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Ice shelf grounding zone features of western Prydz Bay, Antarctica: sedimentary processes from seismic and sidescan images

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Abstract: Several grounding zone wedges were left on the floor and flanks of Prydz Channel in western Prydz Bay by the Lambert Glacier during the last glacial cycle. Seismic profiles indicate that vertical accretion at the glacier bed was the most important depositional process in forming the wedges, rather than progradation by sediment gravity flows. Sidescan sonographs reveal extensive development of flutes on the sea floor inshore from the wedges, indicating deformable bed conditions beneath the ice. The region inshore of the east Prydz Channel wedge features extensive dune fields formed by currents flowing towards the grounding zone. This orientation is consistent with models of circulation beneath ice shelves in which melting at the grounding line generates plumes of fresher water that rise along the base of the ice shelf, entraining sea water into a circulation cell. The Lambert Deep is surrounded by a large composite ridge of glacial sediments. Internal reflectors suggest formation mostly by subglacial accretion. The sea floor in the Lambert Deep lacks dune fields and shows evidence of interspersed subglacial cavities and grounded ice beneath the glacier. The absence of bedforms reflects sea floor topography that would have inhibited the formation of energetic melt water-driven circulation.

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Key words: Amery Ice Shelf, grounding zone, Prydz Bay, sedimentology, seismic, sidescan

Introduction

Ice shelf grounding zones are important regions in Antarctic ice sheet dynamics since they form the zone of interaction between major ice streams and the Southern Ocean, and about 20% of the ablation of the Antarctic Ice Sheet taking place beneath ice shelves (Jacobs *et al.* 1992). The location of grounding zones is also sensitive to the ice sheet's response to sea level and climate change. The conditions at the bed of major ice streams are also thought to contribute to major aspects of ice behaviour (Alley *et al.* 1989, Boulton & Jones 1979). Both the grounding zone and the glacier bed are very difficult to study. Studies of sedimentation in grounding zones have been limited to indirect studies of the beds of ice streams (Alley *et al.* 1989), of modern temperate glaciers (Powell 1990) and small polar ice tongues (Powell *et al.* 1996), work on Northern Hemisphere palaeo-ice margins (King *et al.* 1991, Benn 1996, Hunter *et al.* 1996) and interpretation of seismic data from the Antarctic continental shelf (De Santis *et al.* 1994).

We present seismic reflection and sidescan sonar data from several grounding zone wedges of a major East Antarctic ice stream, the Lambert Glacier–Amery Ice Shelf system in Prydz Bay. These data give insight into the processes active beneath a major Antarctic ice stream as it approached the boundary between grounded ice stream and floating ice shelf and soon after the glacier retreated. The facies model developed from cores taken in the area was described by Domack *et al.* (1998).

Study area

Prydz Bay is a major re-entrant in the East Antarctic coast extending from 69–80°E latitude (Fig. 1). Its geometry reflects the structure of the underlying Lambert Graben, a major crustal structure with a history extending back to the Palaeozoic (Stagg 1985, Cooper *et al.* 1991). Through this structure flows the Lambert Glacier–Amery Ice Shelf ice drainage system, which drains about 20% of the East Antarctic interior, representing 11% of the entire Antarctic Ice Sheet (Allison 1979). This convergence of drainage means that the ice shelf grounding zone should fluctuate significantly with the waxing and waning of the East Antarctic Ice Sheet.

The outer shelf of Prydz Bay comprises relatively shallow banks with depths in the order of 400 to 100 m separated by a large transverse trough, the Prydz Channel, which is 150 km wide and 500–600 m deep at the shelf edge (Fig. 1). Prydz Channel extends inshore to the Amery Depression which occupies the inner part of Prydz Bay. The Amery Depression is mostly 600 to 800 m deep, with some deeper regions such

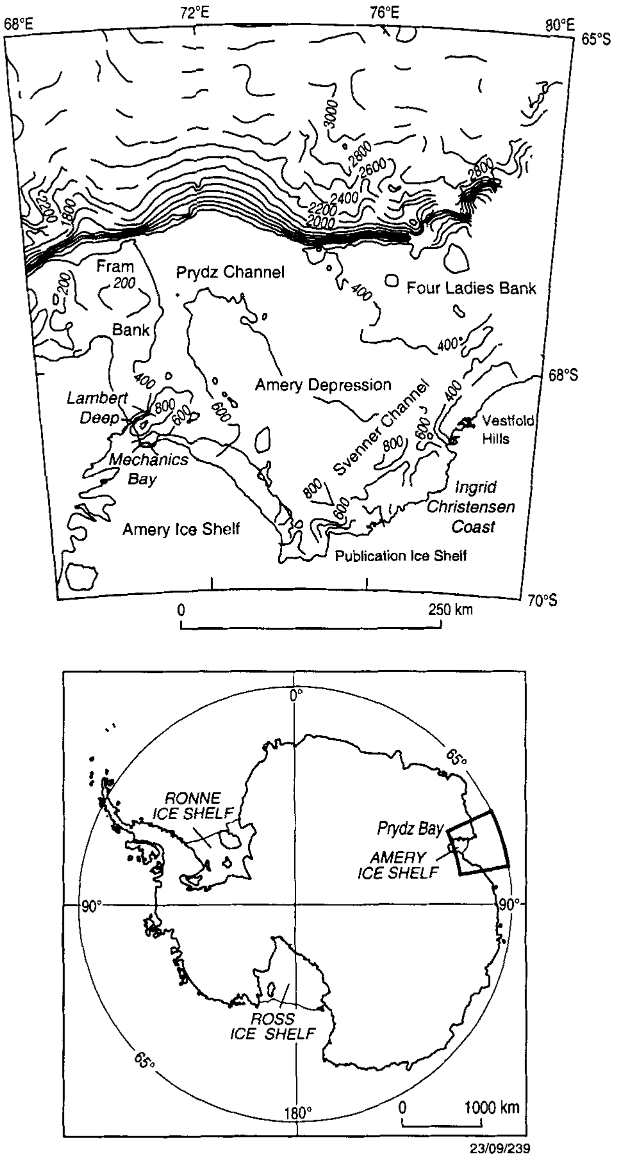

Fig. 1. Location maps of Prydz Bay and Amery Ice Shelf. Major geomorphic features of Prydz Bay are shown. Contours are in metres below present sea level.

as the Lambert Deep in the south-west corner of the bay which reaches 1100 m deep (Fig. 1). The great water depth and relatively sheltered conditions in inner Prydz Bay favour the development of a stable ice shelf through the glacial cycle, and features observed in the geological record there can be related to ice shelf processes.

O'Brien & Harris (1996) concluded that the morphology and stratigraphy of Prydz Bay result from advance of the Lambert Glacier and ice from the eastern side of the Bay to the shelf edge during major glaciations, with a fast-flowing ice stream occupying Prydz Channel. Grounding zone wedges, referred to as moraines, were identified in Prydz Channel, Lambert Deep and the Amery Depression by O'Brien (1994; Fig. 2). O'Brien & Leitchenkov (1997) interpreted the wedges as having formed at grounding line positions temporarily occupied during the retreat of the Lambert Glacier from Prydz Channel, although they recognized the possibility that some of these wedges may have been the limit reached during the Last Glacial Maximum.

Method

Survey lines were planned and topographic features were mapped using seismic and echo sounder date collected by previous cruises to Prydz Bay (Stagg 1985, Mizukoshi *et al.* 1986, Kuvaas & Leitchenkov 1992). New data were collected on the 1996/97 Australian National Antarctic Expeditions (ANARE) marine geoscience program on the RSV *Aurora Australis*. Seismic data were acquired using a single 2.5 l (0.7 generator, 1.8 l injector) bubble-free GI airgun and a 25 m, 4-channel high resolution hydrophone streamer. Sidescan sonar data were recorded with an EG&G 960 tow fish and an EG&G 996 digital modem connected to a Geoacoustics SES 1000 recording system. The sidescan sonar was operated with a swath width of 1125 m. Gravity cores described elsewhere were collected using a 1 tonne bomb connected to 3 or 6 m length, 10 cm diameter core barrels (9 cm diameter PVC core liner, Domack *et al.* 1998).

Sidescan data were examined as analogue paper records. The orientation of linear features was corrected for slant. Seismic data were examined first as single channel monitor records and were then processed by summing the four channels. Important parts of lines were filtered using a bandpass filter (2/4 Hz-100/150 Hz) and various forms of deconvolution and gain enhancement tried using VISTA software on a PC. It was found that, for shallow data, spiking deconvolution allowed detection of reflectors that were otherwise masked by the strong bottom signal.

Prydz Bay grounding zone wedges

Distribution and nomenclature

Examination of existing seismic and echo sounder lines revealed a number of grounding zone wedges and other banks and ridges (Fig. 2). It was not clear from the existing data that all these features are moraines or grounding zone wedges. Iceberg ploughing, in particular, degrades the morphology of those in shallower water. Grounding zone wedges were identified by their asymmetric cross-section and internal reflection geometry suggesting that they were depositional rather than erosional features. They were named according to the major topographic feature they are associated with, and numbered with the most seaward being no. 1 (Fig. 2). The wedges that received the most detailed attention were east Prydz Channel (EPC)-1 and west Prydz Channel (WPC)-1 and Lambert Deep (LD) wedges 1 and 2.

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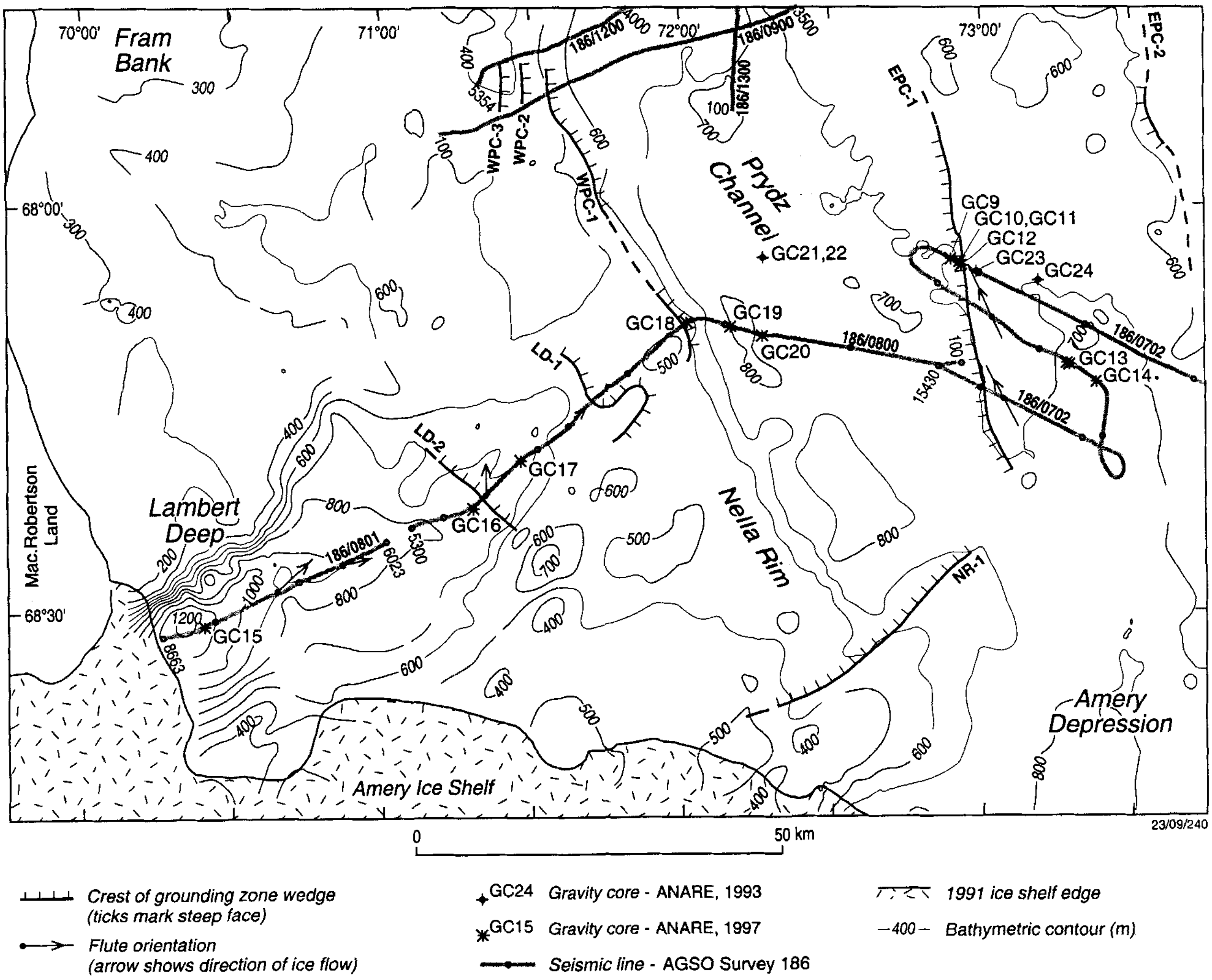

Fig. 2. Location of grounding zone wedges and moraine-like ridges in western Prydz Bay and location of seismic and sidescan lines. Flute orientations also shown. Feature names are abbreviated as follows: EPC: east Prydz Channel, WPC: west Prydz Channel, LD: Lambert Deep, NR: Nella Rim

East Prydz Channel 1: seismic data

East Prydz Channel grounding zone wedges are asymmetric banks 30–50 m high and 15–20 km wide, trending north-north-west across Prydz Channel and the Amery Depression. They have steep western faces (Fig. 3) sloping towards 263° on the most northerly profile, 255° on the central crossing and 275° on the most southerly profile (Fig. 2). The gently sloping eastern side of both wedges displays ridges and swales that O'Brien (1994) interpreted as subglacial flutes oriented at a low angle to the wedge crests.

EPC-1 was crossed by 3 GI-gun seismic sections (Fig. 2). The most southerly, deepest water section shows the wedge as having a steep face sloping towards 275° and three asymmetric steps on its upper surface, each having a steep western face and gentle eastern face (Fig. 3). The other two profiles display a sharp notch in the wedge surface just east of the top of the steep face (Fig. 3). The upper surface then is slightly concave-up, with numerous diffractions emanating from the wedge surface, before a slightly convex-up segment rise towards the eastern end of the wedge. The western face of the wedge is smooth and descends asymptotically to the floor of Prydz Channel (Fig. 3). Internal reflectors are obscured by the strong bottom signal but sub-horizontal to slightly mounded reflectors can still be seen (Fig. 3). Several reflectors show a slight dip from east to west, towards the steep face.

EPC-1 most closely resembles a grounding line wedge from the Weddell Sea described by Anderson (1997) although it is smaller in size than the Weddell Sea example and wedges in the Ross Sea (Shipp & Anderson 1997) and Antarctic Peninsula shelf (Bart & Anderson 1997). EPC-1 displays the low angle internal reflectors seen in other wedges. Its steep face might be interpreted as evidence for progradation of this face however internal reflectors are not parallel to it. If it was constructed by progradation, foresets of similar dip to the face must be present only within the part of the wedge obscured by the bottom reflector (Fig. 3). This arrangement would be consistent

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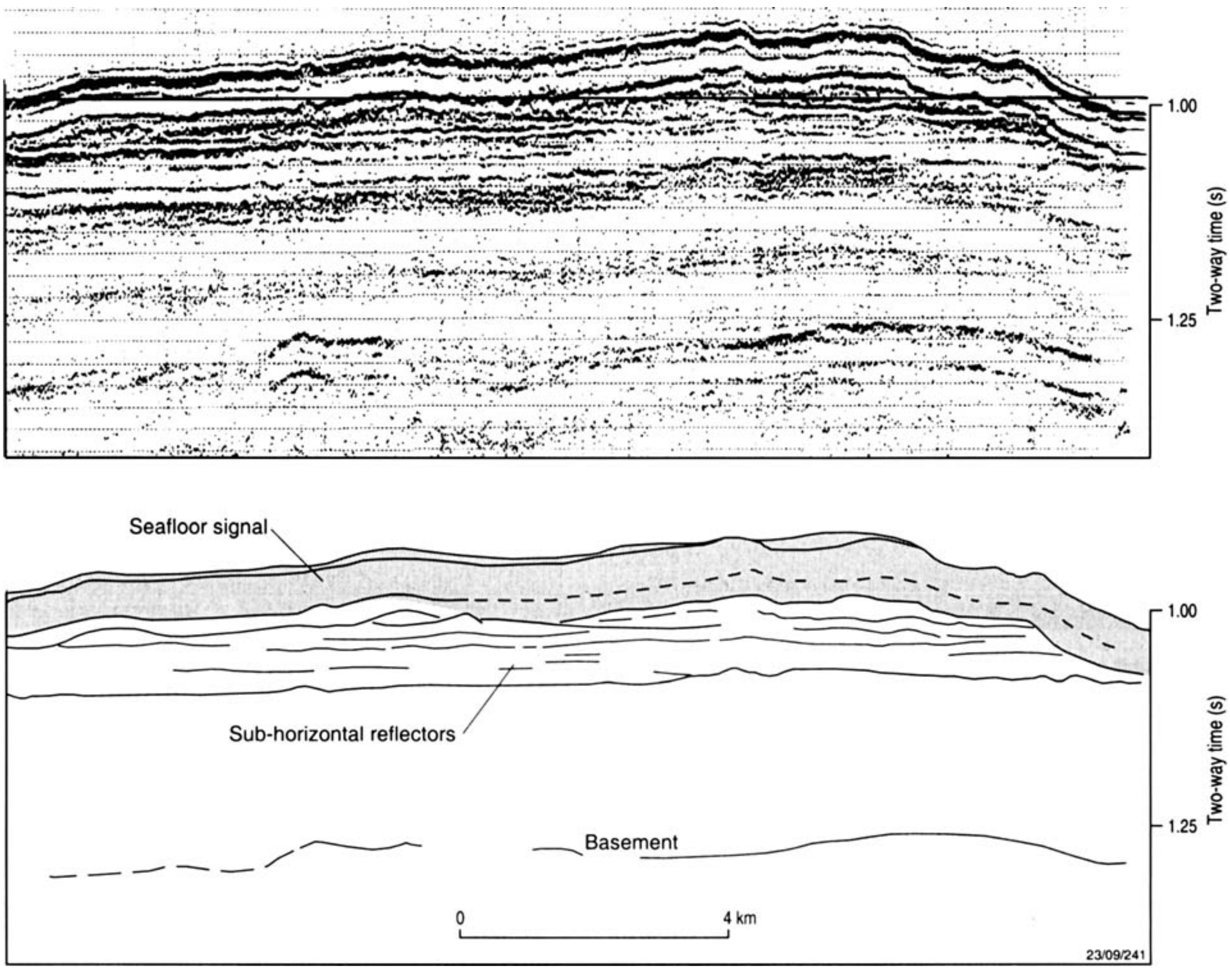

Fig. 3. Sections of seismic line 186/0702 crossing the east Prydz Channel-1 wedge. Seismic data collected with a 2.5 l GI gun and 25 m, 4 channel streamer. Processing sequence: vertical stack, bandpass filter (2/4 Hz-100/150 Hz), spike deconvolution and AGC. Seaward side is to the right, up-glacier side is to the left. Ice motion indicated by flutes is obliquely out towards the viewer. This section is the most southerly, deepest water crossing (Fig. 2) and the least affected by iceberg scouring. It features three small steps on its upper surface and short, sub-horizontal reflectors are visible through the bottom signal.

with high resolution records from the Antarctic Peninsula shelf in which steeper foresets were only observed relatively close to the steep face of a wedge (Vanneste & Larter 1995, Larter *et al.* 1997 fig. 3).

East Prydz Channel-1 - sidescan features

Flutes

Fluted surfaces display linear ridges and troughs that mostly continue for more than 1 km across the sidescan record (Fig. 4). Ridges are up to about 10 m high and 200 m across. Some very fine fluting appears as finely striated sea floor, striae being parallel and unidirectional (Fig. 4). We interpret these features as fluted till surfaces formed by moulding of the subglacial bed because they show extremely uniform orientations and continuity. The flutes are cut by iceberg scours and therefore predate post-glacial open water. Flute orientations vary across the area but groups of flutes show minimal deviation from the overall direction. Two sets of directions are present. Flutes in the Amery Depression trend north to north-east. Flutes closest to the wedge crest trend between 330–360°, indicating ice movement in a northerly to north-north-easterly direction.

Flutes and bedforms

Many surfaces with flutes more than 140 m apart display asymmetric, cresentic to sinuous-crested ridges (Fig. 4). Between each flute, these ridges are parallel and appear identical to current-formed dunes (e.g. Harris 1988). These bedforms are on average 50 m crest to crest and are convex to the south east, except for one set on east Prydz Channel-2 wedge which shows ridges curved to the north-west. The more widely spaced the flutes and the lower flute relief, the less curved are the "dune" crests. In the case of very widely

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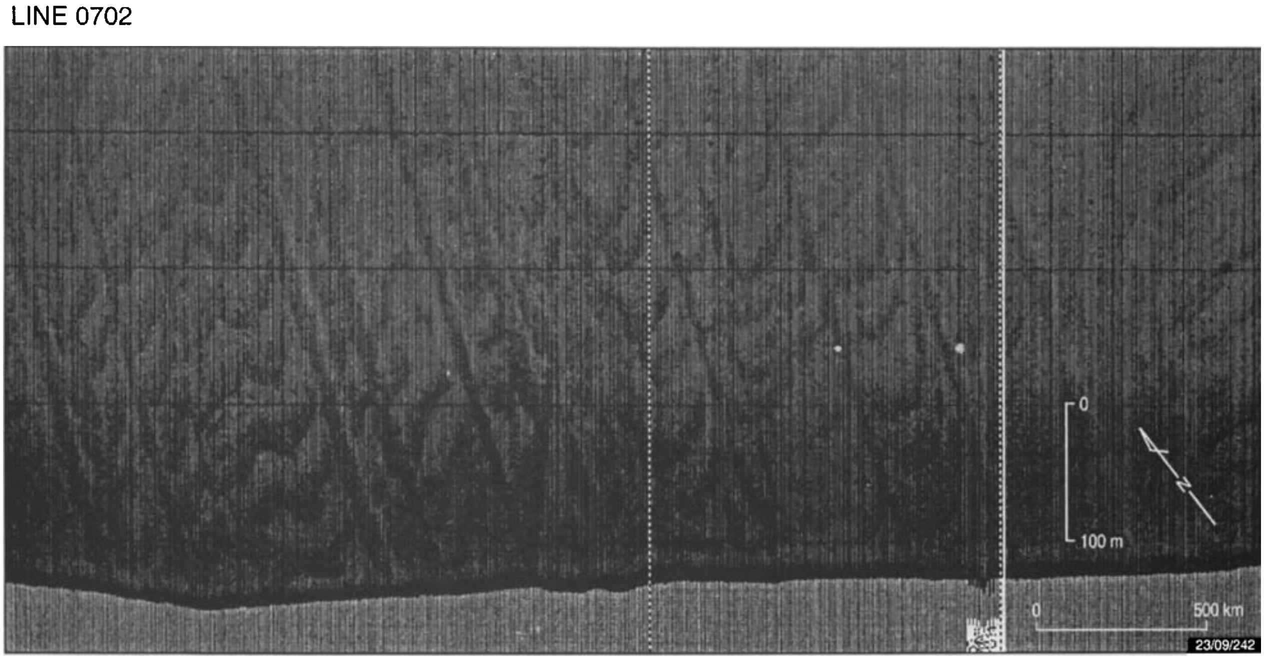

Fig. 4. Flutes and dunes inshore of EPC-1 (Line AGSO 186/0702). Note the change in flute spacing from west to east. Ice flow was from south-east to north-west. Dune crest curvature indicates current flow in the opposite direction.

space flutes (>300 m), dune crests become sinuous. In a few locations, the bedforms seem to pinch out against flute sides.

Fluted surfaces with transverse bedforms have been observed in a number of locations. Solheim & Pfirman (1985) observed "washboard" structures in iceberg scours which they attributed to pushing of the sea floor by an iceberg. These differ from the Prydz Bay features in being confined to one isolated furrow which is clearly an iceberg scour because it changes direction several times on the image. Josenhans & Zevenhuizen (1990) described glacier sole marks (flutes) and transverse ribs formed on till on the floor of Hudson Bay, which they attributed to lift off and touch down of the ice sheet during retreat. Their fig. 4 illustrates features that are less regular than the Prydz Bay forms and seem to disrupt the edges of the associated flutes, in contrast to the EPC bedforms that seem to wedge out against the side of the flutes, and curved features like those in Prydz Bay. The first type clearly involve the material that forms the flutes and the mechanism of ice deformation of the bed suggested by Josenhans & Zevenhuizen (1990) is the most plausible. Those features most closely resembling the EPC bedforms, however, we interpret as dunes. Also the Amery Ice Shelf has a very low gradient base (Hellmer & Jacobs 1992) and its drainage system has a long response time to external influences (Allison 1979) so it is hard to envisage its movements producing push ridges with short wavelengths comparable to the EPC bedforms.

We interpret the EPC bedforms as dunes formed in granular sediment overlying the fluted till surface by current reworking of fine grained material deposited between flutes soon after grounding line retreat. Dune orientations indicate currents flowing parallel to the flute direction but with the reverse sense to ice flow, i.e. towards the south-east. Spacing of around 50 m implies a bedform height in the order of 1 m (Ashley 1991). Such bedforms would have formed under current flows of greater than 0.4 m sec^{-1} (Ashley 1991).

Gravity cores from the area typically recovered silcious muddy ooze (SMO) sharply overlying pebbly muds and diamicton (Harris *et al.* 1997) although one core from the Amery Depression collected on a previous survey did contain fine sand separating SMO and mud that may represent a sample of the dune material (O'Brien *et al.* 1993). Scarcity of sand in the cores need not rule out the interpretation of the bedforms as sandy dunes. Harris *et al.* (1992) found that most cores taken on a subtidal sandbank encountered bioturbated swale deposits. Vibrocorers had to be located with some accuracy on the crest of bedforms to penetrate cross bedded sand. In the case of the EPC-1 bedforms, they are probably a single train of dunes resting on an erosion surface. The SMO layer in all cores formed after current activity waned, draping the dunes and intervening troughs. Iceberg scours cutting the dune fields and the SMO drape indicate that the dunes pre-date the development of open water conditions in the south-western corner of Prydz Bay.

Wedge front features

The steep face of EPC-1 appears dark and relatively featureless on sidescan sonographs (Fig. 5). At the base of the slope, the dark slope material interleaves with light coloured sediment on the floor of Prydz Channel. The interleaving is oriented south-west–north-east, down the slope produced by the wedge front and the regional slope on the side of Prydz Channel. This

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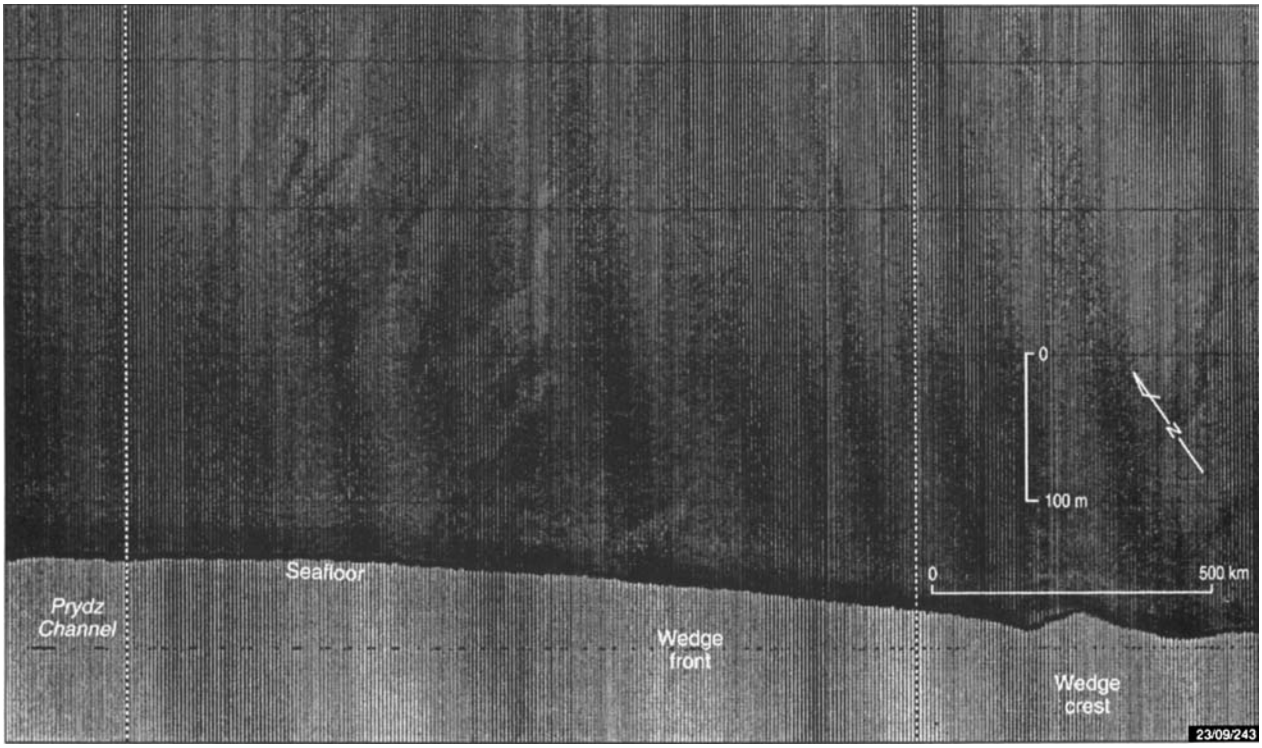


Fig. 5. Sidescan sonograph of the seaward face of wedge EPC-1. Sediments of the wedge front interdigitate in plan view with light coloured sediment flooring Prydz Channel. No debris flow or outwash cones are visible.

pattern was probably produced by minor slumping and sediment gravity flow deposition on the wedge front, resulting in an irregular surface of glacimarine sediment, which was then onlapped by SMO which appears lighter on the sonographs. Large debris cones and outwash fans are not visible on any of the crossings of the wedge front. A gravity core from the wedge front recovered SMO overlying granulated muds and silty clays formed by meltout of debris from a floating ice shelf and one thin turbidite sand (Domack *et al.* 1998).

Smooth sea floor

Smooth, featureless sea floor is confined to Prydz Channel west of EPC-1 and north of WPC-1, and a few small areas between other features in the Amery Depression.

Iceberg scours

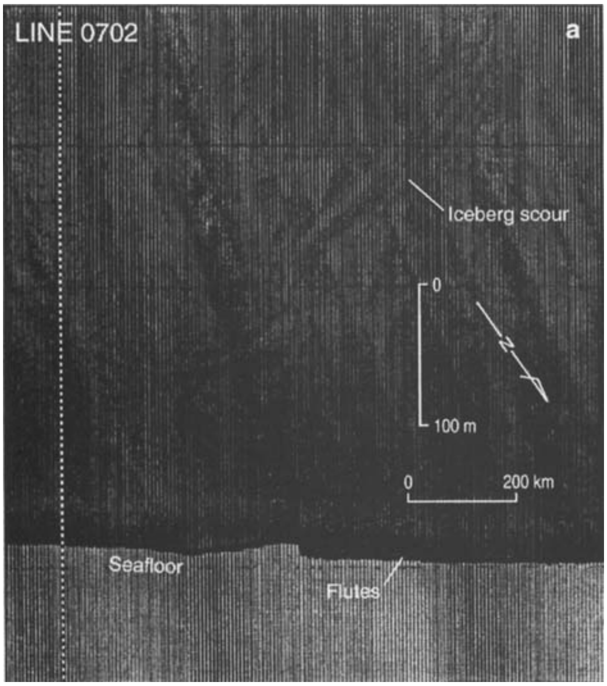
Iceberg scours are straight to meandering troughs with single or multiple keel marks in their floors (Fig. 6). Individual tracks may be a few tens of metres to 100 m across. Berms (Longva & Bakkejord 1990) of thrust sediment are common around the scour. Iceberg scours are most common in shallower water, with most occurring where the sea floor is less than 690 m deep (O'Brien 1994).

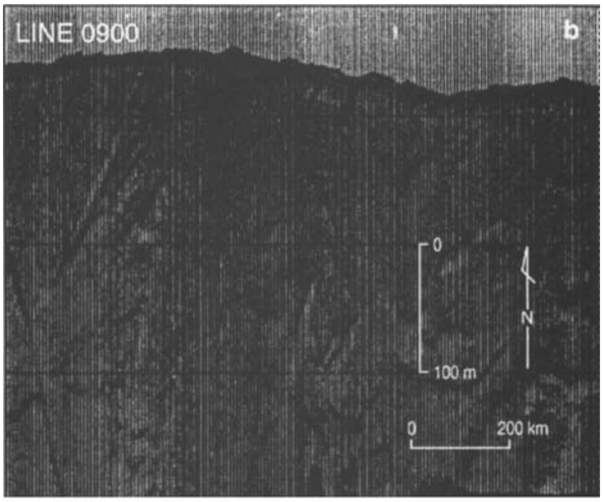
Iceberg scours in shallow water appear sharp, whereas in the deeper parts of Prydz Channel scours appear subdued and rounded with diffuse edges (Fig. 6). These deeper scours are probably older features partly draped by pelagic sediments. This interpretation is supported by a gravity core (AGSO 186/GC22) which recovered horizontal siliceous, muddy ooze (SMO) overlying disturbed muds and SMO fragments representing an ice keel turbate. These older scours are present in water depths deeper than the likely maximum draft of modern icebergs (600 m; O'Brien & Leitchenkov 1997) and so probably formed during a past sea level low stand and were subsequently filled with SMO.

Scattered across the survey region are straight to slightly curved, isolated scours 50–70 m across and 10–20 m deep. They have berms of sediment up to 10 m high adjoining the central valley. These scours are younger than flutes and most other bed features, and continue in water much deeper than the usual limit of iceberg scouring. They trend between north-west and north-east. The observation that these features are younger than most others observed on the sonographs and the presence of berms around them suggest that they are iceberg scours formed by single keels on the base of large icebergs.

Depositional model for east Prydz Channel-1

East Prydz Channel-1 displays many characteristics of a grounding line wedge (Powell & Alley 1997, Anderson 1997, Shipp & Anderson 1997, Bart & Anderson 1997). The glacier bed must have been deformable, because flutes indicate bed moulding almost right up to the wedge crest. Foresets, if present, are probably confined to the outer edge of the wedge,





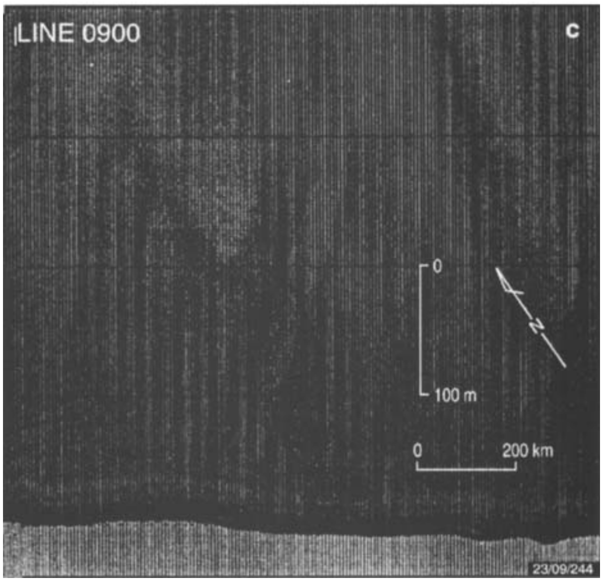


Fig. 6. a. Sidescan sonograph of iceberg scours cutting flutes and dune fields, landward of EPC-1 in the Amery Depression. **b.** Intense iceberg scouring in less than 600 m of water, edge of Prydz Channel (Line AGSO 186/0900). **c.** Buried, relict iceberg scours in Prydz Channel (Line AGSO 186/0900).

and are masked by the sea bed reflection. This suggests that the wedge grew predominantly by vertical accretion at the glacier sole rather than by progradation of debris released at the grounding line in a "till delta" (Alley *et al.* 1989). This is consistent with the cores in which there are very few sediment gravity flow deposits on the wedge front and in Prydz Channel (Domack *et al.* 1998). This is possibly because the ice flow direction was at a low angle to the wedge crest so that the wedge front slope grew from a small amount of debris squeezed out obliquely from the grounding line.

The dune fields formed immediately after lift off of the grounded ice from the wedge, in a circulation cell developed in the cavity under the ice shelf (Fig. 7, MacAyeal 1985, 1985, Jacobs *et al.* 1992, Hellmer & Jacobs 1992). Melting at and just downstream of the grounding line produced a buoyant freshwater plume that rose along the base of the ice shelf, entraining seawater with it. Seawater flowed in along the bed towards the grounding line to replace the entrained seawater outflow. Point sources of englacial meltwater cannot be identified and were probably not involved in the process (cf. Powell *et al.* 1996). Large dunes indicate flows in excess of 0.4 m sec^{-1} (Ashley 1991) which is a much higher velocity than the modelled velocity of such plumes (Macayeal 1985). This high velocity may have been caused by the narrow cavity in the initial phase of ice withdrawal or the wedge acting as a sill on the edge of the sub-ice shelf cavity. Modelled water velocities are much higher at the bottom in a narrow sub-ice shelf cavity (Hellmer & Olbers 1989) or over a sill (Hellmer & Jacobs 1992). Fine material winnowed from the bed was removed from the sub-ice shelf cavity by the return flow of the cell. The drape of SMO on the dunes indicates that the high-velocity regime was short lived, as the cavity expanded and a more complex, low-velocity current regime like the present developed (Williams *et al.* in press).

Lambert Deep wedges - seismic data

Line 186/0801 (Fig. 8) was acquired to study the grounding zone wedges surrounding Lambert Deep (Fig. 2). West Prydz Channel-1 is the largest feature, rising about 300 m above the

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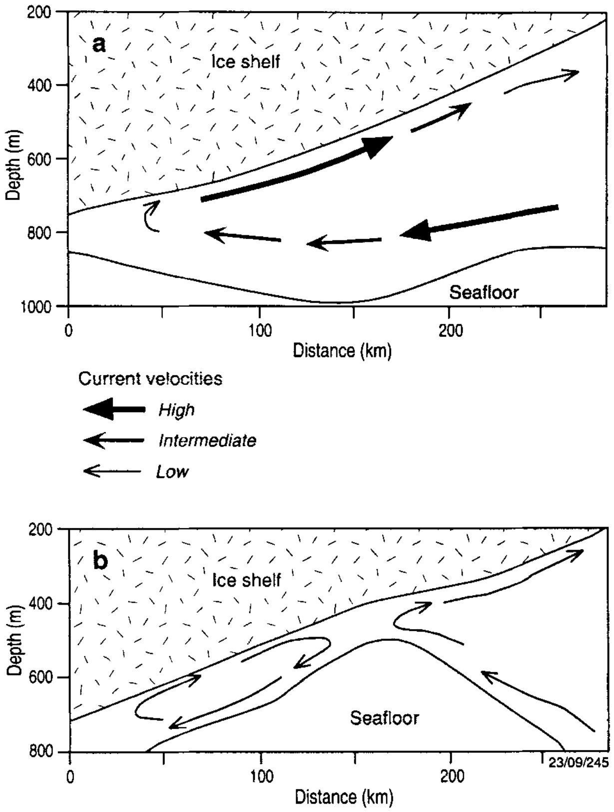

Fig. 7. Currents in circulation cells beneath an ice shelf with different bed configurations (based on figs 6 & 8 of Hellmer & Jacobs 1992). Current velocities shown qualitatively based on stream function contours calculated by Hellmer & Jacobs (1992). **a.** Circulation with a small step in the sea bed like EPC-1. Maximum current velocities occur over the step and beneath the ice shelf. **b.** Circulation with a high hill similar to WPC-1. Two weak cells develop on either side of the hill.

floor of Prydz Channel. It has a steep, slightly concave-up face sloping north-east and a gentler, convex-up face sloping south-west. This slope features two small, asymmetric ridges 10–30 m high and about 5 km across. These are probably smaller grounding zone wedges and so are numbered Lambert Deep 1 and 2. The crest of WPC-1 is shallower than 690 m and is rough from iceberg ploughing. The rest of the surface is smooth apart from a small channel (1–2 km wide and 10 m deep) between Lambert Deep 1 and 2. It is symmetrical in cross section and is probably oriented normal to the contours of Lambert Deep.

The top of acoustic basement is a strong amplitude reflector marking a generally irregular surface, that gradually deepens landward. Locally the basement is faulted and shows asymmetric rift-basins (400 m deep) filled by a wedge of diverging strata (growth fault in sequence PS4 of Cooper *et al.* 1991). In the Lambert Deep, the basement is overlain by a lower sequence featuring low amplitude, parallel folds truncated at the sea floor. This sequence comes close to cropping out through most of the Lambert Deep. In particular, between LD-1 and LD-2 it forms a ridge that would have formed a pinning point from which WPC-1 grew. Beneath west Prydz Channel-1 this sequence is truncated by an unconformity and is overlain by a middle sequence up to 400 m thick that features medium amplitude, continuous and slightly diverging reflectors that dip seaward and are truncated at the sea floor beneath the landward side of the wedge. The crest and steeper side of the wedge are covered by an upper sequence about 100 m thick. The reflectors downlap onto an erosion surface.

Seaward of west Prydz Channel-1, in Prydz Channel, there is a seismic sequence about 200 m thick above acoustic basement. It is characterized by sub-parallel, sub-horizontal, closely spaced, low to medium amplitude reflectors onlapping basement irregularities.

The lower sequence probably comprizes Mesozoic red beds which were identified in ODP site 741 (Turner 1991). This is supported by the presence of red to brown sediment in all cores from the Lambert Deep. The middle seismic sequence is probably composed of glacial sediments deposited downstream of a Mesozoic outcrop pinning point. The gently sloping, divergent reflectors suggest deposition by sub-ice shelf melt out onto a gently sloping surface rather than progradation from a grounding line. The upper sequence comprizes the latest glacial sediments formed by draped sediment deposited from the base of a floating ice shelf or by subglacial till deposition (Domack *et al.* 1998) but some progradation is possible in the case of the steep clinoforms on the seaward slope of WPC-1.

Lambert Deep wedges: sidescan features

Fluted surfaces

Much of the surface of the Lambert Deep is covered with flutes (Fig. 9). They are more closely spaced and better developed than the Amery Depression flutes, mostly less than 100 m apart with an average spacing of about 50 m. The flutes are mostly oriented north-east–south-west parallel to the long axis of the Lambert Deep valley. However, in one area the flutes are oriented more northerly (Fig. 2).

Steps in the fluted surface

In addition to the widespread flutes, the sea floor in Lambert Deep exhibits steps that separate fluted surfaces of slightly different elevation. These steps vary from parallel to normal to the flute direction and commonly bifurcate at varying angles (Fig. 9). They commonly extend for several kilometres and are probably no more than a few metres high. These steps also form the boundaries of some of the other bed types such as smooth surfaces and those displaying lobate features (Fig. 10). The shadows on the sonographs indicate the presence of a small trough at the base of many steps. These steps probably formed as small slip faces at the boundary between patches of grounded ice and cavities (Fig. 11). This

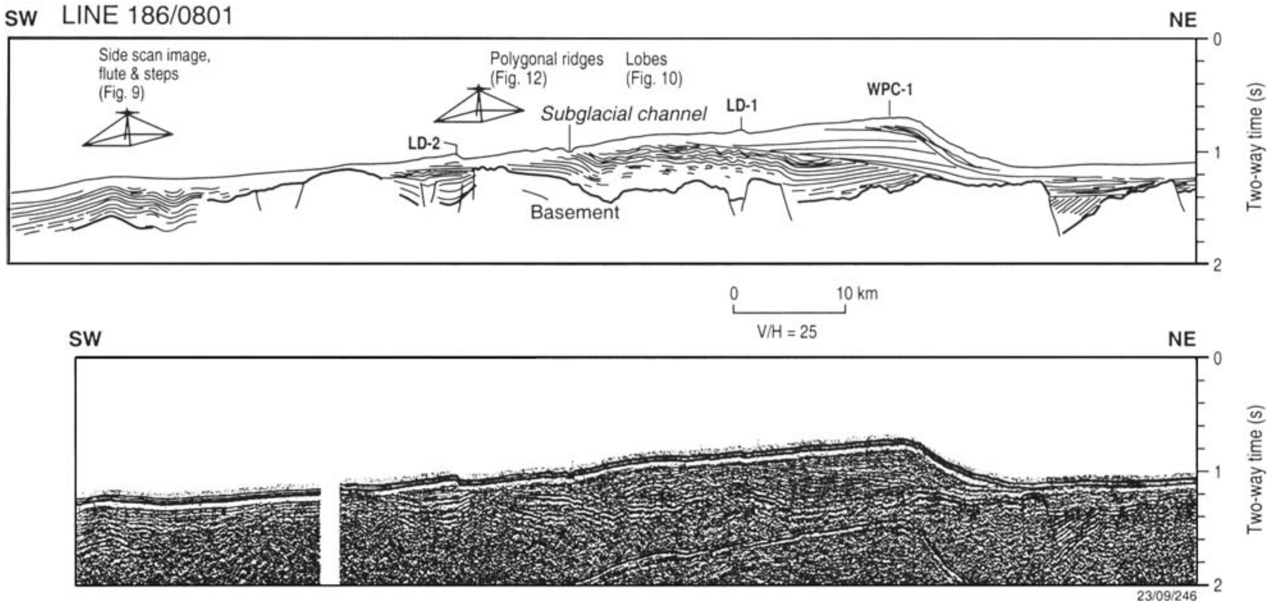

Fig. 8. Seismic line and interpretation crossing wedges WPC-1 and LD-1 and LD-2. Seismic sequences are, from the base, crystalline basement, Mesozoic red beds, Cenozoic glacials forming the bulk of the ridge and the most recent foresets formed on the WPC-1 front. Location of other figures is also shown. Data collected with a 2.5 l GI gun. Single channel monitor record.

interpretation also explains the distribution of smooth surfaces and some hummocky surfaces (see below).

Smooth surfaces

A patch of smooth sediment can be seen on the downstream side of LD-2 and in a few other places where the patches are bounded upstream and on the sides by steps. A few patches show faint traces of fluting, possibly because old flutes are buried by more recent sediment. These areas were probably formed by sediment drape on the floors of late stage subglacial cavities just before ice retreat, so that they were undisturbed by bed deformation (Figs 10 & 11).

Hummocky sediment surfaces

Hummocky, lobate sediment surfaces can be seen in three settings in the Lambert Deep area (Fig. 10). They are:

1) Between a step and an area of smooth sea floor, lobes of sediment extend towards the smooth sea floor (Fig. 10). We interpret these features as lobes of sediment squeezed into a cavity from the local grounding line represented by the step.
2) The transverse channel between LD-1 and LD-2 has lobate sediment on its steepest side, suggesting formation by slumping or creep of sediment on the channel side.
3) The steep faces of LD-1 and LD-2 display sediment lobes, suggesting mass movement on the wedge front.

Transverse ridges with scalloped edges

On the landward sides of LD-1 and LD-2 crests are fluted surfaces with transverse ridges that resemble the dunes on EPC-1 and EPC-2, but are more closely spaced and linear or slightly convex down glacier (Fig. 12). These ridges affect the adjacent flutes, forming a scalloped edge to the field of transverse ridges (Fig. 12). Therefore, they formed simultaneously with the bounding flutes, rather than afterwards as in the case of the EPC dune fields. They are probably push features resulting from irregular movement of the grounding line or episodic lift off caused by tides or, seasonal readvance. They most closely resemble the washboard pattern of Solheim & Pfirman (1985) and the ribbed features of Josenhans & Zevenhuizen (1990). Solheim & Pfirman (1985) interpreted the pattern they observed in the floor of iceberg scours as the result of episodic pushing by a grounded ice berg. Transverse ridges formed by episodic movement of the grounding line may have formed in the Lambert Deep because the ice stream feeding it is small compared to the main Lambert Glacier and so responded rapidly to short-term influences.

Polygonal ridges

Small sediment ridges that are irregular in plan view form networks covering two patches of sea floor in the Lambert Deep (Fig. 12). They are superimposed on flutes and have no preferred orientation, suggesting that they were not formed by moving ice. They closely resemble the rhomboidal pattern ridges described by Solheim & Pfirman (1985). The term polygonal is preferred because the shape of their network is less regular than that described by Solheim & Pfirman (1985).

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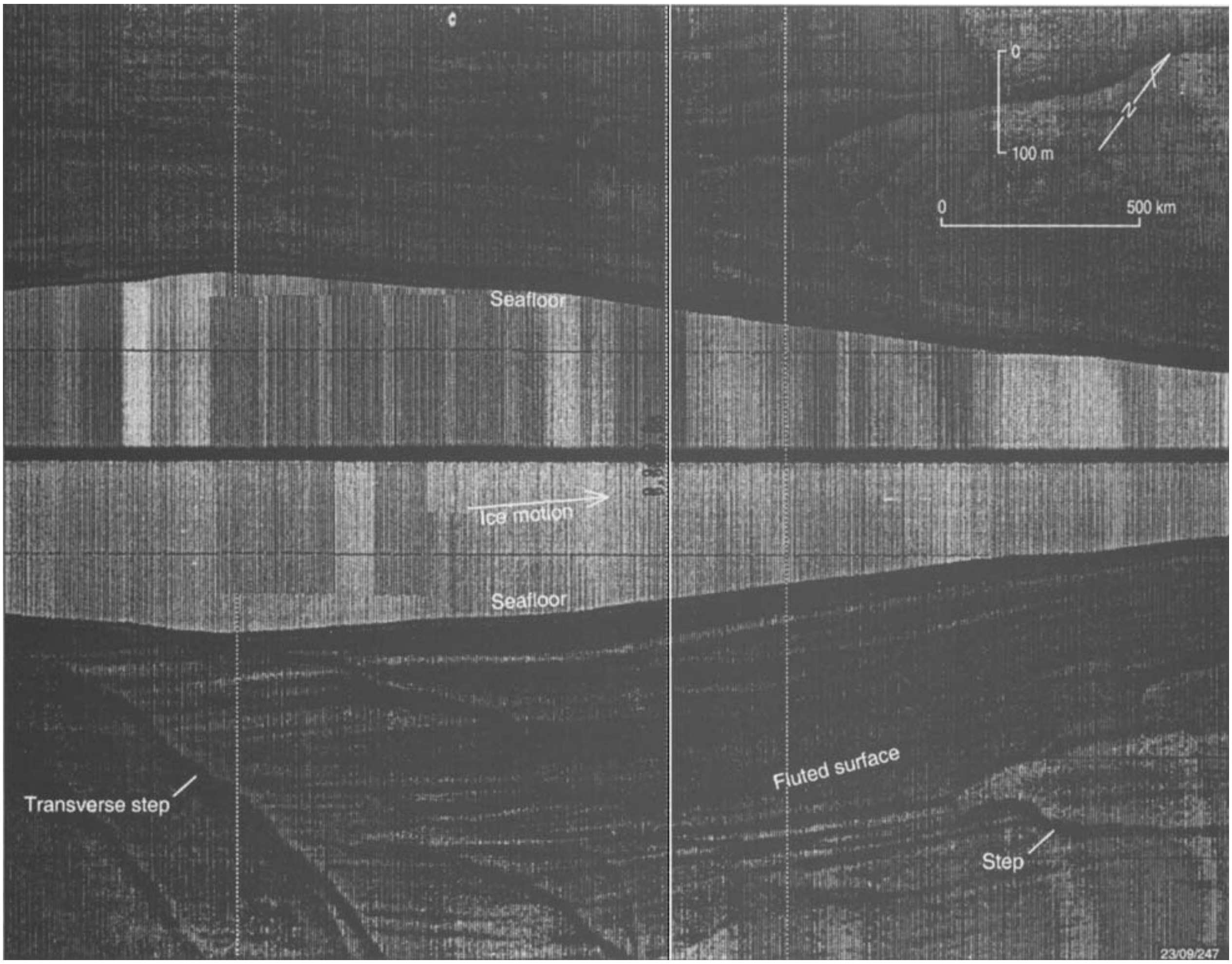

Fig. 9. Sidescan sonograph of fluted surface with steps, Lambert Deep.

We follow Solheim & Pfirman (1985) in interpreting these ridges as the marks of subglacial crevasses filled by upward squeezing of underlying sediment. However the ice need not have been stagnant. Powell *et al.* (1996) report basal crevasses near the grounding line of a modern floating ice tongue. The ridges must have formed just before lift off of the ice. No further down-glacier movement of the ice could have taken place otherwise the ridges would be smeared out into flutes.

Channel

The channel between LD-1 and LD-2 has flutes on its floor oriented at oblique angles to the general flute direction (Fig. 10). Its sides are characterized by a hummocky surface, probably caused by mass movement, and some gullying. There are no signs of recent mobility of the channel floor, such as bedforms or sand ribbons. The channel orientation suggests it formed by water flowing down the slope into the Lambert Deep, probably before the last glacial episode because its floor is fluted. It may be inactive at present or sediment is bypassing the segment that was imaged.

Core data

Cores from the Lambert Deep typically consist of thin SMO overlying porous diamict which in turn overlies stiff, compact diamict. Domack *et al.* (1998) interpret this as resulting from till deposition under progressively reducing vertical effective pressure followed by glacial retreat and open water with SMO deposition.

Lambert Deep model

We interpret the Lambert Deep wedges as having been deposited by predominantly vertical accretion, both as till and as material released from the base of the floating ice shelf (Domack *et al.* 1998). Large scale progradation of mass flows is not evident in the foresets although there is more evidence for mass flows on the wedge fronts than in EPC-1. Clinoforms in WPC-1 exhibit toplap and downlap suggesting vertical

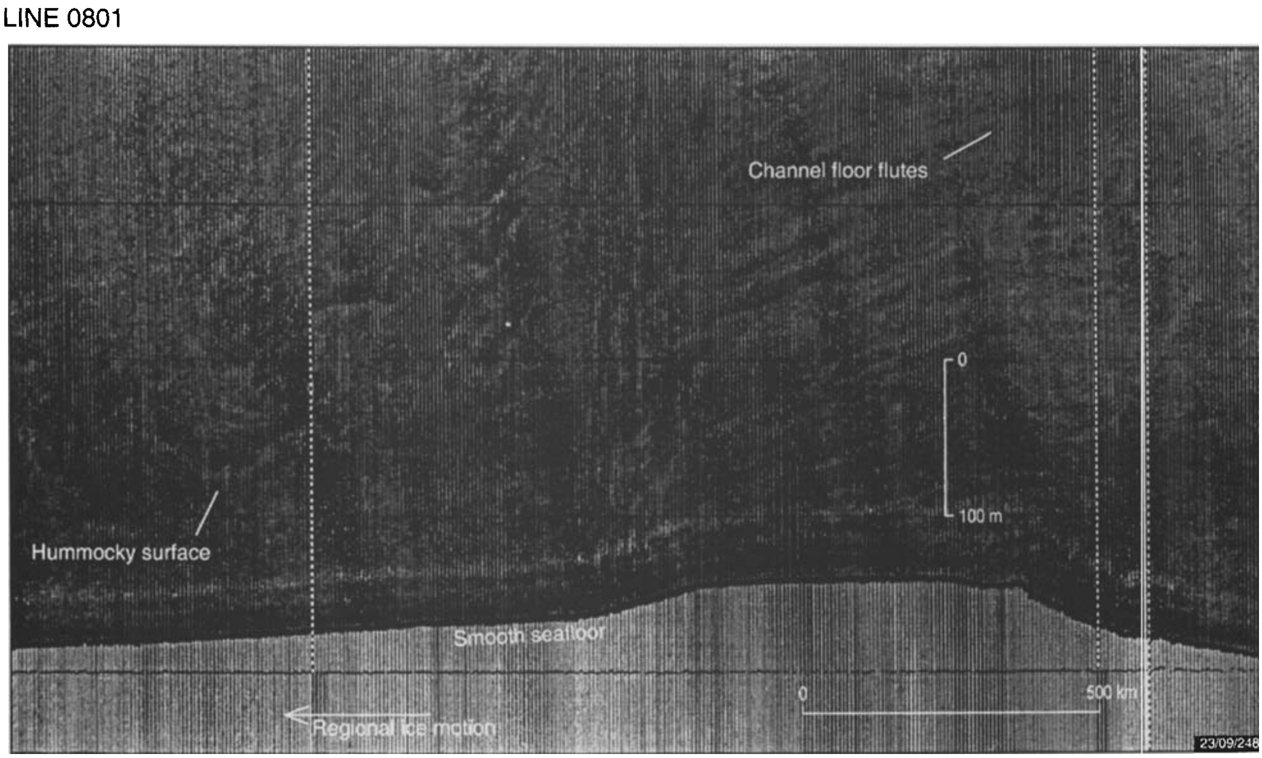

Fig. 10. Channel between LD-1 and LD-2, smooth sea floor and hummocky sediment surface. Flutes in channel base are at an angle to the regional direction.

accretion downstream of a grounding line rather than down-glacier progradation of a till delta. The up-glacier side of WPC-1 exhibits small wedges deposited during minor still stands during retreat.

Subglacial deposition took place beneath a "partially grounded" ice stream where the bed featured patches of grounded and non-grounded ice with moulding, erosion and deposition in a complex pattern. The polygonal ridges indicate the local presence of basal crevasses in the grounding zone. The absence of dune fields in Lambert Deep means that an energetic circulation cell did not develop after lift off.

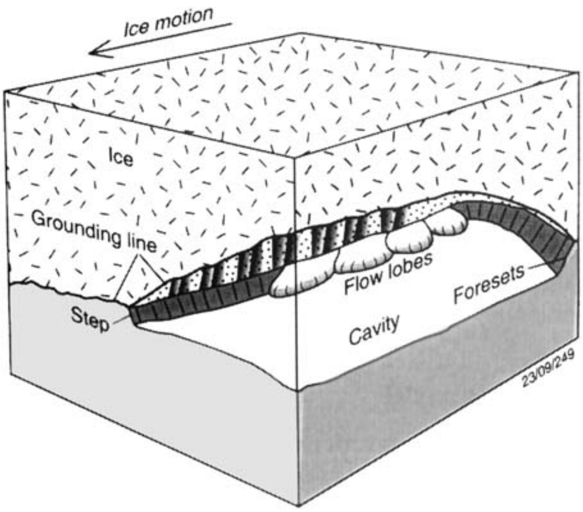

Fig. 11. Formation of steps beneath a partially grounded ice stream. Smooth surface develops in the cavity and hummocky surface develops where sediment squeezes out at the grounding line into flow lobes.

Discussion

Some of the differences between the two sets of wedges may be explained by the fact that the east Prydz Channel wedges were formed by a large inland-draining ice stream whereas the west Prydz Channel–Lambert Deep glacier is draining more coastal ice bodies. WPC-1 is a large composite feature formed downstream of a bedrock pinning point that caused frequent occupation of the same grounding zone by the glacier. The small coastal glacier repeatedly advanced to this point responded quickly to climate fluctuations compared to the main Lambert Glacier. EPC-1 is small because it may have been occupied only once. Wedges in Prydz Channel would have been planed off during major advances to the shelf edge. The preservation of transverse ridges caused by short term pushing of the bed in the Lambert Deep is probably a function of the Lambert Deep glacier's ability to respond quickly to short term changes. The main Lambert Glacier system has a much longer response time so such features would not form. The lower gradient of the Amery Depression also means that

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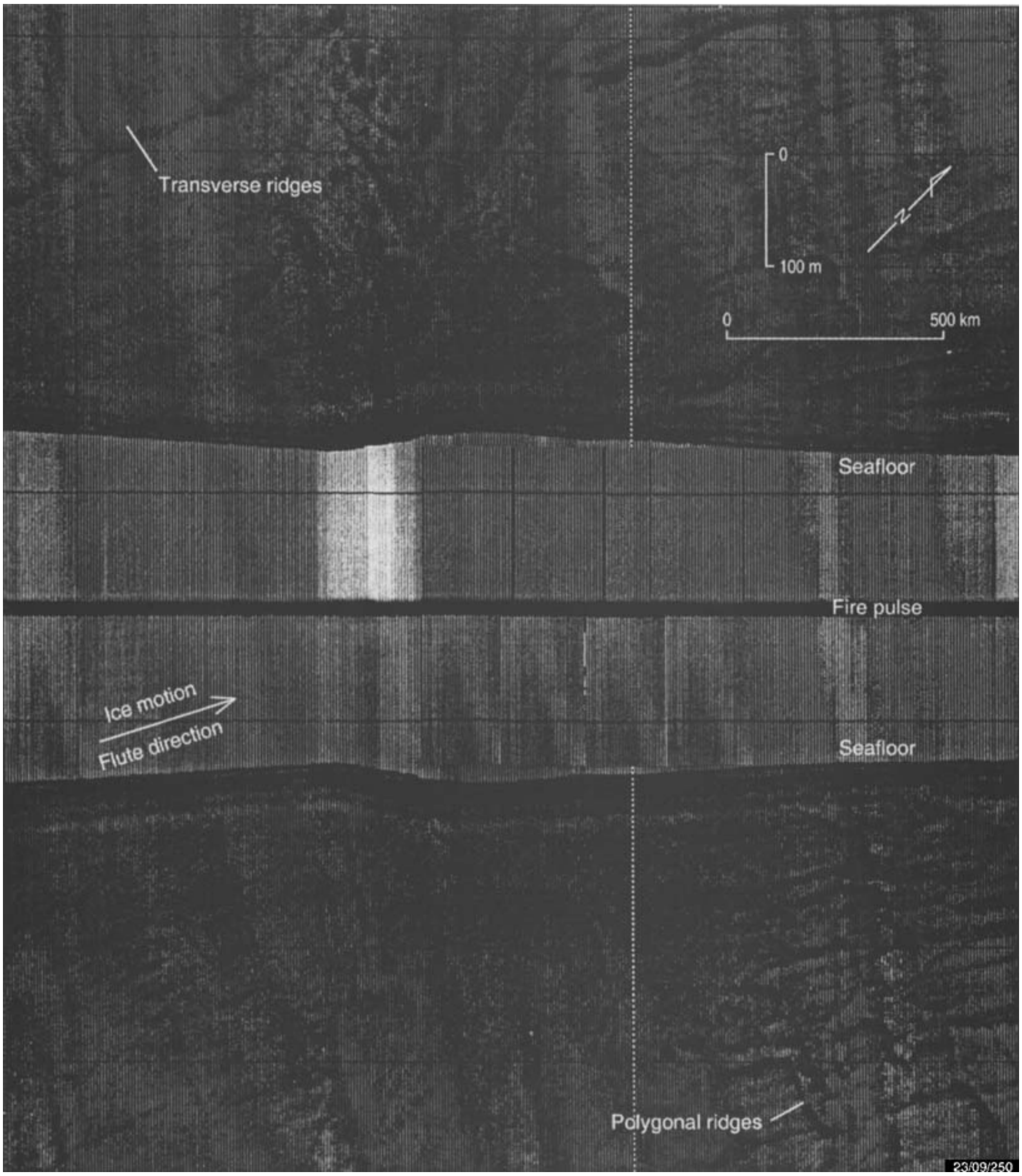

Fig. 12. Polygonal ridges superimposed on fluted surface and transverse ridges with scalloped edges, Lambert Deep. Polygonal ridges form by sediment squeezing up into basal crevasses just prior to lift off of the glacier. Transverse ridges form by short-term readvances of the ice pushing the bed.

the grounding zone of the main glacier would move a long way with mass balance changes so that short period push ridges would not form.

The dune fields developed on EPC-1 are not seen in the Lambert Deep because Lambert Deep is a small enclosed basin with a large sill, WPC-1. This is consistent with the modelling results of Hellmer & Jacobs (1992) who found that an elevation in the sub-ice shelf cavity, of a similar size to WPC-1 (280 m high), greatly reduced the energy of the circulation cell developed beneath the ice (Fig. 7b).

Sidescan images show no subglacial features in Prydz Channel, indicating that the ice did not ground there during the last glacial cycle. This is consistent with core evidence (Domack *et al.* 1998). Grounding line wedge distribution does show that the ice was grounded on large parts of the Four Ladies Bank and Amery Depression.

The lack of current reworking in the Lambert Deep may mean that its bed preserves subglacial features and the evidence of subglacial cavities suggests that it may be representative of the beds of Antarctic ice streams approaching or in their grounding zone. The alternating patches of grounded ice moving on weak, saturated till and cavities is consistent with the style of bed predicted by models of ice stream beds (Alley *et al.* 1989).

Prograding foresets are a feature of many models of grounding zone wedges (Alley *et al.* 1989, Benn 1996, Bart & Anderson 1997, Powell & Alley 1997), leading to a model of debris being carried in a deforming bed and then released at the grounding line from where it progrades seaward (Alley *et al.* 1989, Bart & Anderson 1997, Anderson 1997). Parallel

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reflectors in EPC-1, the minor amount of progradation evident at Prydz Bay wedge crests and the thin layer of weak, water saturated till in cores from Lambert Deep suggests that any layer of deforming subglacial till was quite thin. Depositional geometry and core facies suggest that much debris was transported past the grounding zone in the basal, debris-rich layer of the ice. Low angle seismic facies geometry has been identified in other Antarctic grounding zone deposits (Vanneste & Larter 1995, Anderson 1997, Shipp & Anderson 1997), as well as EPC-1, suggesting that the development of till deltas composed of sediment gravity flow deposits (Alley *et al.* 1989) is less important in the construction of grounding zone wedges around the Antarctic than some authors have proposed.

Conclusions

The Lambert Glacier occupied a series of grounding zones in the Amery Depression and Prydz Bay during the last glacial cycle, and constructed a number of sediment wedges. Upstream of the wedge crests, the glacier flowed on a deformable bed which was moulded into flutes. In the Lambert Deep, the glacier bed featured patches of grounded ice and cavities which can now be seen on the sidescan records. The wedges grew largely by vertical accretion from the grounded glacier sole and from debris rain out from melting of basal ice downstream of the grounding line.

Once the Lambert grounding zone retreated from EPC-1, an energetic circulation cell developed beneath the ice shelf, driven by the buoyant plume of meltwater derived from melting at the grounding zone. Seawater flowed into the cavity towards the grounding zone fast enough to produce extensive dune fields. Similar inflows did not develop in the Lambert Deep because of the very high sill, wedge WPC-1, at the edge of the sub-ice shelf cavity. With further retreat, the area was ploughed by icebergs and draped with open water SMO. The deepest iceberg scours probably immediately post date the Last Glacial Maximum.

These observations confirm the presence of a deformable bed beneath a major Antarctic glacier and the development of sub-ice shelf circulation patterns consistent with model studies. The seismic stratigraphy and core data suggest that Antarctic grounding zone wedges may grow as much by vertical accretion as by progradation of till deltas.

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