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Late Quaternary Iceberg Rafting along the Antarctic Peninsula Continental Rise and in the Weddell and Scotia Seas

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Sediment cores from the continental rise west of the Antarctic Peninsula and the northern Weddell and Scotia Seas were investigated for their ice-rafted debris (IRD) content by lithofacies logging and counting of particles $>$0.2 cm from core x-radiographs. The objective of the study was to determine if there are iceberg-rafted units similar to the Heinrich layers of the North Atlantic that might record periodic, widespread catastrophic collapse of basins within the Antarctic Ice Sheet during the Quaternary. Cores from the Antarctic Peninsula margin contain prominent IRD-rich units, with maximum IRD concentrations in oxygen isotope stages 1, 5, and 7. However, the greater concentration of IRD in interglacial stages is the result of low sedimentation rates and current winnowing, rather than regional-scale episodes of increased iceberg rafting. This is also supported by markedly lower mass accumulation rates (MAR) during interglacial periods versus glacial periods. Furthermore, thinner IRD layers within isotope stages 2–4 and 6 cannot be correlated between individual cores along the margin. This implies that the ice sheet over the Antarctic Peninsula did not undergo widespread catastrophic collapse along its western margin during the late Quaternary (isotope stages 1–7). Sediment cores from the Weddell and Scotia Seas are characterized by low IRD concentrations throughout, and the IRD signal generally appears to be of limited regional significance with few strong peaks that can be correlated between cores. Tentatively, this argues against pervasive, rapid ice-sheet collapse around the Weddell embayment over the last few glacial cycles.

Key Words: **Antarctic Peninsula; Weddell and Scotia Seas; ice-rafted debris; Antarctic Ice Sheet; Quaternary.**

INTRODUCTION

Evidence for the repeated collapse of the eastern margin of the Laurentide Ice Sheet is preserved in the sedimentary record of the North Atlantic in the form of prominent layers of iceberg-rafted debris (IRD), the Heinrich layers (Heinrich, 1988). These layers were deposited during massive discharges of icebergs, predominantly sourced from the Hudson Bay drainage basin of the Laurentide Ice Sheet (Bond *et al.*, 1992; Dowdeswell *et al.*, 1995). Investigation of the Heinrich layers, and other IRD layers in cores from the North Atlantic and adjacent seas (e.g., Bond and Lotti, 1995; Dowdeswell *et al.*, 1999), has allowed inferences to be made concerning the dynamics and stability of ice sheets around the North Atlantic over the last glacial–deglacial cycle.

In the southern hemisphere, the Antarctic Ice Sheet covers an area of 13.6×10^6 km^2, contains about 30×10^6 km^3 of ice, and accounts for ~90% of the total global ice volume (Drewry, 1983; Anderson, 1999). Current estimates suggest that the total eustatic sea level equivalent of the ice sheet is about 66 m (Denton *et al.*, 1991), and its present stability is a focus of continuing investigation and debate (e.g., Binschadler, 1997; Bamber *et al.*, 2000). Much research has concentrated on reconstructing the extent and dynamics of the ice sheet over the last glacial–deglacial cycle using marine geological and geophysical information (e.g., Bentley and Anderson, 1998; Domack *et al.*, 1999; Shipp *et al.*, 1999). Large-scale fluctuations of the Antarctic Ice Sheet also should be documented in the IRD record of the deep-ocean basins surrounding the continent. However, our knowledge of the IRD record around Antarctica and its relationship to past ice-sheet dynamics is still at a preliminary stage (Anderson and Andrews, 1999; Kanfoush *et al.*, 2000; Diekmann *et al.*, 2000).

We present the results of an investigation of the IRD record in two suites of sediment cores from the continental rise west of the Antarctic Peninsula and the northern Weddell and Scotia Seas (Figs. 1 and 2). Our objectives are to investigate whether the cores contain IRD layers that are sedimentologically similar to the Heinrich layers of the North Atlantic and to discuss implications for the Quaternary dynamics of the Antarctic Ice Sheet. The locations of the cores are appropriate to such an

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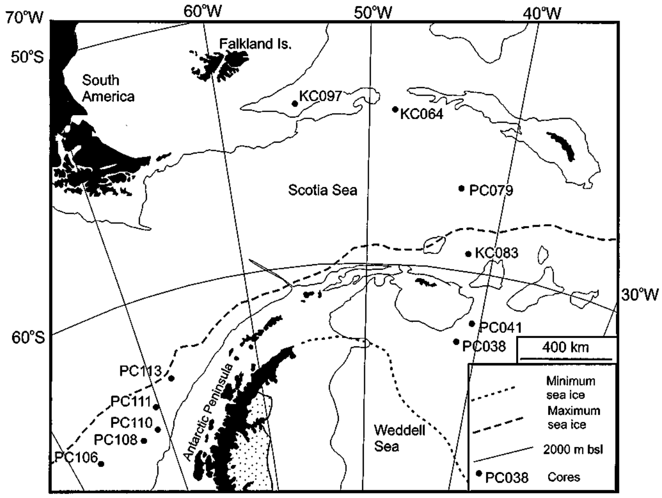

FIG. 1. Map of the Antarctic Peninsula and Weddell and Scotia Seas showing locations of sediment cores discussed in this study. The 2000-m bathymetric contour is shown (bsl = below sea level), as are the maximum (winter) and minimum (summer) sea-ice extents. PC-piston core; KC-kasten core.

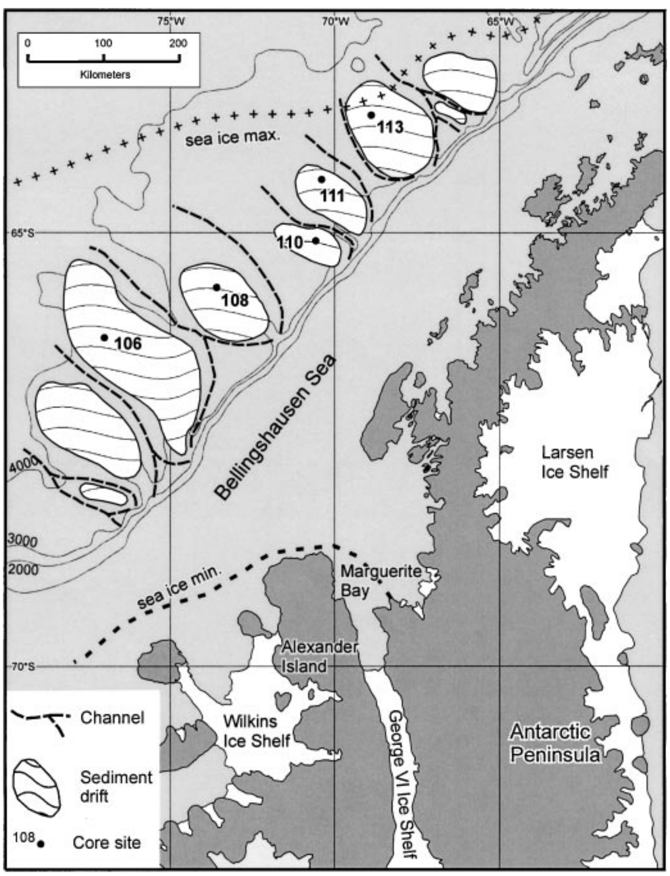

FIG. 2. Map of the Pacific margin of the Antarctic Peninsula showing locations of sediment drifts and piston cores discussed in this study. Bathymetric contours (meters) and drift outlines are from Rebesco *et al.* (1998) and Pudsey (2000). Sea-ice minimum and maximum positions in the region are also shown.

investigation. The core transect west of the Antarctic Peninsula would have been located in the NE–SW oriented drift path of icebergs calved from an expanded, full glacial ice sheet that extended across the continental shelf. Cores PC038, PC041, and probably KC083 from the Weddell Sea are located in the general pathway of maximum iceberg concentration through the Weddell Sea. This paper is a companion to that of Pudsey (2000), which examined the sedimentology and stratigraphy of the cores along the Antarctic Peninsula continental rise.

STUDY AREA

Contemporary glacier cover on the Antarctic Peninsula averages 500 m in thickness and drains both east and west off the peninsula. The Larsen Ice Shelf occupies much of the east coast (Fig. 2). On the western side of the peninsula, ice generally terminates at the coast, with drainage basins only a few tens of kilometers long. Ice shelves draining larger areas are present in the southwestern part of the peninsula, around Alexander Island (Fig. 2), and some of these ice shelves have experienced recent rapid retreat (Vaughan and Doake, 1996; Scambos *et al.*, 2000). In the Amundsen and Bellingshausen seas, icebergs tend to drift southwestward near the coast, then north, and finally east within the Antarctic Circumpolar Current (Keys, 1990).

The Weddell Sea receives drainage from the East and West Antarctic ice sheets, as well as from ice on the Antarctic Peninsula. The East Antarctic Ice Sheet is predominantly grounded above sea level, while its western counterpart is largely marine based. Ice streams drain the West Antarctic Ice Sheet into the southern Weddell Sea and converge into the Ronne-Filchner Ice Shelf (532×10^3 km^2; Anderson, 1999). Icebergs calved into the Weddell Sea from ice shelves around its landward margins drift clockwise in the Weddell Gyre, eventually exiting into the Scotia Sea (Swithinbank *et al.*, 1977; Moreton, 1999).

LAST GLACIAL MAXIMUM

A variety of marine geological and geophysical evidence, including overconsolidated diamicts and linear seafloor features, indicates that during the last glacial maximum (LGM), grounded glacier ice extended across the Antarctic Peninsula continental shelf (Pope and Anderson, 1992; Pudsey *et al.*, 1994; Bentley and Anderson, 1998; Canals *et al.*, 2000). However, whether grounded ice reached the shelf break along the length of the margin remains under debate (Pudsey *et al.*, 1994; Larter and Vanneste, 1995; Bart and Anderson, 1996). Radiocarbon dates indicate that deglaciation of the mid-outer shelf had taken place by 12,400 yr B.P. (Pope and Anderson, 1992), and the inner shelf was ice-free by 8,000–6,000 yr B.P. (Pudsey *et al.*, 1994; Shevenell *et al.*, 1996).

Marine and terrestrial geological data reveal that during the LGM, the West Antarctic Ice Sheet probably expanded significantly into the southern Weddell Sea embayment and locally may have extended onto the outer shelf via cross-shelf troughs (Bentley and Anderson, 1998). By contrast, the East Antarctic Ice Sheet does not appear to have extended far onto the eastern Weddell Sea continental shelf during the LGM, but rather retreated from its maximum position by 26,000–28,000 yr B.P. (Bentley and Anderson, 1998). The East and West Antarctic Ice Sheets therefore appear to have behaved diachronously in the Weddell Sea embayment.

METHODOLOGY

The cores investigated in this study (Table 1) were collected during British Antarctic Survey cruises aboard the RRS *Discovery* and RRS *James Clark Ross*. Cores were collected using kasten and piston corers. The former is a 3-m-long, 15-cm-square gravity corer that uses a 1-ton core head. A Driscoll-type piston corer was used, with a 1.2-m trigger corer. Cores were split and logged from x-radiographs of the archive halves, and lithofacies were identified (Table 2). Measurements were also made from the x-radiographs of the number of particles >0.2 cm per cm of core as an index of iceberg rafting. For each core, the number of clasts >0.2 cm in diameter was counted in intervals of 1-cm thickness. Counting of this size fraction also avoids the potential problem with finer grain sizes, whereby, in locations close to a continental source, delivery of particles <0.2 cm in diameter may be by processes other than iceberg rafting. Magnetic susceptibility was measured on the split archive half of each core at intervals of 2 cm using a Bartington susceptibility meter with a MS2F probe.

CORE STRATIGRAPHY

The cores were dated using a combination of biostratigraphy (diatoms and radiolaria) and chemical (barium) and isotope ($^{230}Th_{excess}$ dating) stratigraphy. These methods have allowed the identification of warm and cold isotope stages in the cores. Figure 3 shows the chronology for cores KC064 and KC083 from the Scotia Sea and PC106 from the Antarctic Peninsula margin. Biogenic barium was used as a paleo-productivity indicator to identify interglacial periods (cf. Shimmield *et al.*, 1994; Frank *et al.*, 1995; Nürnberg *et al.*, 1997; Bonn *et al.*, 1998; Pudsey and Howe, 1998; Pudsey, 2000). These authors have demonstrated that in the Scotia, Weddell, and Ross Seas, as well as the southeast Atlantic Ocean, biogenic barium is consistently high in warm isotope stages 1, 5e, 7, and 9, but low during glacial/cold stages 2–4, 6, 8, and 10. The downcore relative abundance of the radiolarian *Cycladophora davisiana* was also used to distinguish between glacial and interglacial periods in cores from the Weddell and Scotia Seas. In the southern ocean, *C. davisiana* has been shown to be abundant during glacial maxima but forms a low proportion of total radiolarian fauna in interglacial periods (Hays *et al.*, 1976). Uranium and thorium analysis was performed at the Heidelberger Akademie der Wissenschaften. Th and U activities were determined by alpha-spectrometry and excess ^{230}Th (from the water column) was calculated by subtracting the amount of ^{230}Th that is in equilibrium with ^{234}U for each sample (Frank *et al.*, 1995).

Quaternary warm isotope stages 1, 5, and 7 were identified in cores from the Antarctic Peninsula rise based on biogenic barium and $^{230}Th/^{234}U$. The isotope stage 2/1 boundary and position of the LGM were identified in cores from the Weddell and Scotia Seas using biogenic barium and the relative downcore abundance of *C. davisiana*. Thus, the upcore transition from stage 2 to stage 1 in KC064 and KC083 is recorded by a decrease in *C. davisiana* but increase in biogenic barium (Fig. 3). In

TABLE 1
Site Information on Sediment Cores Discussed in This Paper from the Continental Rise of the Antarctic Peninsula and the Weddell and Scotia Seas[1]

	Core number	Location	Water depth (m)	Recovery (m)
Antarctic Peninsula	PC106	66°18.8′S, 76° 58.7′W	3662	9.27
	PC108	65°42′S, 73° 38′W	3601	9.15
	PC110	65°08.8′S, 70° 35.3′W	3025	7.55
	PC111	64°19′S, 70° 26.2′W	3357	10.93
	PC113	63°27.3′S, 68° 58′W	3552	10.80
Weddell and Scotia Seas	PC038	63°10.0′S, 42° 43.5′W	3802	5.96
	PC041	62°04.0′S, 40° 35.0′W	3310	9.35
	KC083	59°22.2′S, 42° 43.5′W	3900	2.3
	PC079	56°45.0′S, 43° 16.9′W	3733	8.0
	KC064	53°52.1′S, 48° 20.3′W	4304	3.2
	KC097	53°21.0′S, 54° 41.0′W	3058	2.82

[1] Core locations are shown in Figures 1 and 2. PC = Piston Core; and KC = Kasten Core.

TABLE 2
Lithofacies Codes Used in Description of Cores from the Antarctic Peninsula Margin and Weddell and Scotia Seas (see Figs. 3 and 4)

Lithofacies	Description
Gravel	
Gm	Gravel, massive
Gs	Gravel, stratified
G	Thin gravel layer or lag
Sand	
Sm	Sand, massive
Ss	Sand, stratified
Sg	Sand, normally graded
S	Thin sand layer
Mud	
Fl	Mud, well laminated
Flw	Mud, weakly laminated
Fs	Mud, stratified
Fsw	Mud, weakly stratified
Fm	Mud, massive
F(G)-	Mud, gravelly
F(S)-	Mud, sandy

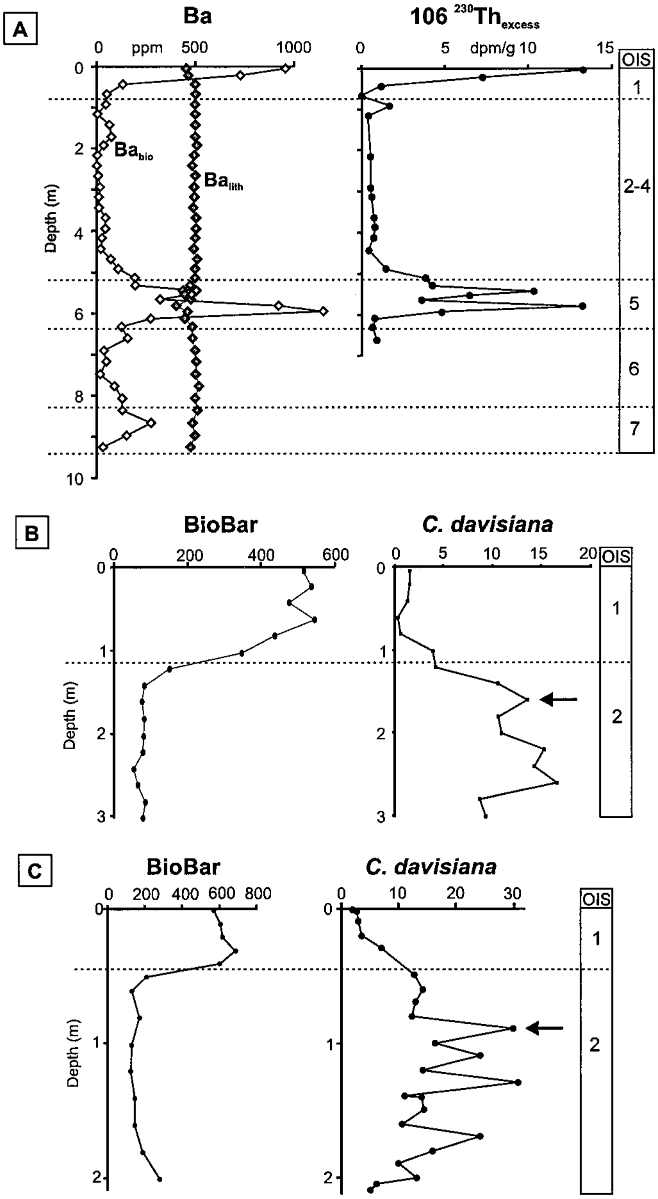

FIG. 3. Chemostratigraphy, oxygen isotope stratigraphy and biostratigraphy of sediment cores PC106 from the Antarctic Peninsula continental rise and KC083 and KC064 from the Scotia Sea (Fig. 1). (A) Biogenic barium (open symbols), lithogenic barium (closed symbols), and $^{230}Th_{excess}$ (filled circles) in core PC106. (B) Biogenic barium and relative abundance of radiolarian *Cycladophora davisiana* in core KC064. Arrow marks inferred position of LGM based on the first downcore abundance peak in *C. davisiana*. (C) Biogenic barium and relative abundance of *Cycladophora davisiana* in core KC083. Arrow marks inferred position of LGM based on the first downcore abundance peak in *C. davisiana*. Biogenic barium measured in parts per million (ppm) in both KC083 and KC064. Relative abundance of *C. davisiana* plotted as a percentage of the total radiolarian fauna, based on counts of at least 300 individuals per slide for both cores.

general, all the cores are poor in biogenic carbonate and therefore it was not possible to obtain an oxygen isotope curve from foraminifera. The Antarctic Peninsula cores are also low in total organic carbon (TOC; 0.1–0.3%), but the Scotia Sea cores contain sufficient TOC for accelerator mass spectrometry (AMS) radiocarbon dating of bulk samples. The results confirm the position of the isotope stage 2/1 boundary for core PC079 (Moreton, 1999) and KC064 and KC097 (R. Hale, personal communication, 2000).

Antarctic Peninsula Margin

The five cores from the Antarctic Peninsula margin are all from the distal sides of a series of sediment drifts extending along the continental rise (Fig. 2). The cores are predominantly fine grained and exhibit a cyclicity in color, composition, and sedimentary structures that corresponds to glacial–interglacial cycles (Pudsey and Camerlenghi, 1998; Pudsey, 2000). Lithostratigraphically, the cores comprise thick, grey, terrigenous laminated units deposited during glacial periods (oxygen isotope stages 2–4 and 6), alternating with thinner, bioturbated, brown, diatom- and foraminifer-bearing units deposited during interglacial periods (oxygen isotope stages 1, 5, and 7; Fig. 4). There is no evidence for significant hiatuses in the form of sharp lithological changes or increases in sediment firmness.

Interglacial units range from 0.5 to 2 m thick and generally comprise dark greyish brown to olive brown, diatom or foraminifer-bearing, massive to weakly laminated mud that is commonly bioturbated (Fig. 4). The bases of these units are designated by upcore increases in biogenic material (silica and carbonate). These characteristics are consistent with a low-energy depositional environment, dominated by hemipelagic settling of fine-grained material and bottom current reworking. Provisional sedimentation rates were calculated based on the assumption that the succession is continuous from the seabed downward and there are no hiatuses (Pudsey, 2000). Sedimentation rates during stage 7 are 1.1–1.9 cm per thousand years. Sedimentation rates for stage 5 are 0.7–3.8 cm per thousand years, while sedimentation rates during stage 1 are 0.7–2.9 cm per thousand years but are considered unreliable because of loss of core-top material.

Glacial units range from 2.3–7.7 m in thickness and consist predominantly of laminated mud with a low biogenic content (Fig. 4). Acoustic data indicate that these sediments thicken inshore across the drifts (Pudsey, 2000). Glacial units are marked by either a sharp color change to dark greenish grey or dark grey clayey mud in association with the disappearance of bioturbation or by an abrupt decrease in diatom content. Prominent silt laminae are present in stages 2–4 in cores PC111 and PC113. The laminae have sharp bases, sharp or gradational tops, and the thicker silts are normally graded. Similar graded, sharp-based silt laminae and very thin fine sand beds are also common in stage 6 and exhibit parallel and cross-lamination. Collectively, these units are interpreted as the product of sedimentation by fine-grained turbidity currents and suspension-settling from meltwater plumes. Average sedimentation rates for stages 2–4 and stage 6 are 4.6–7.6 cm per thousand years and 3.6–6.4 cm per thousand years, respectively.

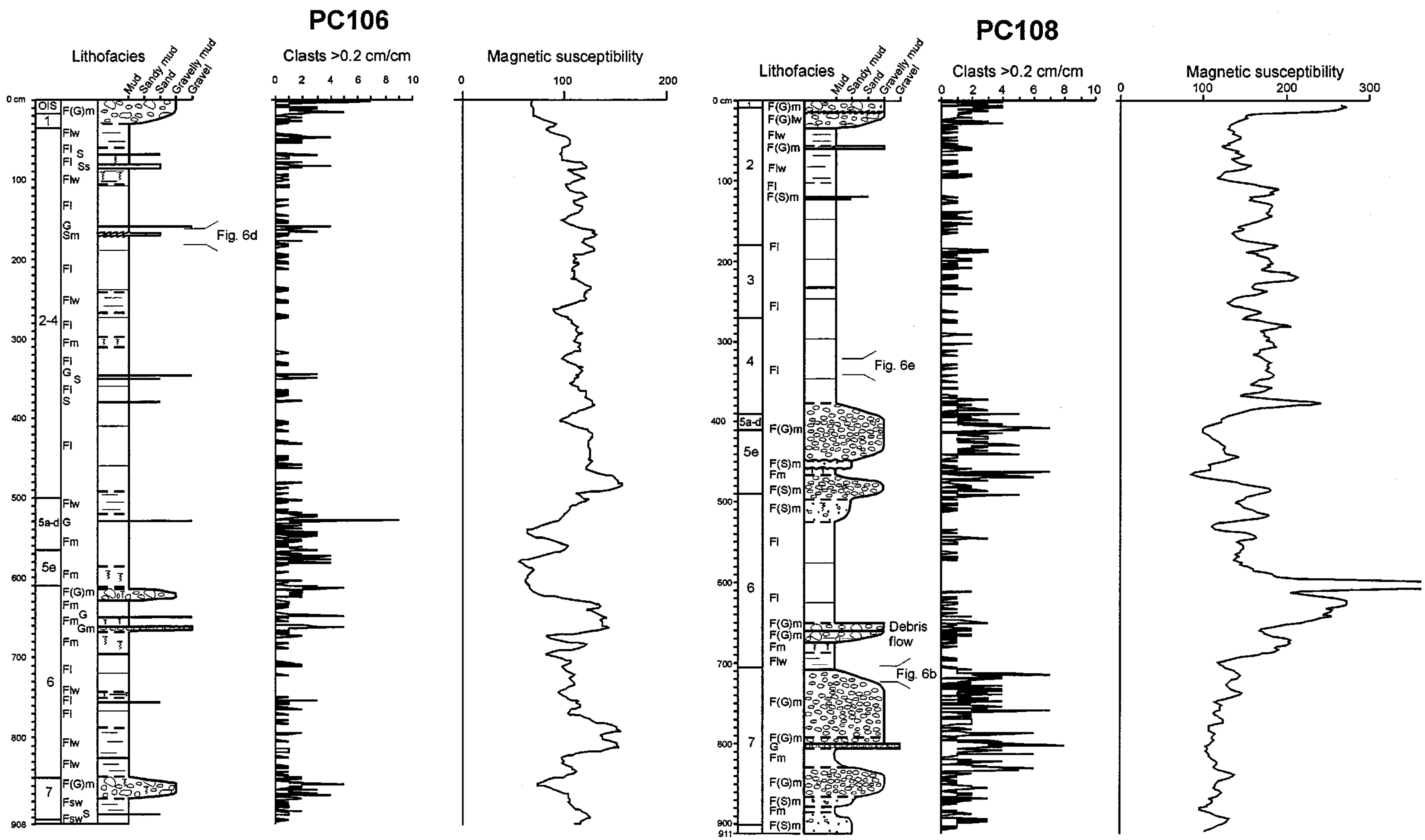

FIG. 4. Lithofacies logs, coarse particle counts (particles >0.2 cm diameter per cm), and magnetic susceptibility records of sediment cores from the continental rise west of the Antarctic Peninsula. Magnetic susceptibility is measured in SI units and is a dimensionless ratio. Oxygen isotope stages 1, 2–4, 5, 6, 7 and 8 are also shown. Core locations and site information are shown in Figures 1 and 2 and Tables 1 and 2.

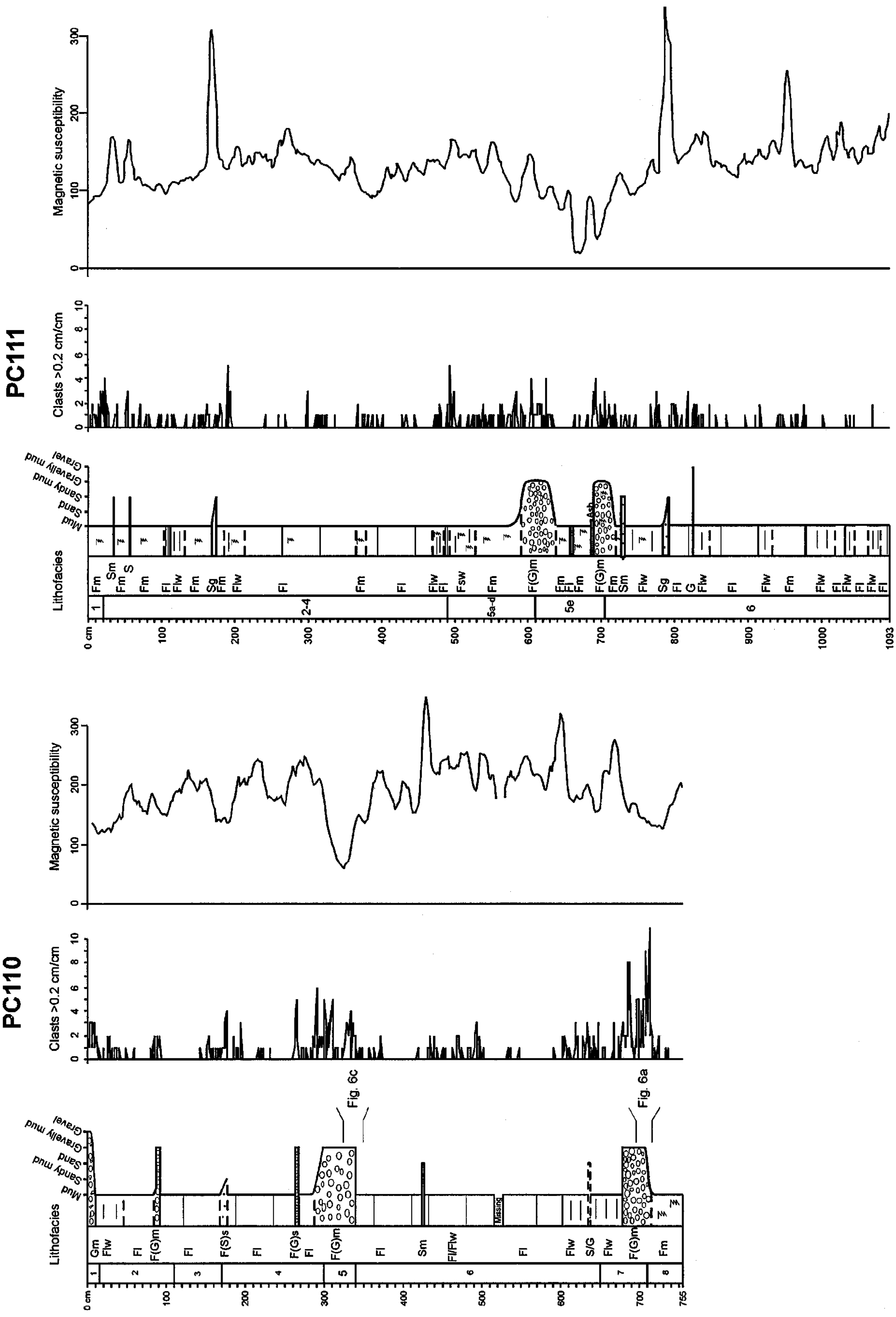

FIG. 4—*Continued*

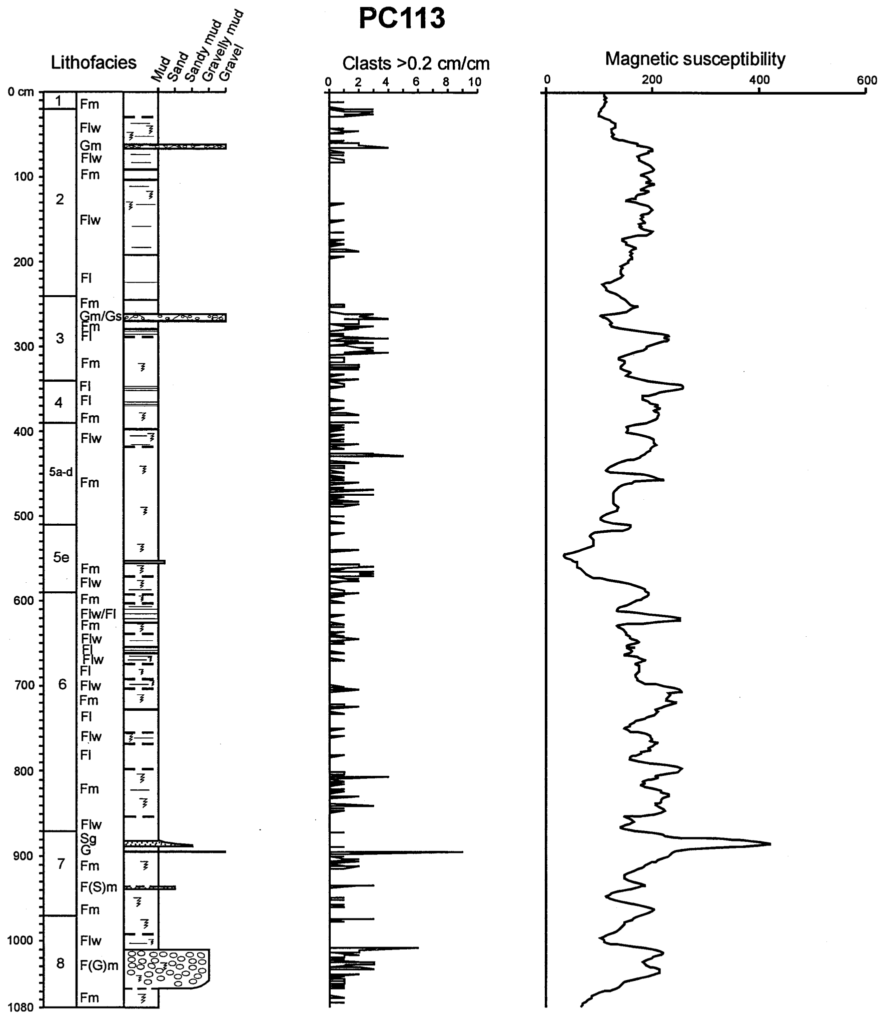

FIG. 4—*Continued*

Weddell and Scotia Seas

Cores were collected from sediment drifts (cores KC064, KC083, KC097, and PC079; Howe and Pudsey, 1999; Howe *et al.*, 1997; Pudsey and Howe, 1998) and areas of fine-grained, hemipelagic sediment (cores PC038 and PC041; Pudsey, 1992). Core site selection was based on 3.5-kHz acoustic profiles that were used to map areas of rapid, continuous sediment accumulation suitable for obtaining high-resolution Quaternary records in sediment cores. The cores are predominantly composed of homogeneous to crudely laminated, bioturbated, silty clay and muddy sand that sometimes contain bioturbated ash layers (Fig. 5). Poorly to moderately well sorted, homogeneous or crudely laminated, bioturbated silty clays and sandy muds are interpreted as muddy contourites. Lamination, where present, is commonly faint and often disturbed by burrowing or bioturbation-induced mottling. Locally, sandy contourites are present as homogeneous, bioturbated, moderately sorted sand containing foraminifera (e.g., top of KC097).

ICE-RAFTED DEBRIS

Antarctic Peninsula Margin

IRD-rich units occur in all the cores with, in some cases, up to 10 particles per cm of core thickness (Fig. 4). The thickest IRD units occur in interglacial stages. These are commonly greater than 20 cm thick, in some cases reaching up to almost 1 m in thickness (e.g., PC108, 707-805; Fig. 4). On x-radiographs, these interglacial IRD-rich units range from massive to crudely stratified in structure and are characterized by angular to rounded (dominantly subangular-subrounded) clasts in a muddy matrix, often with sand grains scattered throughout (e.g., PC108 from 375–448 cm and 707–792 cm; PC110 from 287–342 cm and 678–717 cm; PC111 from 592–638 cm; Figs. 4 and 6). Clasts are generally dispersed but occasionally exhibit local clustering. Stratification, where present, is the result of textural variation, involving transitions from coarse to finer (less IRD-rich) sediment (Fig. 6c) and the units may be bioturbated. Contacts with

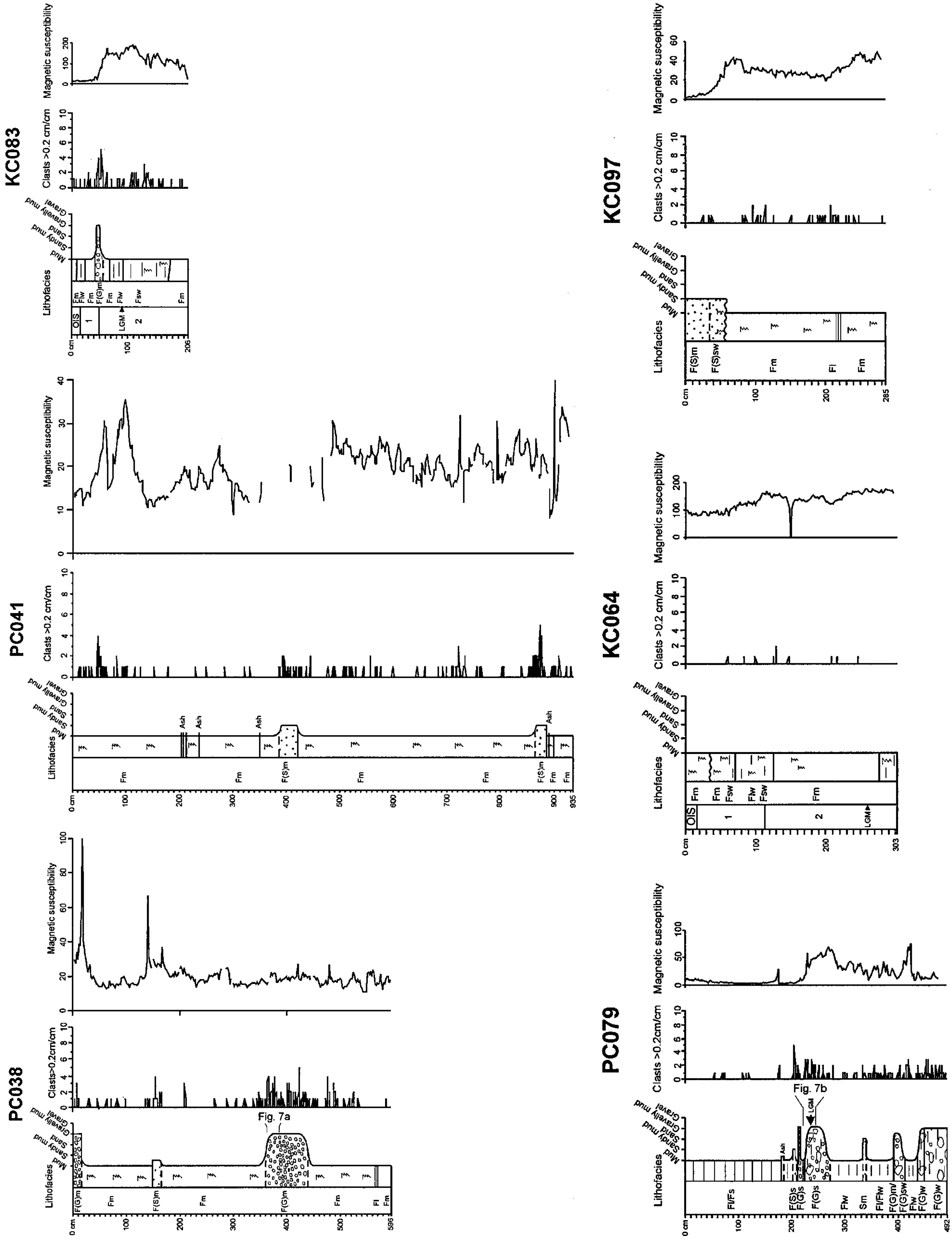

FIG. 5. Lithofacies logs, coarse particle counts (particles >0.2 cm diameter per cm), and magnetic susceptibility records of sediment cores from the Weddell and Scotia Seas. Magnetic susceptibility is measured in Si units and is a dimensionless ratio. Oxygen isotope stage 2/1 boundary is shown for cores KC064 and KC083, and the position of the LGM is shown for PC079 and KC064. Core locations and site information are shown in Fig. 1 and Tables 1 and 2.

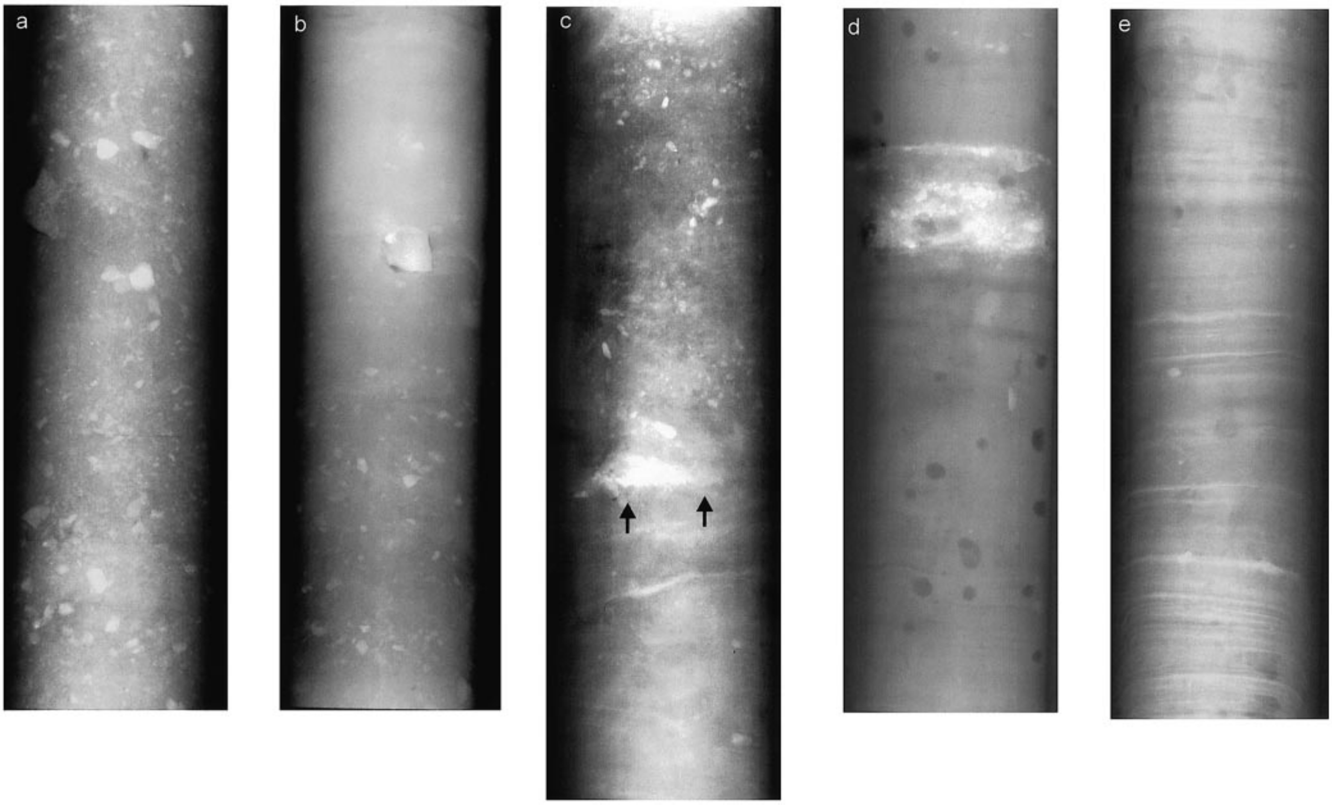

FIG. 6. X-radiographs of ice-rafted debris (IRD)-rich units in sediment cores from the continental rise west of the Antarctic Peninsula (Fig. 2). (a) IRD-rich pebbly mud, PC110, 696–716 cm. The unit is massive in structure, but subtle textural variation is present from areas of coarse to slightly finer sediment. (b) Weakly laminated IRD-poor mud grading downward into massive pebbly mud. Note large angular dropstone just above center of core section, PC108, 703–723 cm. (c) Pebbly mud, PC110, 325–350 cm. Note development of crude stratification defined by textural variation and sharp contact (arrowed) with laminated clast-poor mud. (d) Gravelly sand layer in weakly laminated, clast-poor mud, PC106, 161–181. Note the sharp upper and lower contacts of the layer and development of stratification bounding the coarse massive center. (e) Laminated clast-poor mud, PC108, 321–341 cm.

surrounding IRD-poor sediment range from sharp to gradational (Figs. 4, 6b, and 6c).

By contrast, the IRD-rich units in glacial periods are generally restricted to much thinner (typically 0.5- to 8-cm-thick) coarse-grained layers or lags of gravel or gravelly sand, bounded by clast-poor laminated or massive mud (e.g., PC106 from 82–85 cm; 166–169 cm; and 663–668 cm; and PC113 from 40–45 cm and 265–272 cm; Figs. 4, 6d, and 6e). Contacts with bounding IRD-poor facies range from sharp to gradational to interstratified. In some cases, the layers are characterized by a central massive zone that becomes interstratified toward the upper and lower contacts of the unit (e.g., PC106 from 166–169.5 cm; Figs. 4 and 6d). The massive center corresponds to the coarsest part of the layer. Exceptionally, these glacial IRD-rich unit reach up to almost 0.5 m in thickness (e.g., PC113, 1010–1057 cm). These thicker units are bioturbated and have sharp to gradational contacts with bounding sediment.

Based on counts of the >0.2 cm size fraction, several cores exhibit a cyclicity in their IRD content, with zones of abundant IRD separated by zones in which IRD is less frequent (commonly 1–3 clasts per cm core thickness; Fig. 4). This crude cyclical pattern is best developed in PC106, PC108, and PC110. In these cores, maximum IRD concentrations occur predominantly in stages 1, 5, and 7, with lower concentrations in stages 2–4 and 6 (Fig. 4). In PC110, however, the zone of abundant IRD from 262–372 cm extends upcore from stage 5 into the lower part of stages 2–4. Cyclicity is less well developed in PC111 and PC113. However, in PC111, IRD is more abundant, albeit in low concentrations (1–5 clasts per cm thickness), within stages 5 and 1 than in stages 2–4 and 6.

IRD composition also shows cyclicity, as noted by Pudsey (2000). In stages 2–4 and 6, IRD predominantly comprises volcanics, while stages 5 and 7 contain a wider variety of grain types with more quartz, feldspar, and acid plutonic fragments. The magnetic susceptibility of the interglacial IRD-rich units is generally lower than that of glacial IRD-units (Fig. 4). However, the most prominent peaks in magnetic susceptibility correlate to individual sandy units (e.g., PC111 from 170–176 cm and 783–793 cm; PC113 from 882–888 cm; Fig. 4).

Weddell and Scotia Seas

Cores from the Weddell and Scotia Seas generally contain low numbers of clasts >0.2 cm and their maximum IRD content

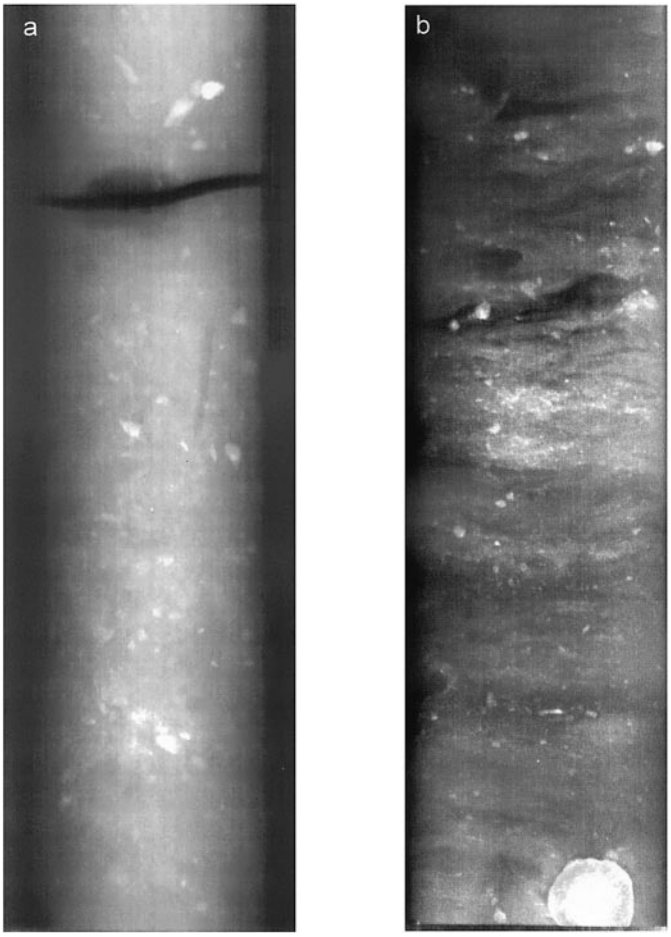

FIG. 7. X-radiographs of ice-rafted debris rich units in sediment cores from the Weddell Sea and Scotia Seas (Fig. 1). (a) Massive gravelly mud, PC038, 362–385 cm. (b) Stratified gravelly mud, PC079, 221–245 cm. Note abrupt textural variation from coarse to finer sediment, particularly in the upper third of the image and the large well-rounded dropstone at the base.

(as defined by individual peaks in the number of clasts >0.2 cm per cm of core) is only 50% of the corresponding maximum in the Antarctic Peninsula cores (Fig. 5). In PC041, KC064, and KC097, x-radiographs show that, where present, clasts >0.2 cm occur as isolated particles floating in a massive mud matrix (Fig. 7a). However, KC083 and PC041 contain gravelly and coarse sandy units at 43–56 cm in KC083, and 387–421 cm and 864–884 cm in PC041. The sandy units in PC041 are massive, have sharp bases, and appear as a slightly lighter tone on x-radiographs.

PC038 and PC079 also contain thick sections where IRD content low and restricted to occasional floating lonestones. However, the IRD content of both these cores increases with depth and they contain sections of more abundant IRD (e.g., 364–383 cm in PC038; 334–340 cm in PC079; Figs. 5 and 7). These coarse-grained units range from massive to stratified and contain dispersed clasts in a muddy or sandy mud matrix (Figs. 7a and 7b). Contacts with surrounding IRD-poor sediment are sharp or gradational. In contrast to the Antarctic Peninsula margin, cores from the Weddell and Scotia Seas contain IRD in their glacial intervals that is more varied petrographically and includes plutonic and volcanic rocks. Holocene IRD is restricted to sedimentary and low-grade metasedimentary rocks (Pudsey and Howe, 1998).

IRD-LAYERS FROM THE ANTARCTIC MARGIN: GENESIS AND SIGNIFICANCE

Sedimentology of Heinrich Layers

Based on studies from the Labrador Sea and Baffin Bay, it is now recognized that the Heinrich layers and their correlative detrital carbonate (DC) lay ers exhibit considerable sedimentological variability, depending on proximity of the depositional site to the former ice margin (Wang and Hesse, 1996; Hesse and Khodabakhsh, 1998; Andrews *et al.*, 1998). At ice-proximal sites, the depositional mechanisms by which Heinrich layers form appear to include a wider range of processes than simply iceberg rafting. On the Labrador Slope, proximal Heinrich layers generally comprise laminated to thinly bedded, carbonate-rich muds that were deposited by turbidity currents or from the nepheloid layer. IRD is either dispersed throughout these muds or is concentrated in laminae. Contacts with bounding sediments range from sharp to gradational. Similarly, DC layers in cores from the proximal southeastern Baffin Island slope frequently comprise laminated muddy turbidites containing dispersed IRD (Andrews *et al.*, 1998). Proximal Heinrich layers deposited close to the mouth of Hudson Strait are up to about 1 m thick (Dowdeswell *et al.*, 1995; Andrews *et al.*, 1998).

Distal Heinrich layers from beyond the Labrador Slope and basin, and from sites in the central and eastern North Atlantic up to several thosand kilometers from their source in Hudson Strait, decrease to <5 cm in thickness and consist of carbonate-rich mud with ubiquitous IRD that was deposited through a combination of iceberg rafting and hemipelagic sedimentation (Bond *et al.*, 1992; Wang and Hesse, 1996; Hesse and Khod abakhsh, 1998). Sorting in these units is commonly poor, and IRD is either dispersed throughout or occurs in discrete layers. Internally, beds are massive, apart for some occasional faint parallel lamination. Contacts with over- and underlying sediments range from sharp to gradational. Bioturbation is slight to moderate and microfossils are rare or absent.

Antarctic Peninsula Margin

IRD-rich units in sediment cores from the Antarctic Peninsula are thickest in isotope stages 1, 5, and 7. Increased delivery of IRD to the Antarctic Peninsula continental rise during interglacial periods would be expected, given that warmer climatic conditions would result in the breakup of fringing ice shelves and retreat of the calving margin inland, thereby exposing the debris-rich basal ice layers (cf. An derson and Andrews, 1999). This situation is currently taking place in the region today with breakup of the ice shelves around the peninsula (Vaughan and Doake,

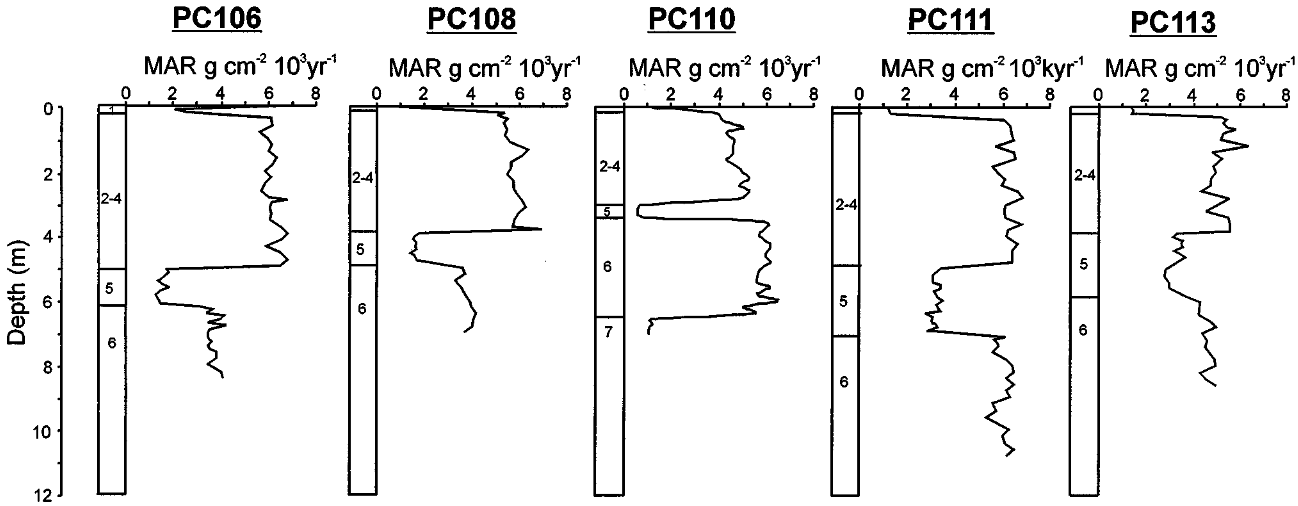

FIG. 8. Mass accumulation rates (MAR); (g cm^{-2} 10^3 yr^{-1}) for sediment cores from the continental rise west of the Antarctic Peninsula. Location of cores is shown in Fig. 2. Note marked decrease in MAR during interglacial periods versus glacial periods.

1996; Scambos *et al.*, 2000). By contrast, during full glacial periods, deposition of coarse-grained debris at the grounding line of ice shelves fringing the grounded ice sheet would prevent the calving of debris-rich icebergs (cf. Drewry and Cooper, 1981) and, hence, suppress the delivery of coarse-grained IRD to the deep ocean. This would explain the restricted occurrence and thinness of the glacial IRD layers in the cores relative to their interglacial counterparts. Thus, any IRD record of catastrophic collapse of ice-sheet drainage basins around the Antarctic Peninsula is more likely to be found in the interglacial rather than the glacial stages of the cores.

The relatively thick interglacial IRD units that we observe are similar sedimentologically to distal Heinrich layers (cf. Wang and Hesse, 1996; Hesse and Khodabakhsh, 1998). These units comprise massive or crudely stratified beds of gravelly mud. Clasts are commonly dispersed but occasionally exhibit local clustering. The matrix ranges from mud to more poorly sorted muddy sand, and bed contacts are sharp to gradational. Clast shape ranges from angular to rounded, indicating a combination of basal and supraglacial debris sources for the IRD.

However, several lines of evidence indicate that both the interglacial *and* glacial IRD-rich units from the Antarctic Peninsula margin are not the true equivalents of Heinrich layers in terms of their glaciological significance; that is, as indicators of ice-sheet drainage basin collapse. First, although the thickest IRD-rich units occur during oxygen isotope stages 1, 5, and 7, it is important to note that sedimentation rates were lower during these stages than in stages 2–4 and 6 (in some cases by 50%). The apparent concentration of IRD in interglacial periods in the peninsula cores could therefore be a function of lower sedimentation rates. This possibility was tested by applying the maximum glacial sedimentation rate to the interglacial stages in the same cores. The result is a similar concentration of IRD in interglacial and glacial periods, thereby confirming that the enhanced interglacial IRD signal reflects lower sedimentation rates rather than increased iceberg rafting. This is also supported by the mass accumulation rates (MAR; g cm^{-2} 10^3 yr^{-1}) of the peninsula cores which are markedly lower during interglacial periods versus glacial periods, in some cases by as much ~80% (Fig. 8). Given that the cores were recovered from the distal sides of a series of contourite drifts (Pudsey, 2000), current winnowing during sedimentation is likely and is probably reflected in the crude stratification and textural variation of some of the IRD-rich units. Such winnowing would serve to enhance the concentration of coarse-grained sediment and IRD and thus accentuate the IRD signal (cf. Pudsey *et al.*, in press). Additional support for current winnowing is shown by the fact that the cores with the best-developed cyclicity in IRD occurrence (PC106, 108, and 110) also show a clear cyclicity in their fine fraction size distribution. Samples from stages 1, 5, and 7 in these cores have a higher silt : clay ratio (0.8–2.3) and are better sorted (sigmaG = 2.0–3.0) than samples from the glacial stages (silt : clay 0.3–0.8, sigmaG-3.0–3.5). The northern cores 111 and 113 are siltier overall and show a comparable glacial–interglacial cyclicity in silt : clay ratio, but this is not clearly related to IRD distribution.

Second, gravel layers, 0.5–7 cm in thickness, occur in cold stages 2–4 and 6 (e.g., PC106 from 82–85 cm, 166–169 cm, and 663–668 cm; PC113 from 40–45 cm and 265–272 cm; Fig. 4). However, none of these layers can be correlated across each of the cores along the transect. For example, PC113 contains two prominent gravel units in stages 2–4 (Fig. 4) but these are absent in PC111, which is from the adjacent drift. Similarly, PC113 and PC106 mark the north and south ends of the transect, respectively. Both these cores contain prominent gravelly layers in stages 2–4. However, even though sedimentation rates in these stages were the same for both cores (7.5 cm per thousand years), the IRD layers cannot be correlated. IRD-layers in stages 2–4 and 6 are therefore interpreted to record the occasional passage of icebergs over the core sites, rather than major collapses of ice-sheet drainage basins, which would be expected to have a stronger regional signal. Furthermore, we note that bioturbation is strongly developed in some of the glacial IRD-rich units (e.g., PC113 from 1009–1041 cm), an observation difficult to reconcile with rapid deposition during massive discharges of icebergs.

It is unlikely that sea-ice rafting was responsible for deposition of these coarse-grained units. Sea-ice rafted debris is typically fine grained, whereas icebergs transport and deposit debris of heterogeneous grain size ranging from clay to boulders (Pfirman *et al.*, 1990; Dowdeswell *et al.*, 1998). This reflects the processes of debris entrainment where sea ice predominantly incorporates debris by eolian processes and the freezing on of turbid seawater. Hence, the dominant grain size of sea-ice rafted sediment is silt and clay. Furthermore, there are few sources of debris for Antarctic sea ice, given the relatively deep shelf (>50 m), lack of turbid meltwater production, and the widespread glacier-covered coastline (Drewry *et al.*, 1982). Counting of the >0.2 cm size fraction thus largely eliminates the possibility for dilution of the iceberg-rafting signal by deposition from sea ice.

Based on the existing core chronology, therefore, these results provisionally imply that ice-sheet drainage basins have not undergone large-scale catastrophic collapse along the western Antarctic Peninsula margin during the late Quaternary.

Weddell and Scotia Seas

In general, there are few significant peaks in IRD in cores from the Weddell and Scotia Seas. Although IRD-rich units are present in some cores (PC038, PC079), these are of lower concentration (≤5 clasts/cm) than in cores from the Antarctic Peninsula margin. Poor chronological control means that we cannot yet determine if these units are the product of enhanced iceberg delivery from ice-sheet drainage basins surrounding the Weddell Sea, or, if alternatively, they record enhancement of the IRD signal by low sedimentation rates and/or current winnowing. However, it is noteworthy that there are few large peaks of IRD that can be correlated across the core sites, suggesting that an event of the magnitude of the rapid collapse of an ice-sheet drainage basin on the order of 10^5–10^6 km^2 may not have taken place over the last few glacial cycles. This will be tested by ongoing research. In PC079, the LGM falls within the upper part of the gravelly mud unit from 225–270 cm, and this gravelly unit also corresponds to an abrupt increase in magnetic susceptibility (Fig. 5). This suggests that iceberg rafting was occurring immediately before attainment of the LGM in the Weddell Sea.

CONCLUSIONS

Five sediment cores from the continental rise west of the Antarctic Peninsula and six from the Weddell and Scotia Seas were investigated for their IRD content by lithofacies logging and counting of particles >0.2 cm from core x-radiographs. Cores from the Antarctic Peninsula margin all contain prominent IRD-rich units, with maximum IRD concentration in isotope stages 1, 5, and 7. Sedimentologically, these IRD units are comparable to distal Heinrich layers from the Labrador Sea and North Atlantic. However, the greater concentration of IRD in interglacial stages is the result of a combination of low sedimentation rates and bottom current winnowing, rather than regional-scale episodes of increased iceberg rafting. This is supported by the mass accumulation rates of the cores, which are markedly lower during interglacial periods versus glacial periods. Thin IRD-layers in isotope stages 2–4 and 6 cannot be correlated throughout the core transect and hence are interpreted as recording the intermittent local transit of icebergs rather than major collapses of ice-sheet drainage basins, which would be expected to have a much stronger regional signal. These results imply that ice-sheet drainage basins on the western Antarctic Peninsula margin have not undergone catastrophic collapse during isotope stages 1–7. Cores from the Weddell and Scotia Seas are characterized by low IRD concentrations throughout, and there are few strong peaks of IRD that can be correlated regionally between cores. There appears to have been an increase in iceberg rafting immediately before attainment of the LGM in the Weddell Sea, although the signal is weaker and regionally limited, relative to the pervasive nature of the North Atlantic Heinrich layers. Such limited regional significance and generally low concentrations of IRD tentatively argues against rapid collapse of the large ice-sheet drainage basins around the Weddell embayment over the last few glacial cycles. These preliminary interpretations will be further tested by ongoing work on sediment cores from the Antarctic Peninsula margin.

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