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Till characteristics, genesis and transport beneath Antarctic paleo-ice streams

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[1] Marine geophysical data from the Antarctic continental shelf indicate the former presence of ice streams that drained through bathymetric troughs during the last glacial cycle. Streaming flow is recorded by elongate subglacial bedforms, formed in the upper part of an acoustically transparent sediment layer. Cores from the layer demonstrate that it is a weak and porous subglacial till ("soft till"). Shear within the soft till was concentrated in zones that were 0.1–0.9 m thick. The soft till is a "hybrid" till, formed by a combination of subglacial sediment deformation and lodgment. The base of the soft till is marked by a strong reflector which represents the top of a denser and stronger "stiff till." The form of this reflector ranges from flat and continuous to deeply grooved and irregular, implying the operation of different mechanisms of sediment mobilization and incorporation into the soft till layer. The irregular form of the basal reflector is consistent with grooving, whereas the flat and continuous form is more consistent with sediment mobilization as a subglacial traction carpet related to changes in basal effective stress. Geophysical evidence for large-scale advection of the soft till, combined with evidence for deformation partitioning into relatively thin layers up to 0.9 m thick, indicates that localized shear zones integrated to transport significant volumes of sediment beneath Antarctic paleo-ice streams.

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1. Introduction

[2] Ice streams are fast-flowing, linear elements within ice sheets that attain velocities of between 0.5–12 km a^{-1} and are surrounded by slower flowing ice (<0.1 km a^{-1}). They are important because they are responsible for most of the drainage from large ice sheets in Greenland and Antarctica and thus regulate ice-sheet mass balance and contribution to sea level [*Alley and Bindschadler*, 2001; *Rignot and Kanagaratnam*, 2006]. The behavior of ice streams overlying an unconsolidated substrate in West Antarctica has been shown to be related closely to conditions at the ice stream bed. Theoretical and observational studies have shown that the rapid motion of these ice streams is the result of deformation of the subglacial sediment layer and/or enhanced basal sliding [*Alley et al.*, 1986; *Engelhardt and Kamb*, 1998; *Tulaczyk et al.*, 2000; *Kamb*, 2001; *Clarke*, 2005]. Deformation of this subglacial sediment layer was originally modeled using a viscous rheology and was believed to be pervasive over several meters [*Blankenship et al.*, 1986; *Alley et al.*, 1987]. More recently, borehole measurements from Whillans Ice Stream have shown, for that ice stream at least, that deformation occurs by Coulomb-plastic failure in thin zones of about 3 cm in thickness [*Engelhardt and Kamb*, 1998]. This contrasts with borehole measurements carried out over a longer time period from Ice Stream D that showed bed deformation at depth and ~80% of ice stream motion by sediment deformation [*Kamb*, 2001]. On the basis of recent modeling it has been proposed that replenishment of this weak deforming till layer and its transport beneath the ice stream occurs through disturbance and ploughing by an irregular ice stream base [*Tulaczyk et al.*, 2001].

[3] Marine geophysical and geological investigations of the Antarctic continental shelf have provided detailed information on past ice sheet extent and dynamic behavior during the Last Glacial Maximum (LGM). (We use the term LGM here in the "local" sense; i.e., to refer to the period of maximum glaciation during the last glacial cycle in Antarctica.) A consistent finding of these studies has been the identification, within ice sheets, of zones of former streaming flow (paleo-ice streams) that extended to the shelf edge through bathymetric troughs [e.g., *Pudsey et al.*, 1994; *Larter and Vanneste*, 1995; *Shipp et al.*, 1999; *Canals et al.*, 2000; *Wellner et al.*, 2001; *Ó Cofaigh et al.*, 2002, 2005a; *Anderson et al.*, 2002; *Lowe and Anderson*, 2002; *Dowdeswell et al.*, 2006; *J. Evans et al.*, 2005, 2006; *Heroy and Anderson*, 2005]. In general, the main focus of these studies has been reconstructing ice-sheet extent, dynamics and the timing of deglaciation in specific areas around the

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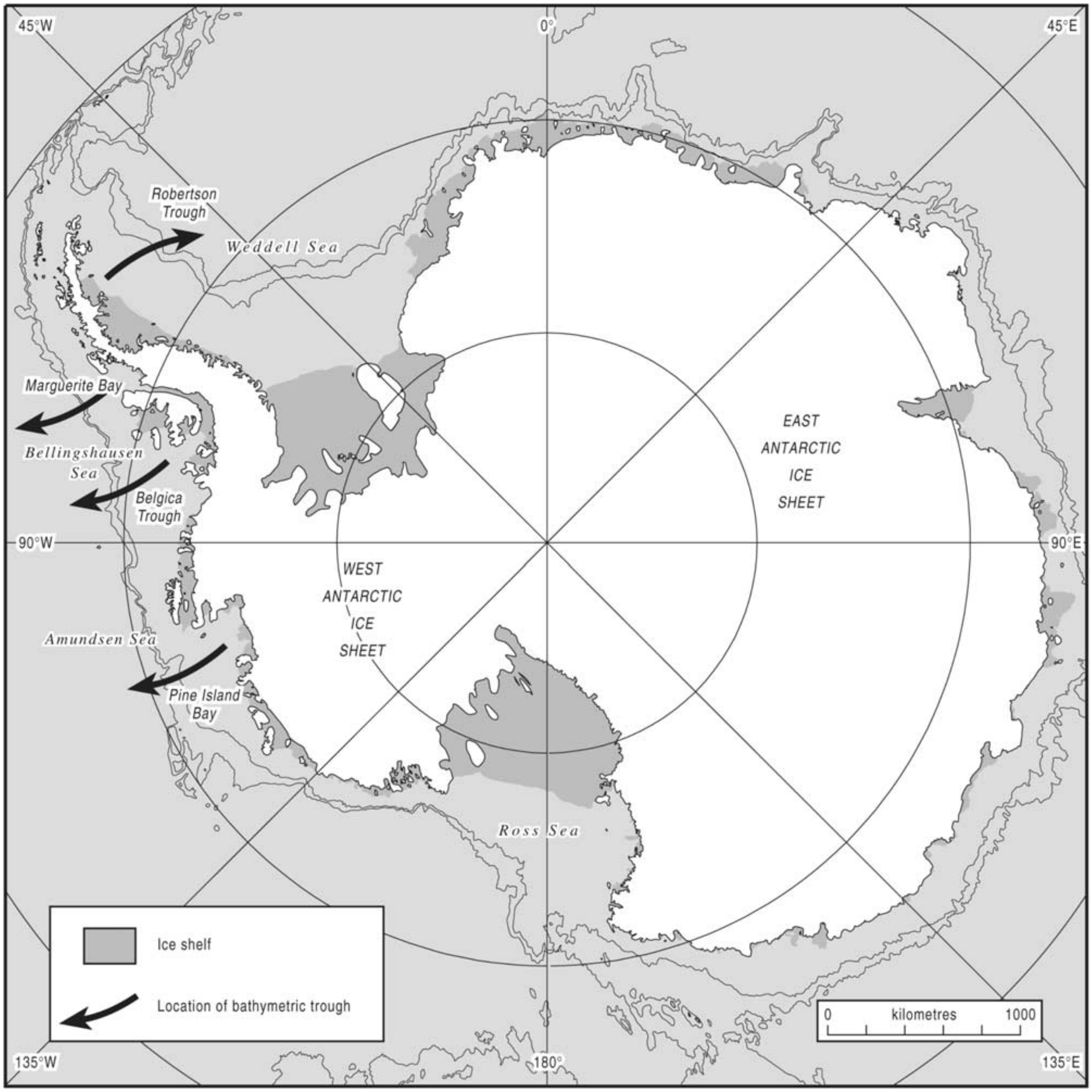

Figure 1. Map of Antarctica showing the four study areas and place names referred to in text. The 1000-m and 3000-m bathymetric contours are shown.

Antarctic continental margin. There have been relatively few studies [*Dowdeswell et al.*, 2004a; *Ó Cofaigh et al.*, 2005b; *Evans et al.*, 2005] that have utilized these data to investigate the genesis of the sub-ice-stream till layer, and none that have investigated how sediment was mobilized and transported beneath these ice streams. These are the aims of the current paper.

[4] We present marine geophysical data, supplemented by sediment core evidence, from four paleo-ice streams which extended to the edge of the continental shelf through bathymetric troughs during the last glacial cycle. The data come from the Amundsen Sea (outer continental shelf offshore of Pine Island Bay), the Bellingshausen Sea offshore of Eltanin Bay and the Ronne Entrance, Marguerite Bay on the west side of the Antarctic Peninsula, and Robertson Trough on the east side of the Peninsula (Figure 1). Geophysical evidence for streaming flow in these troughs has been presented in detail in previous publications for each of these individual areas [*Ó Cofaigh et al.*, 2002, 2005a, 2005b; *Dowdeswell et al.*, 2004a; *J. Evans et al.*, 2005, 2006] and is only summarized here. Our principal focus in this paper is the TOPAS subbottom profiler records of shallow acoustic stratigraphy and the associated sediment core records from the four ice stream

beds. We discuss the implications of these data for the characteristics and genesis of the sub-ice-stream till layer, as well as for mechanisms of sediment mobilization and transport.

2. Methods

[5] Geophysical data on the nature of the seafloor and sediments beneath it were acquired during four cruises of the RRS *James Clark Ross* to the Antarctic continental shelf using hull-mounted Kongsberg-Simrad EM120 multibeam swath bathymetry and Topographic Parametric Sonar (TOPAS) subbottom profiling systems. The EM120 system emits 191 beams, each with dimensions of 1° by 1°, frequencies in the range of 11.25–12.75 kHz and a maximum port and starboard-side angle of 75 degrees. In practice the system is typically run with maximum port and starboard-side angles of 68 degrees, which, in water depths of about 500 m, is equivalent to a total swath width of about 2.5 km. The system allows detailed mapping of the sea floor. Data processing involved removal of anomalous data points and application of corrected sound-velocity profiles generated from expendable bathythermographs (XBTs). Vertical and horizontal uncertainties are about 1 m and 5 m, respectively.

[6] The TOPAS parametric acoustic profiler uses parametric interference between primary waves to produce a narrow (5°) beam with user-specified secondary frequencies in the range of 0.5 to 5 kHz. It is used to profile the sub-sea-floor at high spatial resolution. Vertical resolution is better than about 2 m. The maximum depth of penetration by TOPAS is variable and depends on the nature of the sediments. In general, fine-grained sediments can be imaged to greater depths (>100 m penetration can be achieved) than coarser grained and poorly sorted deposits (typically <40 m). In this study TOPAS generally penetrated sediments to depths of between 2 and about 30 m on the Antarctic continental shelf. Navigation data were acquired using differential GPS.

[7] The geophysical data were supplemented by over 50 cores collected using 6-m-long gravity and vibro-corers. The grain size, sedimentary structures, bed contacts, geometry, sorting, clast shape and texture of the sediments were recorded. Shear strength measurements were performed every 10 cm (or closer depending on lithological boundaries) using a Torvane. Ten sediment samples from selected units were collected for thin section preparation and analysis of microstructures in order to aid interpretations of sediment genesis and depositional history.

3. Geophysical and Geological Data

3.1. Sea Floor Morphology

[8] In all four regions discussed in this paper, well defined bathymetric troughs extend from the inner continental shelf to the shelf edge. Typical water depths in these troughs are 450–700 m, although over-deepened areas can occur with water depths greater than 1000 m (e.g., inner Marguerite Bay, Pine Island Bay and Eltanin Bay). The troughs are bounded by shallower banks on either side that are generally less than 400 m deep. Streamlined subglacial bedforms occur along the floors of all these troughs (Figure 2). In the inner shelf regions of Marguerite Bay, Pine Island Bay and the Belgica Trough region of the Bellingshausen Sea (Figure 1) the substrate comprises crystalline bedrock and the sea floor is typically irregular with a rough appearance on swath bathymetric records, and sediment cover is thin or absent. Bedforms on the inner to midshelf generally comprise streamlined bedrock and drumlins (Figure 2a). This contrasts markedly with the outer continental shelf where sedimentary strata up to 2 km thick occur [*Larter et al.*, 1997; *Nitsche et al.*, 1997]. Streamlined subglacial bedforms formed in this outer shelf sedimentary substrate are much more elongate. Megascale glacial lineations (MSGL) [*Clark*, 1993] formed in sediment can reach up to 20 km in length and have elongation ratios of up to 90:1 (Figures 2b–2e). In some cases suites of cross-cutting lineations can be observed (e.g., Robertson Trough). These streamlined bedforms record the former presence and flow direction of paleo-ice streams on the continental shelf at the LGM.

3.2. Acoustic Stratigraphy

[9] The MSGL that we image on our swath bathymetric records are formed in the upper part of an acoustically transparent sediment unit (Figures 3, 4, 5, and 6) [*Dowdeswell et al.*, 2004a; *Ó Cofaigh et al.*, 2005a, 2005b; *J. Evans et al.*, 2005, 2006]. This unit is confined to the troughs and does not extend onto the adjacent banks, indicating that it is either absent there or is so thin as to be below the resolution of the TOPAS system (better than 2 m). The transparent unit ranges in thickness from 1 to 19 m. In Marguerite Bay and Robertson Trough the unit thickness is generally <6 m; on the outer shelf offshore of Pine Island Bay and on the Bellingshausen Sea margin it is usually less than about 12 m thick. The transparent unit is typically acoustically homogeneous (e.g., Figures 3a, 3c, 4a, 4c, 4d, 5b, and 6b) and internal reflectors are only occasionally observed (Figures 3b and 6a). There is often an abrupt break between the unit and adjacent areas where it is absent (Figure 3c).

[10] The nature of the basal reflector of the transparent unit is variable and ranges from distinct, smooth and continuous, to irregular and undulating (Figures 3, 4, 5, and 6) [*Ó Cofaigh et al.*, 2005b; *J. Evans et al.*, 2005, 2006]. In Marguerite Bay the basal reflector is overwhelmingly smooth, continuous and often flat on both longitudinal and transverse subbottom profiler lines (Figures 3a and 3b). In only one location is it undulatory (Figure 3c), and this was relatively minor, extending over a distance of only about 4 km, out of a total of 4330 km of TOPAS acquisition. In Robertson Trough and the Bellingshausen Sea, the areas where the basal reflector is smooth and continuous occur in close proximity (within less than 3 km) to areas where it is irregular or undulating (Figures 4c, 4d, 4e, and 6a). In inner Robertson Trough (Figures 4a and 4b) a flat to wavy subbottom reflector is present beneath, and in some cases appears to be truncated by, the irregular basal reflector of the overlying acoustically transparent unit. This indicates the presence of a sedimentary unit beneath, and incised by, the hummocky basal reflector of the transparent unit. It suggests an erosional event before, or contemporaneous with, emplacement of the latter unit.

[11] In the outermost shelf-trough offshore of Pine Island Bay a grooved basal reflector is widespread (Figures 5a, 5b

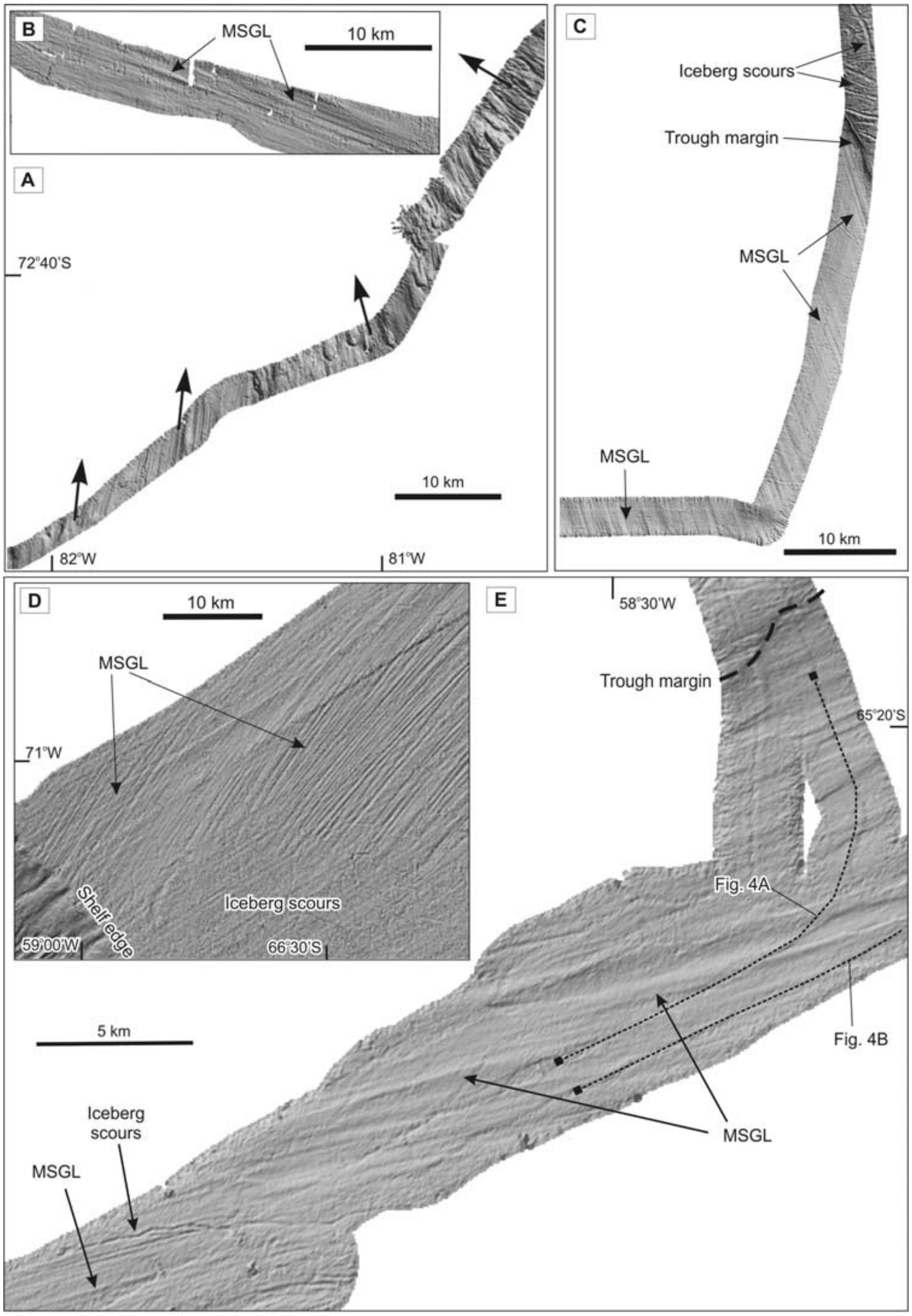

Figure 2. EM120 sun-illuminated swath bathymetry records of streamlined subglacial bedforms that record paleo-ice stream flow through the cross-shelf bathymetric troughs discussed in this paper. (a) Streamlined subglacial bedforms (drumlins and ice-molded bedrock) on the floor of Eltanin Bay which record flow convergence into Belgica Trough, Bellingshausen Sea margin. Cell size of the swath bathymetry grid is 100 m × 100 m. (b) Megascale glacial lineations (MSGL) from the Ronne Entrance, Bellingshausen Sea margin. Cell size of the swath bathymetry grid is 50 m × 50 m. (c) MSGL in the outer shelf trough, Pine Island Bay. Iceberg scours occur on the adjacent shallow banks. Cell size of the swath bathymetry grid is 50 m × 50 m. (d) MSGL in the outer shelf trough of Marguerite Bay. The lineations extend to the edge of the continental shelf and are locally cross-cut by irregular iceberg furrows. Cell size of the swath bathymetry grid is 50 m × 50 m. Note that the lines perpendicular to the shelf edge and parallel to the boundaries of the swath coverage are artifacts of the swath data related to variations in the sound velocity structure of the water. (e) Subglacial bedforms from Robertson Trough, Larsen-A region, Antarctic Peninsula. Cell size of the swath bathymetry grid is 50 m × 50 m.

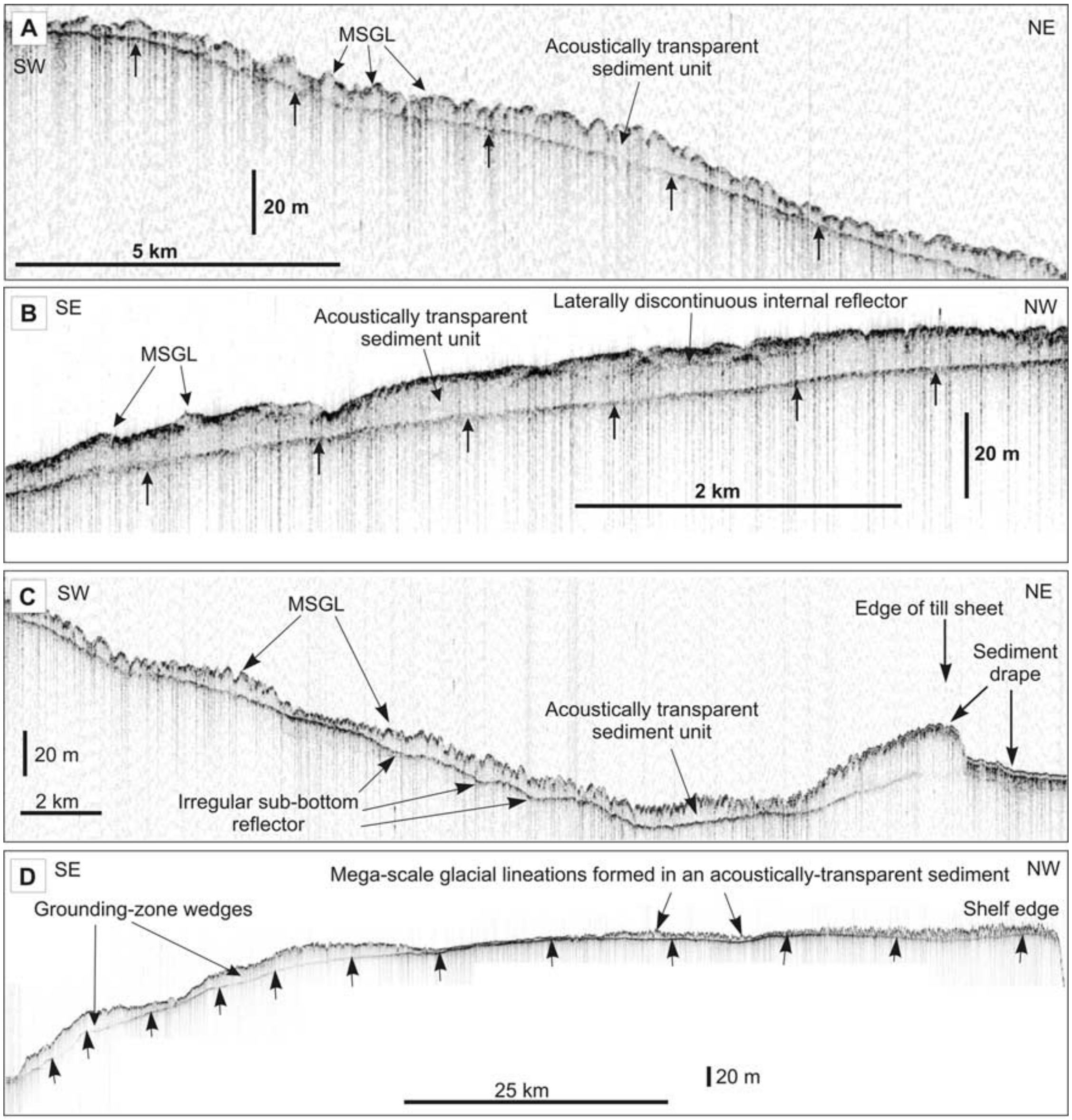

Figure 3. TOPAS subbottom profiler records showing acoustic sedimentary units from outer Marguerite Bay. (a) Transverse profile crossing the megascale glacial lineations (MSGL) at right angles. The MSGL are formed in acoustically transparent sediment and located above a smooth subbottom reflector (arrowed). (b) Line parallel to trough long axis showing MSGL formed in acoustically transparent sediment and located above a flat subbottom reflector (arrowed). The TOPAS line is orientated at about 12° to the MSGL shown in Figure 2d. (c) Transverse profile showing MSGL formed in transparent sediment unit. Note localized shallow grooves in the subbottom reflector at base of the acoustically transparent unit (arrowed), and the abrupt lateral margin of the unit (arrowed). (d) TOPAS line showing distribution of the transparent sediment unit that overlies a strong subbottom reflector (arrowed) along the outer shelf trough of Marguerite Bay.

and 5c), separated locally by regions where the basal reflector is relatively smooth and horizontal. In this region the transparent unit is sometimes distributed across the flanks and crests of the grooves (Figure 5b). In contrast, further inshore, the basal reflector is mainly smooth and horizontal (or gently undulating), and only locally is it irregular. As in the case of inner Robertson Trough, a wavy or inclined subbottom reflector is imaged beneath, and in some cases is cut off by, the hummocky basal reflector of the overlying transparent unit (Figure 5b). The unit between these two reflectors is composed of transparent sediment that is organized into either a layer or dome-shaped lenses corresponding to subglacial bedforms associated with an earlier phase of ice sheet flow.

[12] A TOPAS line running ∼100 km along the outer shelf trough in Marguerite Bay to the shelf edge and cross-cutting the MSGL at a low angle is shown in Figure 3d. The acoustically transparent unit is thickest at the southern end

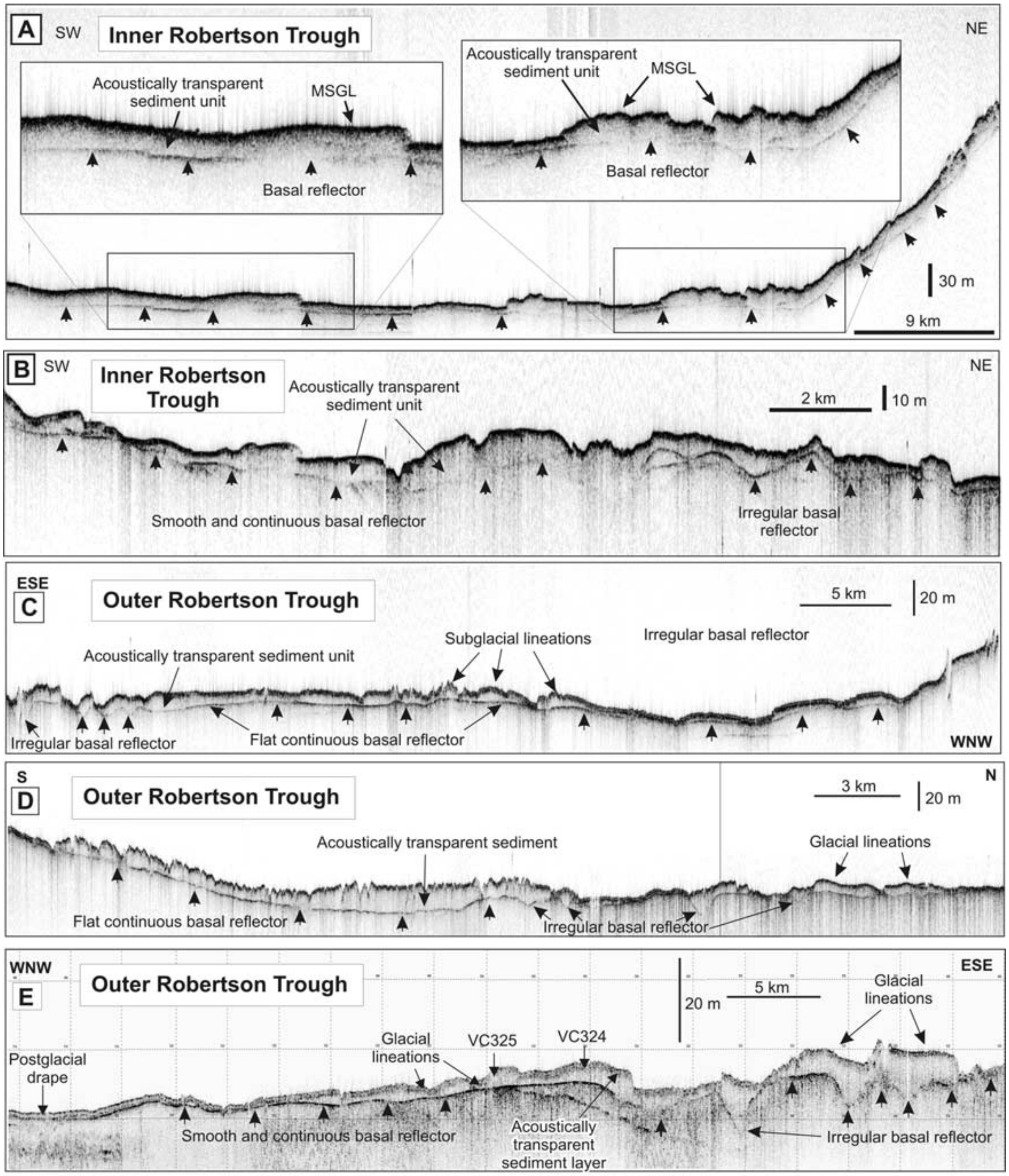

Figure 4. TOPAS records of shallow acoustic stratigraphy from Robertson Trough. (a, b) Inner Robertson Trough. (c, d, e) Outer Robertson Trough. Note contrasting nature of the basal reflector of the uppermost acoustically transparent sediment unit from smooth, flat and continuous to highly irregular over distances of a few kilometers.

of this line where it forms two prominent accumulations of sediment up to about 15 m thick on the adverse slope emerging from a topographic depression. These sediment accumulations also appear on a series of adjacent TOPAS lines from this region of the trough. They represent a series of sediment ridges that are orientated across the trough, transverse to ice flow. On this basis they are interpreted to be grounding-zone wedges formed at the transition from grounded to floating ice. Swath bathymetric data show that MSGL continue uninterrupted across the surface of the grounding-zone wedges indicating that the wedges were overridden by streaming flow after their formation. The transparent unit thins to about 2–5 m immediately downflow of the grounding-zone wedges. It then gradually increases in thickness along the trough, reaching 10 m at the shelf edge. Adjacent TOPAS lines show the acoustically transparent unit thinning in the last ~25 km to the shelf edge.

3.3. Cores

[13] Cores were collected from the acoustically transparent unit in Marguerite Bay and Robertson Trough (Figures 7–10).

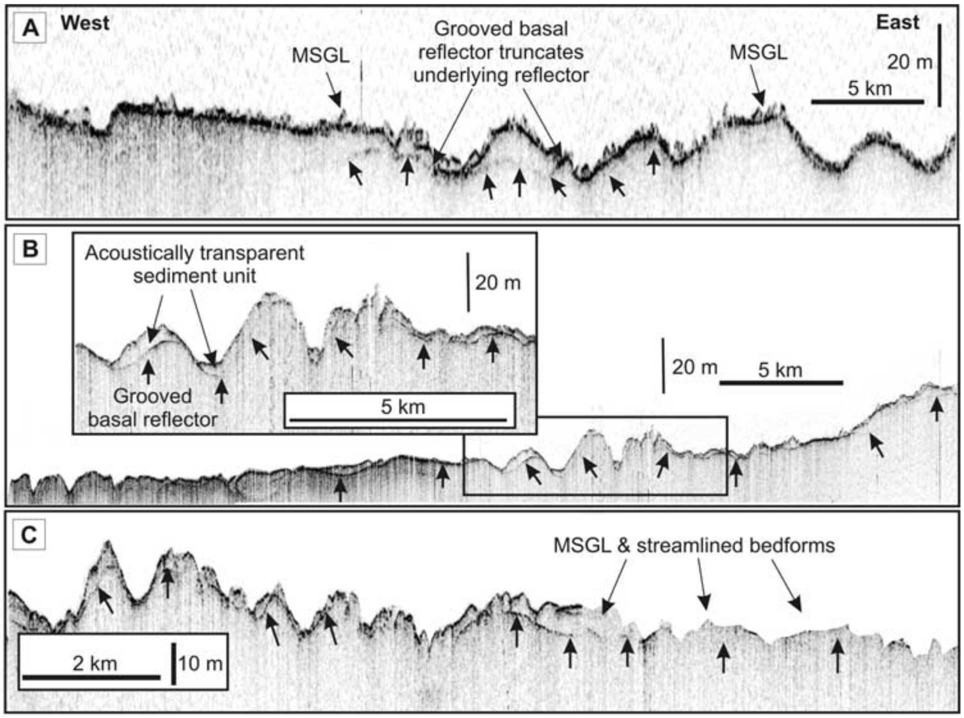

Figure 5. Acoustic stratigraphy from the outer shelf offshore of Pine Island Bay. (a) TOPAS record showing acoustically transparent unit in the outer shelf trough. The transparent unit overlies a basal reflector (arrowed) and has been incised by an irregular grooved reflector, on top of which small MSGL are developed (arrowed). (b) Acoustically transparent unit with a horizontal to highly irregular or hummocky basal reflector. Note the cross-cutting reflectors, each with an identical transparent layer above, along the trough margin. (c) TOPAS record from the outer shelf trough. The subbottom reflector that marks the base of the transparent unit is arrowed.

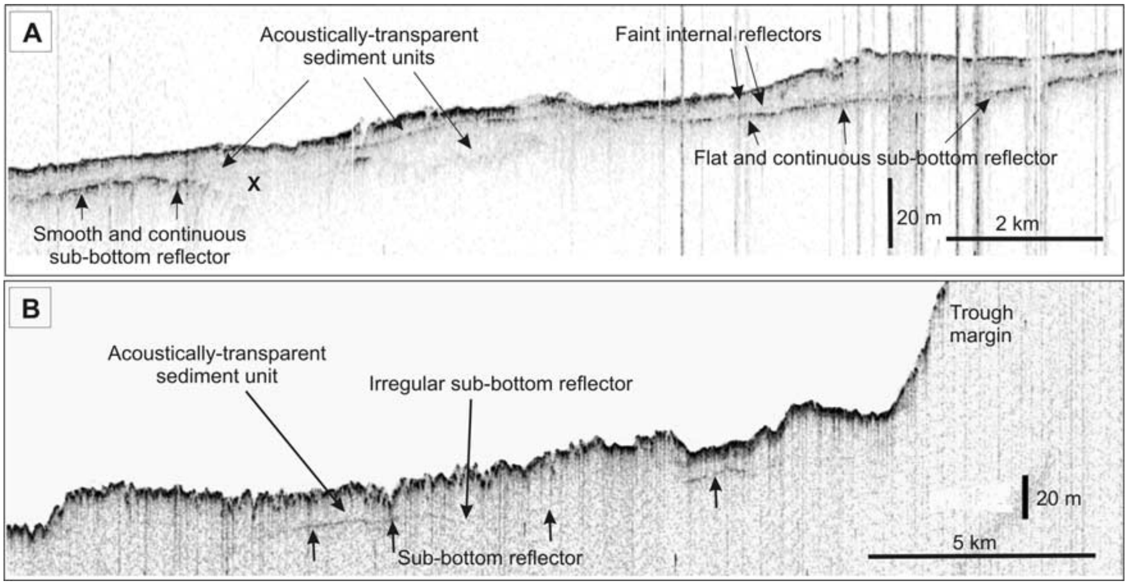

Figure 6. Acoustic stratigraphy from Bellingshausen Sea continental margin. (a) TOPAS record from the Ronne Entrance. Line is perpendicular to the paleo-ice flow direction. Note varying nature of basal reflector of the transparent sediment unit (arrowed) which ranges from flat to locally grooved (cross). (b) TOPAS record of acoustic stratigraphy in outer Belgica Trough.

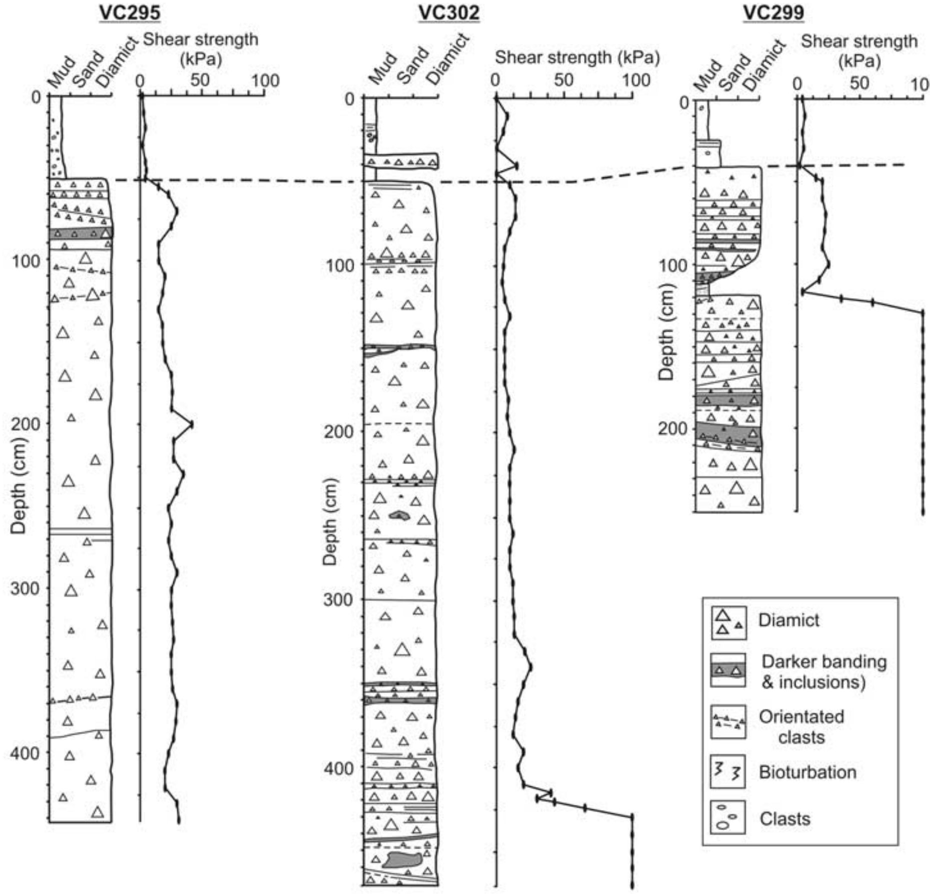

Figure 7. Sedimentary logs and associated shear-strength (kPa) profiles of representative cores from Marguerite Bay. Note low shear strength massive (soft) diamict with numerous shear planes underlain by high shear strength (>98 kPa) (stiff) diamict. The horizontal dashed lines mark the contact between the soft till and overlying deglacial sediments.

The cores show that the transparent unit comprises massive, matrix-supported diamict that is generally poorly sorted and contains variable concentrations of striated, subangular to subrounded gravel-sized clasts dispersed within a clayey/silty mud matrix [see *Dowdeswell et al.*, 2004a; *Ó Cofaigh et al.*, 2005b; *Evans et al.*, 2005]. In Marguerite Bay, shear strength within the diamict is usually less than 20 kPa (range 0–40 kPa) (Figure 7 and Table 1), average porosity is 34% (range 29–40%), and the clay content ranges from 11 to 24%. Shear strength shows internal variability of 2–15 kPa over typical sediment thicknesses of 0.1–0.5 m. Several cores show an abrupt increase in shear strength toward the top of the diamict (e.g., cores VC295 and VC302, Figure 7). In Robertson Trough, the shear strength of the diamict ranges from 1 to 19 kPa and porosity ranges from 40 to 59% (Figure 10 and Table 1). Here shear strength shows internal variability of 2–7 kPa over typical sediment thicknesses of about 0.1–0.3 m. The maximum sediment thickness over which shear strength varies ≤ 1 kPa in the diamict is ~ 0.6 m in Marguerite Bay and 0.9 m in Robertson Trough. We refer to this unit as the ‘‘soft diamict.’’ The soft diamict is confined to cores recovered from the bathymetric troughs and is absent from cores recovered from the adjacent banks.

[14] In core section and on x-radiographs the soft diamict is massive, apart from the presence of occasional subhorizontal shear planes, aligned clasts and rare attenuated soft-sediment clasts of silty to sandy mud that occur within or near the base of the facies (Figures 7, 8, and 10). Investigation of the soft diamict from Marguerite Bay shows that it also contains shear planes and aligned clasts at a micromorphological scale. The shear planes are closely associated with circular structures (interpreted to be products of rotation), sediment banding and folding (Figure 9).

[15] The soft diamict directly overlies a much stiffer, massive matrix-supported diamict (Figures 7 and 10 and Table 1). In Marguerite Bay shear strengths within this stiffer diamict are >98 kPa, clay content ranges from 6 to 11% and average porosity is 24% (range is 23 to 29%). This ‘‘stiff diamict’’ also contains a series of micromorphological structures in the form of lineaments and circular structures. In Roberston Trough, the stiff diamict is characterized by shear strengths of 20–98 kPa, water content of <19% and a porosity of 27–39% (e.g., core VC326, Figure 10). This stiff diamict was recovered in cores from both within the trough (where it underlies the soft diamict) and also from the adjacent shallower banks. Shear strength profiles indicate that the upward transition from stiff to soft diamict can

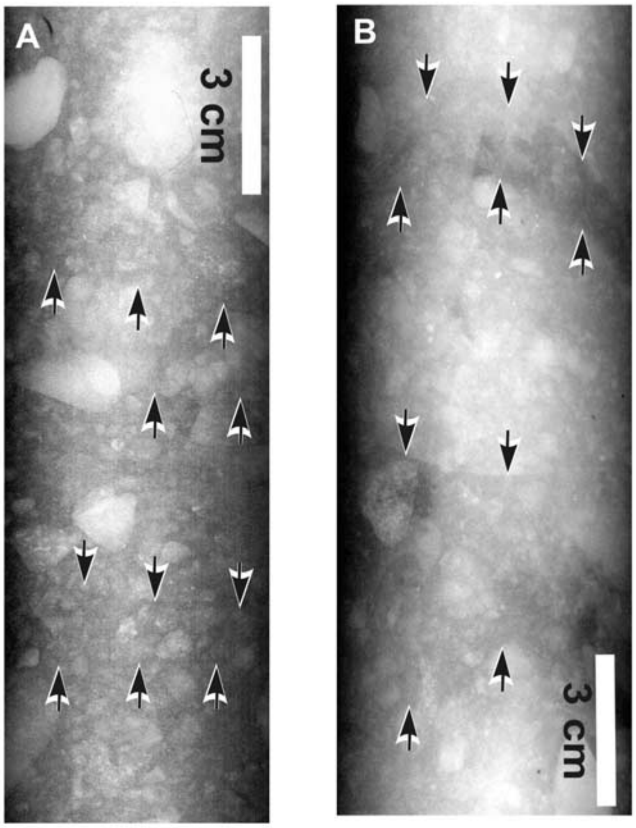

Figure 8. X-radiographs of soft diamict facies. (a) Core GC300, Marguerite Bay. Soft diamict facies with horizontal and subhorizontal planar structures (arrowed). (b) Core VC302, Marguerite Bay. Banding in soft diamict facies, defined by alternating light and dark toned sediment. Bedding contacts are arrowed.

be relatively abrupt (similar to Marguerite Bay; see above) or is gradational over centimeters, decimeters or several meters. Occasionally, interlayering of stiff and soft diamict occurs (e.g., core VC340, Figure 10). The lithologies of clasts within the soft diamict in Robertson Trough are similar to those in the stiff diamict on the inner middle shelf [*Pudsey et al.*, 2006]. This implies that the soft diamict is derived from the stiff diamict. The prominent subbottom reflector that marks the base of the acoustically transparent unit on the TOPAS records coincides with the abrupt changes in shear strength and porosity between the soft and stiff diamicts.

[16] Core VC299 was recovered from close to the edge of the trough in Marguerite Bay from an area where the soft diamict is not seen on TOPAS records. However, the soft diamict is present in the core, but it is separated from the underlying stiff diamict by a thin (7 cm) unit of massive, sheared clayey mud (Figure 7). The mud indicates a period of subaqueous deposition after emplacement of the stiff diamict, but before formation of the soft diamict. Core VC299 is the only core where such a stratigraphy of stiff diamict–sheared mud–soft diamict was found.

[17] Sediment cores were not recovered from the acoustically transparent layer in the outer shelf trough offshore of Pine Island Bay. However, core NBP9902-PC39 was recovered from an area of MSGL in 495 m of water (no iceberg scouring present) on the middle shelf of Pine Island Bay, west of Burke Island (72°11′12.1″S, 105°40′14.2″W) [see *Lowe and Anderson*, 2002]. The core contained massive, poorly sorted diamict with low shear strengths (15–19 kPa), high water content, mineralogical homogeneity and uniform magnetic susceptibility (Table 1). *Lowe and Anderson* [2002] interpreted the diamict as a subglacial deformation till formed beneath a paleo-ice stream.

4. Interpretation and Discussion

4.1. Identification of Paleo-Ice Streams on the Antarctic Continental Shelf

[18] Ice flow within the troughs of the four study areas of West Antarctica and the Antarctic Peninsula is inferred to have been in the form of fast-flowing paleo-ice streams. This is based on the following geomorphological and sedimentological evidence that match criteria for the identification of paleo-ice streams [cf. *Stokes and Clark*, 1999]. These criteria are, in turn, based on modern West Antarctic analogues for ice stream setting and bed character: (1) The highly elongate streamlined subglacial bedforms occur in cross-shelf bathymetric troughs, and such troughs are commonly associated with modern ice streams and fast-flowing outlet glaciers [*Vaughan et al.*, 2003; *Bennett*, 2003]. Seismic investigations of the bed beneath such ice streams also show the presence of streamlined subglacial bedforms [*King et al.*, 2004; *Smith et al.*, 2005]. (2) Characteristically the streamlined bedforms become progressively more elongate along the troughs from short bedrock drumlins and ice-molded bedrock on the inner shelf, to highly attenuated drumlins and lineations on the midshelf, to MSGL on the outer shelf [*Wellner et al.*, 2001; *Ó Cofaigh et al.*, 2002]. The most elongate bedforms (MSGL with elongation ratios up to 90:1) are typically associated with a soft bed on the outer shelf. This pattern is consistent with the highest inferred ice stream velocities occurring over the soft bed [cf. *Dyke and Morris*, 1988; *Shipp et al.*, 1999; *Wellner et al.*, 2001]. (3) Bedform orientation indicates convergent ice flow into the troughs. (4) MSGL are formed in a thin, acoustically transparent sediment unit comprising soft, porous sediment, which is similar to the weak till layers described from beneath modern West Antarctic ice streams [*Blankenship et al.*, 1986; *Vaughan et al.*, 2003; *King et al.*, 2004; *Smith et al.*, 2005]. (5) Finally, published geophysical and core records from the continental slopes offshore of the trough mouths show evidence for slope progradation and, where cores have been recovered, matrix-rich debris flow deposits similar in texture and color to the soft tills recovered from the troughs [*Ó Cofaigh et al.*, 2003, 2005a; *Dowdeswell et al.*, 2004b, 2006]. The debris flows and associated slope progradation are inferred to be a consequence of downslope transfer by sediment gravity flow of glacigenic sediment delivered directly to the trough mouths by paleo-ice streams [cf. *Larter and Cunningham*, 1993; *Laberg and Vorren*, 1995; *Dowdeswell et al.*, 1996; *Vorren et al.*, 1998].

4.2. Sub-Ice-Stream Till Layer

4.2.1. Characteristics

[19] In the four areas of the Antarctic continental shelf discussed above, streamlined subglacial bedforms record

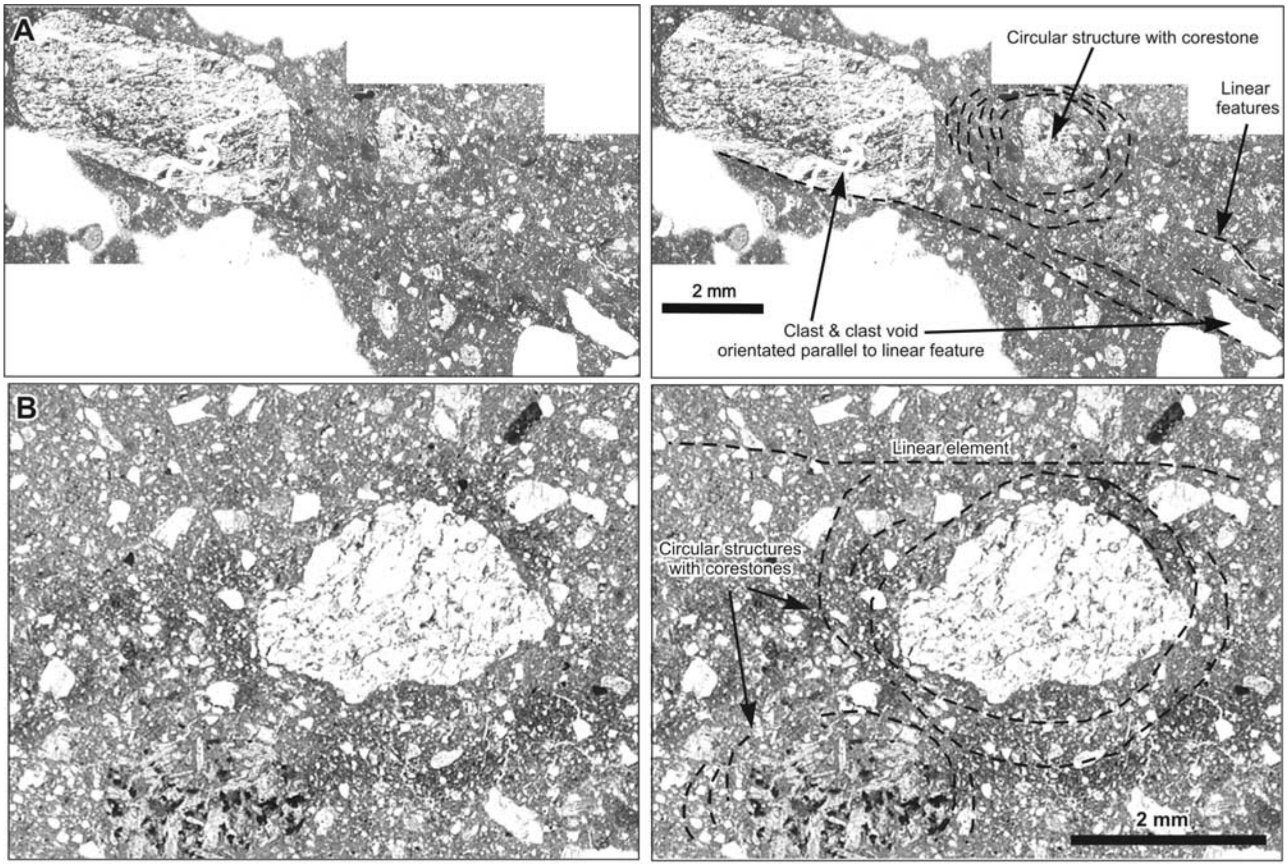

Figure 9. Representative thin sections from the soft diamict facies, Marguerite Bay. The samples are viewed in plane light. The annotated right-hand image of each pair is an interpretation of the structures present in the left-hand image. (a) Core GC300, 129–135.7 cm depth. Linear features with aligned clasts/clasts voids (interpreted as shear zones) and associated circular structures (interpreted as the product of rotation). (b) Core GC300, 88.8–95.3 cm depth. Circular structures with corestones. Note the close association of upper circular structure with subhorizontal linear feature (marked).

the former flow of ice streams through cross-shelf bathymetric troughs to the shelf edge or outermost continental shelf during the last glacial cycle. The sediments associated with this streaming flow comprise an acoustically transparent unit. Commonly, this transparent unit is internally homogeneous on TOPAS records although locally it may contain discontinuous internal reflectors. The transparent unit is confined to the troughs and is not observed on TOPAS records from the adjacent banks, although we accept that this pattern could, in part, reflect the action of iceberg scouring in shallow water. Sediment cores from the unit show that it is composed of a soft (typical shear strengths of 0–20 kPa) massive, matrix-supported diamict containing dispersed, striated clasts in a muddy matrix. Characteristically the diamict shows internal variability in shear strength of about 2–15 kPa over sediment thicknesses of ~0.1–0.5 m, although there are zones where variation in shear strength is ≤1 kPa over sediment thicknesses of up to 0.6 m in Marguerite Bay and up to 0.9 m in Robertson Trough. Porosities within the unit average 34% in Marguerite Bay and 45% in Robertson Trough (Table 1). Structures within this soft diamict include attenuated and inclined soft sediment clasts, shear planes and shear zones, banding, aligned clasts, and circular structures (indicative of clast rotation) (Figures 7, 8, 9, and 10). On the basis of this evidence, we interpret the soft diamict as a subglacial till and further discuss its precise genesis below.

[20] On the TOPAS records, the base of the soft till is marked by a prominent and abrupt subbottom reflector. Vibrocores from both Robertson Trough and Marguerite Bay penetrated through the base of this soft till layer into the underlying sediment. The cores show that sediments beneath this reflector also consist of massive, matrix-supported diamict (Figures 7 and 10), with a range of structures including shear planes, sediment banding and, in thin section, rotational structures and faint plasmic fabrics. On the basis of these data we also interpret this lower diamict as a till. However, the lower till unit is markedly stiffer and less porous than the overlying soft till (in Marguerite Bay the average porosity of this stiff till is 24% and range is 23–29%; in Robertson Trough, the average porosity is 31% and range is 27–39%). Thus the prominent basal reflector of the transparent unit (the soft till) coincides with an abrupt downcore increase in shear strength and corresponding decrease in porosity, coupled to lower water content.

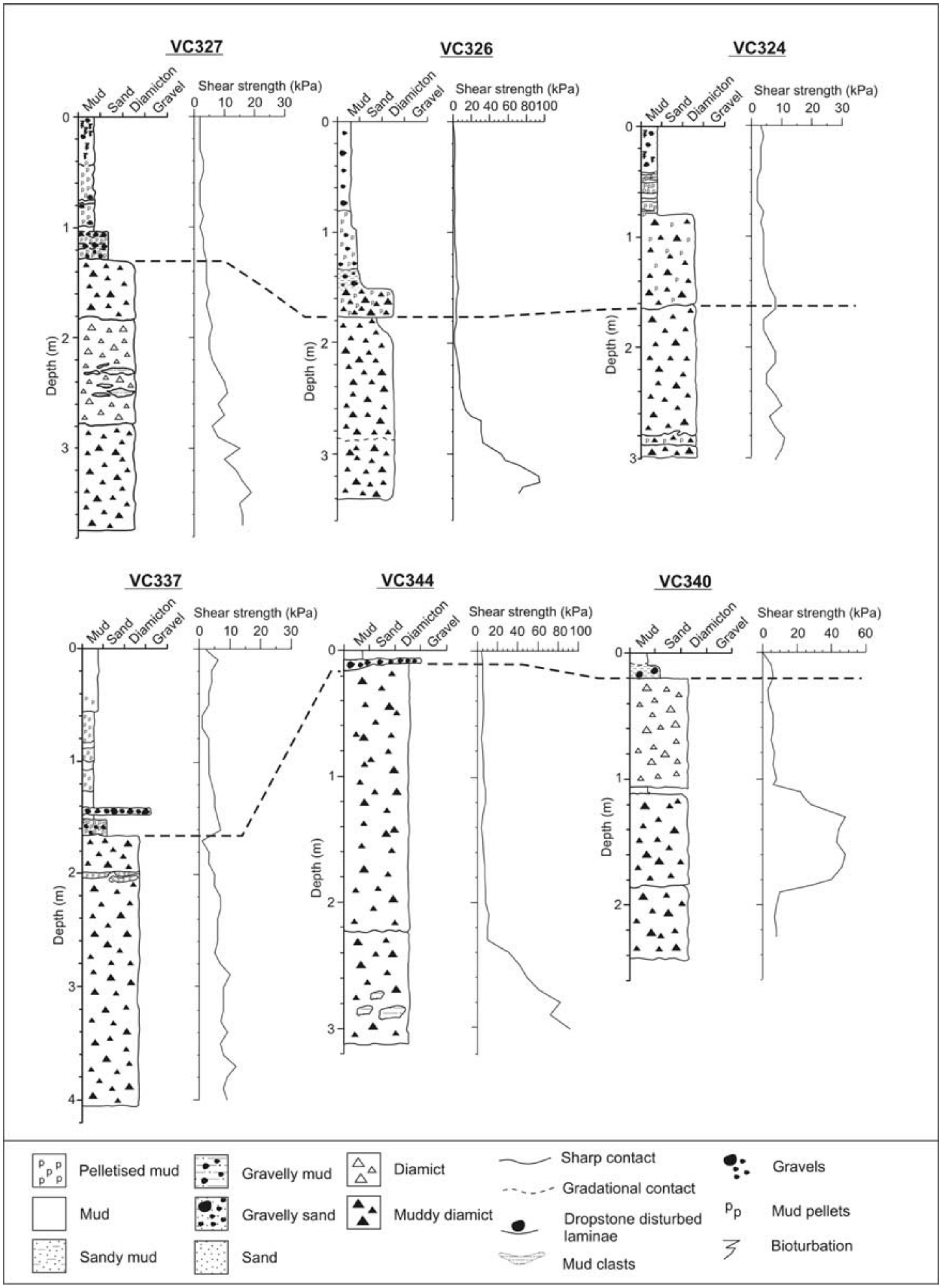

Figure 10. Sedimentary logs and shear-strength (kPa) profiles of representative cores from Robertson Trough. The horizontal dashed lines mark the contact between the soft till and overlying deglacial sediments. The deglacial sediments are more texturally and structurally variable than the till, with increased stratification and grading and they are also associated with a color change from grey (till) to brownish gray.

Table 1. Summary of Physical Characteristics of Sub–Ice Stream Tills From Cross-Shelf Bathymetric Troughs Described in This Study[a]

Location	Sedimentology	Shear Strength	Porosity
Marguerite Bay	diamict, matrix-supported; internally massive apart from occasional subhorizontal shear planes; MSGL formed in upper part of unit; at a micromorphological scale the diamict contains shear planes which are closely associated with circular structures (product of rotation), sediment banding and folding	0–40 kPa; typically <20 kPa; internal variability of 2–15 kPa over typical sediment thicknesses of 0.1–0.5 m; the maximum sediment thickness over which shear strength varies ≤1 kPa is ∼0.6 m	range = 29–40%; average = 34%
	diamict, matrix-supported; internally massive; at a micromorphological scale it contains lineaments (shear planes) and circular structures (product of rotation)	>98 kPa[b]	range = 23–29%; average = 24%
Robertson Trough	diamict, matrix-supported; contains rare attenuated soft-sediment clasts of silty to sandy mud near the base, inclined shear planes and aligned clasts	1–18 kPa; internal variability of 2–7 kPa over typical sediment thicknesses of 0.1–03 m; the maximum sediment thickness over which shear strength varies ≤1 kPa is ∼0.9 m	40–59%; average = 45%
	massive, matrix-supported diamict	20–>98 kpa[b]	27–39%
Pine Island Bay [*Lowe and Anderson*, 2002]	massive, poorly sorted diamict with mineralogical homogeneity and uniform magnetic susceptibility	15–19 kPa	not reported

[a] Location of place names shown in Figure 1.

[b] Maximum measurement of the instrument is 98 kPa.

[21] In Pine Island Bay, gravity cores did not penetrate through the base of the acoustically transparent layer of soft till. However, the same acoustic facies is seen on TOPAS records from both Pine Island Bay and Belgica Trough, namely, a transparent sediment unit (soft till) that is underlain by a prominent basal reflector. We therefore consider that all four paleo-ice streams were underlain by a similar weak, deformable, and porous sediment substrate.

4.2.2. Genesis

[22] We now discuss the genesis of the soft till and the significance of the upward transition from stiff to soft till. We present three hypotheses by which the soft till and this sequence might be explained, and we attempt to discriminate between them to achieve a plausible explanation of till genesis.

4.2.2.1. Hypothesis 1

[23] Till deposition occurs during separate glacier advances. In this explanation the stiff and soft tills represent deposits formed during separate glacial advances. In the case of Marguerite Bay, support for this interpretation is provided by core VC299 (Figure 7). In this core, the stiff and soft tills are separated by a unit of sheared glacimarine mud, which indicates an interval of subaqueous deposition following formation of the stiff till but prior to formation of the soft till. It is also indirectly supported by the grounding-zone wedges from the midshelf (Figure 3d) which, based on the MSGL extending continuously across their surface, predate ice-streaming and formation of the soft till.

[24] There are two explanations for this pattern: (1) the stiff till records one or more extensive pre-LGM ice advances across the shelf followed by deglaciation and glacimarine deposition. Subsequently, during the LGM, an ice stream developed in Marguerite Bay and deposited the midshelf grounding-zone wedges. The grounding-zone wedges were then overrun and reworked by the ice stream during its advance to the shelf edge. Alternatively, (2) the stiff till was deposited during ice advance across the shelf at the LGM. This advance extended outside of the trough and across the adjacent banks. This was followed by ice-sheet retreat and glacimarine sedimentation, with stabilization and grounding-zone wedge formation on the midshelf. Subsequently an ice stream developed and overrode the grounding-zone wedges to form the soft till.

[25] Core VC299 is the only core which contains a unit of glacimarine mud between the stiff and soft tills. The absence of such mud in cores from the center of the trough could reflect more pervasive sediment reworking there in association with the main zone of streaming flow. There is no direct evidence for multiple ice advances being responsible for till formation in Robertson Trough.

4.2.2.2. Hypothesis 2

[26] The upward transition from stiff to soft till reflects a change in the till-forming process from lodgment to deformation. Previous work from the Antarctic continental shelf has interpreted overconsolidated ‘stiff’ tills as the product of lodgment based primarily on their high shear strength, and overlying soft tills within MSGL as deformation tills [e.g., *Wellner et al.*, 2001; *Shipp et al.*, 2002]. Thus initial ice advance across the shelf at the LGM could have deposited an overconsolidated lodgment till (the stiff till). Following the LGM, streaming flow developed in the troughs and the stiff till was reworked and deformed into a soft till.

[27] Such an hypothesis is consistent with some of the sedimentological and geotechnical evidence: in all cases the stiff till is massive and overconsolidated; the soft till is weak, very porous, and shows evidence of deformation in the form of inclined shear planes, folded and deformed intraclasts and micromorphological evidence for subglacial

shear notably the association of shear planes and circular structures (suggestive of rotation of particles adjacent to shear zones in the till) [cf. *van der Meer*, 1997; *Hiemstra and Rijsdijk*, 2003].

[28] An interpretation of the stiff till as a "lodgment till" implies that it formed by the grain by grain plastering of glacial debris from the base of a warm-based, sliding glacier. Lodgment is likely in the case of larger clasts which would have ploughed through the matrix [cf. *Brown et al.*, 1987] until frictional drag overcame forward motion of the clast. However, this process would also cause deformation of sediment in front, and to either side, of the clast and it is difficult to envisage grain by grain lodgment of the finer matrix. Although direct evidence in the form of a macroscopically massive structure and evidence for shear are consistent with lodgment, these features are also compatible with subglacial deformation, as is the presence of circular structures [cf. *van der Meer et al.*, 2003; *D. J. A. Evans et al.*, 2006]. Indeed, on the basis of a similar range of evidence, the soft till could also be a product of both lodgment and deformation.

4.2.2.3. Hypothesis 3

[29] Upward increase in dilatancy associated with A/B horizons in a deforming till. In this explanation, pervasive deformation of a dilatant A-horizon results in a porous and massive till underlain by a stiffer, nondilatant till (B-horizon) [cf. *Boulton and Hindmarsh*, 1987]. There are elements of the sedimentological, geotechnical and TOPAS data that are broadly compatible with this interpretation, namely: the similarity of the stiff till/soft till sequence to the two-tiered structure (A/B horizons) of tills from the forefields of modern Icelandic glaciers [cf. *Sharp*, 1984; *Boulton and Hindmarsh*, 1987]; the presence of deformation structures within both tills; and the abrupt decrease in shear strength and increase in porosity from the stiff to soft till.

[30] However, we note that at a micromorphological scale, deformation appears to have been restricted to thin zones of up to few centimeters in thickness, and occurs at a variety of depths within the till rather than distributed throughout. Furthermore, although in some cores (e.g., VC326; Figure 10) the soft till does show a general upward decrease in shear strength throughout, as might be expected in a classic A-horizon till [cf. *Boulton and Hindmarsh*, 1987], this pattern is not ubiquitous (e.g., see VC324, VC327, VC340; Figure 10). Indeed, the soft till frequently contains internal inhomogeneities in shear strength and in some cores shows an abrupt increase in shear strength toward its top (VC295 and VC302; Figure 7).

4.2.3. Interpretation

[31] Any plausible explanation of the genesis of the soft till must be compatible with the following observations: (1) the acoustically transparent layer in which the MSGL are formed comprises a soft porous till which contains deformation structures; (2) this soft till is confined to the troughs and does not occur on the adjacent shallow banks; (3) the shear strength of the soft till is generally low but there is repeated intratill variability over thicknesses of 0.1–0.9 m; and (4) the bottom of the soft till is marked by a strong reflector and this marks the top of the denser and stronger "stiff till." The three hypotheses presented above for formation of the soft till are regarded as "end members." There are features of the till which are compatible with each hypothesis and on this basis we interpret the soft till as having formed through a combination of these mechanisms.

[32] The soft till is confined to the bathymetric troughs and is associated with geomorphic evidence for streaming flow. This suggests that the till formed beneath ice streams flowing through the troughs and over a substrate of stiff till. On the basis of the sedimentological and geotechnical data presented above we interpret the soft till as a 'hybrid' till [cf. *Nelson et al.*, 2005; *D. J. A. Evans et al.*, 2006] which formed by a combination of subglacial sediment deformation and lodgment. It is probable that these processes were partitioned according to grain size, with ploughing and lodgment of larger clasts, and deformation of the surrounding finer-grained matrix. The till contains macroscale and microscale features indicative of brittle (shear planes) and ductile (folding and circular structures) deformation. At a micromorphological scale, deformation within the soft till was localized into relatively thin zones of a few centimeters in thickness or along discrete planes [cf. *Iverson et al.*, 1998; *Scherer et al.*, 1998; *Tulaczyk et al.*, 1998, 2000]. The deformation structures are distributed throughout the depth of the soft till and are not restricted to the upper few centimeters. Deformation partitioning is also supported by the shear strength measurements which show frequent intratill variability on the order of 2–15 kPa over sediment thicknesses of typically 0.1–0.5 m, reaching a maximum of 0.9 m, and the presence of occasional, discontinuous internal reflectors within the soft till imaged by TOPAS (e.g., Figure 3). The abrupt increase in shear strength at the top of the till in Marguerite Bay (Figure 7) implies a period of stronger ice-bed coupling toward the end of deposition of the soft till, and immediately prior to ice stream retreat. Such bulge-shaped shear strength profiles have been documented from other paleo-ice stream tills and have been explained by freezing of the ice stream to the underlying till, which results in till dewatering and consolidation [*Christoffersen and Tulaczyk*, 2003]. Weak/strong till interlayering is also present in cores from Robertson Trough.

[33] Collectively, these observations are inconsistent with pervasive deformation throughout the thickness of the soft till (>10 m). Rather they imply incremental deposition of the till as a series of layers 0.1–0.9 m thick. Thus the maximum thickness of the deforming layer at any given time was 0.9 m. Such abrupt changes in shear strength may reflect episodic changes in porewater pressure/content during formation of the till. These observations are also consistent with recent modeling from modern fast-flowing glaciers and ice streams that predict alternating zones of stiff and weak till with depth in a deforming till sheet [e.g., *Tulaczyk*, 1999; *Truffer et al.*, 2000].

[34] The internal characteristics of the overconsolidated stiff till are also consistent with formation through a combination of lodgment and deformation. Deposition of the stiff till is proposed to have occurred during ice sheet advance across the shelf at the LGM, possibly prior to the development of streaming flow in the bathymetric troughs. The simplest explanation for the initiation of ice streaming was a change in basal effective stress and thereby an increase in basal lubrication [cf. *Fischer and Clarke*, 2001; *Boulton et al.*, 2001; *Parizek et al.*, 2002]. During this streaming flow, preexisting sediments including the stiff till and, in Marguerite Bay, the grounding-zone wedges,

were remobilized by a combination of deformation and ploughing, and this material was advected downflow. Such advection could have been accomplished by either transport in a deforming traction layer of sediment, or by subglacial meltwater or in a zone of debris-rich basal ice, or by some combination of these mechanisms. We suggest that in this case the first of these mechanisms was dominant as meltwater sediments were not observed in cores or on geophysical records from the outer shelves, and also on account of the difficulty of accreting thick sequences of debris into basal ice beneath rapidly moving, active ice streams. Deposition of this material as a soft till took place incrementally by a combination of lodgment and progressive immobilization of these thin deforming layers, probably in response to changes in porewater content/pressure. The absence of thin zones of sorted, meltwater-derived sediments within the soft till [cf. *Piotrowski and Tulaczyk*, 1999; *Larsen et al.*, 2004] implies that although porewater pressures were probably high during periods when ice streaming was occurring, they were insufficient to achieve extensive basal decoupling. Thus we explain the overall vertical stratigraphic sequence of stiff overconsolidated till overlain sharply by highly porous, weak till, through an upward increase in porewater content/pressure from the stiff to the soft till.

[35] In the case of Marguerite Bay, the explanation is slightly more complex. If the mud layer interpreted as glacimarine in origin between the tills in core VC299 is representative of conditions in Marguerite Bay as a whole, the stiff and soft tills are interpreted to be the product of deposition during separate ice advances. We suggest that deposition during a single glacial cycle is more likely than during multiple glaciations. In this explanation the stiff till was deposited by a combination of lodgment and deformation when the ice sheet advanced across the shelf during the LGM. Following grounding-line retreat back to the midshelf (Figure 3d), an ice stream developed in the trough and extended to the shelf edge forming the soft till. In the case of Robertson Trough, no sedimentological evidence was observed for ice sheet retreat and glacimarine conditions between the stiff and soft tills and they are therefore regarded as the product of formation during a single advance.

4.3. Subglacial Sediment Mobilization and Transport

[36] The TOPAS data show that the reflector which marks the base of the soft till layer is very distinct and abrupt, but they also show that its form varies both between and within individual troughs from smooth, continuous and often flat, to irregular and grooved. Areas characterized by a flat and smooth reflector can occur within a few kilometers of areas where the reflector is highly irregular and grooved.

[37] An irregular and grooved reflector at the base of the soft till implies that sediment was mobilized and added to the soft till layer through grooving of the stiff till at the ice-bed interface. This interpretation is also supported by the incision of preexisting sediments by the irregular reflector which marks the base of the soft till (Figures 4b and 5a), and by the distribution of soft till in the outer shelf trough offshore of Pine Island Bay which locally occurs across the flanks and peaks of some of the grooves/ridges (Figure 5b). This latter pattern is inferred to result from subglacial sediment mobilization and deformation, whereby sediment is eroded and pushed forward during the grooving process [*J. Evans et al.*, 2006]. Thus a zone of deforming till is generated along the sides and the tops of the grooves and would be advected downflow. Grooving could have occurred by several mechanisms including erosion by boulders entrained in the base of the ice stream [cf. *Brown et al.*, 1987], larger bedrock rafts or plugs of mobile sediment, or irregular shaped keels generated from roughness elements at the ice stream base [cf. *Tulaczyk et al.*, 2001]. The scale of the grooves that we observe on our TOPAS records, with wavelengths up to 0.5–1 km and depths of greater than 10 m, is difficult to reconcile with erosion by boulders although this mechanism could contribute to the production of grooves with smaller dimensions.

[38] In contrast, the flat, smooth and continuous reflector which characterizes the base of the soft till in parts of Robertson Trough, Pine Island Bay, Belgica Trough and especially Marguerite Bay, represents an abrupt transition from highly porous weak till downward into much stiffer and less porous sediment. The flat and smooth nature of the basal reflector suggests that the top of the stiff till was mobilized as a subglacial traction carpet that was advected downflow. The base of this traction carpet represents the contact between the stiff and soft tills. Such mobilization is likely to be due to changes in basal effective stress whereby an increase in porewater pressure at the top of the stiff till facilitated its deformation and remobilization [cf. *Fischer and Clarke*, 2001; *Boulton et al.*, 2001; *D. J. A. Evans et al.*, 2006]. We also acknowledge, however, that sediment could have been liberated upflow through the action of ploughing. On the basis of the micromorphological and geotechnical data presented above, the thickness of this mobile traction layer at any one time was $\leq$0.9 m. Thus the thick sequence of soft till that characterizes the outer shelf troughs would have been formed incrementally through the progressive deposition of relatively thin sediment layers ($\leq$0.9 m).

[39] Mobilization of the stiff till and preexisting sediment to form the soft till would be expected to result in the downflow advection of sediment toward the ice-stream terminus. Evidence for such sediment advection is provided by three lines of evidence. Firstly, in Marguerite Bay the TOPAS line shown in Figure 3d indicates that the soft till thickens downflow from the grounding-zone wedges on the midshelf to the shelf edge. These grounding-zone wedges were overrun by the ice stream as indicated by MSGL which extend continuously across their surface. Downflow thickening of the soft till from these grounding-zone wedges suggests that till formation was associated with significant sediment advection in a subglacial deforming layer to the outer shelf. Secondly, geophysical data from Pine Island Bay, Marguerite Bay and the Bellingshausen Sea indicate that the inner shelf in these regions is characterized by an irregular bedrock substrate with relatively little sediment. This scarcity of sediment on the inner shelf contrasts with the outer shelf where up to 2 km of Cenozoic sediments occur [*Bart and Anderson*, 1995; *Larter et al.*, 1997; *Nitsche et al.*, 1997; *Lowe and Anderson*, 2002; *Ó Cofaigh et al.*, 2002, 2005a]. This implies subglacial erosion and evacuation of sediment from the inner to the outer shelf, probably over successive glacial cycles [cf. *Hooke and Elverhøi*, 1996]. Thirdly, diamictic sediments similar in

texture and color to the soft tills have been recovered in cores from the continental slope in front of the ice stream troughs in Marguerite Bay, Belgica Trough and Robertson Trough [*Dowdeswell et al.*, 2004b; *Evans et al.*, 2005; *Hillenbrand et al.*, 2005], and are associated with large-scale slope progradation in some cases [*Ó Cofaigh et al.*, 2005a]. Thus the soft till is interpreted as a product of reworking of the stiff till and preexisting sediment.

[40] Collectively this implies advection of significant volumes of subglacial sediment beneath the paleo-ice streams and delivery of this sediment onto the continental slope, albeit probably over several glacial cycles. A partial modern analogue for such sediment advection beneath contemporary West Antarctic ice streams is presented by *Smith et al.* [2005] who used reflection seismic data from the Rutford Ice Stream to show that removal and accretion of subglacial sediment on the order of 6–10 m vertical thickness can occur in less than a decade. Thus our data demonstrate that while, on the one hand, bed deformation beneath paleo-ice streams on the Antarctic continental shelf was restricted to shear zones of 0.1–0.9 m in thickness, these localized shear zones can integrate [cf. *Iverson and Iverson*, 2001] to produce large-scale sediment advection.

5. Conclusions

[41] 1. Marine geophysical data from bathymetric troughs on the Antarctic continental shelf provide evidence for the former presence of fast-flowing ice streams during the last glacial cycle. Streaming flow is recorded by elongate subglacial bedforms, especially megascale glacial lineations, in Marguerite Bay, Robertson Trough (Larsen-A region), offshore of Pine Island Bay, and Belgica Trough on the Bellingshausen Sea margin.

[42] 2. TOPAS subbottom profiler data show that the lineations are formed in the upper part of an acoustically transparent sediment layer. Sediment cores from the layer demonstrate that it is a weak and porous till, the base of which is marked by a strong reflector which represents the top of a denser and stronger "stiff till."

[43] 3. The soft till is characterized by a range of structures indicative of subglacial shear. Shear was concentrated in zones which were typically 0.1–0.5 m thick (maximum thickness of 0.9 m). Thus deformation was not pervasive throughout the soft till and the maximum thickness of the subglacial deforming layer was ~0.9 m.

[44] 4. Both the stiff and soft tills are "hybrid" tills that formed by a combination of subglacial sediment deformation and lodgment. Initiation of streaming flow and formation of the soft till are inferred to relate to changes in bed lubrication and porewater pressure/content.

[45] 5. The TOPAS data show that the form of the reflector which marks the base of the soft till layer is variable within and between individual troughs and ranges from flat and continuous to irregular and grooved. These data are interpreted to indicate the operation of different mechanisms of sediment mobilization and incorporation into the soft till layer. The irregular basal reflector is consistent with a grooving origin through some combination of keels at the ice stream base and/or boulders/bedrock rafts entrained within the ice. The flat, smooth and continuous reflector is more consistent with mobilization of the upper part of the stiff till and/or preexisting sediment as a subglacial traction carpet.

[46] 6. Geophysical evidence for large-scale sediment advection of the soft till toward the ice stream terminus, combined with sedimentological and geotechnical evidence for deformation partitioning into zones 0.1–0.9 m thick within the soft till, implies that these localized shear zones integrate and result in the downflow advection of significant volumes of sediment beneath Antarctic paleo-ice streams.

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