ANTARCTIC CIRCUMPOLAR DEEP WATER: A QUATERNARY PALEOFLOW RECORD FROM THE NORTHERN SCOTIA SEA, SOUTH ATLANTIC OCEAN

JOHN A. HOWE* AND CAROL J. PUDSEY
British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 OET, U.K.
* Present address: Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, Oban, PO Box 3, Argyll, PA34 4AD, U.K.
e-mail: JAHOW@dnm.ac.uk

ABSTRACT: In the northern Scotia Sea, the main pathway of Circumpolar Deep Water (CPDW) flows north to pass through a deep gap in the North Scotia Ridge before turning east into the Falkland Trough. A sediment drift has developed on the seabed since the Early–Middle Miocene, coincident with the opening of Drake Passage and the inception of deep-water flow. Seismic and acoustic surveys show that the drift covers an area of 10,500 km² and forms a broadly asymmetrical feature of deep-water flow. The drift is 1500 m thick along the crest, and thinner basally, and can be divided into a glacial and an interglacial phase. The glacial phase is characterised by subtle bedding, bioturbation, and relatively coarse sediment, while the interglacial phase is characterised by more distinct bedding, larger bioturbation, and finer sediment. The sediment drift is bounded to the north by the South Shetland arc and the South Scotia Ridge, and to the south by an antecedent ridge off the South Sandwich arc. The basin itself is the result of a series of back-arc and oceanic spreading episodes, and the relative eastward migration of the evolving South Sandwich arc and trench (Barker et al. 1991). The area south of Shag

INTRODUCTION

Four cores 3–9 m long have been recovered from the crest and margins of the drift in water depths of 3900–4300 m. Biostratigraphy and chemostratigraphy reveal that the longest core extends down to oxygen isotope stage 10 (approx. 370 ka). The sediments are predominantly fine-grained contourites and diatom-rich hemipelagites, capped by sandy–silty contourites rich in the planktonic foraminifer Neogloboquadrina pachyderma. Grain-size analysis of the fine fraction, finer than 4 phi (63 μm), combined with radiocarbon (AMS) dating and magnetic susceptibility, provide an indication of relative CPDW strength over the last 18 ka. Shortly after the last glacial maximum (LGM), at approximately 17 ka, CPDW flow stabilized, becoming less vigorous but with 4 phi to up to 6.25 phi; this increased current winnowing is indicative of an unstable CPDW, with stormier glacial benthic conditions producing sporadic, high-energy currents across the drift crest and flanks. At approximately 12,280 ka, an increase in sediment sorting is noted, indicative of a strong flow of CPDW over the drift crest, suggesting an unstable and fluctuating deep-water flow. During deglaciation and into the Holocene, at approximately 10 ka, CPDW flow stabilized, becoming less vigorous across the drift crest and flanks with silt modes from 6 phi to 5.5 phi accompanied by increased sorting of the sediments. The gross average sedimentation rate from the crest of the drift is 11.2 cm/ky compared to 2.3 cm/ky on the southeastern flank. The unsteadiness of CPDW during glacials compared to interglacial periods may be the result of stronger wind forcing and a northward shift in the Polar Front. Older CPDW flow records from the cores suggest variable and cyclic bottom-current flow corresponding to glacial–interglacial episodes. Modern CPDW flow across the crest of the drift averages 11.6 cm s⁻¹ but with intermittent benthic storm activity resuspending the fines.

REGIONAL SETTING

Physiography

The Scotia Sea extends from the southernmost tip of South America at 56°S 65°W to the Antarctic Peninsula, and eastwards to the South Sandwich Arc at 59°S 27°W (Fig. 1A). The sea is bounded in the north by the North Scotia Ridge at 54°S and in the south by the South Scotia Ridge at 60°S (Fig. 1B). Both of these ridges are topographically irregular, reaching sea level in only a few places. The North Scotia Ridge contains one deep gap, located at 48°W. Zenk (1981) called this Shag Rocks passage, where water depths increase from < 1500 m on the ridge to over 3500 m. Generally, depths within the Scotia Sea average 3000–4500 m.

Tectonic Development

The Scotia Sea is an area of complex tectonic development. Its present configuration has evolved since about 40 Ma, in relation to the breakup of Gondwana and the ensuing movement of South America relative to Antarctica. The basin itself is the result of a series of back-arc and oceanic spreading episodes, and the relative eastward migration of the evolving South Sandwich arc and trench (Barker et al. 1991). The area south of Shag...
Rocks passage is characterized by east–west spreading. To the west of the study area the relict spreading center is characterized by a bathymetric low, oriented approximately north–south (Fig. 1C), with water depths up to 5000 m. Magnetic-anomaly measurements from the oceanic crust in this region give an approximate age of 23 Ma, from anomaly 6b (Barker and Burrell 1977). With the opening of Drake Passage as a deep-water pathway by 20–22 Ma, most sediment deposition in the Scotia Sea has been influenced by the Antarctic Circumpolar Current (ACC) (Barker and Burrell 1977; Locarnini et al. 1993; Pudsey and Howe 1998). The main control on sediment thickness and deposition is not the age of the ocean floor but its proximity to the Polar Front, and therefore the axis of main ACC flow. In the northern Scotia Sea, mounds of sediment have accumulated up to 1 km thick on Miocene-age ocean floor. These are surrounded by clean current-swept oceanic basement, suggesting that the mounds are developed in localized lees, the product of the rough basement topography.

**Oceanography**

The ACC is the largest current system in the World Ocean, transporting some 110–144 Sv of water from west to east around the Southern Ocean (Grose et al. 1995; 1 Sv = 10⁶ m³ s⁻¹). The northern Scotia Sea is dominated by the eastward and northeastward flow of ACC. The main axis of flow is constrained by the position of the Polar Front, the northernmost extent of Antarctic Surface Waters, passing through the center of Drake Passage and turning north across Shag Rocks passage, and over the North Scotia Ridge (Fig. 1B). The ACC is essentially a westerly wind-driven flow extending from the surface to the seabed (Nowlin and Klinck 1986). The deeper water mass, below 1000–2000 m, termed Circumpolar Deep Water (CPDW), is the deepest element of the ACC and is the one with the most influence on sedimentation across the drift (Orsi et al. 1995; Frank 1996). Lower CPDW (below 2000 m) is characterized by the influence of cold temperatures and high salinities of Antarctic Bottom Water and North Atlantic Deep Water. These are both thermohaline, density-driven contributions to the mainly wind-driven current (Corliss 1983; Frank 1996).

**METHODS**

Single-channel airgun seismic-reflection profiles, 10 kHz precision echosounder profiles, and 3.5 kHz sub-bottom reflection profiles were acquired across the area of a sediment drift, south of Shag Rocks passage (Fig. 1C).
Using survey data from earlier geophysical cruises, certain areas of the Scotia Sea were identified as sites of probable contourite drift sedimentation (Pudsey and Howe 1998). During Cruise 4 of the RRS James Clark Ross (Feb.–Mar. 1993), some of these areas were selected for detailed surveying and coring. Single-channel seismic lines were shot using a single, short Bolt 1500C airgun streamer, with a 4.9 liter (300 cu inch) chamber. The system was towed at 4–8 m depth depending on ship speed, which varied from 6 to 8 knots.

The two single-channel seismic lines BAS 923 S24 and S22 were band-pass filtered (13–220 Hz) and deconvolved using a deterministic deconvolution (operator derived from 50 summed seafloor reflections). Further seismic processing procedures applied include a spherical divergence correction, a twofold stack, a second bandpass filter (13–70 Hz), and a three-trace running mix. The 3.5 kHz profiles presented in this paper are from original shipboard analogue records plotted on a Raytheon electrostatic line scan recorder.

Situated on the crest of the drift in 3956 m water depth was current meter mooring 9 (CMM9; Fig. 1C). Two Anderaa RCM8 current meters were located at 12 m and at 50 m above the seabed, with a sediment trap at 21 m. The mooring was deployed in February 1993 and recovered in March 1995. The upper meter recorded data for the whole 762-day deployment period, and the lower meter for only 359 days, because of battery failure. The lower meter recorded transmittance, but only for the first 40 days. The upper meter recorded data for the whole 762-day deployment, and the lower meter recorded great variability in current speed and direction, characteristic of the wind-driven ACC flow in the Polar Front Zone (Foster and Middleton 1984; Peterson 1988; Orsi et al. 1995). Arithmetic mean speeds obtained from the near-seafloor meter were 11.6 cm s⁻¹ with 11.2 cm s⁻¹ for the upper meter. Vector-averaged speeds for the one-year and two-year periods were only 2.9 cm s⁻¹ towards 077° and 065°. Figure 2B is a progressive vector diagram for both meters; Figure 3 is a speed plot for the first 80 days of the lower meter, showing the occurrence of benthic storms and of periods of slow flow when fine particles could settle out of suspension. The correspondence between fast flow across the drift crest and the water turbidity (an indicator of nepheloid-layer activity) is poor, suggesting that the sediment was held in suspension and transported to the drift rather than involving resuspension in situ. The modal speed measured from both meters was 7 cm s⁻¹. Flow was faster than 15 cm s⁻¹ for 22–24% of the time and slower than 5 cm s⁻¹ for 18–24% of the time (Pudsey and Howe 1998). The plot of in situ temperature for the upper meter recorded temperature variations of between 0.4 and 0.6°C during the two-year deployment, and there appears to be no relation between current direction (see Fig. 2B) and any warming or cooling trends.

Sediment Trap.—The trap was located between the two meters, 21 m off the sea floor, and collected 36.2 g of sediment in 762 days, equating to 182.5 mg/m²/day or 66.6 g/m²/year. This corresponds to a sedimentation rate of 4.2 cm/ky. Total average sedimentation rate from core PC063 is 11.2 cm/ky calculated from the radiocarbon ages. The drift growth rate assumed from the seismic reflection profiles is 3.5 cm/ky, close to the sediment-trap rates. Composition of the trap material is 13% CaCO₃, 1% organic carbon, and 44% biogenic silica, with lithogenic fragments making up the remaining 42%. The carbonate is foraminifera, mainly poorly preserved N. pachyderma, and fragmented calcareous nannofossils. The biogenic silica is mainly diatoms (dominated by Fragilariaopsis kerguelensis, an open-ocean taxon; sea-ice-indicator species are absent) with less common radiolarians, silicoflagellates, and sponge spicules. The sand fraction forms 10% by weight of the total trap material. Of this, one third is terrigenous sand, very fine, well sorted, and angular in shape. Half is biogenic silica (radiolarians, sponge spicules, few diatoms) and foraminifera. The presence of fine terrigenous sand in a trap 21 m above the seabed demonstrates the energetic nature of flow in this area.

AMS ¹⁴C ages were determined on two samples of sediment-trap material: bulk organic carbon and N. pachyderma picked from the coarser than 2 μm (≥ 250 μm) size fraction (the ages are given in Table 2). The

Table 1.—Summary core information. Piston core (PC) and kasten core (KC).

<table>
<thead>
<tr>
<th>Core</th>
<th>Water Depth</th>
<th>Length</th>
<th>Position</th>
<th>Location on drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC063</td>
<td>3956 m</td>
<td>6.5 m + 1.00 m</td>
<td>53°56.00'S</td>
<td>Crest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Trigger core)</td>
<td>48°52.06'W</td>
<td></td>
</tr>
<tr>
<td>KC064</td>
<td>4304 m</td>
<td>3.05 m</td>
<td>53°52.01'S</td>
<td>NW Flank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>48°20.03'W</td>
<td></td>
</tr>
<tr>
<td>PC065</td>
<td>4200 m</td>
<td>3.50 m + 0.88 m</td>
<td>54°04.20'S</td>
<td>SW Flank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Trigger core)</td>
<td>48°23.20'W</td>
<td></td>
</tr>
<tr>
<td>PC066</td>
<td>4129 m</td>
<td>8.5 + 1.00 m</td>
<td>53°59.01'S</td>
<td>E. Flank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Trigger core)</td>
<td>47°30.08'W</td>
<td></td>
</tr>
</tbody>
</table>

Remaining ages were determined on bulk organic carbon. Organic carbon (AMS) samples were soaked overnight in 1M HCl, the pH checked to be < 7, and the samples rinsed acid-free in distilled water. All samples were dried at 105°C in a vacuum oven, homogenized, and combusted to CO₂ in quartz tubes at the NERC Radiocarbon Laboratory in East Kilbride and analyzed at the University of Arizona National Science Foundation facility in the United States.

For chemostratigraphic analyses, the trace element barium has been identified as a useful paleo-productivity indicator (Dymond et al. 1992). XRF analysis was conducted at Geoscience Analytical Services, University of Keele. Samples were dried and crushed to pass through a 3 μm (125 μm) sieve after large-volume dilution to remove the salt. A powder pellet was made for trace-element analysis.

RESULTS

Current-Meter Records: Modern CPDW

Water Masses.—Most of the water column is occupied by Circumpolar Deep Water. Bottom potential temperature is +0.13°C (in situ temperature was +0.4°C; Fig 2A). The irregularity of temperature profiles in the upper 800 m of the surface waters is typical of the mixing and meandering of the Polar Front Zone in the Scotia Sea, north of 59°S (Grose et al. 1995).

Current-Meter Data.—Both the current meters on mooring 9, 50 m and 12 m above the seabed, recorded great variability in current speed and direction, characteristic of the wind-driven ACC flow in the Polar Front Zone (Foster and Middleton 1984; Peterson 1988; Orsi et al. 1995). Arithmetic mean speeds obtained from the near-seafloor meter were 11.6 cm s⁻¹ with 11.2 cm s⁻¹ for the upper meter. Vector-averaged speeds for the one-year and two-year periods were only 2.9 cm s⁻¹ towards 077° and 065°. Figure 2B is a progressive vector diagram for both meters; Figure 3 is a speed plot for the first 80 days of the lower meter, showing the occurrence of benthic storms and of periods of slow flow when fine particles could settle out of suspension. The correspondence between fast flow across the drift crest and the water turbidity (an indicator of nepheloid-layer activity) is poor, suggesting that the sediment was held in suspension and transported to the drift rather than involving resuspension in situ. The modal speed measured from both meters was 7 cm s⁻¹. Flow was faster than 15 cm s⁻¹ for 22–24% of the time and slower than 5 cm s⁻¹ for 18–24% of the time (Pudsey and Howe 1998). The plot of in situ temperature for the upper meter recorded temperature variations of between 0.4 and 0.6°C during the two-year deployment, and there appears to be no relation between current direction (see Fig. 2B) and any warming or cooling trends.
FIG. 2.—A) Temperature profiles through the water column (two XBT casts to 700 and 900 m, one full-depth CTD cast) above the drift crest. The surface-water mixing characteristics of the Polar Front Zone of the Antarctic Circumpolar Current is visible in the top 1000 m. B) Progressive vector diagram for both current meters. The great variability in CPDW speed and direction is seen from both plots. The lower meter, (heavy black line) has an arithmetic mean speed of 11.6 cm s$^{-1}$ with 22% of hourly speed values faster than 15 cm s$^{-1}$ and an average velocity vector of 2.9 cm s$^{-1}$ to 077°. Flow was slower than 5 cm s$^{-1}$ for 24% of the recording period. The upper meter (light gray line) has an arithmetic mean of 11.2 cm s$^{-1}$ with 24% faster than 15 cm s$^{-1}$ and an average velocity vector of 2.9 cm s$^{-1}$ to 065°. Flow was slower than 5 cm s$^{-1}$ for 18% of the time.
position of the sediment trap within the nepheloid layer means that it collected resuspended material as well as particles settling from the sea surface. This may explain the age discrepancy between the foraminifer age (forams are large grains that settled from the surface during the mooring deployment) and the bulk carbon age (carbon in small particles, easily resuspended and transported in the ACC, thus likely to include old carbon). Note that the bulk carbon age of 1480 yr BP is only slightly greater than the Antarctic marine reservoir correction of 1300 yr suggested by Ingolfsson et al. (1998), and that the foraminifer age is very young by Antarctic standards (Gordon and Harkness 1992, Berkman et al. 1998).

**Description and Interpretation of the Drift**

The sediment drift studied covers an area of approximately 10,500 km², to the south of Shag Rocks passage, the main entry point of CPDW into the Falkland Trough (Fig. 4). The drift is 70 km wide (NW–SE) and approximately 150 km long (N–S). Morphologically, the drift is asymmetrical and irregular, containing a number of minor crests along its northwestern flank, rising to the main crest at a height of 600 m above the northwestern moat (Fig. 5). Sediments thicken toward the southeast, from an average of < 200 m thick under the western moat, to 750–800 m beneath the main

### Table 2.—Radiocarbon age samples and results for core PC063. Sample types indicated; Foram. (foraminifera), C (organic carbon), CMM9 (Current-meter mooring site 9). Gross average sedimentation rates are shown for the top 1.40 m of the core. Foraminifera are present only at the top of the core, so all the downcore dates are on bulk organic carbon.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample</th>
<th>¹⁴C Enrichment (% Modern ± 1σ)</th>
<th>AMS Radiocarbon Age (Years BP ± 1σ)</th>
<th>Corrected Radiocarbon Age (−1300 yr)</th>
<th>% Carbon Content</th>
<th>δ¹³C PDB ± 0.1‰</th>
<th>Average Sedimentation Rates cm/1000 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA-22654</td>
<td>CMM9</td>
<td>95.37 ± 0.72</td>
<td>380 ± 60</td>
<td>NA</td>
<td>11.4</td>
<td>−0.1</td>
<td>/</td>
</tr>
<tr>
<td>AA-22659</td>
<td>CMM9-C</td>
<td>83.19 ± 0.42</td>
<td>1,480 ± 40</td>
<td>190</td>
<td>1.0</td>
<td>−25.4</td>
<td>/</td>
</tr>
<tr>
<td>AA-22653</td>
<td>TCO63-0.00</td>
<td>66.73 ± 0.54</td>
<td>3,250 ± 65</td>
<td>1950 or 2870</td>
<td>10.0</td>
<td>1.0</td>
<td>/</td>
</tr>
<tr>
<td>AA-22655</td>
<td>Foram.</td>
<td>49.30 ± 0.48</td>
<td>5,680 ± 80</td>
<td>4380</td>
<td>0.2</td>
<td>−23.9</td>
<td>/</td>
</tr>
<tr>
<td>AA-22656</td>
<td>TCO63-0.00C</td>
<td>19.79 ± 0.34</td>
<td>13,010 ± 140</td>
<td>11710</td>
<td>0.2</td>
<td>−23.8</td>
<td>3.4</td>
</tr>
<tr>
<td>AA-23442</td>
<td>TCO63-0.3C</td>
<td>18.46 ± 0.21</td>
<td>13,575 ± 90</td>
<td>12275</td>
<td>0.2</td>
<td>−23.9</td>
<td>14.1</td>
</tr>
<tr>
<td>AA-22657</td>
<td>TCO63-0.85C</td>
<td>13.63 ± 0.17</td>
<td>16,010 ± 100</td>
<td>14710</td>
<td>0.3</td>
<td>−23.7</td>
<td>21.3</td>
</tr>
<tr>
<td>AA-22658</td>
<td>PC063-1.40C</td>
<td>10.46 ± 0.15</td>
<td>18,140 ± 110</td>
<td>16840</td>
<td>0.4</td>
<td>−23.6</td>
<td>25.8</td>
</tr>
</tbody>
</table>
Fig. 4.—3.5 kHz echo-character map, showing the area of thickest drift development, zone of erosion, and moated area surrounding the main drift development. Echo types on the drift are shown in Figures 5 and 6; surrounding echo types (oceanic basement etc) were illustrated by Pudsey and Howe (1998).

crest, to approximately 400 m under the eastern moat (thicknesses based upon an assumed acoustic velocity of 2.0 km s\(^{-1}\) for sediment and 1.5 km s\(^{-1}\) for water). The oceanic basement beneath the sediment cover across the drift is very irregular, rising to within \(< 100\) m of the seafloor in a number of places, where the sediments thin as a result of active seabed erosion. A zone of nondeposition or erosion extends along the northwestern flank of the drift, from the moated area up onto the drift sediments themselves. This may be the result of accelerated current flow around the rough oceanic basement and seamounts. The erosion of the northwestern drift flank is visible from regular reflectors rising to the seabed in the airgun line BAS 923 S24, and the condensed reflectors in the accompanying 3.5 kHz line illustrated in Figure 6. A corresponding change in acoustic character is apparent in the older sediments, now exposed at the seabed, from the irregular to acoustically transparent reflectors in the airgun line, to the highly reflective low penetration reflectors in the 3.5 kHz profile. A small debris flow is visible in Figure 5, partially infilling the northwestern moat, having originated from the flanks of the mound. Sediment mass wasting may be the result of high sediment supply on the drift flanks, or, more likely, oversteepening of the flanks from the accelerated bottom current flow near the seamount, producing localized sediment instability.

**Description of Sediment**

The four cores across the drift all contain broadly similar types of fine-grained lithologies, subdivided into lithofacies (A–C) based upon visual description, x-radiographs, and PSA (Figs. 7–10). Throughout the cores, ice-rafted debris (IRD) is rare.

**A. Brown Sandy Muds.—**This lithofacies caps all the cores, extending to a depth of up to 0.33 m in KC064 (Fig. 8). It comprises homogeneous, heavily bioturbated, dark grayish brown sandy muds (up to 20% sand, of which 15% is carbonate). The deposit is poorly sorted with a mode at 5 \(f\) (medium-coarse silt). Foraminifera are common, with *N. pachyderma* dominating the assemblage, as well as siliceous diatoms and radiolarians; biogenic silica is up to 30–40%. Recognized from x-radiographs are well-developed *Zoophycos* burrows, particularly visible in the trigger core of PC066 (Fig. 11A). Contacts with the lower lithofacies are sharp and burrowed.

**B. Homogeneous Silty Clays.—**This dominates the cores, occurring in units up to 2 m thick. The dark greenish gray silt- and clay-rich muds (Fig. 11B) also contain monosulphidic knots and sporadic light green and dark green laminae. No carbonate is present and the sediments contain 10–20% biogenic silica. The unit is moderately well sorted, with a modal size distribution between 5 and 6 \(f\) (medium-coarse silt). Layers of diatom ooze with a high water content are also present. Contacts are gradational.

**C. Laminated Silty Muds.—**Units of this facies alternate with the homogeneous silts and clays and occur as units up to 1 m thick, clearly visible in x-radiographs and more subtly in the fresh core surface. The silty laminations are commonly disturbed by burrowing and mottling, visible in x-radiographs (Fig. 11B). No carbonate is present. Biogenic silica constitutes
10–20% of the sediment. Particle-size analysis reveals moderately well-sorted coarse–medium silts with a modal size distribution at 5–6 μm. Common quartz sand grains are visible in smear slides. The silts are present in millimeter-scale coarsening- and fining-upward sequences. The background sediments are homogeneous greenish gray silty muds. Contacts are gradational.

**Interpretation of Sediment**

**Brown Sandy Muds.**—Poorly sorted, medium–coarse silts and sands with associated intense bioturbation, homogenizing the sediment, indicate that burrowing kept pace with deposition. These deposits are sandy–silty contourites. The high proportion of biogenic material in the form of planktonic foraminifera suggests relatively warm open marine conditions, with deposition near the Polar Front. Howe et al. (1997) describe similar contourites from the tops of cores in the western Falkland Trough.

**Homogeneous Silty Clays.**—This commonly occurring lithology is suggestive of a hemipelagite, being rich in clay and diatomaceous layers. Sediment may have been deposited in a low-energy environment, from the water column. However, the moderate sorting may indicate the presence of weak bottom currents over the drift.

**Laminated Silty Muds.**—The alternating fining- and coarsening-upward sequences in the silts indicate some degree of current sorting. The coarsening-upward (-ve) sequences indicate an increase in current speeds, and the fining-upward (+ve) sequences represents a decrease in current speeds. These moderately sorted deposits are muddy–silty contourites. Down-core, laminated silt and homogeneous units alternate on a meter scale (visible on x-radiographs), which is suggestive of cyclic, longer-term fluctuation in bottom currents.

**Stratigraphy**

**Drift Age.**—The presence of magnetic anomaly 6b (Tectonic map of the Scotia Arc 1985) near the crest of the drift gives an approximate age of the oceanic crust as 23 Ma. The drift is about 800 m thick at the crest, which suggests a mean sedimentation rate for the drift of 3.5 cm/1000 yr.

**Radiocarbon AMS Dates.**—AMS radiocarbon 14C results (Table 2) show dates obtained from core PC063, from the crest of the drift. The marine reservoir effect around the Antarctic Peninsula has been discussed by Bjorck et al. (1991), Berkman et al. (1998), and Ingolfsson et al. (1998). The residence time of a 14C atom in the ocean is approximately 1000 yr, and Southern Ocean seawater has an average age 1200–1400 yr older than the atmosphere (Bjorck et al. 1991; Bard et al. 1993). The dates obtained here were corrected using the 1300 yr reservoir age suggested by Ingolfsson.
et al. (1998). Correcting the foraminifer core-top age by 380 yr, the 14C age of the sediment-trap foraminifers, gives an age of 2870 yr BP, still apparently younger than the organic carbon in the same sample. Ages of several thousand years for core-top sediment indicate that some material was lost during coring. Using a Holocene sedimentation rate derived from the 14C ages at 0 and 25 cm (3.4 cm/ka; Table 2), the loss of only 10 cm of sediment would result in a core-top age of 2870 yr. In a high-energy area such as this, it may be misleading to compare trapped sediment directly with cores; once inside a trap, material rarely escapes, whereas particles deposited on the sediment surface are still available for resuspension. The oldest corrected age obtained is 16,840 yr BP, from below the base of the carbonate-bearing core top (lithofacies 2) and below the diatom abundance peak from a depth of 1.4 m. An estimate of the gross average sedimentation rate for the top half of the core (including the trigger-core section), taken from all the radiocarbon ages, is 4.4 cm/1000 yr (individual sedimentation rates for the top 1.40 m of PC063 are displayed in Table 2).

**Biostratigraphy**

**Radiolarians.**—Down-core relative abundances of the radiolarian *Cycladophora davisiana* (Hays et al. 1976) were used to determine the position of the Last Glacial Maximum in cores KC064 and PC066 by Pudsey and Howe (1998) (Figs. 8, 10). Hays et al. (1976) determined that in the Southern Ocean *C. davisiana* is abundant in glacial stages (10–25%) and rare during interglacials (1–2%). In the Scotia Sea, the first down-core abundance peak is correlated to stage 2, the Last Glacial Maximum (Pudsey and Howe 1998). In core KC064, the abundance of *C. davisiana* remains high from the peak at 1.6 m to the base of the core. In PC066, there are abundance peaks at 0.3–2.7 m, 3.7–4.2 m, 5.4–6.0 m, and 8.0–8.6 m.

**Diatoms.**—Down-core diatom percentages are shown with the core logs of cores PC063 and PC065 (Figs. 7, 9). The diatoms show abundance peaks corresponding to stages 1 and 2 in all the cores, and stage 5 in PC063, PC065, and PC066. Stage 7 is present in core PC066 only (Fig. 10), identified in PC066 by the rare occurrence of *Hemidiscus karstenii* at 5.6 m.

**Dinoflagellates.**—A pilot study showed indications of cyclic changes in abundance and species composition down-core; detailed work is in progress. Preliminary analysis of cysts from cores PC063 and PC066 indicates low-diversity assemblages dominated by the cyst species *Selenopemphix antarctica* (Harland, personal communication 1997; Harland et al. 1998). Down-core, the assemblages alternate between low and high abundance of cysts per gram of sediment. This may be a reflection of glacial–interglacial cyclicity, with the Last Glacial Maximum present in core PC063 from 1.00 m to 1.45 m (< 16,840 yr BP from the radiocarbon dates), which is also reflected by a trough and a peak in the magnetic susceptibility. In core PC066, a correlation with oxygen isotope stage 5a may be present at 2.85 m, with stage 5c at 3.35 m, with stage 5e 4.05 m, and with stage 6 at approximately 4.90 m. These stages are present in the cores as magnetic-susceptibility peaks, and as changing abundances of *Selenopemphix antarctica*, with lesser percentages of *Algidasphaeridium? minutum* (Harland, personal communication 1997).

**Chem stratigraphy.**—The use of biogenic barium as a paleoproductivity indicator has now been demonstrated in several areas of the Southern Ocean (Shimmield et al. 1994; Bonn 1995; NuÈrnberg et al. 1997). High barium values correspond to high productivity during warm stages 1, 5e, 7, and 9. In this study only core PC066 was analyzed for barium. In core PC066, the thin Holocene section was not sampled for geochemistry. High values of barium at 4.1–4.7 m, 6.1–6.6 m, and 7.8–8.1 m are interpreted as stages 5e, 7, and 9, respectively. This gives a gross average sedimentation rate, down to stage 9, of 2.3 cm/ka. The peaks at 2.2 m and 3.1–3.5 m are tentatively interpreted as Stages 5a and 5c (Fig. 10). This chem stratigraphy agrees with preliminary results from U/Th dating, which shows high values of 230Th excess from 4.1 to 4.8 m (M. Frank, personal communication), interpreted as Stage 5e.

**Magnetic Susceptibility**

Data on magnetic susceptibility appear to display a direct correlation between silt content and diatom content. This in turn is a reflection of glacial–interglacial cyclicity, although it is assumed that the silt fraction across the drift is transported by bottom currents rather than by direct ice rafting. Biogenic dilution by diatoms and radiolarians and, at the top of the cores, foraminifera naturally causes decreases in the magnetic susceptibility. Glacial episodes generate greater volumes of silt without the dilution
effects of interglacial biogenic productivity and hence display the higher magnetic-susceptibility values.

Comparison between the magnetic-susceptibility records of each of the cores indicates that of the four cores, PC066 and PC065 represent the most condensed sequences. KC064 and PC063 represent the more expanded sequences recovered from the drift. This may reflect the positions from which the cores were recovered on the drift: KC064 from a small false crest on the northwestern flank, and PC063 from the main crest of the drift.

Results of Particle-Size Analysis

With the exception of the silty laminae in lithofacies C, all the sediments display a generally poorly sorted to moderately sorted trend. Characteristic sorting values of all the cores are displayed with the graphic core logs in Figures 7–10. All the size analyses were initially carried out on the complete sediment fine fraction, including biogenic carbonate and silica grains. Selected samples were treated with 10% HCl (to dissolve carbonate) or 1M NaOH (to dissolve biogenic silica), rinsed, and reanalyzed. Representative results are shown in Figure 12. After dissolution of biogenic material, both from the carbonate-rich lithofacies A, and from the lower siliceous-rich lithofacies (B and C), the mode shifts from 5.5 $\phi$ to 5.00 $\phi$, and the peakedness increases. This suggests that a significant quantity of comminuted biogenic debris is also present in the silt fraction (Fig. 12A, B).

The cohesive and noncohesive (i.e., sortable) boundary in the silts at finer than 7.5 $\phi$ (8–10 $\mu$m) noted by Robinson and McCave (1994), and represented by a dip in the PSA curve, was not noted in this study. The ability of bottom currents to transport material coarser than 4 $\phi$ ($>63 \mu$m) is limited, suggesting that bottom current sorting is restricted to the finer than 7.5 $\phi$ range; however, we find no evidence of a silt–cohesive boundary. A number of samples were rerun on the SediGraph, and no boundary was noted.

All cores display variations in the silt mode with depth, which we interpret to result from relative changes in the velocity of paleo-CPDW flow across the drift. McCave et al. (1995b) suggest that the technique of paleocurrent speed evaluation using variation in the silt-size sediment may not be valid in areas of high eddy kinetic energy, like the Antarctic Circumpolar Current, where unsteady flows associated with activity of benthic storms could mask the background of steady bottom current flow. They argue that for a valid interpretation of the particle-size signal, areas of high eddy kinetic energy should be avoided. The unsteady nature of the ACC has been discussed by Pudsey and Howe (1998) in areas of drift development where mudwaves activity is limited. The original source sediment of the contourites is unsorted; the grains are subjected to repeated settling, resuspension, and transport by the ACC the final size distributions therefore reflect the ACC flow upstream as well as at the core site.

Glacial–Interglacial Variation.—The grain-size plots show certain dif-
ferences between the textures of the glacial and interglacial silts (Fig. 12C). Generally the glacial sediments are poorly to moderately sorted silts with an occasional well sorted sand fraction, with the interglacial sediments having moderate sorting, a broader mode, and a larger fine component (finer than 8 φ; fine silts) compared to the glacial. During the Last Glacial Maximum (LGM), silt modes shifted between 5.5 φ and 6.25 φ, with the sediments becoming increasingly poorly sorted. Fluctuating percentages of well-sorted sands are also present, indicative of unsteady current activity with episodic high-energy flow enabling transportation of the sands. During the last deglaciation, and into the Holocene, current flow appears to have moderated and stabilized. A smaller average shift in silt modes was noted from 5.75–6 φ to 5.5 φ with an increased sorting of the silts. In the Holocene samples, the fine silts (finer than 8 φ) appear more abundant, possibly as a result of comminuted biogenic debris carried in transport.

Samples from the LGM in PC063 display broader, polymodal size distributions between 4.5 and 6 φ. Comparison with the deeper glacial episode, stage 6, below 5.5 m in core PC063, reveal grain-size plots with slightly smoother and more peaked distributions, suggesting steadier and stronger current flows than preserved in the LGM samples and without the input of well-sorted sands. Comparison of the deeper interglacial episode samples of stage 5e with the Holocene samples also shows similar differences in sorting. Compared to the Holocene, interglacial stage 5, where present in the cores, consists of poorly sorted sediments with a mode at about 6 φ. There is also much less biogenic carbonate than in the Holocene, and a reduction in the expanded biogenic silts finer than 8 φ, suggesting different surface water conditions. The best sorted silts, and hence the strongest relative flow of CPDW, are in cores PC063 and KC064 from the crest and western flank of the drift at approximately 12,280 yr BP. This event produced moderately sorted silts with a mode at 5.5 φ with reduced fines and well sorted sands, also a characteristic of the last glacial episode. This event is well defined in these two cores but difficult to find in the other cores because of the lack of accurate age constraints.

**DISCUSSION**

**Formation and Migration of the Drift**

Inception of the drift may have been related to the onset of deep-water ACC flow during the Early–Middle Miocene (24–15 Ma), concurrent with the opening of Drake Passage at 20–22 Ma (Barker and Burrell 1977; Lawver et al. 1992). The growth of the drift was linked not only to deep-water flow through Drake Passage but also to the tectonic activity of the nearby spreading center. Evidence from both the 3.5 kHz data and the single-channel seismic reflection profiles suggests that the drift is presently active, and vertically aggrading under the influence of CPDW. The zone of erosion extending along its western flank may reflect a change in current pathway. The main axis of CPDW became relocated to the east, either by a regional shift in ACC surface water boundaries (such as the Polar Front) or as localized seabed movements possibly by either tectonic or seismic shifts or the drift itself having reached a certain size and shape sufficient to produce perturbations in the flow (Stoker et al. 1998). The minor crests and broad asymmetry of the mound are a possible reflection of irregular flow and the eddies produced by CPDW flow over the drift. McCave and Carter (1997) speculate on the asymmetry of deposition and erosion in areas of drift accumulation: 50 m of sediment may take 1 million years to be deposited at 5 cm/ky, but only 50 ky to be eroded at 1 mm/yr. At these rates, a single glacial episode, with increased CPDW flow, would be suf-
sufficient to produce erosion on the drift flank. The rough bathymetry of the seafloor provides a lee from the current flow to allow fallout from suspension, enough to allow growth of the mound. Usually, the drift is not mantled with mudwaves, a common feature of drift morphology in the World Ocean. The paucity of mudwaves in the Scotia Sea as a whole has been interpreted by Pudsey and Howe (1998) as being an indication of the high eddy kinetic energy of the ACC. The unstable flow prevents the formation of mudwaves, which need steady unidirectional flow across the drift to form.

The old radiocarbon ages at the top of the trigger core and in the sediment trap lend weight to the argument that older sediments become resuspended and entrained in an active nepheloid layer (possibly by the action of benthic storms). Present-day occurrences of benthic storms were recorded by the current meter on the crest of the drift, with storm frequencies of one or two events every ten days. During the LGM, this activity may have been considerably stronger, with increased wind forcing and therefore stronger eddy kinetic energy. During the HEBBLE experiment on the Nova Scotia rise, 8–10 benthic storms were recorded over a twelve-month period, with peak velocities of 15–40 cm s^{-1} (Hollister and Nowell 1991), similar to mooring 9. These events resuspend and transport large volumes of sediment in the nepheloid layer, not only in a localized setting such as the drift but across the northern Scotia Sea, suggesting that the drift is not only a center of large-scale deposition but also, periodically, of sediment export. The activity of the drift during glacial times is therefore balanced between sediment supply and sediment resuspension and removal by strong bottom-current activity.

**Quaternary Paleoflow**

The main differences between the LGM and the present interglacial concern both flow energy and surface-water environments. In terms of CPDW flow during the Holocene, the flow appears stable and moderate compared to the episodic and stormy glacial period. Comparisons can be made with other deep-water and terrestrial (ice core) environments.

**Last Glacial Maximum.**—All the cores across the drift record uneven, high-energy CPDW flow during the last glacial episode. Broad cycles of episodic current activity are evident from x-radiographs and particle-size plots. Turbulent glacial episodes resulted in increased sand transport and the laminated silty lithofacies, as a result of increased activity of benthic storms. Increased storminess during the LGM has been inferred by a number of authors in the Southern Ocean. In the Scotia Sea, this may have been the result of combined northward migration of the Polar Front, possibly as far north as the Falkland Plateau (Pudsey and Howe 1998), and with higher glacial wind speeds driving the ACC (DeAngelis et al. 1987). Sediment supply, although still in moderate volumes when compared to areas such as the glacial progradation of the Antarctic Peninsula margin, is increased by a 120 m lowering of sea level exposing Burdwood Bank, to the west of the study area (Fig. 1B), and the shelf areas around Drake Passage (Fairbanks 1989; Larter and Barker 1991; Cunningham et al. 1998). The scarcity of ice-rafted debris (IRD) in the cores suggests that ice rafting was unimportant compared with other mechanisms of sediment supply. Pudsey and Howe (1998) interpreted high suspended-sediment supply as originating mainly from the Antarctic Peninsula. In a similar study in the Falkland Trough, Howe et al. (1997) describe reduced ACC flow across a sediment drift during the LGM. This reduction may stem from the contribution of decreased intensity of the Weddell Gyre and hence reduced Weddell Sea Deep Water inflow into the Falkland Trough, combined with reduced sea levels creating a backwater in an isolated trough setting. The drift described here is located in a more open bathymetrically setting, almost along the Polar Front, and hence maximum ACC flow. A number of authors have commented on the contribution of both Antarctic Bottom Water (AABW), flowing from the Weddell Gyre, and North Atlantic Deep Water (NADW) to the ACC through inputs of heat and salinity, and hence...
to climate change in Antarctica (Pudsey 1992; Bender et al. 1994). It has been suggested that the reduced outflow of AABW from the weaker Weddell Gyre, and possibly to a greater extent thermohaline NADW in the high-latitude North Atlantic, may have precipitated a Southern Hemisphere glaciation, through withdrawal of heat to CPDW (Bender et al. 1994; Sowers and Bender 1995; Charles et al. 1996). Reduced thermohaline-driven NADW, combined with reduced AABW, may have removed the moderating influence on the CPDW, hence becoming wholly wind-driven, with increased wind forcing during the stormier (i.e., an increased frequency of benthic storm activity via the mechanism of wind forcing) LGM. Deposition on the drift would hence have become more erratic and dependent upon the activity of benthic storms because of increased eddy kinetic energy from the surface. Comparison with published Northern Hemisphere ice-core records showing stable conditions (Dansgaard et al. 1993). Across the area, the present-day position for the Polar Front suggests surface water conditions favorable for the production of foraminifera over the drift, but the Polar Front lies to the northwest of the drift, and the area is still well within the mixing zone between warmer South Atlantic and cold Antarctic waters. During the last interglacial, the Polar Front Zone may have lain farther north, suggesting there was cooler surface water conditions than at present across the drift, although no evidence for instability and oscillation of the Polar Front position is present. Either the carbonate-rich sediments were never deposited across the drift during stage 5e, or sediment was removed by bottom currents or deposited and corroded in situ, by a change in deep-water chemistry.

CONCLUSIONS

(1) A pear-shaped sediment drift (70 km × 150 km) has been identified in the northern Scotia Sea, to the south of the North Scotia Ridge, in water depths of 3500–4500 m and covering an area of 10,500 km² with sediments 800 m thick at its crest. The drift is asymmetrical in morphology with a number of minor crests and moats at its western and eastern margins. CPDW flows across the mound to the northeast, towards a gap in the North Scotia Ridge termed Shag Rocks passage, the main entry point of deep-
water flow into the Falkland Trough. A zone of erosion extends along its western margin, with small debris flows suggesting possible high sediment supply and strong bottom-current flow oversteepening the drift flanks, accentuated by the rough seafloor topography. No sediment waves have been identified from the drift, an indication of irregular, intermittent bottom-current flow.

(2) Four cores across the mound, in water depths of 3900–4300 m, from crest to margins record the activity of CPDW flow over the drift during the last 370,000 yr. The cores are predominantly fine-grained contourites and diatom-rich hemipelagites. AMS Radiocarbon dating coupled with fine-fraction (finer than 4 \( \mu \)m) grain-size analysis provides an indication of relative CPDW flow over the last 18 ka. Average sedimentation rates for core PC063, on the drift crest, is 11.2 cm/ky, decreasing to 2.3 cm/ky for PC066 on the southeast flank. During the Last Glacial Maximum, current flow was stronger but intermittent and unstable, suggesting wind-driven CPDW in the stormier glacial Scotia Sea. Unsteady flow may be the result of a shutdown of thermohaline-driven Antarctic Bottom Water produced in the Weddell Sea. An episode of strongest flow was recorded in two cores from the crest and flank at 12,280 yr, with an associated increased sorting in the silts. During deglaciation and into the Holocene, current flow stabilized and slowed across the drift. A southward shift in the Polar Front produced foraminifera-rich sandy contourites at the tops of the cores. However, the last interglacial (stage 5e) did not produce carbonate-rich sediments across the drift, suggesting cooler surface water conditions than at present.
(3) The drift is presently active and migrating under the influence of modern CPDW flow. The position of the drift, south of the main entry point of CPDW into the Falkland Trough, is an indication of the high volumes of sediment held in suspension in the nepheloid layer. The drift has formed in an area of strong bottom-current activity, along the axis of the Polar Front, and in the lee along rough topography. Inception of the drift is related to the onset of deep-water flow during the Early–Middle Miocene (24±15 Ma), concurrent with the opening of Drake Passage at about 20±22 Ma.

(4) A current-meter mooring at the crest of the drift has provided data on modern CPDW flow. Two meters located 50 m and 12 m above the seabed at 3956 m recorded great variability of in current speed and direction, characteristic of CPDW. Average current speed recorded was 11.6 cm s\(^{-1}\) for the lower meter. Bottom potential temperature is +0.13°C. The incidence of benthic storms is high, with on average two high-energy events (> 15 cm s\(^{-1}\)) every ten days.

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