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14. Prydz Channel Fan and the History of Extreme Ice Advances in Prydz Bay[1]

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ABSTRACT

During the late Neogene, the Lambert Glacier–Amery Ice Shelf drainage system flowed across Prydz Bay in an ice stream that reached the shelf edge and built a trough mouth fan on the upper continental slope. The adjacent banks saw mostly subglacial till deposition beneath slower-moving ice. The fan consists mostly of debris flow deposits derived from the melting out of subglacial debris at the grounding line at the continental shelf edge. Thick debris flow intervals are separated by thin mudstone horizons deposited when the ice had retreated from the shelf edge. Age control at Ocean Drilling Program Site 1167 indicates that the bulk of the trough mouth fan was deposited prior to ~780 ka with as few as three debris flow intervals deposited since then. This stratigraphy indicates that extreme advances of the Lambert Glacier-Amery Ice Shelf system ceased during the mid-Pleistocene. Possible causes for this change are progressive over-deepening of the inner shelf, a reduction in maximum ice volumes in the interior of the East Antarctic Ice Sheet caused by temperature change, and a change in the interaction of Milankovich cycles and the response time of the ice sheet.

INTRODUCTION

The East Antarctic Ice Sheet is presently the largest ice mass on Earth and it is the longest lived, having been initiated in the Paleogene (Bar-

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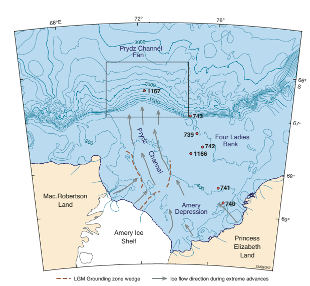
ron et al., 1991; O'Brien, Cooper, Richter, et al., 2001). Since its formation, it has played a central role in global climate and in higher-order sea level change. Although global ice volume/temperature changes can be estimated using low-latitude $\delta^{18}O$ records, the distribution of ice on the continent and the evolution of the Antarctic Ice Sheet through glacial–interglacial cycles requires direct evidence from Antarctica. Prydz Bay, East Antarctica, was drilled during Leg 188 to sample the record left by the Lambert Glacier–Amery Ice Shelf drainage system that flows from the interior of the East Antarctic Ice Sheet. The results from Leg 188, when combined with results from Leg 119, also drilled in Prydz Bay, provide a record of the extensive erosion of the shelf by ice advances, starting in the late Eocene to early Oligocene but becoming intense from the middle Miocene onward (Barron et al., 1991; O'Brien, Cooper, Richter, et al., 2001). Erosion has removed large parts of the record in places, but the erosion surfaces can be traced into their correlative conformities on the continental slope, where the debris carried by the grounded ice has been deposited in trough mouth fans (Cooper et al., 1991; Kuvaas and Leitchenkov, 1992; Bart et al., 2000). These fans form where fast-flowing ice streams reach the shelf edge during episodes of extreme ice extent and should contain a record of intervals not represented on the shelf (Vorren and Laberg, 1997; Boulton, 1990). They should consist of thick mass flow deposits formed from debris released from the basal ice at the shelf break interbedded with thin hemipelagic and pelagic intervals deposited when the ice was shoreward of the shelf edge.

Trough mouth fans might hold the answer to a problem that has become apparent with the greater understanding of the position of the Antarctic ice grounding zone during the Last Glacial Maximum (LGM) (18–12 ka). There is evidence for grounding of the ice sheet at the shelf edge in many places (e.g., Mac.Robertson Land [Harris et al., 1996], eastern Ross Sea [Shipp et al., 1999; Domack et al., 1999], and Antarctic Peninsula [Pusdsey et al., 1994]). LGM grounding zone deposits have been identified in the western Ross Sea well back from the shelf edge (Licht et al., 1999; Shipp et al., 1999; Domack et al., 1999). The East Antarctic continental shelf displays abundant evidence of ice advance to the edge of the continental shelf (Vanney and Johnson, 1985; O'Brien and Leitchenkov, 1997; Bart et al., 2000). However, Anderson et al. (2002) reviewed the literature on East Antarctic Ice Sheet LGM grounding zone positions and concluded that around most of the margin, the LGM grounding zone is in a mid-shelf position or near its present location. In the case of Prydz Bay, Domack et al. (1998) and O'Brien et al. (1999) mapped LGM grounding zone wedges around Prydz Channel more than 130 km from the continental shelf edge (Fig. F1). Seaward of these wedges, the floor of Prydz Channel lacks flutes and other subglacial features and is blanketed by thick glaciomarine clays and oozes (O'Brien et al., 1999; Domack et al., 1998) indicating that the Lambert Glacier did not ground there during the last glacial cycle. This raises several questions:

1. Why did large parts of the East Antarctic Ice Sheet including some large interior-derived ice streams not reach the shelf edge during the LGM?
2. When did the ice sheet last reach the shelf edge if not during the LGM?
3. What sort of glacial episode is required to make the ice advance to the shelf edge?

F1. Bathymetry of Prydz Bay, p. 17.



Domack et al. (1998) suggested that relatively long periods of low sea level and increased ice volume might be needed for the interior ice sheet to respond and advance to the shelf edge. Site 1167 of Ocean Drilling Program (ODP) Leg 188 was intended to investigate these questions by sampling a record through the trough mouth fan at the mouth of Prydz Channel that would provide a history of Pleistocene advances.

In spite of their potential value as records of past glaciation, trough mouth fans were not drilled in the Antarctic margin until ODP Leg 188. Site 743 was drilled during Leg 119 on the Prydz Bay slope but to the east of the Prydz Channel Fan on a steep, eroded part of the slope (Barron, Larson, et al., 1989; O'Brien and Leitchenkov, 1997).

Regional Setting

Prydz Bay is the downstream end of the Lambert Glacier–Amery Ice Shelf ice drainage system, which drains ~16% of the East Antarctic Ice Sheet (Allison, 1979; Fricker et al., 2000). The Lambert Glacier–Amery Ice Shelf system responds to mass balance fluctuations in the interior of the East Antarctic Ice Sheet that are then reflected in the sediments of Prydz Bay and the adjacent slope and rise (Fig. F1). Prydz Bay is typical of the Antarctic shelf in having its deepest areas inshore, near the front of the Amery Ice Shelf in the Amery Depression (Fig. F1). On the eastern side of the bay, the seafloor shoals to depths as shallow as 200 m in Four Ladies Bank. Four Ladies Bank is separated from the Princess Elizabeth Land coast by a series of deeps and saddles collectively known as the Svenner Channel. The Amery Depression is linked to the shelf edge by Prydz Channel, which occupies the western part of the bay and has depths from 700 meters below sea level (mbsl) at its inshore end to ~500 mbsl at the shelf edge.

Prydz Channel Fan can be seen in bathymetric contours as a smooth seaward bulge directly north of the mouth of the Prydz Channel and in isopach contour as locally thick sediment overlying the surface (pp-12) that defines the base of the fan (Fig. F2) (O'Brien, Cooper, Richter, et al., 2001). The fan extends to water depths of ~2400 m and has a surface slope of ~2°.

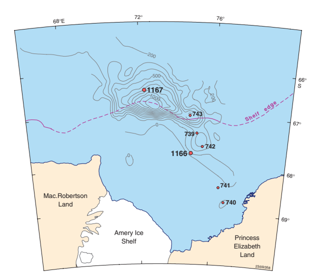
O'Brien and Harris (1996) inferred that the Prydz Channel and Fan developed in the early to mid-Pliocene, when the amount of ice accumulating in Princess Elizabeth Land on the southeastern side of Prydz Bay increased to the point where it deflected the flow of the main Lambert-Amery system westward. The system then formed a fast-flowing ice stream that cut Prydz Channel and deposited debris on the upper slope.

Prydz Channel Fan Seismic Stratigraphy

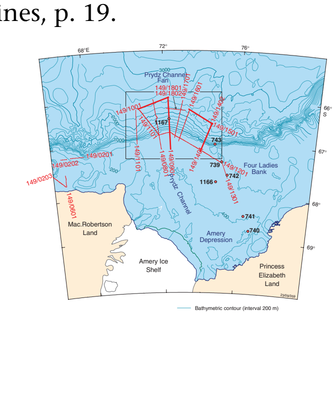
Data

The Prydz Channel Fan is imaged by a number of seismic surveys; however, the most comprehensive network of data is Australian Geological Survey Organisation (AGSO) Survey 149, which consisted of lines collected in 1995 using a single generator-injector (GI) gun (45-in^3 generator chamber) and a four-channel, 25-m streamer (Fig. F3) (O'Brien et al., 1995). The lines were arranged with dip lines normal to fan contours and tie lines at the base of the fan and on the shelf. Two lines were shot on the slope west and east of the fan to investigate contrasting settings. Ice conditions made the collection of along-slope lines in midfan impossible in 1995, and again in 1997, a large iceberg re-

F2. Isopach map of the Prydz Channel Trough Mouth Fan, p. 18.



F3. 1995 ANARE/AGSO survey lines, p. 19.



stricted the length of along-slope lines that could be shot (Harris et al., 1997).

Reflection Geometry

In dip section, the Prydz Channel Fan slopes seaward in a continuous concave-upward curve with an average slope of 2° (cf. Laberg and Vorren, 1995) and with only small steps in the profile (Fig. F4). The fan sediments extend >50 km from the shelf edge. The steps on the upper fan are probably small slump scars or, near the shelf break, ice keel scours. Farther down the fan, the steps are down to basin and are probably the noses of debris flows that have halted on the slope. Internally, the fan displays clinoforms in packages that pinch out at the base of the fan or, in the case of the uppermost packages, in midfan where the pinchout corresponds to a step in the seafloor profile (Fig. F4). In sections across the slope in midfan, the fan forms a broad mound with smaller-scale mounds on its surface (Fig. F5). These vary from 0.5 to 30 km across. Small gullies with levees are present in a few places, but these are not common. At the toe of the fan, the overall mound shape is less obvious on strike sections, but the smaller mounds and channel-levee systems are more obvious. Mounds are up to a few kilometers across and 10 to 20 ms high and overlap in an irregular fashion (Fig. F6). The channel-levee systems are of similar scale but comprise levees arranged symmetrically about a channel with a floor that produces high-amplitude reflections (Fig. F6).

The fan foreset reflectors form moderately continuous packages 10–20 ms thick of high-amplitude reflectors separated by reflection-poor intervals (Figs. F4, F6). The reflector packages pinch and swell, and some channel structures are present. Reflection-poor intervals show faint reflectors parallel to the basal or mounded reflectors (Figs. F4, F6).

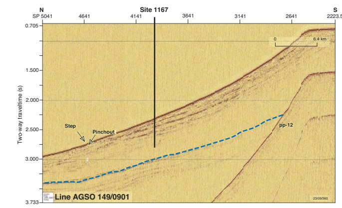
The foresets forming the upper continental slope seaward of Four Ladies Bank extend some 25 km from the shelf edge and are concave upward, sloping as much as ~4° (Fig. F7). Several mounded deposits are visible on the surface, suggesting slump deposits. Foreset reflections are less continuous than in the trough mouth fan seaward of Prydz Channel and show abundant mounding and channeling.

The prominent surface at the base of the fan, surface A of Mitzukoshi et al. (1986), was mapped on both the 1995 data and on older, lower-resolution lines. It can be traced along the slope adjacent to the trough mouth fan and onto Four Ladies Bank. This surface marks the beginning of fan growth, as determined by tracing surface A beneath the continental slope to a paleoshelf break that is linear across Prydz Channel and parallel to the shelf on both sides of the fan. On the GI gun lines, 12 horizons that show some truncation or downlap could be seen; however, only 5 could be mapped confidently on most lines. These are surfaces pp-2, pp-4, pp-5, pp-7, and the fan base (surface A), herein designated pp-12 (Fig. F8). Close examination of an expanded display of the seismic data indicates that pp-12 intersects Site 739 within the early Pliocene interval that includes Cores 119-739C-13R to 15R (105.9–130.3 meters below seafloor [mbsf]) (Barron et al., 1991).

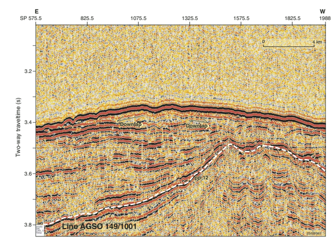
Topset-Foreset Relationships

The seismic stratigraphy of both the Prydz Channel Fan and the adjacent Four Ladies Bank provides some insights into sedimentation processes at the head of trough mouth fans. Line AGSO 149/0901 runs

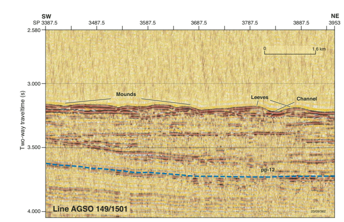
F4. Dip section through axis of Prydz Channel Trough Mouth Fan, p. 20.



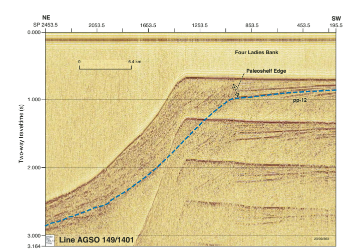
F5. Broad mounded geometry of recent units, p. 21.



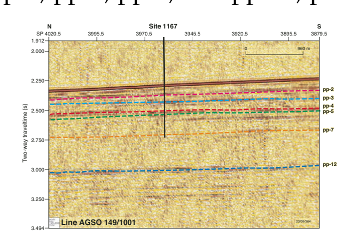
F6. Channel-levee units and depositional mounds, p. 22.



F7. Shelf edge and upper slope of Prydz Bay east of the Prydz Channel Fan, p. 23.



F8. Intersection with pp-2, pp-3, pp-4, pp-5, pp-7, and pp-12, p. 24.



along the fan axis into Prydz Channel (Fig. F3). Prior to fan deposition, the shelf aggraded. The base of the fan (surface pp-12) shows as a high-amplitude reflector with a convex-upward seaward dip that passes landward into a horizontal, high-amplitude topset reflector (Fig. F9). Surface pp-12 passes offshore into steeply dipping, undulating reflectors of poor continuity and variable amplitude. From pp-12 time onward, shelf aggradation occurred on the edge of Prydz Channel but was minor in the center of the channel where progradation prevailed.

Seaward of the pp-12 paleoshelf edge, overlying foresets offlap against gently seaward-dipping topsets ~0.15 s two-way traveltime (TWT) thick (Fig. F9). This geometry is repeated but with the base of successive sequence-bounding topsets being progressively higher.

On Four Ladies Bank, away from the trough mouth fan, paleoshelf edges aggraded vertically by 0.25 s TWT until ~pp-4 time with only minor prograding of the paleoshelf edge between pp-12 and pp-7 (Fig. F10). From pp-7 time onward, the shelf edge prograded rapidly, forming an upper slope wedge with greatest thickness beneath the present shelf edge. Topsets display high amplitudes, especially those pp-12 and older. Surface pp-12 is onlapped by topsets to a point ~8 km landward of the pp-12 paleoshelf edge (Fig. F10).

Thickness Relationships

A series of isopach maps illustrates several major features of fan deposition. The total fan thickness (seafloor to pp-12) (Fig. F2) shows that the locus of fan deposition was beneath the present shelf break where the axis of Prydz Channel crosses the shelf break (Fig. F2). Prydz Channel has very thin post-pp-12 sediments, whereas Four Ladies Bank shows a relatively thick, horizontal layer of similar age sediments. On the slope, post-pp-12 sediments are slightly thicker on the eastern side of the Prydz Channel axis than on the western side. Also, sediments thin more rapidly on the western side than the eastern side.

The initial phase of fan sedimentation (pp-12 to pp-7) produced a low-relief wedge of slope sediments that was slightly thicker beneath the eastern side of the area seaward of Prydz Channel (Fig. F11). This suggests that a broad channel fed sediment to the shelf edge, although the contours are influenced by the thick topsets deposited on Four Ladies Bank prior to surface pp-7 (Fig. F10). The next phase (Fig. F12) (pp-5 to pp-7) saw deposition of a pronounced lobe seaward of the present Prydz Channel axis. Prydz Channel appears to become narrow during this phase of deposition, leading to an approximation of a point source for fan sediment and rapid progradation of the shelf edge along the channel axis. Subsequent sequences show seaward displacement of the locus of thickest deposition (pp-2 to pp-5).

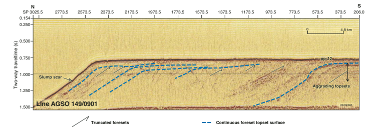
The final stage of fan sedimentation (Fig. F13) (pp-2 to surface) consists of a relatively thin layer that drapes the fan and thickens to the west, with the thickest parts of the sequence on the middle to western side of the fan.

SITE 1167

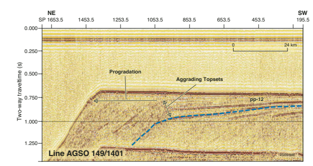
Drilling History

Site 1167 was located midfan to obtain as complete a section as possible without drilling too great a thickness and also to avoid shelf edge

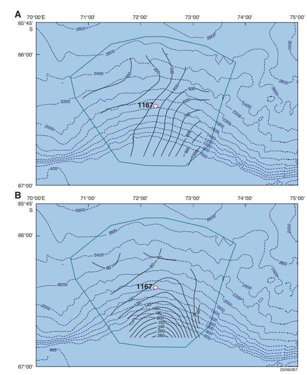
F9. Topsets in the axis of Prydz Channel, p. 25.



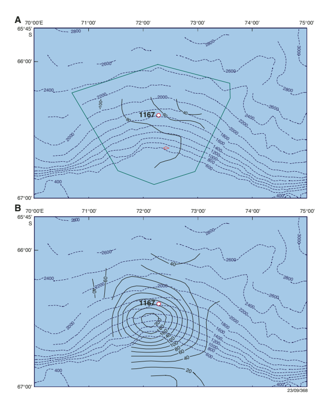
F10. Topset geometry on Four Ladies Bank, p. 26.



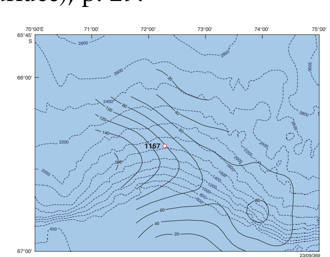
F11. Thickness of sediments deposited (pp-7 to pp-12), p. 27.



F12. Surfaces pp-5 and pp-4 and pp-4 to pp-2, p. 28.



F13. Latest mappable unit (pp-2 to surface), p. 29.

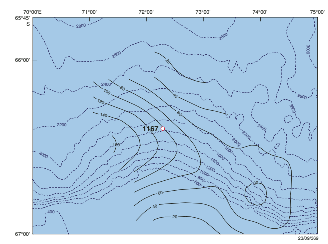


slumps. Hole 1167A was spudded in 1640 m water depth and drilled to 447.5 mbsf, achieving ~40% recovery. Because of the incomplete recovery, it was decided to cease core drilling and attempt wireline logging. This was unsuccessful, so Hole 1167B was drilled with logging-while-drilling (LWD) tools. This hole reached 261.8 mbsf before time ran out.

Lithostratigraphy

Site 1167 intersected predominantly clayey silty sands with dispersed rock clasts, minor beds of clays, and coarse sands. Two units were recognized by O'Brien, Cooper, Richter, et al. (2001) (Fig. **F14**):

F14. Lithostratigraphy of Site 1167, p. 30.

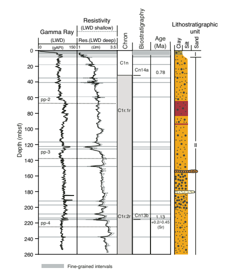


1. Unit I extends from the seafloor to 5.17 mbsf. It consists of olive to red-brown clay and sandy clay with isolated beds of fine sand and sand beds that grade from granular at the base to medium sand at the top. Lonestones are rare, and diatoms and sponge spicules form as much as 2% of the clay beds.
2. Unit II makes up the rest of the section. It consists of four facies:
   a. Facies II-1 makes up most of the section. It is dark gray to reddish gray poorly sorted sandy silt, silty sand, clayey sand with dispersed granules, and pebbles and clast-poor diamicton. Foraminifers are a minor component, but diatoms, radiolarians, and sponge spicules are absent. Some benthic foraminifers are typical of the adjacent continental shelf. A few gravel beds (60% gravel and 40% matrix) are present.
   b. Facies II-2 is represented by only a few beds, up to 3 m thick, of moderately sorted quartz coarse sand with granules and mud clasts.
   c. Facies II-3 consists of decimeter-scale beds of dark gray clay and clay with thin (<1 mm) silt laminae and burrowed intervals. This facies has sharp upper and lower contacts with other facies. Rare sand grains are present but the facies lacks lonestones.
   d. Facies II-4 comprises centimeter- to decimeter-scale beds of greenish gray to dark gray clay with dispersed sand and granules. Foraminifers and nannoplankton are common. Foraminifers are both planktonic forms (*Neogloboquadrina pachyderma,* sinistral) and benthic forms usually associated with midbathyal environments (O'Brien, Cooper, Richter, et al., 2001).

Lithostratigraphy from Logging-While-Drilling Data

The low recovery in the hole made it impossible to estimate the number of glacial–interglacial episodes based solely on core samples. However, the LWD tools provided this information for the upper 260 m of the hole. LWD tools collect geophysical measurements of the sediment in the borehole wall using sensors in drill collars just behind the bit and are used where poor hole conditions prevent conventional logging (see the ODP Guide to Logging at **www.ldeo.columbia.edu/BRG/ODP/LOGGING/TOOLS/tools.html**). The configuration of LWD tools used at Site 1167 gave shallow and deep resistivity and spectral gamma readings (Fig. **F15**).

F15. Logs, lithologies, and age control points, p. 31.



The combination of deep and shallow resistivity and natural gamma logs clearly shows 16 fine-grained interbeds within the 260 m logged. These clay-rich interbeds appear as low-resistivity spikes, commonly associated with small gamma peaks. Two resistivity peaks at 40 and 60 mbsf correspond to gamma lows, indicating that they are sand beds. The fine intervals represent interruptions to debris flow deposition, caused by retreat of the ice from the shelf edge. The thickest interval of low resistivity is Unit I. It has a lower gamma response than other fine intervals, probably because of a higher proportion of nonradioactive biogenic material such as diatoms. The other fine intervals are likely composed of Facies II-3 and II-4.

The thick intervals of high resistivity are mostly Facies II-1. Within these intervals, the log values are fairly uniform but blocks of slightly different resistivity suggest stacked individual Facies II-1 beds 5–20 m thick (Fig. **F15**).

Seismic to Drill Hole Tie

In the absence of a sonic log or hole velocity survey, seismic data were tied to Site 1167 stratigraphy using a two-way traveltime vs. depth curve derived from core velocities corrected for rebound. Converting two-way traveltime for reflectors at the well intersection on line 149/0901 to depth in the hole produces an equivocal correlation to the hole stratigraphy with reflector depths not exactly matching major changes in lithology observed on the LWD logs. However, none of the reflector depths are more than 10 m from a significant lithologic change. The frequency content of the air gun used to collect line 149/0901 is such that 10 m is less than or equal to the limit of temporal resolution of the signal (Kallweit and Woods, 1982). This, coupled with uncertainties in the velocity model for the hole, make it difficult to determine with certainty if the reflectors really correspond to mudstone units or more subtle lithologic changes seen on the logs closer to the predicted depth. The fact that the surfaces were mapped on the basis of truncation and downlap suggests that they should not necessarily correspond to mudstones in the drill section. Therefore, each surface that intersects the hole should be considered independently.

Surface pp-2 is predicted to be at 68 mbsf at Site 1167, just below a major shift in gamma ray and resistivity logs at 62 mbsf (Fig. **F15**). This level also features a major discontinuity in magnetic susceptibility values. A mudstone horizon is present at 59 mbsf. It seems likely that pp-2 is the seismic expression of the lithologic change seen in the geophysical logs. Surface pp-3 at 133 mbsf is ~12 m below the nearest overlying mudstone and 8 m above the next below (Fig. **F15**). It does correspond quite closely to a step in the gamma log that may represent a change to slightly cleaner, thicker units within this fairly uniform interval. Surface pp-4 at 226 mbsf is just below major changes in geophysical logs and sediment composition including magnetic properties (Shipboard Scientific Party, 2001), grain size, and clay mineralogy (Forsberg et al., 2001). Surfaces pp-5 and pp-7 do not intersect the logged part of the section. Surface pp-5 probably intersects the hole at 265 mbsf, whereas pp-7 is close to total depth.

Interpretation

The combination of sediment facies in the hole and the seismic facies indicate that the Prydz Channel Fan is dominated by debris flows with thin interbedded facies. Unit I records a period of hemipelagic deposition, as indicated by the fine-grained sediments and diatoms and sponge spicules. The lonestones are likely ice-rafted detritus, and normally graded sand beds are turbidites. Unit I in Hole 1167A is identical to the sediments recovered from across the fan in shallow cores (O'Brien et al., 1995; Golding, 2000).

For Facies II-1, poor sorting, abundant floating clasts, reworked shelf benthic foraminifers, and lack of visible grading indicate deposition as debris flows derived from ice grounded at the shelf break. On seismic lines, the debris flows show as reflection-poor intervals that may be mounded and, in places, show chaotic mounded reflectors. The downslope terminations of some of the youngest flows can still be seen as down-to-basin steps in the lower fan surface. The spacing of seismic reflectors is consistent with the scale of unit thickness of Facies II-1 at Site 1167 as indicated by the logging data. The GI gun used has a signal with a frequency content that allows the resolution of interfaces 10 m apart, which is similar to the minimum thickness of Facies II-1 packages (Fig. **F15**). Lenticular units with chaotic fill represent slumps formed by failure of fan sediment rather than primary debris flows derived directly from the grounding zone.

Facies II-2 probably represents turbidites generated by mass movement on the fan surface or by sinking of dense, turbid plumes (Hunter et al., 1996). Turbidity currents are also suggested by presence of the channel-levee units visible on seismic lines. The rarity of channel-levees is consistent with the rarity of Facies II-2 at Site 1167. Facies II-3 and II-4 represent interruptions to debris flow sedimentation. Laminated Facies II-3 is probably bottom-current deposits, whereas Facies II-4 is hemipelagic sediment deposited with little current activity.

At the fan top on the shelf, the high amplitude of the pp-12 reflector and several prefan shelf reflectors suggest high impedance contrasts that may result from sustained erosion and/or overcompaction associated with either a hiatus or relatively severe subglacial erosion (Cochrane et al., 1995; Cochrane and Cooper, 1991; Solheim et al., 1991). The change from higher aggradation to stronger progradation suggests a reduction in the volume of subglacial till deposited on the shelf compared to the volume of material delivered to the shelf edge at the glacier sole. This could indicate an increase in basal shear stress or a reduction in the strength of the subglacial till. Both such effects are consistent with the development of a fast-flowing ice stream (Alley et al., 1989). The contrasting persistence of vertical aggradation post-pp-12 times shown in Four Ladies Bank might result from deposition by slower-moving ice that did not transport much debris to the shelf edge (Boulton, 1990).

The sequence of events that led to the geometry seen in Prydz Channel must have been as follows:

1. A period of foreset progradation,
2. Erosion of any topsets and the top of the foresets,
3. Deposition of the seaward-dipping topsets and associated foresets,
4. Another episode of erosion that removed some but not all of the topsets, and
5. Deposition of topsets and foresets in a higher-level sequence.

The pattern of foreset truncation followed by topset preservation suggests cycles of erosion followed by increased sediment accommodation on the shelf. On nonglaciated margins, such cycles would be the result of sea level cycles superimposed on subsidence (Posamentier et al., 1988). In the case of Prydz Bay, tectonic subsidence is probably low compared to the rates of glacial erosion and deposition; however, some isostatic subsidence of the shelf edge induced by shelf progradation is possible (Boulton, 1990; ten Brink et al., 1995).

Consideration needs to be given to the controls on subglacial deposition. Glacial erosion and deposition are controlled by a range of factors (Boulton, 1990). High ice velocities produce high basal shear stress, which favors erosion. High vertical effective pressure, which is the weight of ice thickness minus water pressure at the bed, also produces high basal shear stress. Till rheology also influences erosion and deposition (Boulton and Hindmarsh, 1987; Murray, 1997). Till deposition is favored by lower velocities, lower vertical effective pressure, and rapid basal melting that delivers sediment to the glacier sole. Basal freezing is thought to entrain sediment in the basal ice (Alley et al., 1997).

For a major ice mass grounded at the shelf edge, vertical effective pressure is likely to vary with sea level change though the glacial cycle as well as ice volume (Boulton, 1990). The pattern of truncated foresets separated by a topset that passes into a foreset can be explained by the response of the ice stream to a sea level cycle. Falling sea level increases the height of ice above buoyancy and increases the depth of the deforming bed, eroding the sediments beneath. As sea level begins to rise, the process reverses, depositing a subglacial topset bed as the ice decouples from the deforming bed (Murray, 1997) overlain by grounding zone deposits and proximal glaciomarine facies if the grounding zone retreats from the shelf (Boulton, 1990). This retreat phase produces the foreset–topset unit. The preservation of topset beds in Prydz Channel from successive erosion episodes could result from relatively minor erosion beneath the outer part of the glacier during each major advance. The slight seaward dip of topsets suggests that preservation was enhanced by subsidence of the outer shelf sediment wedge caused by differential compaction and loading of the crust (ten Brink et al., 1995).

Although the tie between the drill site and seismic section is uncertain, consideration of the likely processes on the fan surface might explain why the mapped surfaces do not correspond to the obvious fine-grained units. It is thought that trough mouth fans grow primarily during episodes when the ice is grounded at the shelf edge (Boulton, 1990; Vorren and Laberg, 1997). The erosion surfaces mapped within the fan probably formed during periods of relative sediment starvation when the ice had retreated. During such periods, the fan surface could be reworked by contour currents or have a hemipelagic drape deposited on it, forming mudstone intervals. Boulton (1990) points out that debris deposited near the top of the fan may be reworked during such "interglacial" periods. This is also suggested by the surficial slump scars near the top of the Prydz Channel Fan (Fig. **F4**). Therefore, the erosion surfaces mapped within the fan could conceivably be overlain by thin debris flows as well as by hemipelagic intervals. Such reworked debris flows might contain less clay and so appear to have lower gamma and resistivity values than debris flows beneath. This may be the case for surfaces pp-3 and pp-4, which correspond to subtle changes in logging values (Fig. **F15**). Such debris flows may also contain foraminifers with "interglacial" isotope values.

The isopach maps show that the Prydz Channel started as a fairly broad feature that deposited the more sheetlike interval pp-12 to pp-7 but deposited a strongly lobate fan from pp-7 to pp-2. This suggests preferential downcutting and sediment transport along the channel axis through that time. The last stage of sedimentation (pp-2 to present) produced a more drapelike deposit with debris flows and, finally, hemipelagic sediments deposited evenly across the fan.

CHRONOLOGY AND SEDIMENTATION RATES

The chronology for sediments at Site 1167 is derived from paleomagnetic measurements on cores, diatoms in the uppermost core, a few occurrences of nannoplankton, and Sr isotope dates from samples of planktonic foraminifers (Fig. F15), (O'Brien, Cooper, Richter, et al., 2001). Although these data sources do not provide tightly constrained ages, they can be used to estimate a range of sedimentation rates, even though there are probably unresolved disconformities in the section.

Diatoms are restricted to Core 188-1167A-1H, which extends to 5.25 mbsf. They include elements of the *Thalassiosira lentiginosa* Zone, which indicates the age of these sediments is <0.66 Ma (O'Brien, Cooper, Richter, et al., 2001). Nannoplankton of Subzone CN14a (200–900 ka) are found at 37.4 mbsf. Two age data points below this level are a Sr date of 1.13 +0.25/–0.45 Ma on planktonic foraminifers at 218 mbsf and nannoplankton of Zone CN13b between 218 and 228 mbsf, giving an age range of 900 ka to 2 Ma for the interval. The paleomagnetic record is marked by normal polarity near the top of the section with a downward shift to reversed polarity at 32 mbsf. Shipboard Scientific Party (2001) interpreted this to be the Brunhes/Matuyama boundary (780 ka) on the basis of proximity to the nannoplankton at 37.4 mbsf. Reversed polarity then continues to the base of the hole. We interpret the apparent absence of the Jaramillo normal episode as the result of an disconformity or a break in core recovery.

Most of the debris flow deposition occurred prior to 780 ka. There are only three debris flow intervals above this level and they are much thinner than the units below (Fig. F15). If the average sedimentation rate above 32 mbsf is calculated by dividing depth by age, a rate of only 0.041 m/k.y. is obtained. Below 32 mbsf (Brunhes/Matuyama boundary), the minimum Sr age allowed by the nannoplankton is 900 ka. Using the maximum age for the Sr date at 218 mbsf (1.38 Ma), the minimum sedimentation rate obtained is 0.31 m/k.y., an order of magnitude higher than that above. This rises to 0.53 m/k.y. for the central age of 1.13 Ma. The maximum rate, using the minimum age for the sample at 218 mbsf (900 ka), is 1.55 m/k.y.

This apparent large reduction in sedimentation rate and the lesser number of debris flows shallower than 32 mbsf implies a reduction in the frequency of debris flow episodes after 780 ka. This in turn suggests that the Lambert Glacier advanced to the shelf edge only a few times after 780 ka. The uncertainties in the age dating make it difficult to determine when the last advance took place. An approximate date for the last debris flow may be obtained by using the average sedimentation rate for the upper 32 m (0.041 m/k.y.) and lower part of the hole (0.31–1.55 m/k.y.) to estimate the age of the uppermost debris flow at 5.17 mbsf (base of Unit I). If this sedimentation rate is used, the age of the top of the uppermost debris flow is ~126 ka. However, the sedimentation rate estimate for the upper 32 m included 26.8 m of debris flows, which were likely deposited much faster than the hemipelagic sediments of Unit I above 5.17 mbsf. Therefore, estimates using the rates for debris flow deposition in the lower part of the hole may be more realistic. Using these rates, this 26.8 m of sediment would have taken between 17.3 and 86.5 k.y. to accumulate after 780 ka, resulting in age estimates of 693.5 to 762.7 ka for the uppermost debris flow. Using the central Sr age for the sample at 218 mbsf, the uppermost debris flow was deposited at 729.4 ka.

DISCUSSION

Fan History

Our age model is imprecise because of the scarcity of datable material and the likely presence of erosion surfaces within the stacked debris flow intervals that may have removed parts of the succession. In spite of these problems, the results do indicate that extreme ice advances to the shelf edge in Prydz Bay either ceased in the mid-Pleistocene or have been very rare since then. A better age model awaits refinements in methods for dating the material in the hole, but the broad picture is still clear.

The sedimentary record at Site 1167 suggests that most fan growth took place between the early Pliocene and early Pleistocene when glacial episode duration was dominated by 41-k.y. cycles (Berger and Jansen, 1994). The late Pleistocene climatic regime, dominated by 100-k.y. cycles, produced few if any extreme advances. This is the first observation that an ice drainage system sourced the interior of the East Antarctic Ice Sheet changed its behavior in the mid-Pleistocene. The cause of this change is unknown at present. Three possible mechanisms could be involved, singly or in combination.

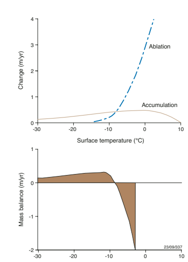
The first is shelf overdeepening. Advances of an ice sheet onto a continental margin produces overdeepening of the inner shelf by a combination of erosion and isostatic loading (Boulton, 1990). With each successive advance, the inner shelf deep excavated by the Lambert Glacier became deeper so that greater ice volume was required for subsequent advances to reach the shelf edge (ten Brink et al., 1995). The reduction in frequency of advances around the mid-Pleistocene may reflect the passing of a threshold of overdeepening, after which only very large increases in ice volume in the Lambert–Amery system caused it to reach the shelf edge. This mechanism may apply only to systems like the Lambert–Amery, which have had a very long erosional history. It has eroded to at least 2200 mbsl near its grounding zone (Fricker et al., 2001). However, the failure of ice streams to reach the shelf edge in the western Ross Sea during the LGM (Shipp et al., 1999; Domack et al., 1999) may mean that a mechanism affecting the whole East Antarctic Ice Sheet is more likely.

The second possible mechanism is related to global cooling in the late Pleistocene. Late Pleistocene glacial–interglacial cycles of Northern Hemisphere ice sheets are thought to be related to major reorganizations of the ocean-atmosphere system (Berger and Jansen, 1994). The changes that caused Northern Hemisphere ice sheets to expand after the mid-Pleistocene may have reduced Antarctic temperatures.

Robin (1977) suggested that precipitation over the Antarctic is controlled by advection of moisture in the troposphere. The rate of snowfall is proportional to the water available in the atmosphere, which is a function of temperature above the inversion layer, which in turn is related to surface temperature. Thus, the present accumulation rates in Antarctica are highest near the coast, decreasing into the interior with falling temperatures (Fig. F16), (Giovinetto and Bentley, 1985; Warrick and Oerlemans, 1990; Drewry and Morris, 1992). This reduction in accumulation with falling temperatures is also supported by ice core data comparing paleotemperatures derived from isotope measurements with accumulation rates (Lorius, 1989).

An early Pleistocene glacial temperature regime warmer than the late Pleistocene could have produced sufficient precipitation in the interior

F16. Temperature, accumulation, and ablation, p. 32.



to drive the interior ice to the shelf edge during glacial episodes. Mid-Pleistocene cooling reduced vapor transport and precipitation in the East Antarctic interior, which reduced the volume of ice flowing down the main Amery–Lambert drainage system and curtailed advances to the shelf edge. This second process may explain regional differences in ice behavior such as that between the eastern and western Ross Sea (Domack et al., 1999; Bart et al., 2000). The western Ross Sea receives its drainage from the West Antarctic Ice Sheet.

The third process that may contribute to greater ice advances prior to the mid-Pleistocene is the interaction of the response time of the interior of the East Antarctic with 41-k.y. climatic cycles that were dominant prior to the mid-Pleistocene. We estimate that ice deposited near the drainage divide at the head of the Lambert–Amery system takes ~20 k.y. to reach the grounding zone. The extra ice deposited during warm parts of the 41-k.y. cycles would have reached the grounding zone near the sea level minimum of the cycle, reinforcing seaward advance of grounded ice.

Quantification of the volumes of erosion in the Amery Depression and isostatic loading effects will be needed to see if overdeepening alone is capable of stopping extreme advances of the Lambert–Amery system. The temperature-precipitation hypothesis and the role of climate cycles will need to be investigated by gathering further data on Antarctic sedimentation patterns and paleotemperatures spanning the mid-Pleistocene climatic transition. These suggested processes would predict that outlet glaciers fed by ice from the East Antarctic interior such as in the western Ross Sea and eastern Weddell Sea would have also reached the shelf edge more frequently prior to the mid-Pleistocene. Site 1167 requires further detailed work to see if uphole changes in sediment composition can be related to the progress of erosion and/or ice volume changes.

CONCLUSIONS

From the early Pliocene onward, the Prydz Channel Fan was deposited mostly by sediment gravity flows formed from basal debris delivered to the continental shelf edge by ice flowing through Prydz Channel during extreme ice advances. The adjacent bank saw minor progradation and vertical aggradation, probably because the ice was slower moving. Site 1167 shows that the Lambert Glacier–Amery Ice Shelf system deposited most of the fan before 780 ka. As few as three advances may have taken place since that time. This suggests that extreme advances of the East Antarctic Ice Sheet may have occurred mostly before the mid-Pleistocene climate transition. Further data on mid-Pleistocene conditions in Antarctica and direct sampling of other Antarctic trough mouth fans will be needed to understand the mechanisms responsible for this change in ice sheet behavior.

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Figure F1. Bathymetry of Prydz Bay showing the location of the Prydz Channel Trough Mouth Fan, Prydz Channel, and ODP Site 1167. Last Glacial Maximum (LGM) grounding zone wedges are shown after Domack et al. (1998). Arrows indicate ice flow directions during post-late Miocene extreme advances of the Lambert Glacier–Amery Ice Shelf system (modified from O'Brien and Harris, 1996).

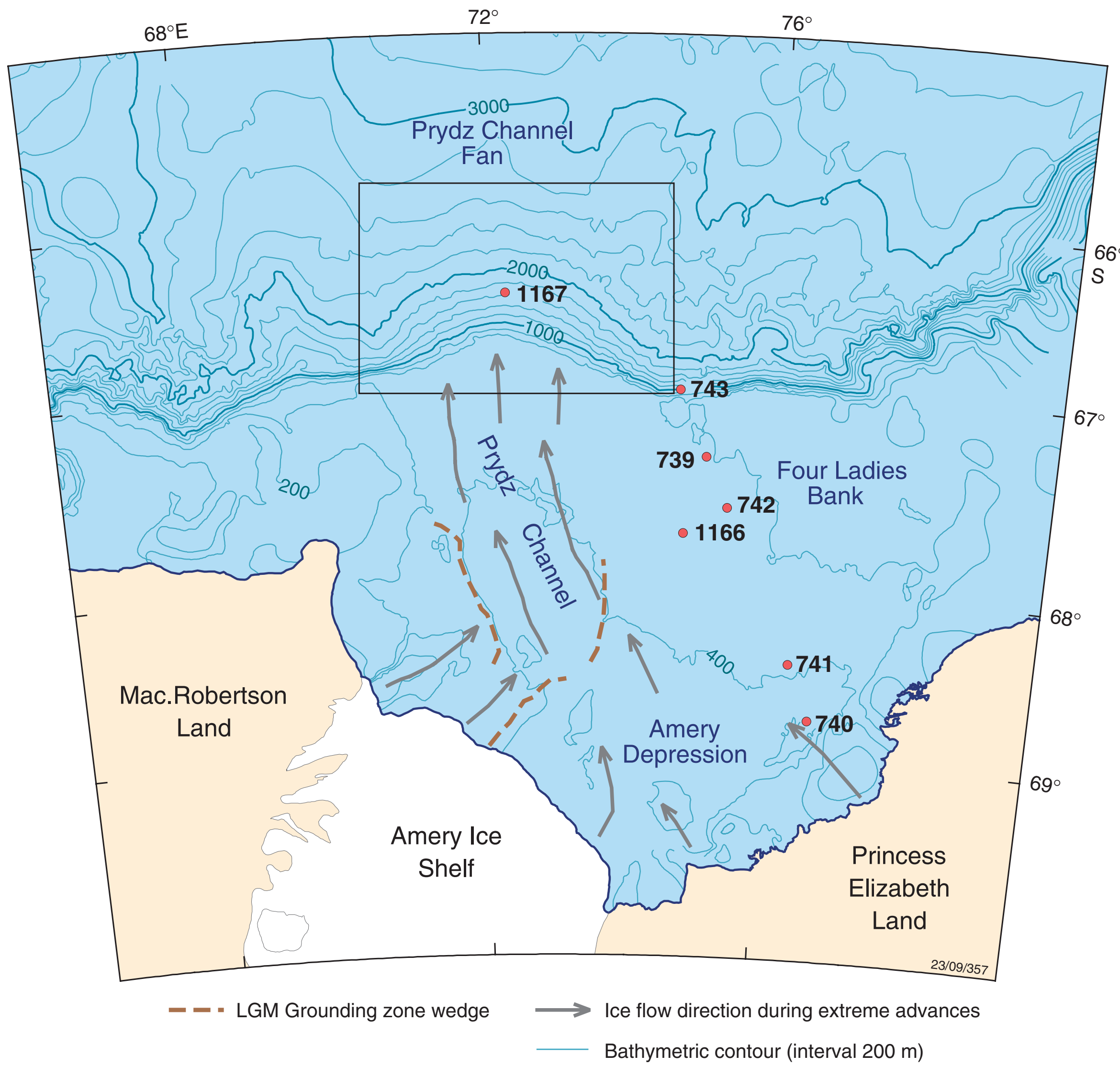

Figure F2. Isopach map of the Prydz Channel Trough Mouth Fan.

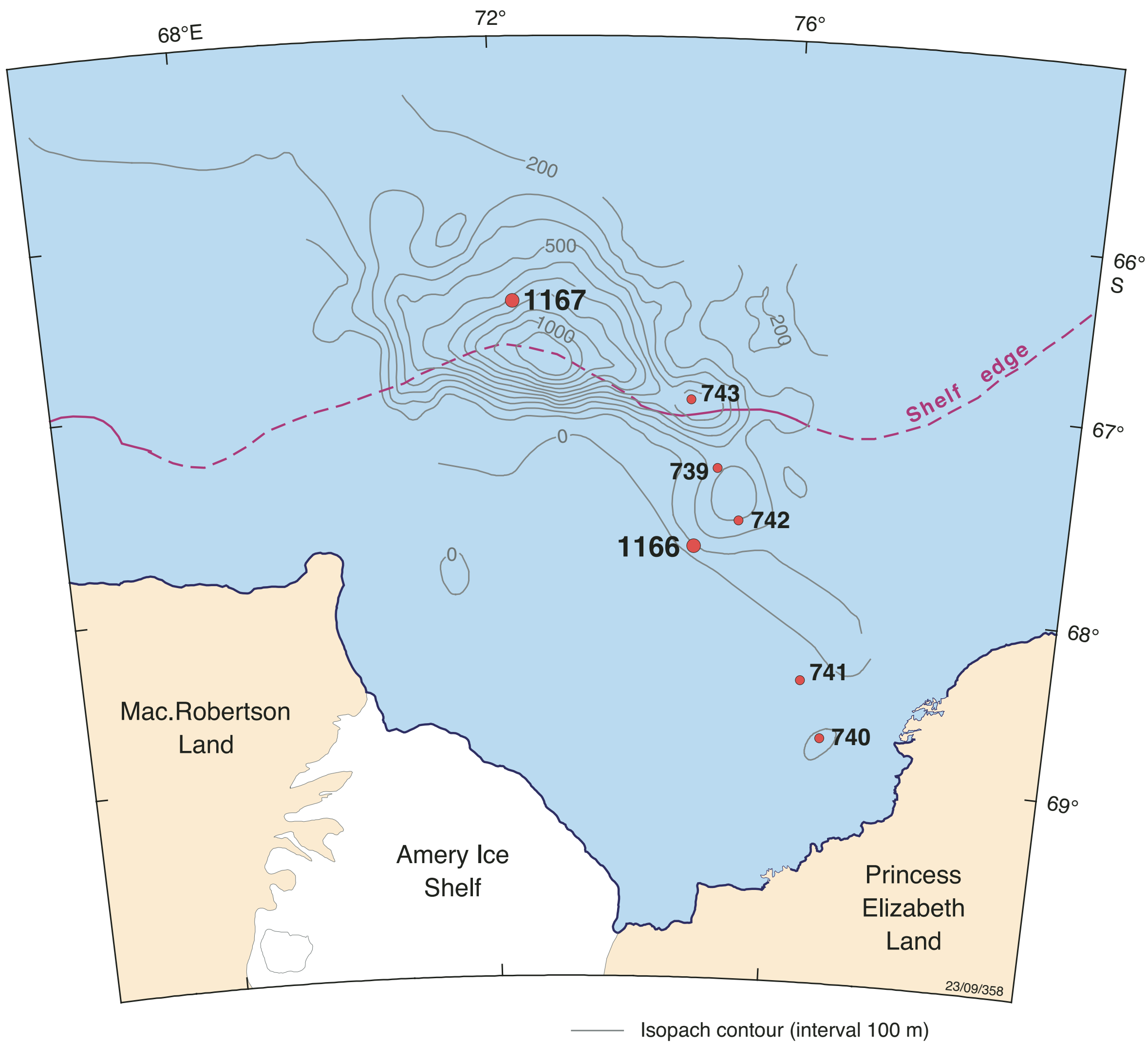

Figure F3. Prydz Bay showing the location of seismic lines collected during the 1995 ANARE/AGSO survey. Figured lines shown in bold.

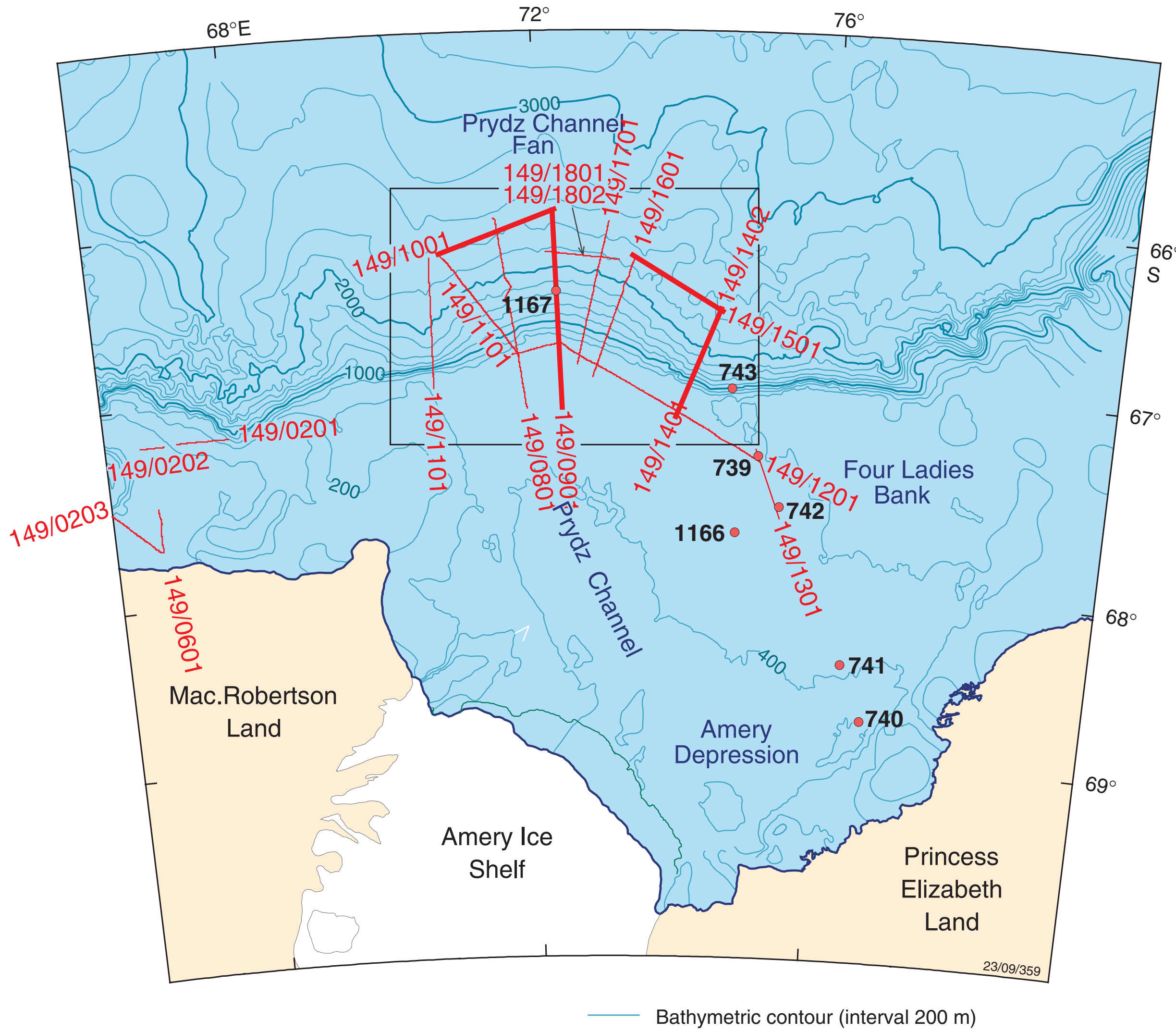

Figure F4. Seismic line showing a dip section through the axis of the Prydz Channel Trough Mouth Fan (line AGSO 149/0901) and Site 1167. Surface pp-12 is the base of the fan. Steps on the fan surface correspond to pinchout of surface units. SP = shotpoint.

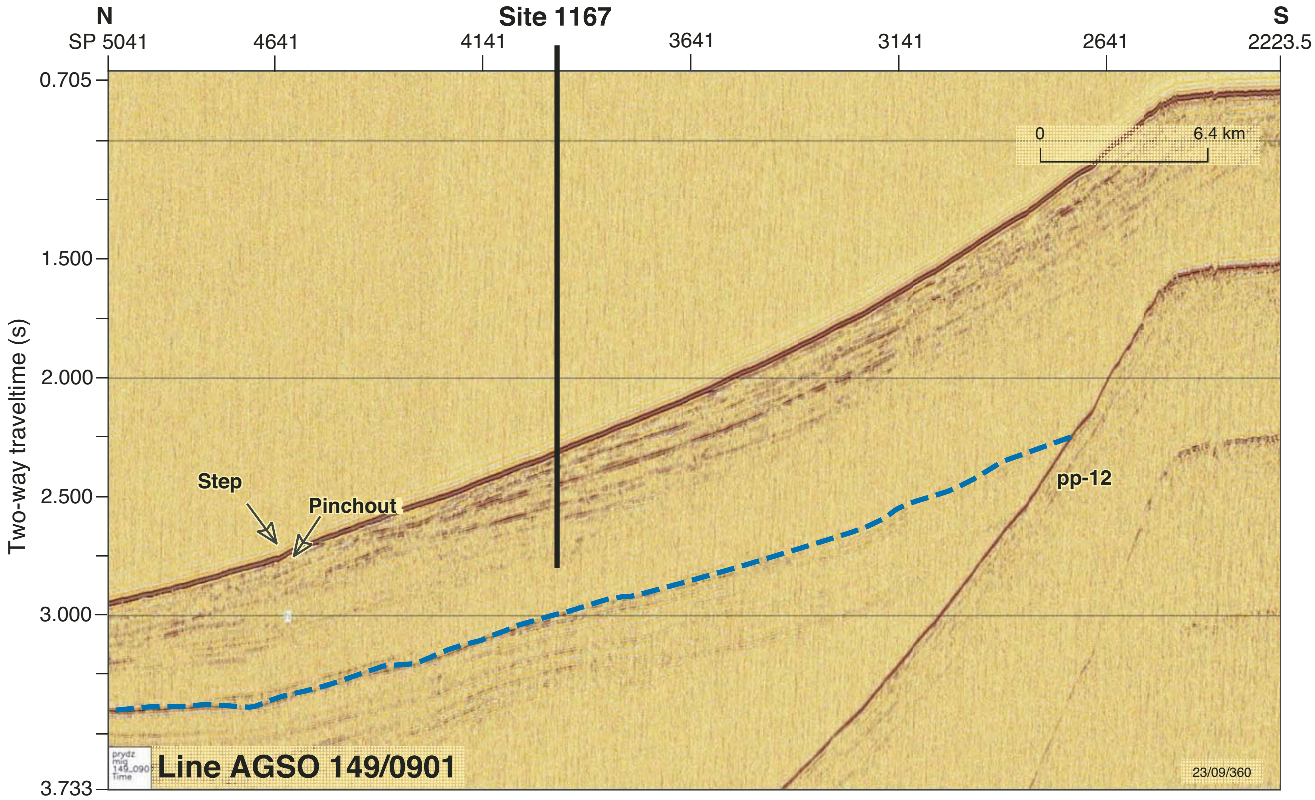

Figure F5. Section across the fan highly compressed to show the broad mounded geometry of recent units (line AGSO 149/1001). Current surface shows some mounding and gullying. The fan onlaps older sediment drift deposits at surface pp-12. SP = shotpoint.

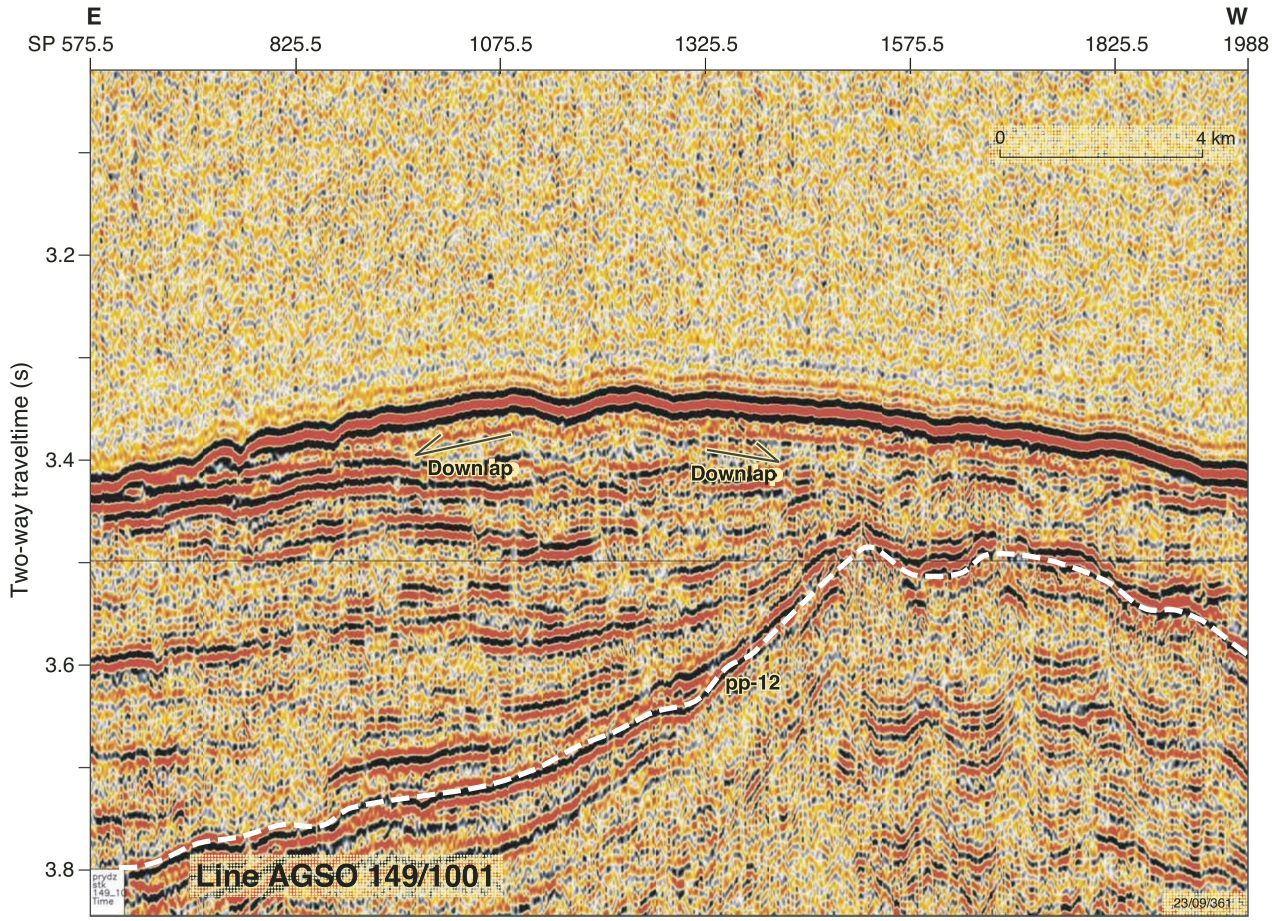

Figure F6. Distal strike section across the fan showing channel-levee units and depositional mounds (line AGSO 149/1501). Internally, the fan consists of reflection-rich and -poor intervals possibly representing thicker debris flow (reflection poor) intervals interbedded with hemipelagic sediment (reflection rich) intervals. SP = shotpoint.

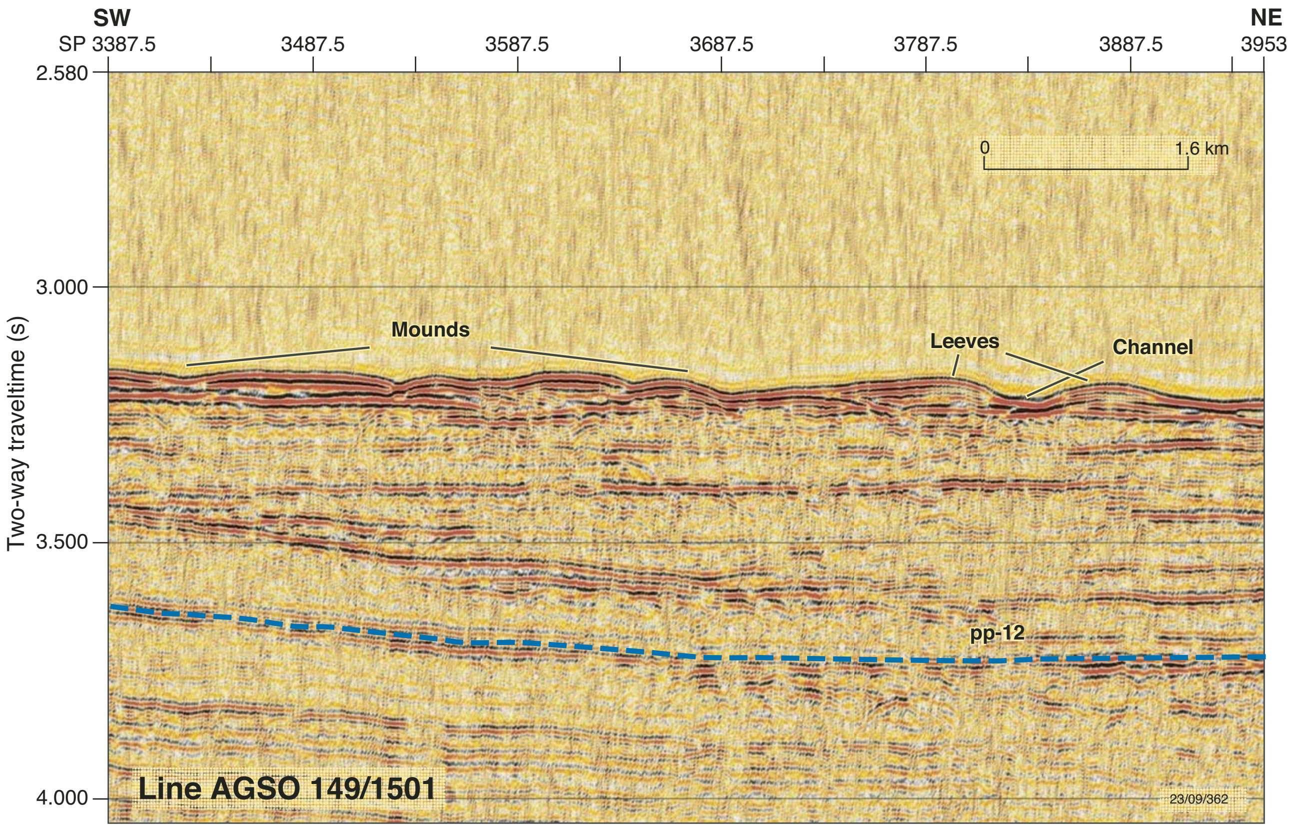

Figure F7. Dip section across the shelf edge and upper slope of Prydz Bay east of the Prydz Channel Fan. The vertical exaggeration is the same as that in Figure F4, p. 20. Surface pp-12 is overlain by near-vertically stacked paleoshelf edges. SP = shotpoint.

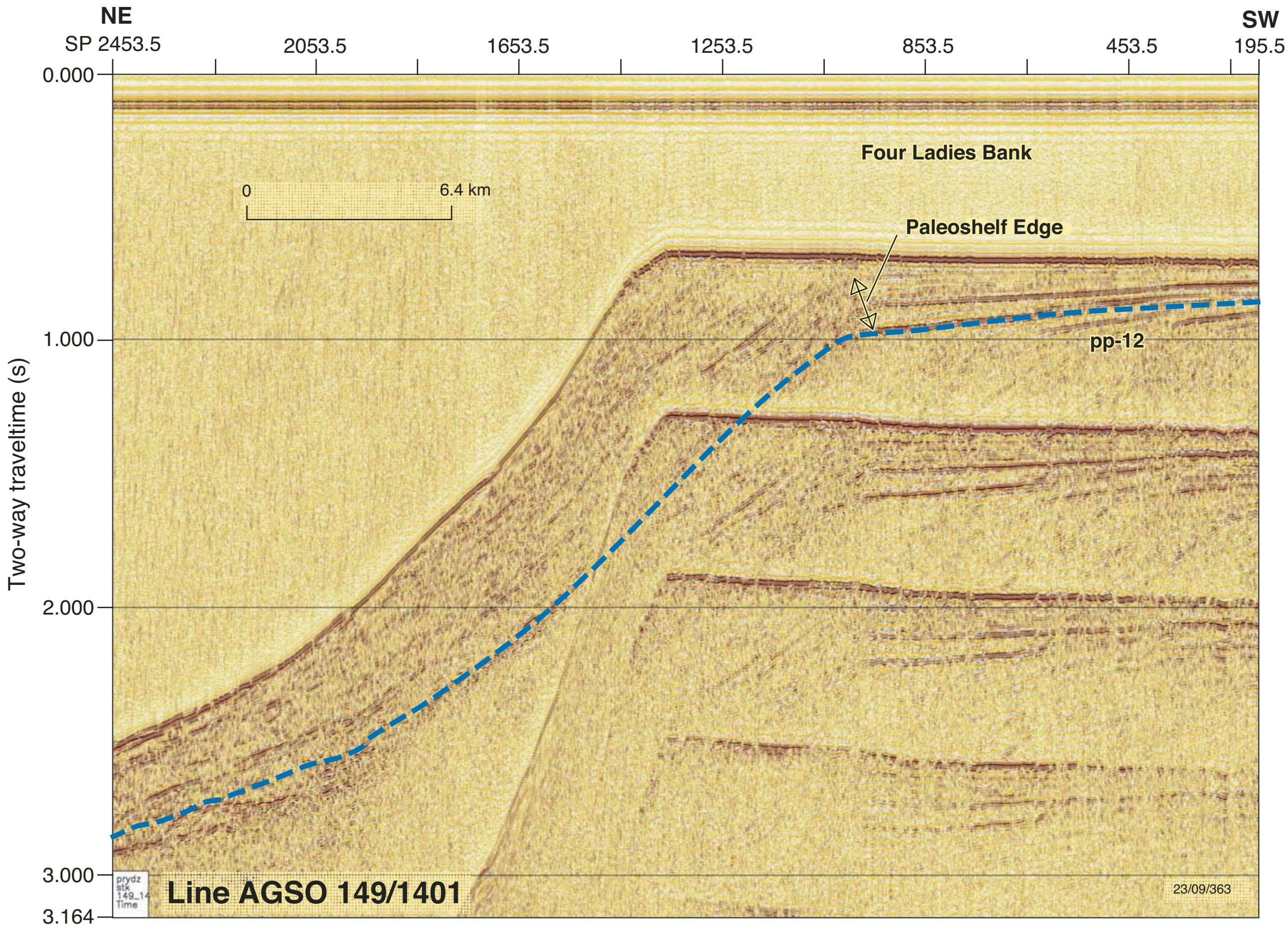

Figure F8. Portion of line 149/0901 showing location of Site 1167 and the intersection with mapped surfaces pp-2, pp-3, pp-4, pp-5, pp-7, and pp-12. SP = shotpoint.

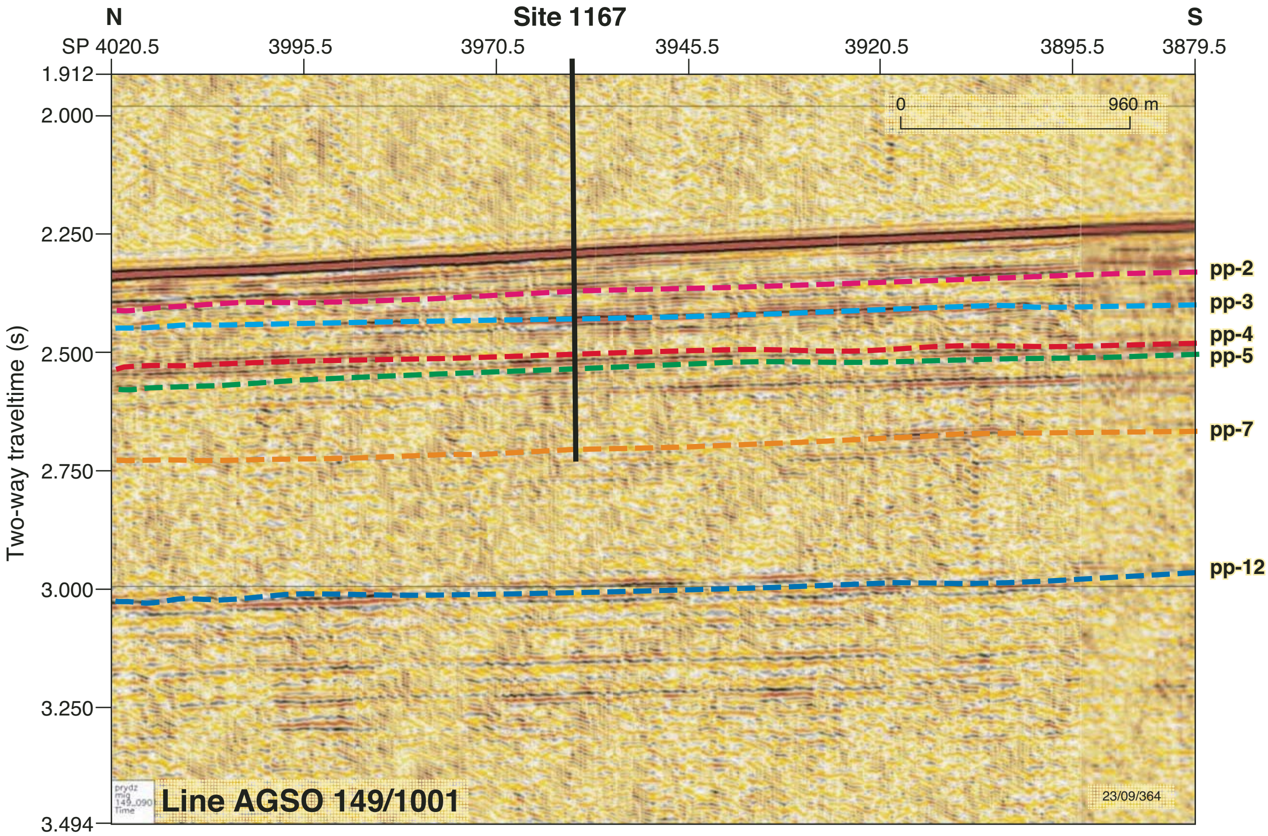

Figure F9. Prydz Channel Fan topsets in the axis of Prydz Channel (line AGSO 149/0901). Before surface pp-12 formed, the shelf shows aggradation. Post-pp-12, the fan exhibits sequences of truncated foresets bounded by horizons which show both foresets and topsets. SP = shotpoint.

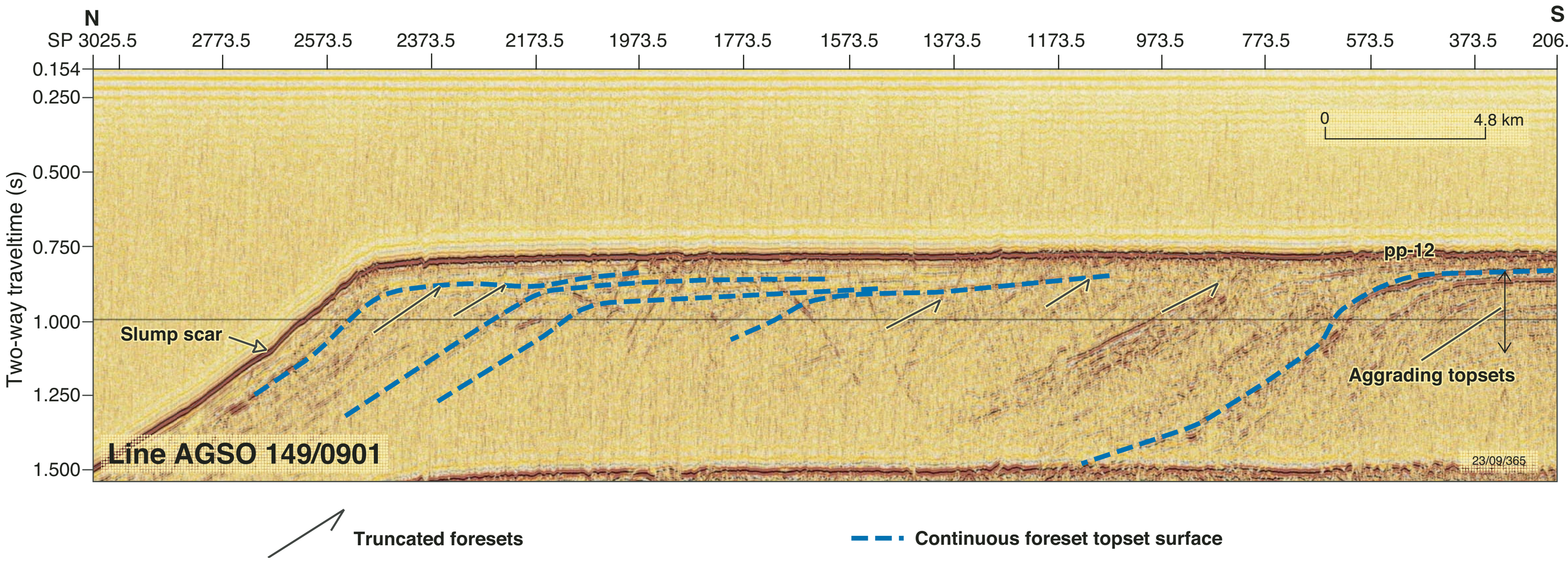

Figure F10. Topset geometry on Four Ladies Bank (line 149/1401). Near-vertical aggradation continued after the cutting of surface pp-12 and ended before late-stage rapid progradation. Topsets include horizons with high impedance suggesting high compaction produced by subglacial erosion. SP = shotpoint.

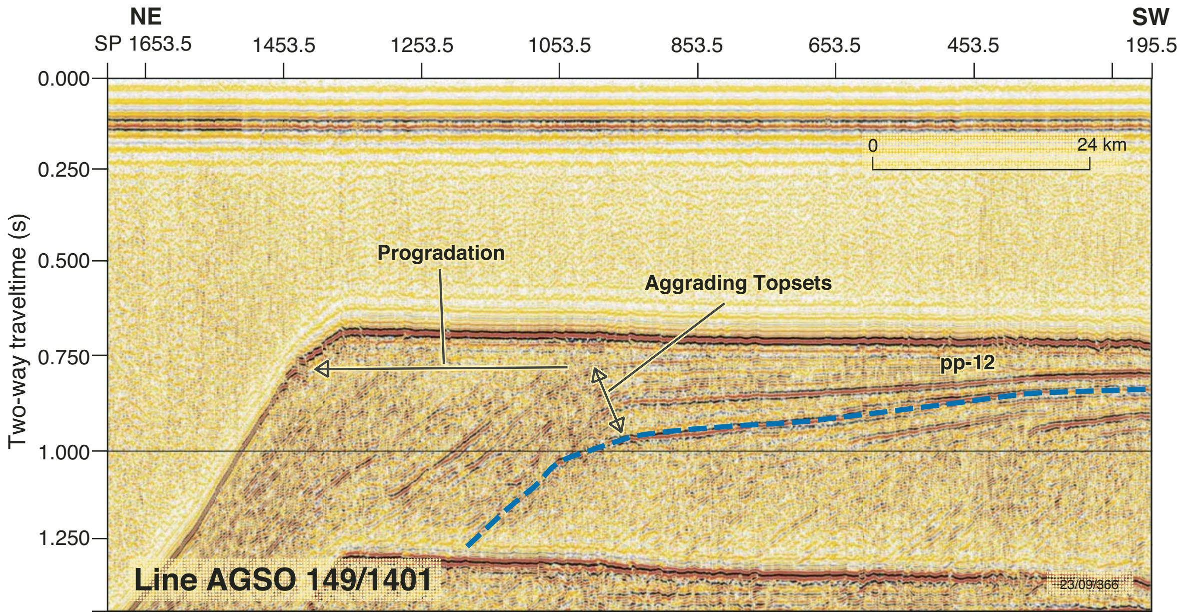

Figure F11. A. Thickness of sediments deposited during the early stage of fan growth (pp-12 to pp-7). The fan started as a broad wedge of sediment. Green polygon shows extent of data in which both horizons are recognizable. **B.** Thickness of sediments between surfaces pp-7 and pp-5. The sediments form a distinct lobe seaward of the axis of Prydz Channel. Colored contours are thickness in milliseconds two-way traveltime. Gray contours are bathymetry in meters.

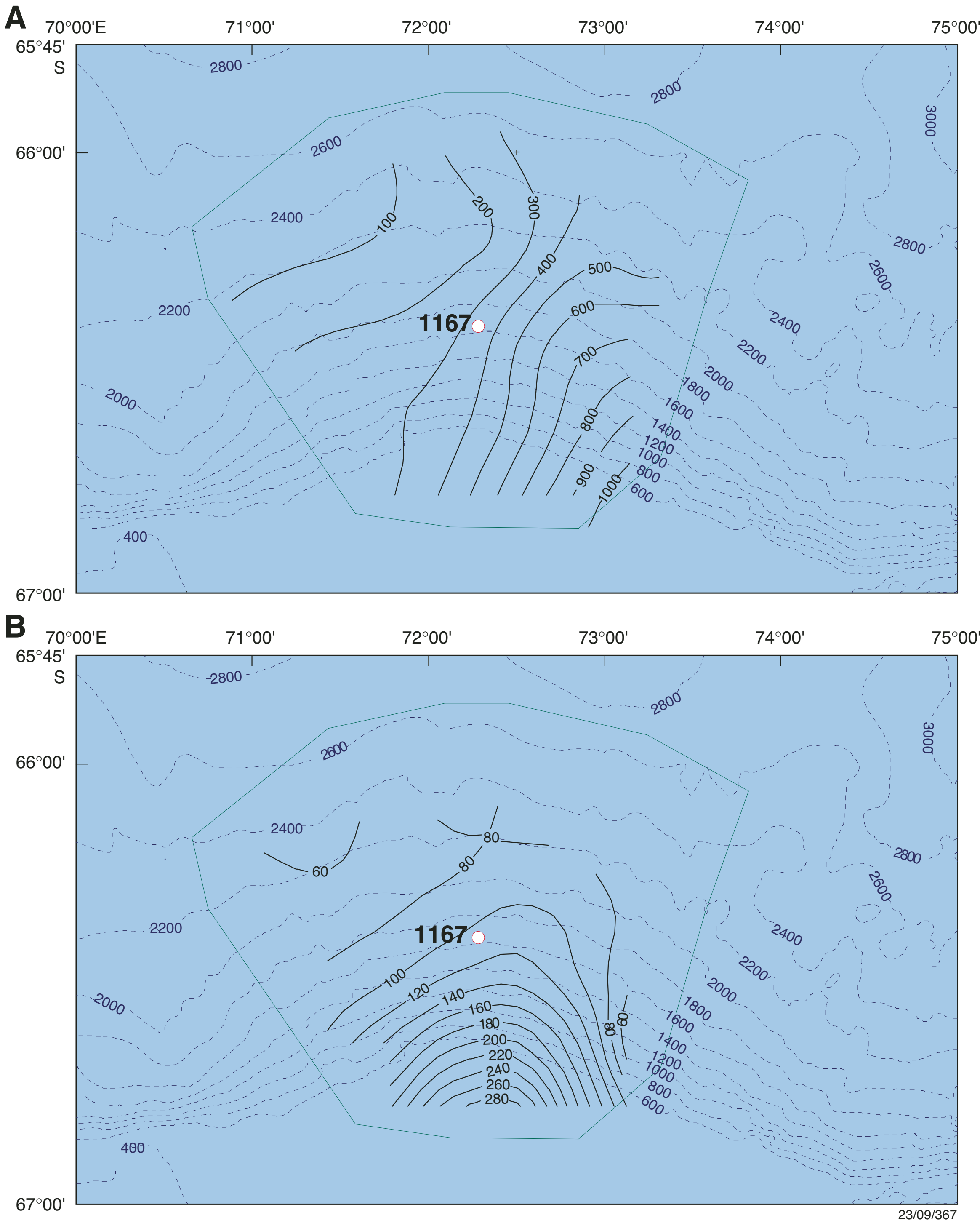

Figure F12. A. Thickness of sediment between surfaces pp-5 and pp-4. These surfaces are close together so the isopach shows as a thin sheet of sediment, slightly thicker on the western side. Green polygon shows extent of data in which both horizons are recognizable. **B.** Thickness of surfaces between pp-4 and pp-2. Deposition between these surfaces produced a sediment lobe in midfan seaward of the Prydz Channel axis. Colored contours are thickness in milliseconds two-way traveltime. Gray contours are bathymetry in meters.

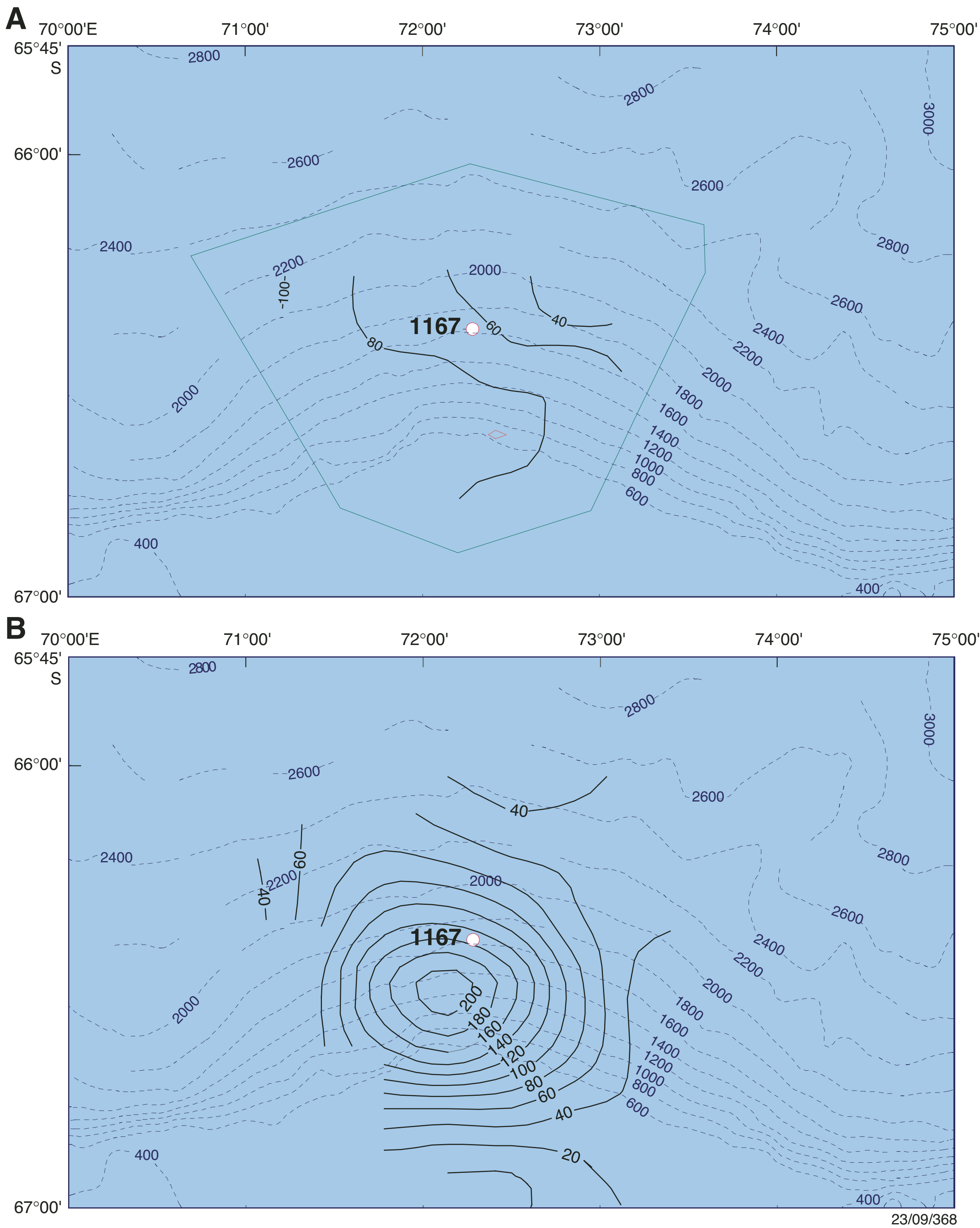

Figure F13. Thickness of sediment between surface pp-2 and the seafloor. This uppermost mappable unit uniformly drapes across the fan with some thickening toward the western side, possibly related to slumping on that side of the fan. Colored contours are thickness in milliseconds two-way traveltime. Gray contours are bathymetry in meters.

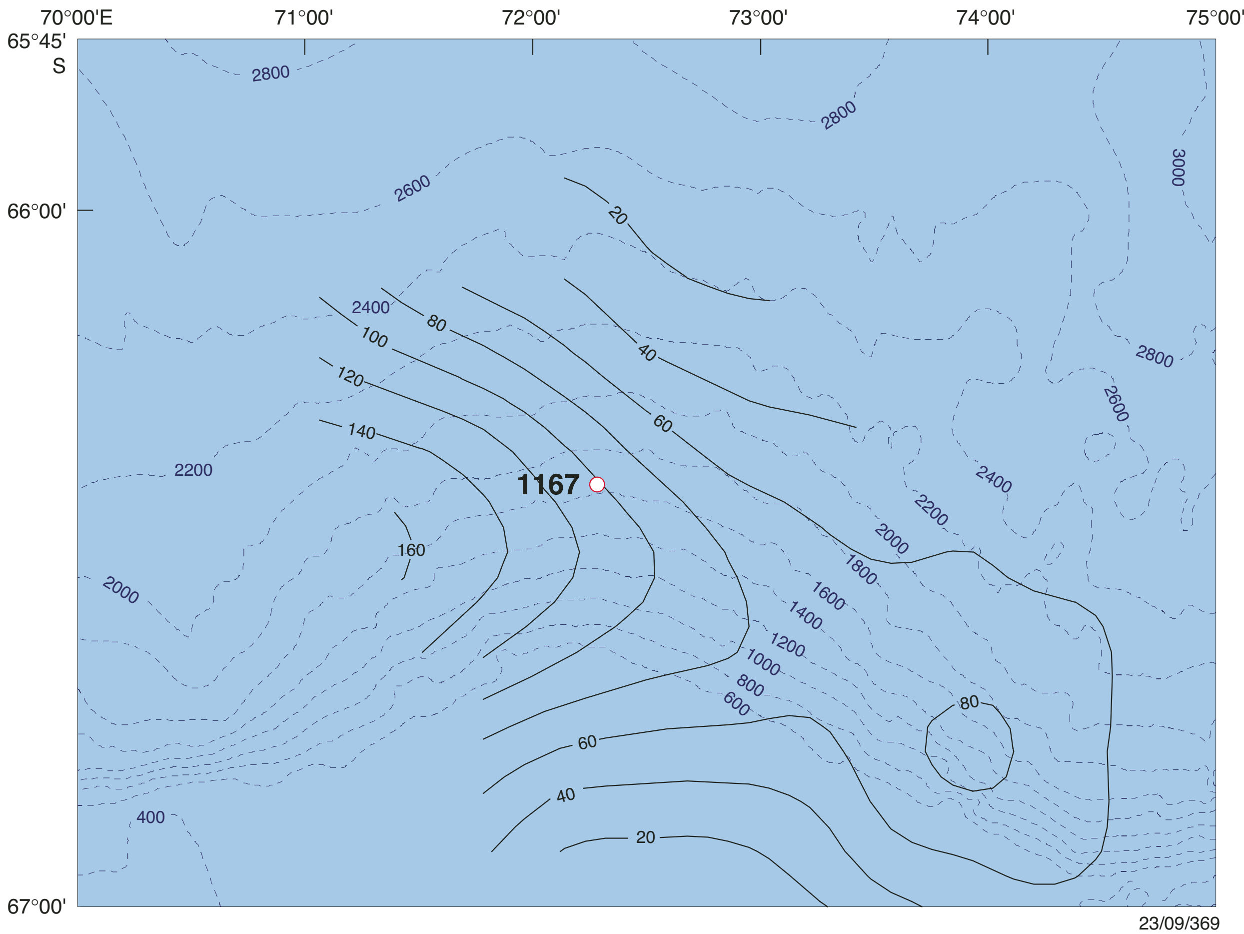

Figure F14. Lithostratigraphic section of Site 1167 (Hole 1167A) (from O'Brien, Cooper, Richter, et al., 2001).

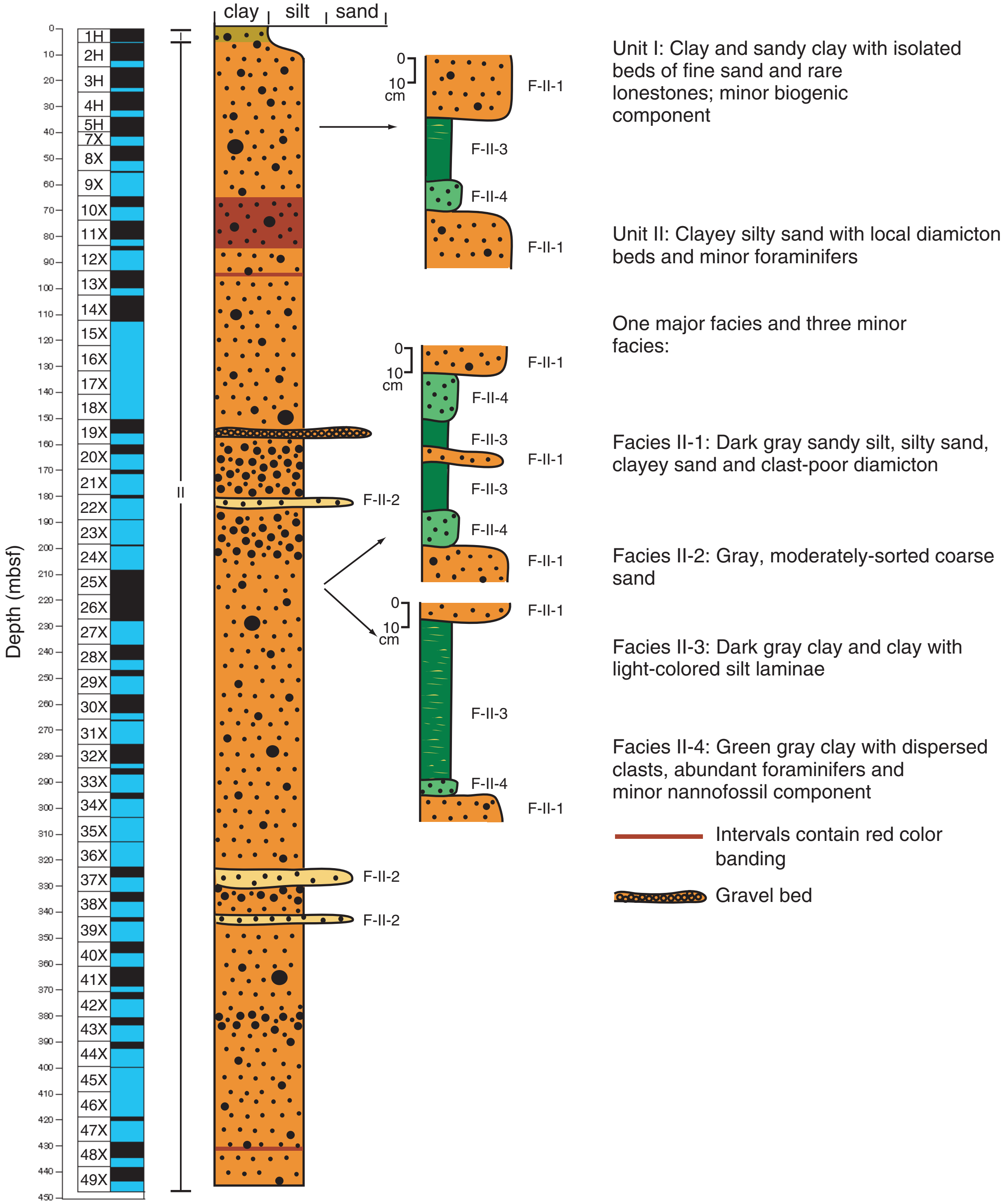

Figure F15. Geophysical logs, lithologies, and age control points for the upper 260 m of Site 1167 (Hole 1167B). Logs obtained by logging while drilling (LWD). Shaded intervals are clay beds, as indicated by low resistivity and high gamma readings.

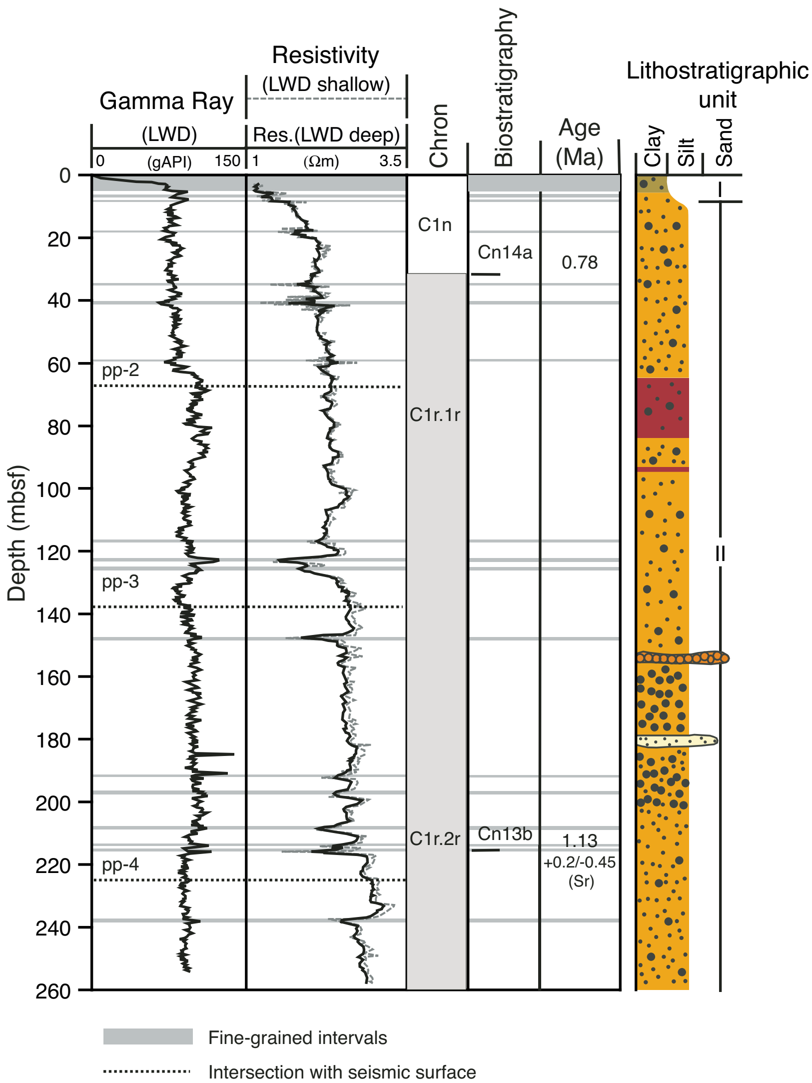

Figure F16. Relationship between temperature, accumulation, and ablation according to Warrick and Oerlemans (1990). The temperature at which mass balance is maximum is around –13°C. Above that temperature, ablation rapidly removes ice; below, the amount of precipitation falls because of falling vapor pressure.