THE STRUCTURAL GLACIOLOGY OF GEORGE VI ICE SHELF, ANTARCTIC PENINSULA

J. M. REYNOLDS

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

and

M. J. HAMBREY

Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

ABSTRACT. Lakes form each summer on the surface of George VI Ice Shelf and their distribution reflects the large-scale structure of the ice shelf. The ice shelf is complex with distinct flow units originating in Palmer Land which maintain their structural integrity as they flow across to, and impinge against, Alexander Island. The dominant structures are longitudinal foliation and crevasse traces. Longitudinal compression results in folding of pre-existing layers but deformation in the ice shelf does not result in overprinting of existing structures, except possibly in narrow zones of intense shear adjacent to Alexander Island. Flow and thickness patterns indicate dynamic inhomogeneity across much of the ice shelf.

Structural investigations on ice shelves are uncommon, although fragments of ice shelves in the Canadian Arctic archipelago have been studied. In the Antarctic only cursory structural studies have been made previously of the Amery, Ross, Maudheim, McMurdo and Ronne–Filchner ice shelves, but with the advent of digital enhancement techniques of multi-spectral scanning satellite imagery (Swithinbank and Lucchitta, 1986) and the availability of Landsat Thematic Mapper images (Orheim and Lucchitta, 1987), much greater resolution of *surface* detail is now possible. However, in none of the surveys (so far published) has the internal structure of an ice shelf been determined, since in areas of net accumulation structures are normally exposed only in the vertical ice cliffs at their seaward fronts, or are limited to only the largest scale features (crevasse fields and ice streams, e.g. Crabtree and Doake, 1986). In this paper we describe a study of George VI Ice Shelf which fills George VI Sound between Alexander Island and Palmer Land on the west coast of the Antarctic Peninsula (Fig. 1a). The ice shelf fills a narrow channel (20–65 km in width) and is constrained for most of its length; only about 100 km of its ice front is unbounded by land out of a total of approximately 550 km. The central portion of the ice shelf, around 4500 km^2 in extent, has zero or slightly negative mass balance, thereby exposing apparent glacial structures over an area of several thousand square kilometres.

In this paper we examine the connection between patterns of supraglacial drainage and of ice structure and the dynamics of George VI Ice Shelf. For the central part of the ice shelf a Landsat multi-spectral scanner composite image of 9 January 1973 (1170–12251–7; Fig. 1b) has proved invaluable, as have several sets of aerial photographs. Ground observations have also been made of exposed ice structures at the western margin of the ice shelf.

The significance of this study is that it provides (i) the first detailed view of the structure of an Antarctic ice shelf, and (ii) the means of pinpointing areas of special interest for later ground examination from a recognition of discrete flow units.

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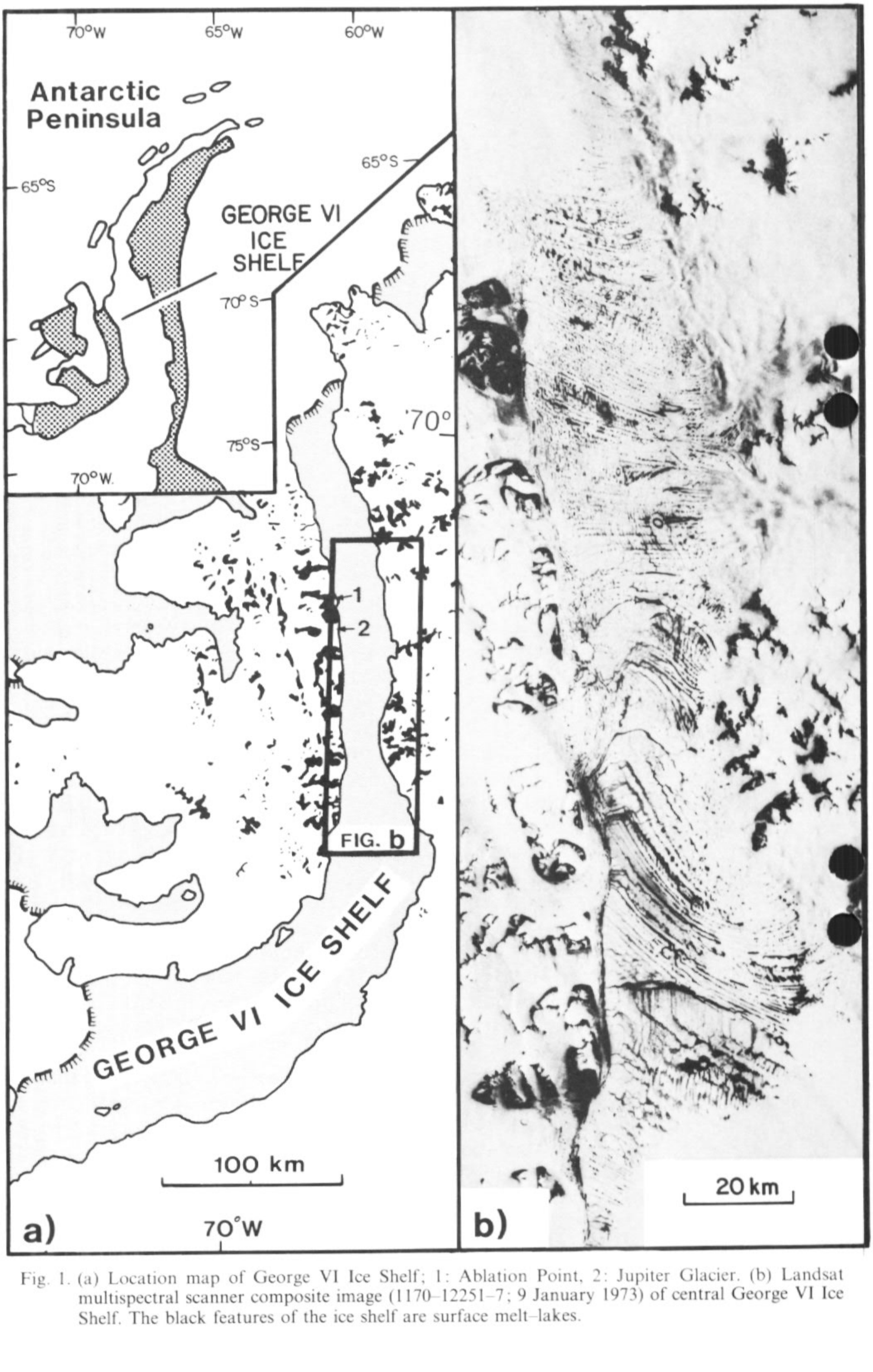


Fig. 1. (a) Location map of George VI Ice Shelf; 1: Ablation Point, 2: Jupiter Glacier. (b) Landsat multispectral scanner composite image (1170–12251–7; 9 January 1973) of central George VI Ice Shelf. The black features of the ice shelf are surface melt–lakes.

Character and Dynamics of George VI Ice Shelf

George VI Ice Shelf varies in thickness (Fig. 3) from about 100 m at the northern ice front to about 475 m at lat. 73° S (Crabtree, 1983). The thickest parts of the ice shelf are associated with major glaciers which drain the Palmer Land ice sheet.

In summer, the ice shelf undergoes extensive surface melting and melt-water lakes form over an area of approximately 4500 km^2 between lat. 70° 15′ S and lat. 72° 00′ S. In this area the mean annual temperature lies between −6 and −10°C, the surface net mass balance is close to zero, and surface drainage is restricted in areas of compressive ice flow (Reynolds, 1981*a*, *b*.)

Two dominant patterns of lakes have been distinguished. The main set forms in troughs between undulations (wavelength *c*. 450 m) that are parallel to flow lines in the ice shelf as determined from velocity measurements (Bishop and Walton, 1981; Pearson and Rose, 1983). The second set, which is less well-developed, often intersects the lakes parallel to flow-lines. It has been suggested that these lakes, which commonly lie parallel to the prevailing wind direction, are wind-induced (Reynolds, 1981*a*).

The ice shelf decelerates as it flows westwards across George VI Sound (Fig. 3) from *c*. 400 m a^{-1} near the grounding line to *c*. 30 m a^{-1} near Alexander Island (Bishop and Walton, 1975, 1981). The ice shelf flows across the sound, in some places with a northerly component to the flow, impinging against local glaciers on eastern Alexander Island in a zone of massive pressure ridges up to 15 m high. The deepest melt-water lakes occur in this zone and are the focus for run-off from the surrounding ice. From a study of mass balance of the entire ice shelf (Potter and others, 1984) the major component of mass wastage is basal melting. Up to 53 km^3 may melt from the base of the shelf annually. The ice shelf volume is maintained by the influx of 46 km^3 a^{-1} of glacier ice from the Palmer Land ice sheet with an additional 12 km^3 a^{-1} from local accumulation.

Interpretation of Structures from Lake Drainage Patterns

The glacier components of George VI Ice Shelf (Fig. 2) and the inferred surface structures (Fig. 3) have been delimited using the melt-water lake patterns depicted in Fig. 1b, in conjunction with ice thickness measurements. Additionally an examination of black and white aerial photographs taken by the US Navy in 1966, and by British Antarctic Survey (BAS) in 1978–79 together with colour oblique aerial photographs taken by one of us (J. M. R.) has enabled the boundary between the ice shelf and the termini of local glaciers on eastern Alexander Island to be identified (Fig. 2).

Geometry of Structures in Valley Glaciers

The melt-water pattern of George VI Ice Shelf bears a striking resemblance to the foliation and crevasse trace patterns of valley glaciers. Foliation consists of intercalated layers of ice of different crystal size and bubble content and tends to form in two geometrical configurations: (i) steeply dipping and longitudinal across the whole width of a glacier tongue, especially where fed by a wide accumulation area, and (ii) longitudinal at the margins but forming convex down-glacier arcs across the middle, often originating in ice-falls or transverse crevasse belts in a vertical attitude but with a decreasing dip down-glacier (Hambrey, 1976; Paterson, 1981). Although individual folia are generally on a scale of a few centimetres to metres, subtle variations of groups of foliae over several hundred metres are visible from at least

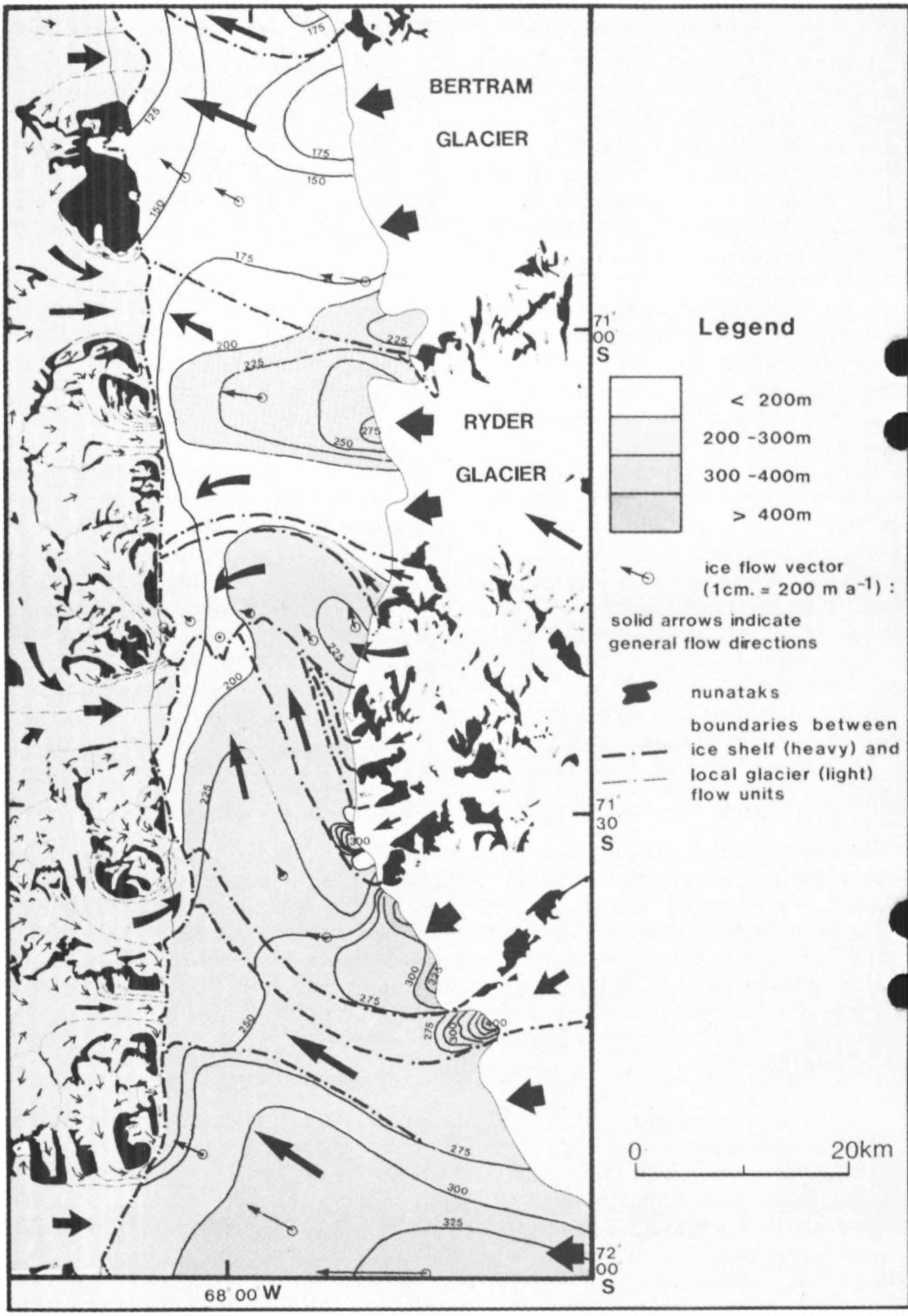


Fig. 2. Flow units of central George VI Ice Shelf. Ice thickness isopleths have been compiled from the British Antarctic Survey ice thickness map, 1:500,000 (Crabtree, 1983).

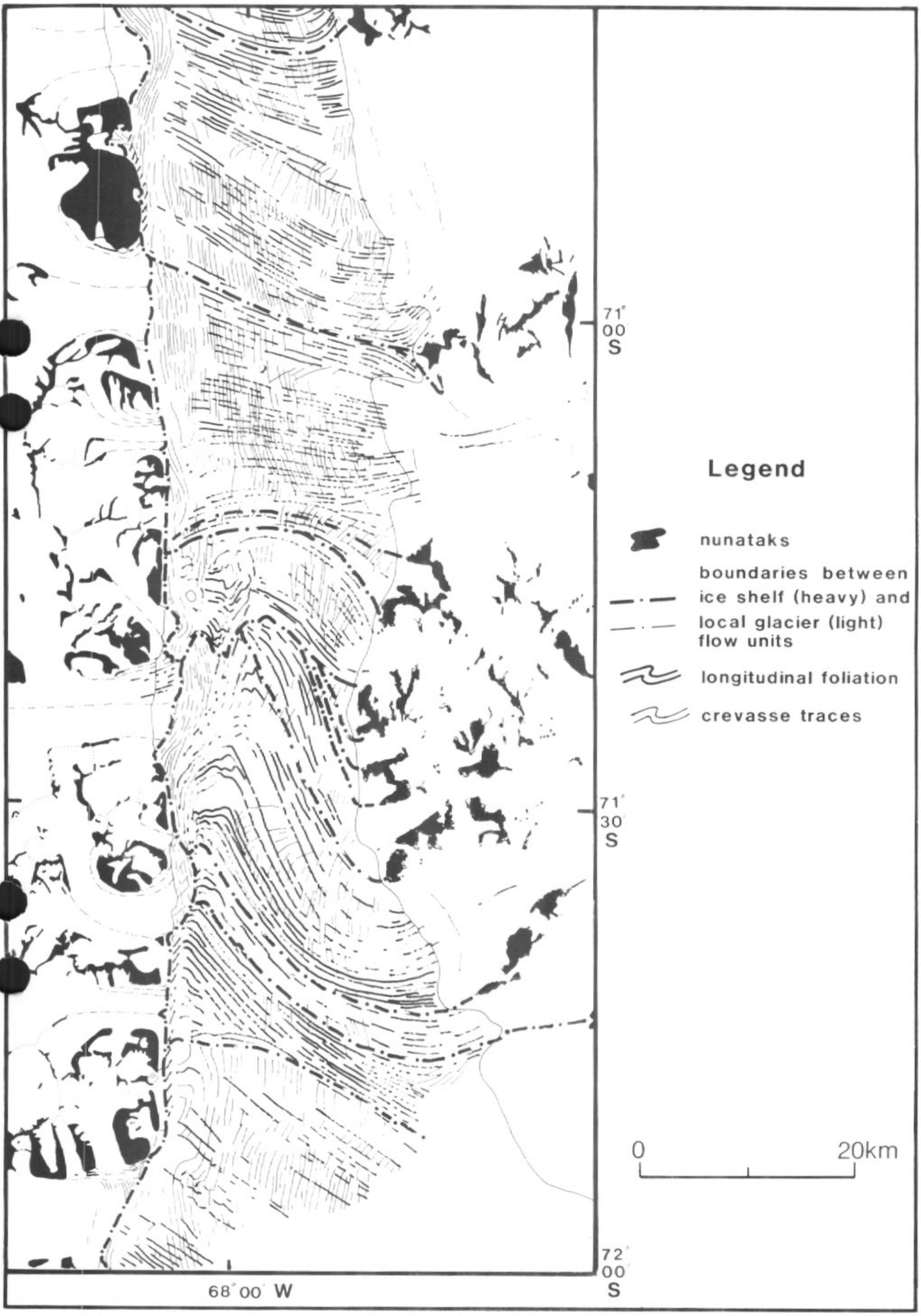


Fig. 3. Structural map of central George VI Ice Shelf.

several kilometres above a glacier. Longitudinal foliation in a constrained channel tends to be parallel to flow lines (Hambrey and Müller, 1978) and may represent large-scale isoclinal folding of stratification as ice enters the channel. If the ice spreads out as a piedmont lobe, the foliation becomes strongly folded by longitudinal compression (e.g. Malaspina Glacier).

Crevasse traces are ubiquitous clear ice layers occurring within and below crevasse belts; hence they have variable orientation and often intersect foliation and each other. Together, foliation and crevasse traces form the bulk of the structures visible in the tongues of dynamically active valley glaciers.

Relation of Structures to Supraglacial Drainage

From studies on temperate glaciers, it is well known that ice structures such as foliation, crevasses and crevasse traces, have a pronounced influence on supraglacial drainage patterns (Stenborg, 1968; Hambrey, 1977; Raymond, 1980). On George VI Ice Shelf the snow cover in the central region is thin since the surface mass balance is close to zero, and penetration of melt-water through a thin snow cover to the underlying ice is likely. As in a temperate glacier, this could lead to differential ablation of foliation and crevasse traces and to the development of structure-controlled drainage networks. Once formed, the drainage pattern would be self-perpetuating because of large albedo contrasts (Reynolds, 1981*a*).

Direct evidence for the formation of a structure-related drainage network in the same area is from Jupiter Glacier (Fig. 4) in eastern Alexander Island. Aerial photographs of the glacier taken in late summer show minimal snow cover and well-developed longitudinal foliation. The supraglacial drainage is obviously dictated by structures within the glacier.

On George VI Ice Shelf the dominant pattern of large elongate melt-water lakes reflects the distribution of surface undulations and lies parallel to flow lines. This pattern of lakes (Fig. 3) is similar to that of structures in valley glaciers, especially ones in which longitudinal foliation is the dominant structure across the glacier's width, a structure which generally is parallel to flow lines. The inference from this is that the elongate melt-water lakes reflect the orientation of longitudinal foliation or the flow-line pattern over the central part of George VI Ice Shelf. Consequently, we have mapped the melt-water lakes as representative of the distribution of longitudinal foliation (Fig. 3). The geographical distribution of some of the curved but regular sets of arcuate lakes (not all orientated parallel to the sound or to the prevailing wind direction) resemble crevasse trace patterns in valley glaciers; often a number of intersecting sets can be noted. The correspondence between crevasses and crevasse traces is found in the parallelism of transverse crevasses on lower Bertram Glacier and the lake patterns immediately below on the ice shelf (Fig. 3). Furthermore, patterns resembling orthogonal sets of crevasse traces are visible on aerial photographs immediately north of Ablation Point. In most cases these lakes do not appear to extend across the boundaries of major flow units. This suggests that the distribution of lakes is dependent upon the dynamics of the individual flow unit containing them.

A geographically restricted set of *en échelon* lakes occurs at the western edge of the ice shelf (Fig. 5) and has been described elsewhere by Reynolds (1983, pp. 11–13). The lakes are commonly pear-shaped with the broad end at the northern end of each lake and fill depressions between distinct corrugations in the ice shelf. The *en échelon* lakes occur only at the westward margin of large glacier units within the ice shelf which have a northerly flow component and which impinge directly on the coastline of eastern Alexander Island or against minor eastward-flowing local glaciers.

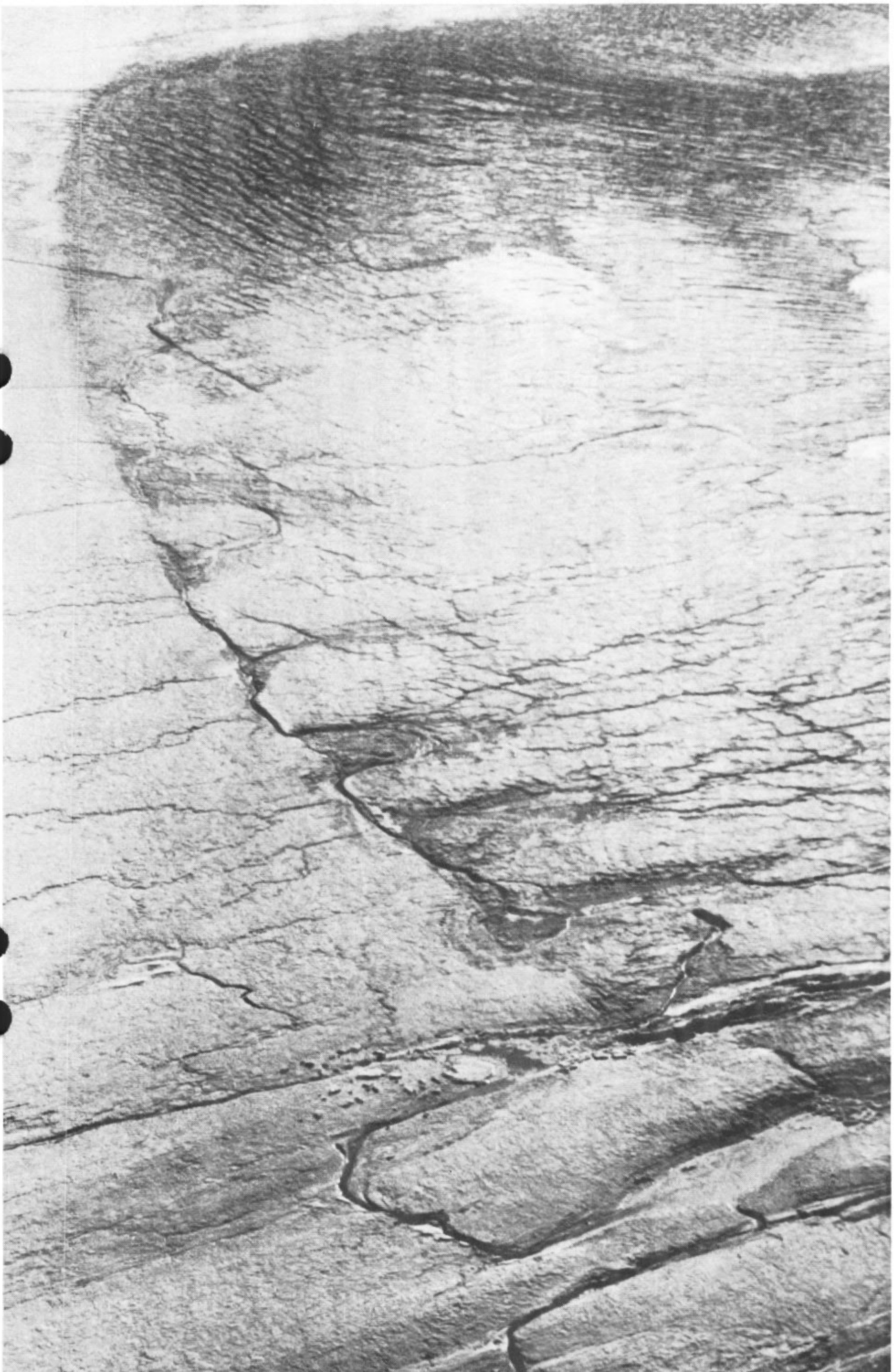


Fig. 4. Supraglacial drainage patterns on Jupiter Glacier, Alexander Island; viewed looking towards the west. (Photo: J. M. Reynolds.)

Fig. 5. Oblique aerial photograph of part of eastern Alexander Island (US Navy; TMA 1800, F-31, M1126-052; 4 November 1966) showing Jupiter Glacier (JG) with 'Upper Lake' arrowed, Moutonnée Lake (ML), Ablation Lake (AL), and pear-shaped *en échelon* lakes and principal features of the ice shelf in the foreground viewed looking to the west.

Structures at the Western Margin of Central George VI Ice Shelf

Aerial photographic coverage is available for the coastal strip of George VI Ice Shelf from the northern flank of Jupiter Glacier (lat. 70° 56′ S) to just north of Ablation Point (lat. 70° 47′ S) (Fig. 5). These photographs have been used in conjunction with ground observations on the ice shelf to determine the structural glaciology of this area. The structures throw light on deformational processes on a scale an order of magnitude smaller than those deduced from the satellite image. Three sections of coastal strip are described below.

Junction of Jupiter Glacier and George VI Ice Shelf

The most significant observation is that the northern flank of Jupiter Glacier wedges out between the cliffs on Alexander Island and the north-westward flowing ice shelf. Despite heavy crevassing over most of the area, strong longitudinal foliation can be clearly seen (A; Fig. 6); it can be traced as it turns northwards in response to the interaction of the glacier with the ice shelf. The contrast in surface morphology between Jupiter Glacier and the ice shelf is striking, the former having a well-developed set of orthogonal crevasse traces, whilst the latter has a marked ridge topography with a complex system of foliation. Thus the junction of the local glacier with the ice shelf can be clearly distinguished (marked by a heavy dot–dashed line in Fig. 6).

The northern flank of Jupiter Glacier is dominated by the drainage of two proglacial lakes. The larger 'Upper Lake' (Heywood, 1977; Fig. 5) drains via the lower proglacial lake (B; Fig. 6) amongst the lateral moraines along the northern edge of Jupiter Glacier. This lateral moraine has been described previously as an 'ice shelf moraine' (Clapperton and Sugden, 1983), a designation which we cannot accept.

The structure exposed within the surface of the ice shelf adjacent to the terminus of Jupiter Glacier is the result of two phases of deformation. The earliest and dominant set of features is orientated parallel to the ice shelf edge and is emphasized by drainage channels, some of which are floored by rock debris. These structures are thought to be transverse foliation related to, or derived from, crevasse traces which originated presumably in association with the flotation of the ice as it passed over the grounding line. The foliation is folded and is cross-cut by fractures which have formed evidently as a result of local shear.

At the mouth of Striation Valley is a lake which has been dammed by the ice shelf margin (C; Fig. 6). The lake is fed by outlet streams from small remnant glaciers in the valley by the outflow from the two proglacial lakes along the northern flank of Jupiter Glacier. The area of the lake shown in Fig. 6 is considerably less than that at its greatest extent, estimated from the aerial photographs to have been 0.15 ± 0.01 km^2. The water level has fallen episodically from its maximum height resulting in at least five terraces being exposed on the flanks of the lake bed. The lake has had two principal drainage outlets; one is at the northern end of the lake (D; Fig. 6) draining northwards along the edge of the ice shelf towards Moutonnée Lake. The second, and the larger of the two outlets, is on the east of the existing lake (E; Fig. 6), from which water has drained catastrophically onto the shelf where there is now a moulin. Drainage resulted in deposition of sediments in the troughs between the pressure ridges adjacent to the terminus of Jupiter Glacier. The major outlet has completely cut through the ridge of supraglacial debris which helped previously to dam the lake. A band of debris lies on the ice shelf edge for about 1.3 km north of the lake outlet and consists of two ridges which are parallel to, and of the same size as, two debris-free ridges on the ice shelf. The debris ridges are cored by clean ice from the ice shelf (R. B. Heywood, pers. comm.). The line along which the westward ice-cored ridge penetrates through the debris cover is taken to mark the western boundary of the ice shelf.

Montonnée Lake area

This area is dominated by an ice front (A; Fig. 7) which has vertical ice cliffs 30 m high (Heywood, 1977) and which protrudes into the lake, and by the prominent bar of debris-covered grounded ice to the north (B; Fig. 7). It is thought that the moraine has formed on a submerged rock bar which may be related to the normal-fault rift system which has formed George VI Sound (Crabtree and others, 1985). Where the ice shelf enters the lake, the foliation is clearly folded in response to ice flow. The dominant structure appears to be curved foliation related to crevasse traces which are

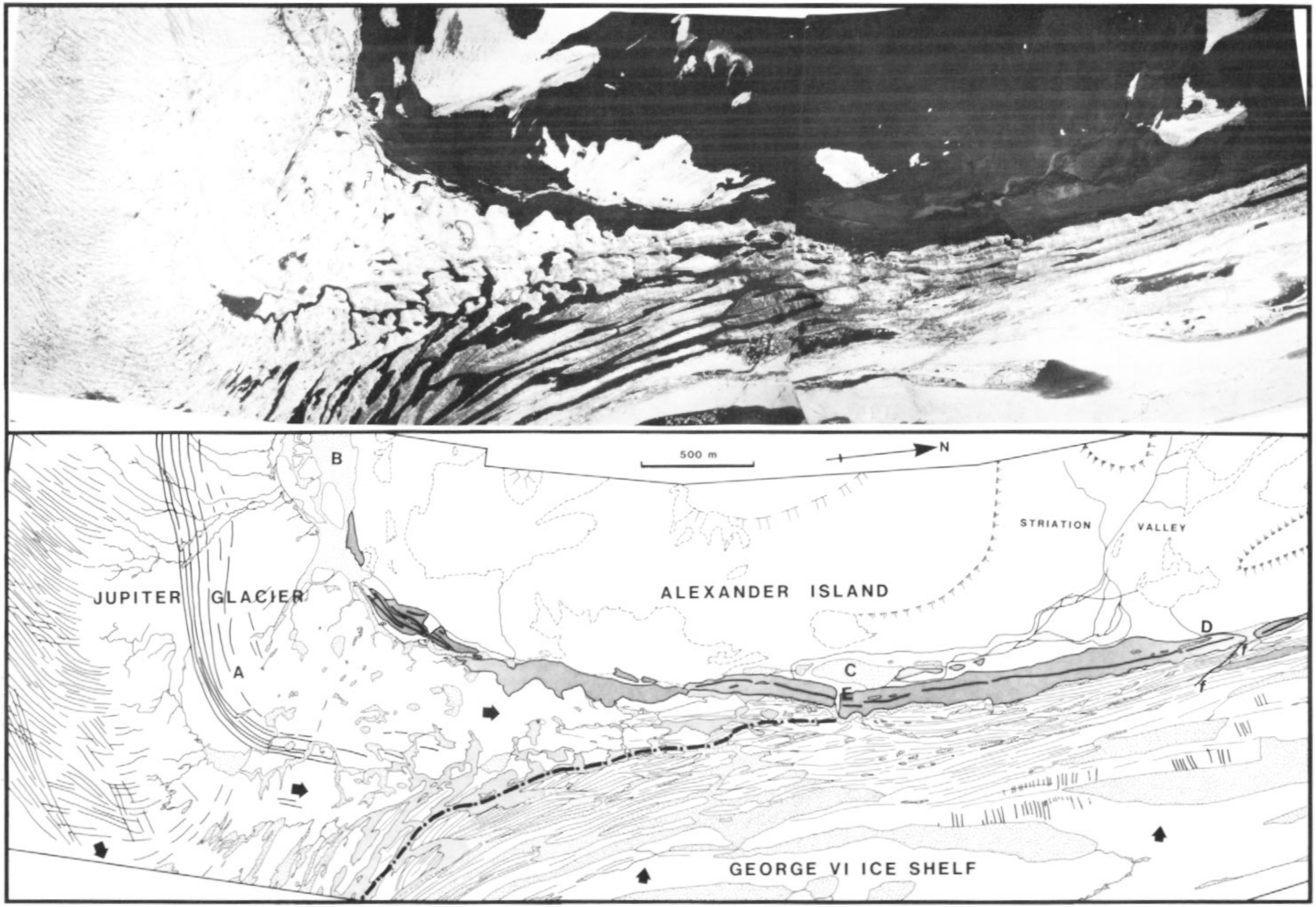
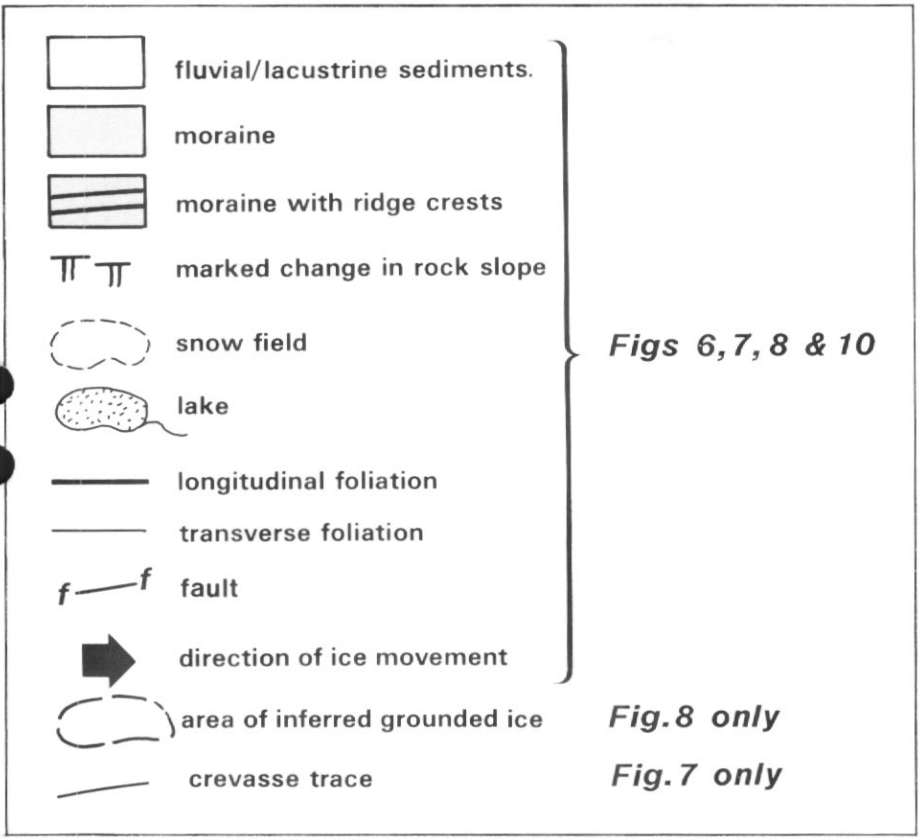


Fig. 6. Junction of Jupiter Glacier and George VI Ice Shelf; (a) aerial photo mosaic (from BAS vertical aerial photo survey 1978–79) and (b) the structural map of the same area. See text for discussion of lettered features. (See p. 89 for legend.)



orientated transverse to the flow direction across the sound. The strongly developed transverse foliation here is a reflection of the considerable compressive strain that results from the ice shelf impinging locally against Alexander Island, whereby the transverse foliation is enhanced at the expense of the longitudinal foliation. The latter cannot fold as it would have done in a piedmont lobe because this particular glacier unit is laterally constrained by other flow units (Fig. 2). However, younger crevasse traces can be seen almost at right angles to the transverse structures (C; Fig. 7). In the cusp in the bulge of the ice shelf near location A (Fig. 7) several large fractures occur, here oriented north-west–south-east. These are thought to have developed parallel to longitudinal foliation, rotated during the local folding (but maintaining their perpendicularity with respect to the transverse structures), and forming lines of weakness which have been exploited by the supraglacial melt-water in draining from the ice shelf towards Moutonnée Lake. Slightly arcuate crevasse traces form a series of small ridges which have a separation of about 25 m and which can clearly be seen at the south-eastern side of the moraine bar. Longitudinal foliation, cross-cutting the transverse structures and orientated more north-west–south-east because of the northerly flow component, can be seen at the right-hand edge of Fig. 7.

The prominent transverse foliation which generally is aligned parallel to the edge of the ice shelf is laterally extensive and because of light and dark banding (Fig. 7) is easy to follow. At the elbow of the bend in the moraine bar (D; Fig. 7) the foliation

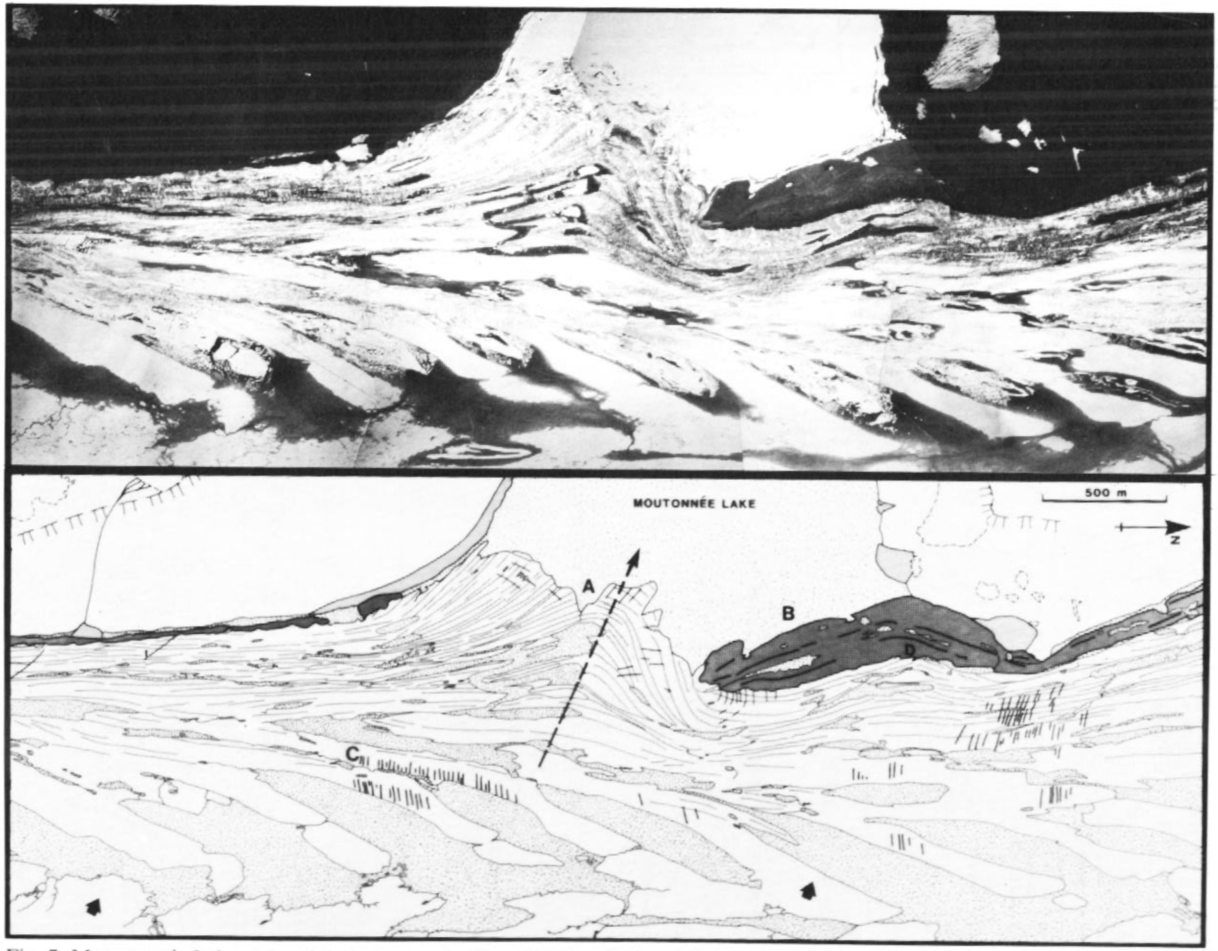


Fig. 7. Mountonnée Lake: (a) aerial photo mosaic (from BAS vertical aerial photosurvey 1978–79) and (b) the structural map of the same area. See text for discussion of lettered features. (See p. 89 for legend.)

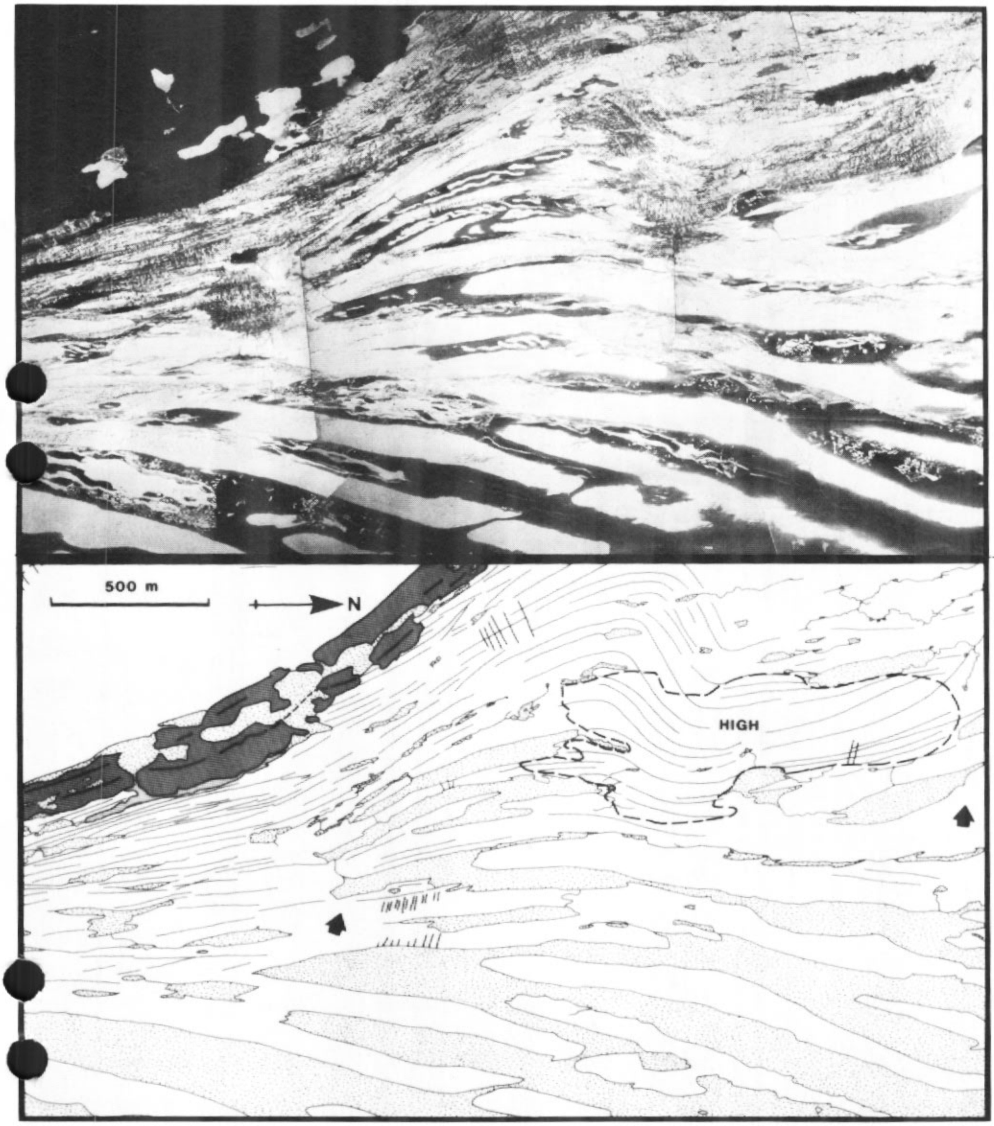


Fig. 8. Southern portion of the Ablation Valley area: (a) aerial photo mosaic (from BAS vertical aerial photosurvey 1978–79) and (b) the structural map of the same area. See text for a discussion of the area labelled 'High'. (See p. 89 for legend.)

within the adjacent ice can be traced obliquely into the debris. By following the trend of foliation from where it is debris-covered onto the exposed ice, it is plain that the ice shelf itself is not charged with debris. The debris has apparently been deposited supraglacially and independently of the ice shelf. A similar situation occurs on the south side of the cusp. Thus we suggest that this moraine is genetically unrelated to the ice shelf, i.e. it is not an 'ice shelf moraine' (Clapperton and Sugden, 1983). The moraine bar itself consists of two morphologically distinct parts. The eastern half (proximal to the ice shelf) has a hummocky and kettle-holed topography typical of

Fig. 9. The glacier tongue in Ablation Lake viewed looking to the west. The grounded part of the ice shelf is seen in the bottom left of the pictures (photo: J. M. Reynolds).

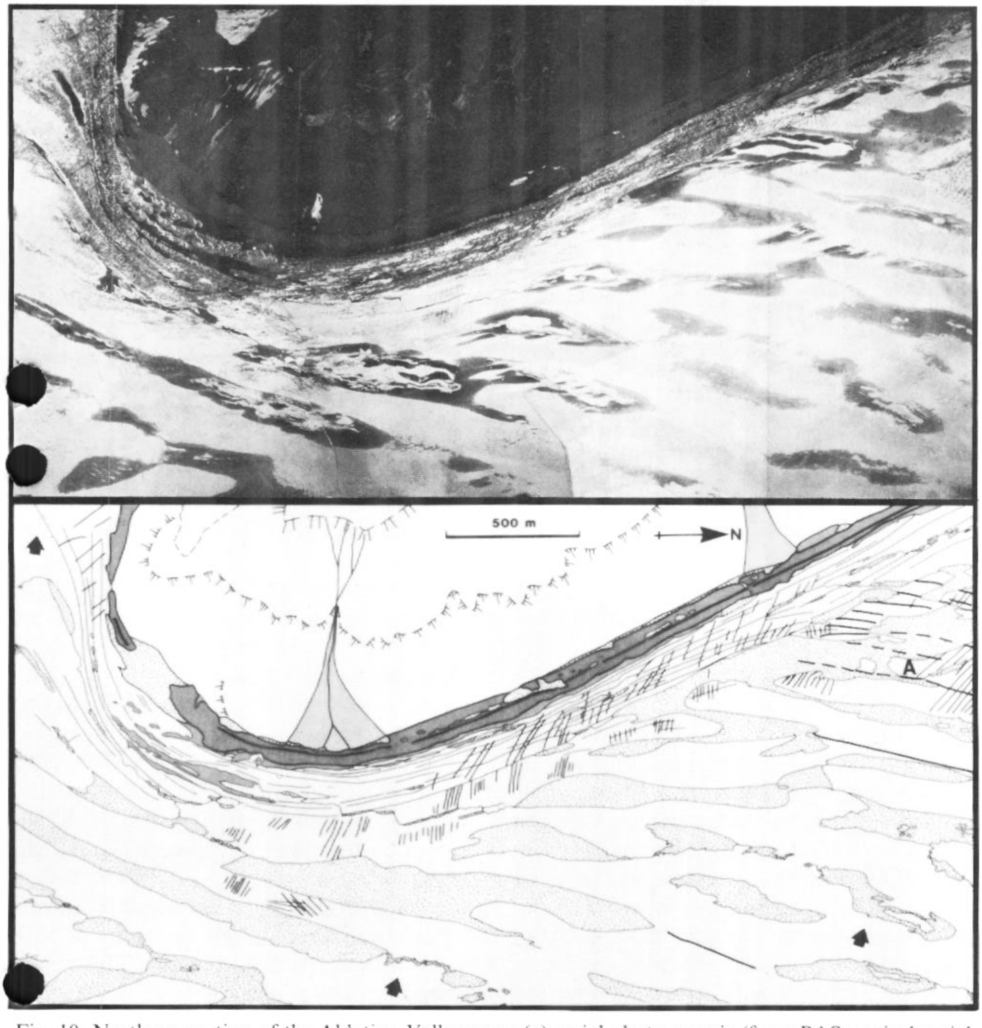


Fig. 10. Northern portion of the Ablation Valley area: (a) aerial photo mosaic (from BAS vertical aerial photosurvey 1978–79) and (b) the structural map of the same area. See text for a discussion of the feature marked 'A'. (See p. 89 for legend.)

ice-cored moraine (e.g. Østrem, 1959, 1964) and in parts exposes clean ice (R. B. Heywood, pers. comm.). The western (distal) half is more regular and wedges out between the debris-covered ice of the shelf and the cliffs of Alexander Island. The western edge of George VI Ice Shelf within the moraine bar is construed as being marked by the boundary between the proximal and distal zones as described above.

Ablation Valley

The types of structures exposed in this portion of the ice shelf are primarily the same as those around Moutonnée Lake. The dominant structure is transverse foliation (Fig. 8) here parallel to the west side of the sound, which is cross-cut by longitudinal foliation some of which has been exploited by supraglacial melt-water to form drainage channels for run-off to Ablation Lake.

A portion of the ice shelf in this region has a slightly elevated topography relative to the surrounding area and is associated with major changes in the orientation of local structures (Fig. 8). It is thought that this raised and disturbed area (shown in Fig. 8 by heavy dashed lines) indicates where the ice shelf is grounded locally, perhaps on a submerged rock bar such as at Moutonnée Lake. The grounded ice inhibits the flow of the ice shelf westwards causing the ungrounded ice to flow around the obstruction and so folds the structures (Figs 5, 8). To the north of the grounded ice, the ice shelf pushes westwards into Ablation Lake and forms a prominent ice tongue about 2.8 km long (Fig. 9). According to Heywood (1977, p. 45) the ice tongue is grounded over its length and does not rise or fall with the tide. The ice tongue splits into two parts with the smaller limb flowing northwards into a small cove where it impinges against the shoreline, while the principal ice tongue flows into the main body of the lake. The divergence in flow has resulted in a chasm in the ice with an area of about 0.17 km^2 (Heywood, 1977, Fig. 4). Comparison of Figs 5 and 9 shows how the shape and size of the chasm has changed between 1966 and 1978–79.

The southern edge of the ice tongue in Ablation Lake consists of 12 lobes separated from each other by embayments which are filled with lake ice and which evidently are orientated parallel to longitudinal foliation.

Crevasse traces can be seen cross-cutting longitudinal foliation to the north of the area (A; Fig. 10). The longitudinal foliation directly influences the orientation of the surface melt-water lakes which are elongated parallel to the foliation. The crevasse traces are clearly seen, as snow picks out the depressions at the ice shelf surface which are shown as a light grey on the aerial photographs. It is important, especially in this area, to distinguish between the morphology associated with these crevasse traces and that of the transverse foliation seen in the swath of the ice shelf to the west. The transverse foliation is parallel to the edge of the ice shelf and is itself cross-cut by oblique open fractures inclined at about 45° to the foliation. The fractures are thought to be a consequence of local shear generated by the swing towards the north of the flow unit as it impinges against the island.

In all of these areas described above, both the transverse and longitudinal foliations observed near the western margin of the ice shelf are demonstrably contiguous with the structures inferred from the pattern of lakes on the satellite imagery. This result gives us greater confidence in the remote sensing interpretation of the structures and, by inference, general ice flow dynamics, of bounded ice shelves generally.

Conclusions

George VI Ice Shelf is structurally complex with a range of foliations and crevasse traces. Component flow units reflect the structure of source glaciers above the grounding line where deformation is controlled by flow as definite units. Velocity vectors indicate that relative motion or shear between adjacent flow units persists well onto the ice shelf. These variations are mirrored in the thickness pattern of the ice shelf. The pre-existing structures of some flow units become contorted by localized lateral spreading and longitudinal compression in the manner typical of piedmont glaciers. Where major flow units impinge directly on the coast of Alexander Island, folding through longitudinal compression is amplified and the dominant structures become orientated parallel to the coast. Studies on the ground are needed to establish the true geometric relations of the different structures but the complex pattern is clearly seen in low-level aerial photographs and from the ground.

We believe that most ice shelves have structures which are inherited from their source flow units and which may be as complex as those in George VI Ice Shelf. Except in a few areas of negative or zero net mass balance, these structures will not be visible. The confinement of the ice shelf within George VI Sound restricts the freedom of flow of the ice. However, the effects of the ice shelf impinging against eastern Alexander Island are restricted to a band about 150 m wide along the western edge of the ice shelf.

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