyed ground control points and used as a base to which the other images were registered and resampled. Features in separate images were identified and matched approximately to pixel precision (*c.* 30 m) and compared in position to an accuracy of about 50 m. Using the position of the ice front in 1966 mapped from aerial photography, they estimated that the ice shelf area decreased from about 2000 km² in 1966 to about 700 km² in 1989. My analysis of more recent ERS-1 synthetic aperture radar images showing only sections of the ice shelf, indicates that the break-up is continuing at a similar pace.

The imagery and earlier maps show that the ice front retreat was punctuated by periods of stasis during which the ice front rested on ice rises. Retreat between periods of stasis was rapid. The major ice rises have apparently played several roles in controlling the ice shelf behaviour. When embedded in the ice shelf they have contributed to the drag on the ice shelf and hence compressed the ice shelf upstream and provided restraint at the grounding line. The Landsat images, however, reveal that they created broken wakes downstream. Introducing weakness into the ice shelf. Furthermore, during ice front retreat the velocity and thickness altered so that areas of crevasses appeared upstream of the ice rises. I assume that the increasing stresses caused by the separation around the ice rise as the ice shelf accelerated eventually became sufficient for fracture (Vaughan, in press). At this stage the ice rises appeared to behave as indenting wedges and contributed to weakening the ice shelf and hastening the break-up. Fracture of ice thus appears to be highly significant in the dynamics of the ice shelf (although at present fracture is not included in mathematical models of ice shelf flow).

Laboratory experiments show that the fracture toughness of ice is reduced at higher temperatures and possibly by the presence of water (Liu & Miller 1979, Sabol & Schulson 1989). Doake & Vaughan (1991) concluded that break-up was triggered by the regional climatic warming, which increased ablation and the amount of melt water and hence the rate of fracture.

Possible effects of the break-up on the inland ice

Changes in the flow of grounded ice could both drive and be driven by changes in the ice shelf. The ice shelf may restrain the flow of inland glaciers; or conversely, the surge of an inland glacier might cause increased flux across the grounding line and into the ice shelf leading to changes in ice shelf extent. In order to determine the effects of the break-up of Wordie Ice Shelf on the inland ice sheet fully I should search for signs of both types of interaction. Fortunately, one set of observations appears to address both questions.

The distance inland from the grounding line that the effect of the ice shelf is transmitted will be broadly dependent on conditions around the grounding line. We might identify two extreme styles of grounding line:

a) where the bed has a shallow gradient and a sliding ice stream becomes floating across a gentle transition. In this case bending and longitudinal stresses are assumed to transmitted across such a grounding line (e.g. Rutford Ice Stream Antarctica).

b) where the ice sheet is frozen to its bed and the bed has a steep gradient causing the ice to be completely broken at the grounding line by bending stresses. It is unreasonable to assume that bending or longitudinal stresses can be transmitted across such a grounding line (e.g. around Brunt Ice Shelf, Antarctica; Thomas 1972).

Glaciers around Wordie Ice Shelf fit between these extremes. Fleming Glacier is known to be sliding over its base. Walford (1972) and Doake (1975) used a radio-echo fading pattern technique to show that 45 km upstream of the grounding line around 30% of the glacier velocity was due to sliding and there is likely to be an increase in the sliding fraction towards the grounding-line. The bed gradients are not sufficient to cause rifting at the grounding line but some surface crevassing does

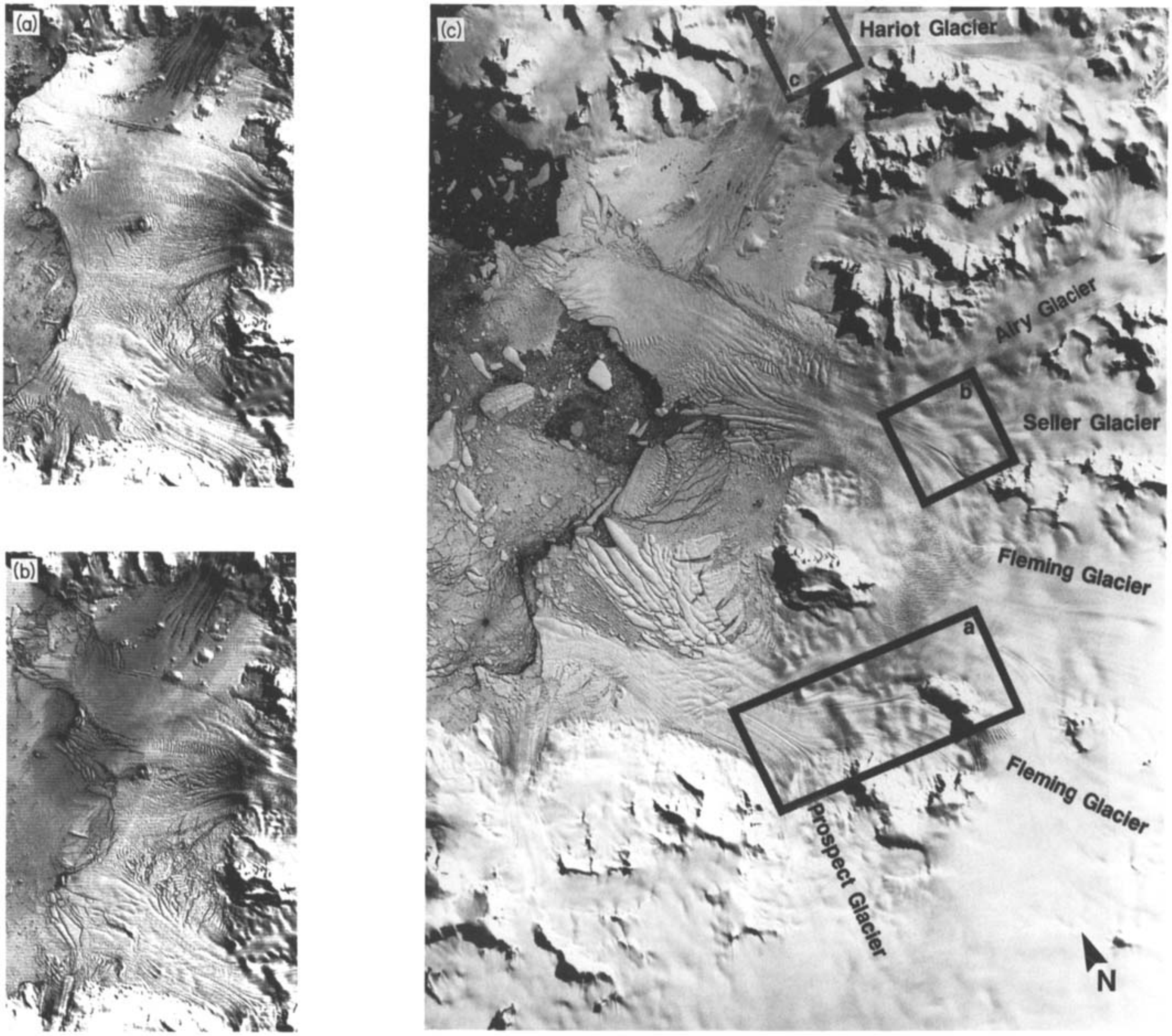

Fig. 2. Landsat subscenes (*c.* 70 x 95 km) showing the condition of Wordie Ice Shelf. **a**. 1974 (MSS), **b**. 1979 (MSS), **c**. 1989 (TM). All the glaciers are named except Meridian Glacier which enters the image halfway across the top edge. All imagery is published by courtesy of EOSAT.

occur. The glaciers around Wordie Ice Shelf are clearly intermediates between the extreme cases and so the distance inland that the influence of the ice shelf extends will also be between zero and the ice stream limit.

Muszynski & Birchfield (1987) presented a scaling analysis of ice streams which showed that the distance upstream of the grounding line that is significantly affected by the ice shelf L_c, can be estimated from the ice velocity U_c, flow law rate factor A_c, surface slope , acceleration due to gravity g, and densities of ice $_i$ (917 kg m^{-3}) and water $_w$ (1030 kg m^{-3}),

For Rutford Ice Stream, where U_c is 400 m a^{-1}, A_c is 10^{-25} s^{-1} Pa^{-3}, is around 3 x 10^{-3} (R.M. Frolich, personal communication 1993), L_c is found to be around 50 km.

A similar calculation for Fleming Glacier yields a value of around 10 km. Despite the large component of sliding Fleming Glacier does not satisfy all the assumptions made by Muszynski & Birchfield, in particular its slope varies significantly along its length. This calculation, however, does provides a useful upper limit on the distance from the grounding line that is directly influenced by the ice shelf.

Observations of the grounded ice sheet

Wordie Ice Shelf is fed by a number of tributary glaciers, which

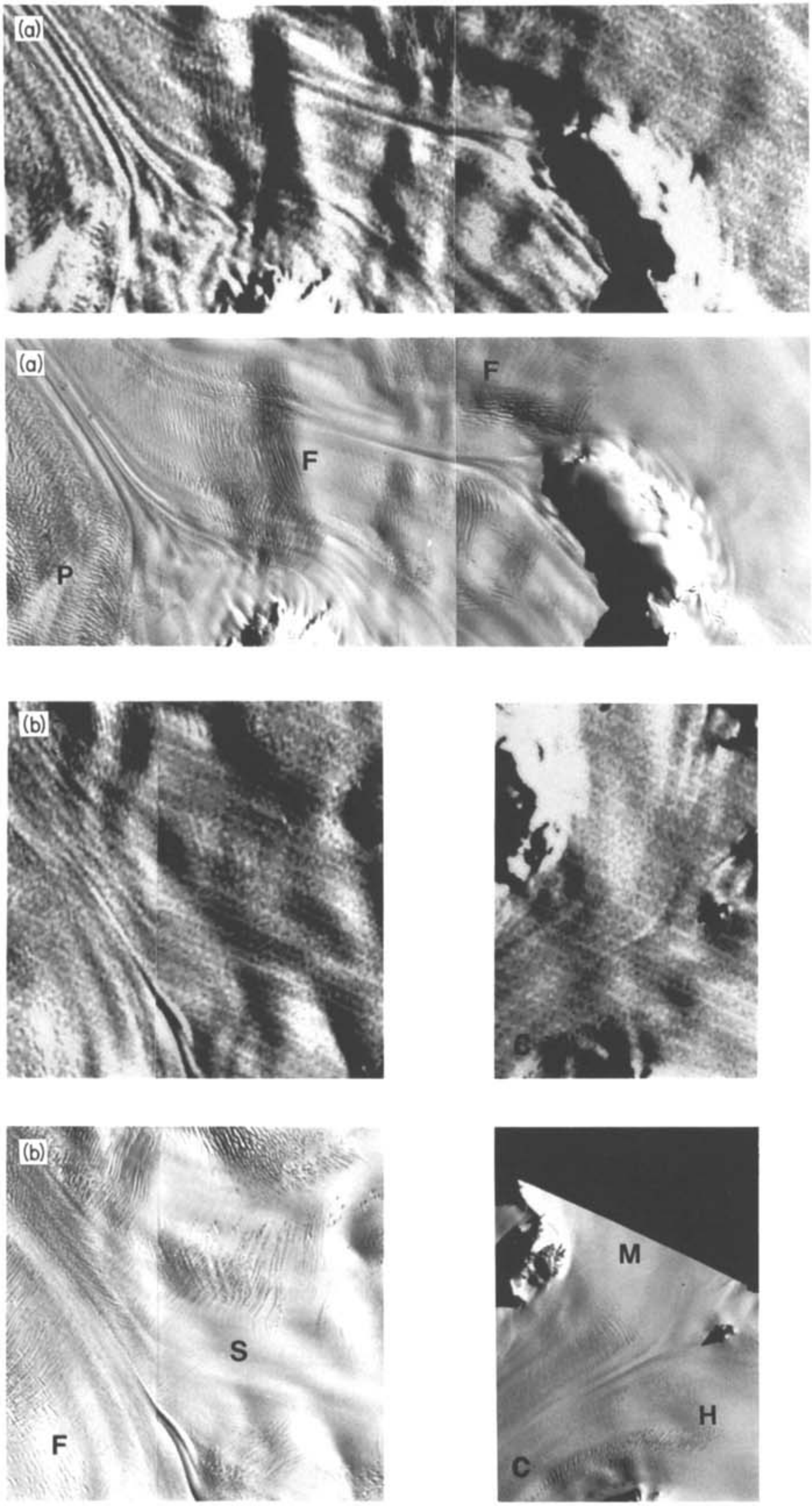

Fig. 3. Landsat subscenes showing medial plumes in 1974 and 1989 for, **a**. Fleming (F) and Prospect (P) glaciers (20 x 8 km), **b**. Seller (S) and Fleming glaciers (9 x 9 km), **c**. Meridian (M) and Hariot (H) glaciers (6 x 9 km).

join to make three main input units (Fig. 2). In the north, Meridian and Hariot glaciers merge 12 km upstream of the grounding-line. The Airy and Seller glaciers and a portion of Fleming Glacier merge around 15 km upstream of the grounding-line, and the other portion of Fleming Glacier and Prospect Glacier merge close to the grounding-line in the south. Ridge-trough features are generated at the confluence of these glaciers; I call these "medial plumes" because of their similarity to medial moraines and after MacAyeal's description of "relict crevasse plumes" (MacAyeal 1988). These features are clearly visible on the Landsat imagery and continue to delineate the ice originating from each of the glacier for several kilometres downstream.

It is reasonable to assume that each of the tributary glaciers has a different pattern and amount of sliding at its base, and hence a different balance between longitudinal and vertical shear stress. A change in the velocity of the glacier below the confluence, either due to a change in ice shelf backpressure or due to a surging tributary would almost certainly cause a change in dominance of the tributaries. This would be manifested by a changed position of the medial plume (cf. MacAyeal 1988). Fig. 3 shows sub-scenes of 1974 and 1989 Landsat images, with their locations marked in Fig. 2. Between 1974 and 1989 I can see no alteration in the positions of the medial plumes between Fleming and Prospect glaciers, between Seller and Fleming glaciers and between Median and Hariot glaciers. When accurately registered the medial plumes appear constant in position to at least the original resolution of the images (70 m). I thus conclude that there has been no detectable alteration in the balance of the tributary glaciers, either causing or responding to changes in the ice shelf extent.

If the break-up of Wordie Ice Shelf had caused a significant change in backpressure at the grounding-line, I might have expected this to have been influential up to the points of confluence. At these points there have, however, been no changes in the relative dominance of the tributary glaciers and I conclude that the ice shelf provided no significant restraint on the inland glaciers. The likely reason for this is the unimportance of longitudinal stress in the dynamic balance of the glaciers compared to side wall and basal drag. Similarly, the absence of fluctuation in the medial plumes shows flow in the tributary system has been steady, providing evidence that the break-up of the ice shelf was not initiated by surging activity on the input glaciers.

Discussion

The results presented here show that even the rapid and almost complete removal of Wordie Ice Shelf has resulted in no appreciable change in dominance within the pairs of tributary glaciers. This strongly suggests that there has been little change in velocity at the points of convergence, between 8 and 20 km upstream of the grounding line. I conclude that the loss of the ice shelf has not caused a significant acceleration in the glaciers feeding it. The absence of such changes implies that the loss of the ice shelf will not result in a rapid loss of ice from the grounded catchment area. Consequently, the effect on eustatic sea level of the break-up of Wordie Ice Shelf will be small. With continued climate warming over the Antarctic Peninsula other ice shelves will be threatened, but the glaciers feeding these are similar in nature to those on Wordie Ice Shelf and so we can assume that the effect on eustatic sea level of the loss of these ice shelves will be similarly small. The climate change in the Antarctic Peninsula is, however, unlikely to be limited to temperature warming. Associated changes in accumulation will alter the amount of ice in the grounded part of the Antarctic Peninsula Ice Sheet and have a direct effect on eustatic sea level.

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