Seismic stratigraphy of Palmer Deep: a fault-bounded late Quaternary sediment trap on the inner continental shelf, Antarctic Peninsula Pacific margin

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Abstract

The Palmer Deep is an enclosed bathymetric depression on the inner portion of the Antarctic Peninsula continental shelf about 30 km southwest of Anvers Island. Three sub-basins, separated by bathymetric sills, comprise the Palmer Deep: Basin I, Basin II, and Basin III. Deep-tow boomer seismic reflection data reveal thick (>50 m) sediment sections in each basin consisting of Holocene diatomaceous mud. The boomer records proved fine-scale resolution of decimetre thick sediment layers within the uppermost (Holocene) seismic unit. Deeper penetration GI and small airgun records obtained in 1997 provide insight into the structural and depositional history of the basins which extends clearly back in time before the Holocene (unit imaged by the boomer records). The Palmer Deep contains a sediment infill estimated at about 270 m thick arranged in a complex (five unit) internal stratigraphy unusual for the inner continental shelf of Antarctica. Combined use of the boomer and airgun sources allows complementary resolution of both deep and shallow stratigraphy with some reflectors common in both records, such as the Middle Basin Reflector at 45 ms twt below seafloor. The Middle Basin Reflector most likely is of latest Pleistocene age (isotopic Stage 2) and therefore 80% of the basin fill pre-dates the classic Last Glacial Maximum. The Palmer Deep is bounded by active extensional faults as evidenced by offset and stratigraphic growth within Holocene sections. To accommodate shelf-wide glaciation on the Pacific margin of the Antarctic Peninsula we suggest a subglacial and subaqueous origin for much of the Palmer Deep basin fill. Hence, the Palmer Deep basins were the locus of subglacial ‘lakes’ beneath the ice sheet at times of glacial maximum. © 1998 Elsevier Science B.V. All rights reserved.

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1. The Palmer Deep

The region known as the Palmer Deep and as described in detail by Kirby et al. (1998) is located on the inner continental shelf west of the Antarctic Peninsula, just south of Anvers Island, in correspondence with the projection of the South Anvers Fracture Zone (Larter et al., 1997) (Fig. 1). This fracture zone belongs to a set of northwesterly transform faults separating segments of ridge-crest that progressively migrated into the trench during the Cenozoic and originated the thermal uplift followed by a long-term subsidence of the margin (Herron and...
Tucholke, 1976; Larter and Barker, 1991). Tectonic segmentation of the Antarctic Peninsula and its offlying islands along the projections of these traverse fracture zones has been suggested by Hawkes (1981). The region is now essentially aseismic, though active shortening is occurring in the South Shetland Trench some 300 km to the northeast (Kim et al., 1995).

The Palmer Deep consists of a linear system of three basins oriented in a SW–NE direction (Fig. 2). The deepest and largest of these is referred to as Basin III (~1400 m uncorrected water depth); a smaller basin (II) appears to be an extension of Basin III at a similar depth, while the shallowest and smallest is Basin I, at just over 1000 m water depth. The three seafloor depressions are filled with a layered sedimentary succession that in cross-section attains an asymmetric V-shape rather than a U-shape or symmetrical geometry.

Piston cores have shown that the uppermost sediments of Basins II and III are mud turbidites from the basin walls, while Basin I contains laminated muds composed of alternations between siliceous biogenic pelagic and siliciclastic hemipelagic sediments. Sediment accumulation rates ranging between 0.13 and 0.24 cm/yr have been calculated for this upper unit based on 14C dating on sediment cores (Leventer et al., 1996), so that, by extrapolation down section, the basins are thought to contain an ultra-high resolution sedimentary record of the Holocene down to at least the Last Glacial Maximum (LGM).

It is within this general framework that we present below the detailed observations of the shallow and deeper seismic stratigraphy within each of the Palmer Deep basins.

2. Methods

The first systematic survey of the Palmer Deep area was undertaken during the 1992 cruise 2 of the
RV *Polar Duke* (U.S. Antarctic Program, USAP). At this time a HUNTEC Deep Tow Boomer (DTB hereafter) very high-resolution seismic reflection system was used (Fig. 2) to provide an appropriate acoustic control on piston core location and core stratigraphy (see Table 1). The boomer data were combined with pre-existing bathymetric data and 12-kHz Precision Depth Records to produce a bathymetric chart (uncorrected water depths) of the region (Kirby, 1993). The DTB seismic data were collected over 959 km (519 n.m.) of track lines during the entire cruise, with 80 km (43 n.m.) from within the Palmer Deep (Fig. 2). DTB data were recorded in analogic form and preserved on both paper records and magnetic tape.

The Palmer Deep was surveyed again with the RV *OGS-Explora* from February 21 to 23, 1997 as part of ODP Leg 178 site survey operations within the ‘Programma Nazionale Ricerche in Antartide’ (PNRA) to provide deeper penetration (although lower resolution) seismic data. The survey was planned on the basis of the available bathymetry (Fig. 2), combining the need to provide crossings of the location of existing cores and proposed ODP drill sites and to avoid diffraction of energy from the steep sides of the basins by crossing the basins where
Table 1
Acquisition parameters

PNRA OGS-Explora 1997 survey

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>Survey A</th>
<th>Survey B</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>GI Gun ‘True GI Mode’</td>
<td>Airgun</td>
</tr>
<tr>
<td>volume</td>
<td>2.5 l (150 in³)</td>
<td>0.25 l (15 in³)</td>
</tr>
<tr>
<td>firing depth</td>
<td>4 m</td>
<td>2 m</td>
</tr>
<tr>
<td>firing interval</td>
<td>6 s (12.5 m at 4 kt survey speed)</td>
<td>5.3s (9 m at 3.3 kt survey speed)</td>
</tr>
<tr>
<td>distance from ship</td>
<td>20 m</td>
<td>20 m</td>
</tr>
</tbody>
</table>

SENSORS (both A and B surveys)
| type               | array of 10 hydrophones, spacing 1.6 m |
| tow depth          | 1 m nominal                            |
| distance from ship | first hydrophone at 35 m               |

DIGITAL RECORDING (for both A and B surveys)
| type           | Sercell               | Delph-2                      |
| hydrophone traces summed | 8                    | 2                             |
| sampling interval | 1 ms (1000 Hz)       | 0.5 ms (2000 Hz)             |
| record length   | 4 s                   | 2.5 s                        |


| SOURCE            | HUNTEC Deep Towed Boomer (DTB; WHOI system), 540 joule |
| firing depth      | 50–100 m below seafloor surface |
| firing interval   | 750 ms (1.5–2.3 m at survey speed) |

SENSORS
| type                  | ten-element Benthos hydrophone streamer attached to tow fish. Internal transducer/receiver was inoperable during survey |

RECORDING
| type                                  | analogic paper and magnetic tape records, 250-ms sweep rate, 1500 and 5000-Hz filter setting, survey speeds speed of 4–6 kt |

they are widest. Two single channel surveys (A and B), with roughly identical line location, have been conducted using different high- to intermediate-resolution seismic sources. In survey A (Table 1, Fig. 2) a 2.5 l (150 in³) GI airgun provided a narrow signature (50 ms in length with frequencies up to 250 Hz) with suppression of the bubble oscillations. The delay between the shots of the two chambers of the gun was set at 32 ms. The survey was designed to resolve the sedimentary units filling the basin and to image the structure of the substratum. In survey B (Table 1, Fig. 2) a 0.25 l (15 in³) conventional (single chamber) airgun providing a less energetic pulse was shot at higher rate than the GI gun to obtain a better definition of the sedimentary units only (higher vertical and horizontal resolution). Individual traces from a 16-m-long hydrophone array were summed and sent to two independent digital acquisition systems, Elics Delph-2 and Sercell SN 358 DMX. The data from the Sercell have been processed onboard with the following processing steps: summation of the eight adjacent traces, spherical divergence correction, far-trace mute, predictive deconvolution, running trace mix (three traces) with time variant trace weighting, time filtering, trace balance using variable windows, time migration using sea water velocity (survey A only).

3. Results

3.1. Airgun survey

The two OGS surveys were conducted in favourable weather conditions. Away from the flat floored basin, the record is affected by diffractions
and lateral reflections produced by the steep and highly irregular sea-bed topography. The highly reflective substratum is overlain in the deepest parts of the basins by up to 300 ms twt of an acoustically laminated unit representing the sediment fill of the Palmer Deep. Survey B provided a higher-resolution image of the acoustically laminated unit, outlining a higher number of reflective events and lateral changes of amplitude and frequency that permit the definition of internal configuration and geometrical relationship of reflectors.

3.2. DTB survey

The DTB data resolved very fine-scale stratification (decimetre scale) down to 80 ms twt below seafloor. The DTB sound source effectively resolves flat, continuous surfaces thus providing an optimal record from the flat-lying basin fill. Most of the Palmer Deep area consists of irregular, steep, hummocky surfaces, therefore lacking detectable reflectors. However, sediment accumulation was observed from these ‘poor’ reflector regions as irregular or discontinuous reflections consisting of single, hyperbolic diffractions. In general four seismic facies were recognized from the DTB survey in the Palmer Deep area: (1) acoustically laminated units with generally continuous reflectors; (2) acoustically semi-layered units with generally discontinuous reflectors; (3) acoustically transparent units (without obvious internal reflectors); and (4) acoustically complex, multiple point source, irregular units without obvious reflection continuity.

The only seismic event clearly recognized in both surveys is the Middle Basin Reflector (MBR after Kirby, 1993) and portions of Unit 1 that bound the MBR. Below we discuss in detail the stratigraphy of each basin and compare the results of each of the surveys.

3.3. Seismic stratigraphy

3.3.1. Basin III

We divide the stratigraphy of Basin III into four distinct seismic units (1–4).

Upper low-reflectivity Unit 1. The uppermost unit appears almost transparent and is characterized by an extremely weak seafloor reflection, in places not even detected using the Automatic Gain Control. Thickness of the unit is 98 ms twt, roughly constant in most of the basin and rapidly decreasing to zero near the southeast side of the basin (Figs. 3 and 4). Six weak (low amplitude) reflective events with poor lateral continuity can be seen within Unit 1. The most prominent of these is called the MBR, which is found about 45 ms below the seafloor. A characteristic of the MBR is an increase in amplitude away from the centre of the basin. The MBR terminates prior to reaching the basin margins, within a chaotic seismic facies. Faulting in association with slumping and debris flow deposits may explain the abrupt termination of the MBR along the northwest flank of Basin III and consequently the chaotic seismic character of adjacent strata. Here it appears that the MBR actually climbs across a series of normal growth faults that mark the northwest boundary of the basin. The depth to the MBR in this instance goes from 45 ms in the centre of the basin to 15 ms northwest near the boundary faults (Fig. 4). The lateral continuity of reflectors in Unit 1 is often interrupted by undulations and local onlaps. The internal reflectors (other than the MBR) obviously onlap the substratum reflectors at the margin of the basin. The onlap is not always horizontal but often curves upward.

High-reflectivity Unit 2. This unit contains six strong reflectors, showing that there are stronger impedance contrasts than within Unit 1, that dip gently toward the southwest, generally with increasing dips down-section on an overall divergent pattern. Lateral continuity of reflectors is interrupted only at the edges of the basin, where internal configuration becomes hummocky. In the lower portion of Unit 2 reflectors are more commonly discontinuous throughout the basin. Two high-amplitude reflectors are present at the upper boundary and at some 50 ms depth within Unit 2. Above the lower strong reflector other reflections are subparallel, while below they are slightly divergent apparently westwards, giving the unit a weakly wedging geometry. The maximum thickness of the unit is 95 ms twt in the northwest sector of the basin, above the depocentre overlying the deepest part of the substratum. The reflectors within Unit 2 onlap the substratum reflectors at the edge of the basins. The onlapping reflectors are clearly horizon-
Fig. 3. (a) GI gun single channel large-scale section (line I97H221G) across Basin III. The section has been migrated using sea-water velocity. (b) Line drawing of (a). Legend: B = a reflective horizon with poor lateral continuity; F = master fault. Location in Fig. 2.
Fig. 4. (a) Close-up on Basin III sediment fill from airgun single channel section I97H228. (b) Line drawing of (a). Legend: MBR = Middle Basin Reflector; numbers 1 to 4b refer to seismic units. Location in Fig. 2.
tal and abrupt along the southeast margin of the basin but the nature of the onlap is less evident and/or disrupted along the northwest margin. This disruption may also be related to normal faulting along the northwest basin margin. Here there is evidence of a 50 ms offset in the strong amplitude reflector pair at the top of Unit 2 (Fig. 4). Yet unlike Unit 1, there is no suggestion of stratigraphic growth across the fault within Unit 2.

Lower high-reflectivity Unit 3. The unit has very limited lateral extent and fills the V-shaped bottom of the basin (Fig. 4). It contains weaker reflectors than Unit 2. The unit is characterized by poor lateral continuity of reflectors and mostly hummocky internal configuration with weak wedge-like geometry. The reflectors clearly onlap the substratum on the southeast side, while the northwest margin is hidden by diffractions and/or structural complexity. The unit has a maximum thickness in the depocentre of 120 ms twt.

Basin flank wedge Unit 4a. Along the southeast margin of Basin III, a wedge (Unit 4a) characterized by high-amplitude discontinuous dipping reflectors that downlap onto a lower unit (Unit 4b, Fig. 4) can be recognized. Some reflectors of Unit 4a appear to interfinger with Units 2 and 3. Resolution of internal reflectors is complicated by the presence of numerous diffractions. The upper termination of the wedge is truncated by a sharp unconformity (see Fig. 3) onto which a semi-transparent lens (up to 200 ms thick twt) draped by a stratified unit occurs. Maximum thickness is in excess of 100 ms twt.

Unit 4b. Unit 4b comprises a lens-shaped package of reflectors limited to the southeast margin of the basin. Clear evidence for onlap by reflectors of Unit 2 and vague indication for downlap by reflectors of Unit 4a exist along the surface boundary of Unit 4b (Fig. 4). Reflectors within Unit 4b are high-amplitude, continuous, and terminate abruptly. The reflectors are curved and have apparent westward dips that are significantly greater than those in Units 2 and 3 (above). Maximum thickness of Unit 4b is about 45 ms twt.

Deep-Tow Boomer Units 1 and 2. The shown DTB survey profile in Basin III extends NE–SW and has an acoustic penetration limited to about 60 ms twt (Fig. 5). We divide the DTB profile into upper and lower units (DTB-1 and DTB-2) with the boundary between the two sections corresponding to the strong MBR. Unit DTB-1 is divided into five distinct subunits and is described in the depocentre from top to bottom (a–e). Subunit 1a consists of an approximately 4–6 ms twt thick acoustically transparent interval bounded at the top by a relatively strong seafloor reflector. A weak internal reflection is present in the deeper half. Subunit 1b consists of 8–13 ms twt thick acoustically laminated sediments where reflections are distinctly subparallel and resolve contrasts in acoustic impedance at the decimetre scale. This unit contains some thin, transparent layers which thin apparently toward the southwest. Subunit DTB-1c consists of a 4–5 ms twt thick acoustically transparent interval. DTB-1d consists of 3–4 ms twt of acoustically laminated sediment similar to DTB-1b. Subunit DTB-1e consists of 8–14 ms twt of acoustically transparent sediment that thins toward the margins of the basin.

The MBR occurs at 30–42 ms twt and is distinctly concave-up. The highest amplitude of the MBR is apparently associated with the northeast side of the basin. Unit DTB-2 lies below the MBR and consists of an acoustically transparent unit near the limits of acoustic resolution. Unit DTB-2 is at least 20 ms twt thick but pinches out toward the northeast, between the MBR and a lower hummocky, discontinuous reflector. The base of unit DTB-2 is not resolved along the southwest end of the profile. The lower, discontinuous reflector represents the acoustic basement of the DTB survey in Basin III.

3.3.2. Basin II

Unit 1. The sea bed in Basin II is only a few metres shallower than in Basin III. The seafloor slopes gently toward the southwest in apparent continuity with the slope of the seafloor in Basin III. An isolated hill in the southwest corner of Basin II rises above the even floor of the basin to a relative height of 200 m (Fig. 2, see location of Core 5). The upper, low-reflectivity Unit 1 contains five reflective events and is similar to Basin III as far as thickness and acoustic character are concerned thought it appears more transparent, continuous and regular on GI sections (e.g. Fig. 6, Basin II) than on airgun sections
Fig. 5. Deep Tow Boomer section across Basin III (location in Fig. 2). The vertical scale is provided by a floating 50 ms twt bar to the right. A seafloor depth in metres is provided to the left for reference. Location of core PD92-28 with scaled depth of penetration is also shown. Legend: MBR = Middle Basin Reflector; numbers 1a to 2 refer to seismic units. Location in Fig. 2.
Fig. 6. (a) Close-up on Basin II sediment from GI gun single channel section I97H222G. (b) Line drawing of (a). Legend: MBR = Middle Basin Reflector; numbers 1, 2 and 4b refer to seismic units; '?' refers to the possible location of the boundary fault. Location in Fig. 2.
Yet the lateral extent of the unit is much smaller because of the smaller size of the basin. The drape of Unit 1 over the isolated hill attains a thickness of about 90 ms twt. On the GI gun record there are two especially prominent reflectors within Unit 1 (Fig. 6). The upper one is recognized as the MBR, extending across the entire width of the basin, as well as all reflectors within Unit 1. The thickness of the part of the unit below the MBR is about 50 ms twt.

**Unit 2.** Unit 2 is outlined by its upper highly reflective boundary dipping slightly to the northwest. Internal reflectors are subhorizontal or slightly dipping toward the northwest. Continuity of reflectors toward the northwest margin is interrupted by a chaotic package (up to 150 ms twt thick) of high-amplitude discontinuous reflectors, whose upper boundary is very irregular, generating diffractions. This chaotic unit extends for almost 1.5 km, thinning toward the southeast, and is underlain by an acoustically semi-transparent interval up to 130 ms twt thick. The lower Unit 3 and the wedge on the SE slope (Unit 4a) apparently are both missing. However, a lens-shaped unit (less than 80 ms twt thick and about 1 km wide) with low-amplitude, discontinuous internal reflectors, similar to that described as Unit 4b in Basin III, is also observed at the base of the southeast steep slope in Basin II (Fig. 6). This lens dips toward the northwest and is onlapped by Unit 2 reflectors.

**DTB Units 1 and 2.** A DTB profile with 85 ms twt penetration (Fig. 7) is oriented in a NE–SW direction (roughly orthogonal to GI gun profile I97H222G shown in Fig. 6) across about 2 km of Basin II. The sea floor of the basin is not flat, but attains several metres of vertical relief in its northeast portion where it is rougher and displays higher reflectivity. Two units compose the sediment package. The upper Unit DTB-1 is divided in two subunits. Subunit DTB-1a consists of 15–24 ms twt of acoustically laminated to transparent intervals, in which reflectors diverge toward the northeast being subparallel to the seafloor at the top and subhorizontal at the base of the subunit. The transparent intervals have a prominent wedge geometry with closure towards the centre of the basin, suggesting the presence of slumped masses of sediments or debris flows at the northeast side of Basin II where the unit attains 24 ms twt thickness. The underlying subunit DTB-1b is a 8–15 ms twt thick interval mostly acoustically transparent, with higher-reflectivity horizons which are markedly concave upward and produce a thinning of the subunit towards the basin margin. The lower boundary of Unit DTB-1 is the high-amplitude reflector previously recognized as the MBR.

The lowest Unit DTB-2 is acoustically transparent with a thickness from 21 to 26 ms twt. Weak and discontinuous internal reflectors are present towards the top of the subunit, just below the MBR. The lower boundary is represented by the acoustic basement of the section, an irregular hummocky reflector, analogous to the acoustic basement in Basin III, identified at 53–65 ms twt below the seafloor reflector. This reflector correlates to the lower of the two prominent reflectors in Unit 1 of the airgun survey.

**3.3.3. Basin I**

**Unit 1.** Unit 1, up to 80 ms twt thick, fills the very narrow basin down to a highly reflective substratum (Figs. 8 and 9). The seafloor reflectivity is particularly low and the unit is almost entirely transparent. The seafloor has apparent and varying slope when crossed in the E–W direction, while it looks flat when crossed along the NE–SW direction of elongation (Figs. 8 and 9). The western side gains about 13 m of elevation in 500 m (≈2°), while close to the eastern wall the seafloor gains 30 m in 310 m (≈6°). The base of Unit 1 is marked clearly by onlap onto an irregular erosional surface. This is distinctly unlike the horizontal and conformable contact between Units 1 and 2 in Basins II and III. There is evidence for internal termination or convergence of weak reflectors in Unit 1 from the northeast to the southwest. In the E–W section the seafloor appears to follow the deeper substrate of the basin along the margins. This is suggestive of a draped rather than a ponded geometry.

**Units 4a and 4b.** Basin I apparently lacks seismic facies 2 and 3, and below Unit 1 the substratum is composed of a series of high-amplitude, hummocky, and truncated reflections (Fig. 9). We divide this highly reflective interval into two units that we name 4a and 4b accordingly to the units of similar acoustic facies in Basins II and III. Unit 4a is characterized by a wedge geometry along the northeast side of
Fig. 7. Deep Tow Boomer section across Basin II. The vertical scale is provided by a floating 50 ms twt bar to the left. The water depth in metres is provided to the right for reference. Location of core PD92-5 with scaled depth of penetration is also shown. Legend: MBR = Middle Basin Reflector; numbers 1a, 1b, and 2 refer to seismic units. Location in Fig. 2.
the basin and it contains high-amplitude internal reflections. Such reflectors are discontinuous and dip steeply toward the centre of the basin. Unit 4b is confined to the bottom of the basin. It is lenticular with an upper erosional contact with the lower boundary of Unit 1. Internal reflectors are of very high amplitude, contorted and discontinuous. Its maximum thickness is 40 ms twt.

Unit 5. Unit 5 lies below 4b and is bounded at the top by a very high-amplitude reflector. This reflector truncates subhorizontal, relatively low-amplitude and discontinuous reflectors found within Unit 5. The base of Unit 5 is ill-defined and may correspond to the limit of acoustic resolution associated with abundant diffractions. Thickness of Unit 5 may approach 200 ms. Mid-way down in Unit 5 a set of three linear, horizontal, high-amplitude reflectors are found (Fig. 9). These reflectors are unique because all three contain sharp lateral terminations indicating lateral changes in acoustic impedance. It is possible that these reflectors are the expression of a fault plane dipping out of the section and striking subparallel to the orientation of the section.

DTB Unit 1. The DTB seismic profile in Basin I (Fig. 10) trends north to south and displays acoustical penetration to at least 70 ms twt. We identify three subunits: Units DTB-1a, -b, and -c. The upper subunit, DTB-1a, is acoustically laminated at the scale of a few decimetres and is ~7 ms twt thick. Reflectors are distinctly subparallel but they are not horizontal. The middle subunit, DTB-1b, consists of a less clearly imaged, acoustically laminated interval approximately 25 ms twt thick that gives the impression of gradual attenuation of reflectivity with depth. Subunits 1a and 1b form a drape across the north flank of the basin. The lowest subunit, DTB-1c, is 18 ms twt thick and acoustically transparent, with occasional but discontinuous reflectors. A stronger single, subhorizontal reflector towards the base of the seismic profile is the acoustic basement.

3.4. Acoustic character of the deeper units

The layered sedimentary units described above rest on a rather homogeneous deeper seismic unit with poor seismic characterisation. High-amplitude reflectors are common, mostly with hyperbolic pattern indicating diffractions from both seafloor topographic features and lithological or structural discontinuities from deeper below. A reflective horizon B with poor lateral continuity is present between 1 and 1.5 s twt below the seafloor reflector below the
Fig. 9. (a) Close-up along the main direction of elongation of Basin I sediment fill from GI gun single channel section I97H223G. (b) Line drawing of (a). Numbers 1 to 5 refer to seismic units. Location in Fig. 2.
Fig. 10. Deep Tow Boomer section across Basin I. The vertical scale is provided by a floating 50 ms twt bar to the left. The water depth in metres is provided to the right for reference. Location of core PD92-30 with scaled depth of penetration is also shown. Numbers 1a, 1b, and 1c refer to seismic units. Location in Fig. 2.
sediment fill of Basin III and its surrounding flanks (Fig. 3). The envelope of this fragmented horizon marks the acoustic basement of the GI gun sections. Migration of the single channel data with uniform velocity (water velocity 1500 m/s) improves the lateral continuity of horizon B which is roughly sub-parallel to the seafloor along the section displayed in Fig. 3. This horizon is much less evident across Basins I and II. Between horizon B and the seafloor only hyperbolic or poorly organised reflections are present with the exception of an eastward-dipping reflector at the western end of Fig. 3 and a package of coarsely laminated units at the eastern end of the same section.

A prominent high-amplitude reflector with apparent dip towards the east located below the depocentre of Basin III is interpreted as the master fault (F) of the half-graben structure that produces active subsidence of the basin. Other weaker reflectors on the footwall side of the master fault may represent a set of conjugate slip surfaces (see details in Fig. 4).

The acoustic character of the deeper units is compatible with both (1) a thick layer of glacial sediments with chaotic geometry, in which case horizon B represents the basal contact of the diamicton resting on a (metamorphic) basement, and (2) a highly tectonised metamorphic complex, dominated by structural discontinuities, in which case horizon B is only coincidentally subparallel to the seafloor.

4. Interpretation

Here we compare the acoustic stratigraphy of the DTB profiles to those from the airgun survey and discuss tectonic and depositional processes that best explain our observations.

4.1. Acoustic velocities and depth conversion

The P-wave velocity of the upper sediments of Unit 1 has been measured on cores and is in the range of 1400 m/s (Bissel, 1993). The acoustic lamination observed in subunit DTB-1a is believed to be the result of slight contrasts in acoustic impedance produced by variations in biogenic silica content (Bissel, 1993). The only lithologic changes observed are between siliceous mud (SM) and hemipelagic sediments and occur at a centimetre or decimetre scale. Given the uniformity of the acoustic character at the airgun and GI gun resolution scale, we extrapolate the same lithology all the way down to the base of Unit 1. Sediment compaction has been likely limited by the extremely high rates of fine-grained sediment accumulation, therefore in the estimation of Unit 1 subbottom depth in metres we preferred to consider as constant the measured sound wave velocity of 1400 m/s, neglecting a possible slight velocity increase below the cores. The higher reflectivity of the lower units suggests a sharp contrast of acoustic impedance in terrigenous, coarser-grained sediments, for which compaction is likely to occur also at high rates of sediment accumulation. In the absence of direct or indirect measurement of sound velocity, we apply corrections with a constant reference velocity of 1800 m/s from Unit 2 to 5, though the occurrence of velocity variations is not discounted. A scheme of the seismic–stratigraphic relationship between the three Palmer Deep basins, on a depth scale, is presented (Fig. 11).

4.2. Basin III

The half-graben structure of Basin III is marked by growth faulting within Unit 1 but limited growth during deposition of Units 2 and 3, the highly reflective intervals. The upper portion of Unit 1 is Holocene SM that contains alternating beds of hemipelagic/ice-rafted debris and diatom mud turbidites (Kirby et al., 1998). The low amplitude of seafloor and internal reflectors in Unit 1 indicate low acoustic impedance contrasts compatible with the lithology of these fine-grained, high accumulation rate sediments, that must retain very high porosity even at depth and do not contain strong physical discontinuities. Sedimentation rates are estimated to range from 0.24 to 0.13 cm/yr based upon recovery of an 11-m-long core (Kirby et al., 1998). Such rapid rates, however, are apparently slow enough to allow observable growth faulting during the Holocene along the down-thrown side of the boundary fault (approximately 15–20 m of displacement, see Fig. 4). This movement on growth faults is consistent with intervals of turbidite generation, reworking of SM, and sediment gravity flow consistent with the overall ponded geometry of the
Fig. 11. Seismic-stratigraphic scheme of units identified in Palmer Deep Basins I, II and III. All stratigraphic columns are at the same scale. All depths are in metres converted from travel time using 1400 m/s reference velocity in airgun Unit 1 and all DTB units, and 1800 m/s reference velocity for deeper units. See text for details; mbf = metres below seafloor.
fill of Basin III. Such redeposition has left a radiocarbon profile for sediment cores that contains numerous apparent stratigraphic inversions within turbidite intervals (Kirby et al., 1998). The boundary between subunits 1a and 1b corresponds to a significant change in magnetic stratigraphy as observed in core 28 (Kirby et al., 1998).

The age of the MBR is conjectural but can be as young as 12.5 ka to as old as 23 ka, using the rates of deposition derived from piston cores in Basin III (see above). This implies that all of Unit 1, including the nearly 40 m of section laying below the MBR, is Late Pleistocene to Holocene in age. The MBR itself must represent a contrast in acoustic impedance within a SM unit, perhaps due to the presence of a sand- or carbonate-rich interval related to a sediment gravity flow. Alternatively a period of reduced sedimentation or hiatus within Unit 1 may have allowed for greater compaction of the sediment.

The basin-fill geometry of the three seismic units (1, 2, and 3) in Basin III (as well as in Basin II) indicates that sedimentation is driven primarily by gravity flows from the steep flanks, where no significant accumulation of sediment occurs, apart from a wedge (Unit 4a) on the eastern slope that is apparently coeval with Units 3 and 2. Deposition of these units was most likely rapid, since there is little evidence for movement on growth faults in these layers (Fig. 4). There is no evidence of glacial erosional features (e.g., glacial troughs, subglacial tunnels, or diffraction of acoustic energy that is typically associated with ice grounding). Moreover the upward convex profile of the Unit 4a wedge and the interfingering between Unit 4a and Units 2 and 3 suggest subaqueous deposition rather than subglacial erosion. The increasing amplitude and the decreasing lateral continuity of reflectors towards the side of the basins in Units 1 and 2 suggest that coarser material and debris flow deposits originating at the foot of the wedge are present at the edges of the basins, while finer, relatively turbiditic sediments are present towards the centre. The overall wedge-like geometry of the lower part of Units 2 and 3 indeed suggests a provenance of debris from the southeast slope of Basin III, which is the steepest and likely most unstable.

A marked difference in sediment texture and composition must exist between the upper low-reflectivity Unit 1 and the two underlying highly reflective Units 2 and 3. We propose that the seismic character of Unit 2 and its stratigraphic position are indicative of proximal glacial marine deposits of siliciclastic character, likely silt and sand interbeds. In this case proximal is used to indicate direct sediment supply from grounded ice along the boundary of the basin. A depositional analogue to Unit 2 can be found today along the inner basin of Brialmont Cove, a bay along the northern Danco Coast, Antarctic Peninsula. Here, approximately 150 m of well stratified silt and subordinate sand turbidites are ponded in front of the Cayley Glacier complex (Domack, 1990; Domack and McClennen, 1996). The sedimentation rate within these deposits is on the order of a few cm/yr, an order of magnitude greater than that observed for Unit 1.

There is no evidence of growth faulting along the fault plane within Units 2 and 3. Indeed, there is some evidence for drag folding of sediments at the margins of the antithetic fault, within the footwall and hanging wall. More complex reflector geometry including discontinuity within deeper reflectors, specifically in Unit 3, may be explained by short segmentation along antithetic faults as illustrated in Fig. 4.

4.3. Basin II

Basin II has the same general stratigraphy as Basin III except that the internal reflectors in Unit 1 appear in the DTB records to be discordant with the seafloor. In addition a well-defined boundary fault is absent along the northwest side of the basin, probably hidden by chaotic or diffracted seismic units suggestive of a large slump complex (Fig. 6). Sediments recovered from the side of the slump appear to contain a condensed section of SM similar to Unit 1 (Kirby et al., 1998). This is consistent with the observation of stratigraphic drape of the upper part of Unit 1 over the slump as seen in the airgun survey (Fig. 6). The slump complex must therefore pre-date the MBR. In the lower portion of Unit 2 we see an angular truncation of reflectors that we interpret as an indication of tilting of the old layers along the boundary fault prior to the end of Unit 2 deposition. The geometry of Unit 4b is most compatible with a deformed sediment package
slumped from the southeast side of the basin at the foot of a sediment wedge. However, we do not have seismic evidence to support this.

4.4. Basin I

In Basin I, Unit 1 does not have a typical ponded (basin fill) geometry and can be considered as a drape of acoustically laminated sediments over a tilted substratum (Fig. 10). The exceptionally low reflectivity of the unit in Basin I is compatible with primarily hemipelagic and high accumulation rate deposition with only occasional turbidite deposition. Cores of the upper 10 m of sediment (Leventer et al., 1996) provide much less evidence of turbidite deposition than in the other two basins and support a hemipelagic to pelagic origin. Well laminated SM within Basin I is accumulating at the rate of 0.3 to 0.4 cm/yr (Leventer et al., 1996) suggesting an age of 19 to 14 ka BP for the base of Unit 1, which is stratigraphically equivalent to the inferred age of the MBR observed in Basins III and II.

The contorted, highly reflective units at the bottom of Basin I (tentatively identified as Units 4–5) are probably composed of coarse-grained debrites and turbidites that include high-density glacigenic terrigenous sediments, able to provide a very high acoustic impedance contrast with the overlying low-reflectivity unit.

5. Inferred history of basin infill

The Palmer Deep region occupies a key position with regard to shelf-wide glacial advance across the continental shelf edge, some 120 km northwest of Palmer Deep. The work of Pudsey et al. (1994) and Rebescos et al. (1998) indicates that the head of a major ice drainage system lies within the Palmer Deep. Here coastal glaciers draining off the Peninsula plateau (via fjord basins) and the Anvers Island ice cap converged in the past and led to constricted drainage across the shelf and deposition of a large wedge of prograded glacigenic sediment at the edge of the shelf. The last recession of grounded ice from the outer shelf is believed to have taken place at around 11,000 radiocarbon years BP, correlative with recession from Last Glacial Maximum (LGM) conditions in the Northern Hemisphere (Pudsey et al., 1994).

The stratigraphic sequence we describe from the Palmer Deep basins is inconsistent with full glacial conditions within Basins III and II during the LGM. Most of the undisturbed basin fill in the deepest portions of the Palmer Deep (Basins III and II) clearly pre-dates the LGM because the MBR is of Late Pleistocene age. In contrast, we suggest that Basin I was indeed fully glaciated during the LGM.

In Basin I the absence of the layered Units 2 and 3 and the occurrence of deformation and erosional truncation of glacial marine sediments of Units 4 and 5 may indicate ice grounding during the last glaciation, and postglacial deposition of the siliceous oozes of Unit 1 on top of the deformed sequence during the Holocene, consistent with the 14–19 ka age estimate for the base of Unit 1.

Deposition of Units 2 and 3 in the deeper Basins III and II is more difficult to explain if the ice sheet was indeed grounded across the entire shelf at the LGM.

We must consider Unit 2 as the product of subglacial deposition within an ice-free cavity beneath the ice sheet, similar to present-day subglacial lakes observed beneath the East Antarctic ice sheet (Os- wald and Robin, 1973; Shoemaker, 1991; Kapista et al., 1996). Maintenance of ice-free conditions within the subglacial basins would be provided by the narrowness and extreme depth (>1400 m) of the basins, which prevent ice deformation and complete grounding if ice flow and thickness are not appropriate. Basin I, however, was filled by ice because it is perched about 400 m higher. In the framework of this model (Fig. 12) subaqueous deposition beneath the ice sheet is dominated by fine-grained sedimentation derived from both fallout of undermelt of basal debris and lateral gravity flows from the inflow of meltwater along the periphery of the basin. While it is difficult to find appropriate analogues for the proposed undermelt of basal debris, there are many examples of glacial gravity-flow processes in the Northern Hemisphere margins (e.g. Bear Island, Laberg and Vorren, 1995; and Baffin Island, Stravers and Powell, 1997). The absence of very large clasts (i.e. boulder size) in Unit 2, suggested by the lack of diffractions otherwise common in the seismic data of proximal glacio-marine sediments, is favoured by
Fig. 12. Cartoon illustrating various stages of glaciation of the Palmer Deep and associated sediment facies. Note that we do not invoke a single cycle from stage 1 to stage 4 for the entire basin fill geometry. Stage 4 represents the present open marine conditions in the three basins. Stage 2 represents subglacial lake conditions that occurred in the two deepest Basins, II and III, during the LGM and possibly in earlier glacial advances. At the same time shallower Basin I was occupied by grounded ice. Stages 1 and 3 represent transitional conditions. See text for further details.

the short transit time of basal debris across and over the narrow confines of the basin, thus not allowing for the adequate melting and release of basal debris. The seismic character of Unit 2 is consistent with fine-grained (silt and clay) intervals interbedded with sand beds (turbidites), and rapid deposition is consistent with the lack of growth across the fault boundary in Basin III.

To follow the subglacial hypothesis further, we need to consider why the basin has not been entirely filled with sediment, since there have presumably been many glaciations across the continental shelf. We propose two explanations for this problem. (1) The activity across the basin boundary fault may be very recent so that earlier periods of glaciation were erosional events that took place across a seafloor that was somewhat shallower than today. In this case preservation of subglacial sediments is basically a product of localised, neotectonic subsidence across the fault. The basin fill therefore would mark deposits that are presumably only one or two glacial stages older than Stage 2. In support of this explanation is the observation of growth faulting within Holocene deposits. (2) It is possible that many ice shelf advances have taken place across the Palmer Deep and that the acoustic contrast we observe between Units 1, 2, and 3 in Basin III are due to progressive compaction of alternate beds of open marine SM and relatively thin siliciclastic intervals that represent slow subglacial accumulation during glaciation. We recognise that we have little information on the debris content, thermal character of basal ice or depositional processes beneath the Antarctic ice sheet, and even less information is available on subglacial Antarctic lakes, the specific analogue we propose for the Palmer Deep. If our age estimates are accurate, the MBR in Basin III is dated to the LGM and correlates with the erosional base of Unit 1 in Basin I. By inference, the deeper portion of Unit 1 in Basin III (below MBR) may correlate with the last interglacial (Stage 5e) or interstadials of Stages 4–3. Analogous alternations of high and low reflectivity in Units 2 and 3 would be linked to alternations of glacial/interglacial deposition. The contrast in interval thickness would be explained by increasing compaction and/or duration of the glacial/interglacial cycle. We speculate that perhaps as many as ten cycles may be preserved within Basin III.
Unit 4a, well developed on the eastern flank of Basin III, is interpreted, in analogy to the glaciomarine facies architecture of the western Spitsbergen continental margin (Boulton, 1990), to represent a wedge likely related to the deposition in a proglacial environment formed during the ice-sheet advance over the basin (Fig. 12). The sharp unconformity that cuts the upper termination of this wedge could be indicative of subglacial erosion, whereas the semitransparent lens above this unconformity could represent a till. The uppermost draping unit, above the semitransparent lens, is probably indicative of postglacial deposition. The wedge of Unit 4a downlaps onto the mound-shaped Unit 4b that probably represents an early stage of the basin fill in all three basins. Therefore, we believe that the contorted highly reflective units at the base of Basins III, II, and I (Units 4b–5) are probably composed of coarse-grained debrites and turbidites that include high-density glacigenic terrigenous sediments, deposited near the bottom of the basin.

We believe that the formation of the proglacial wedge in Basin III can be related to an early stage of ice sheet advance, when the ice-grounding line reaches the edge of a slope, where there is enough accommodation space to release sediments. If the slope is not too steep (Basin III), sediments can be progressively stacked prograding foresets. If the slope is too steep (Basins II and I), sediment tends to by-pass the slope and reach the bottom of the basin (Unit 4b). Another necessary condition for formation of a wedge on the flank of Basin III is also that it was larger than Basins II and I. This means that the transit time of the ice sheet during its advance over the basin margins was longer than in Basins II and I, and was probably long enough to allow melting and release of sediments from the ice base.

6. Conclusions

(1) The Palmer Deep is a fault-bounded extensional basin in which activity of faults is evidenced by stratigraphic offset within Holocene sections.
(2) The Palmer Deep contains a very thick sediment infill up to about 270 m that is arranged in a complex internal seismic stratigraphy.
(3) Comparative use of DTB and airgun sources reveals a complementary resolution of both deep and shallow (decimetre scale) stratigraphy.
(4) The shallow Middle Basin Reflector, correlated between both surveys, is most likely of latest Pleistocene age and therefore about 80% of the basin fill pre-dates the classic LGM.
(5) The two deepest Basins III and II were not filled by grounded ice during the LGM and were therefore subglacial lakes. Grounding of ice during the LGM has occurred only in the shallower Basin I.
(6) The Palmer Deep has acted as a natural sediment trap for glacial/interglacial sedimentation. Interglacial sedimentation is by high accumulation rate siliceous ooze. Glacial sedimentation is by fallout of fine-grained sediments from the basal ice and gravity flows on the basin flanks.

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