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A physical record of the Antarctic Circumpolar Current: Late Miocene to recent slowing of abyssal circulation

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Sediments recovered from a drift deposit lying along the Pacific margin of the Antarctic Peninsula, (ODP Leg 178, Site 1095) provide a physical record of the Antarctic Circumpolar Current since late Miocene time. Determination of the strength of the magnetic fabric, anisotropy of magnetic susceptibility, provides a proxy for current strength. Fabric strength declines throughout the record from high values in the late Miocene; a pronounced step occurs between 5.0 and 5.5 Ma, and values decrease more gradually since about 3.0 Ma. The mass accumulation rate of terrigenous sediment derived from the Antarctic Peninsula indicates stabilization of the Antarctic Peninsula Ice Cap prior to about 8.5 Ma.

1. Introduction

The Southern Ocean lies south of 50° S latitude and its easterly circulation (the Antarctic Circumpolar Current, or ACC) is unimpeded by land. This unique geography and oceanography at the southern extent of the Earth's ocean conveyor (Broecker, 1991) make it especially important in the mixing and global distribution of water, heat, and nutrients from all other oceans. Deep, cold, northern-source water (North Atlantic Deep Water, or NADW) moves south along the bottom of the western Atlantic basin until it joins the ACC. Deep water forms off the Antarctic continent in the Weddell and Ross Seas to create Antarctic Bottom Water (AABW), which flows east and north. In addition to deep water, high latitude surface waters from the Pacific, Indian, and Atlantic Oceans are mixed by the ACC, creating intermediate water masses and the Pacific Deep Water (Wright et al., 1991; Sun and Watts, 2002).

Flow of the modern ACC initiated when tectonically-controlled gateways opened between East Antarctica and Australia (Tasmanian gateway) around 33.5 Ma (Exon et al., 2004;Kennett and Exon, 2004; Stickley et al., 2004),) and between South America and the Antarctic Peninsula (Drake Passage) (Berggren and Hollister, 1977; Barker and Thomas, 2004). Timing for the opening of Drake Passage is problematic, as the location and movement of several small continental blocks in the vicinity of the passage are not precisely known. Lawver and Gahagan (2003) state Drake was definitely open by 28.5 Ma, and was probably open to deep water circulation as early as 30 Ma (Barker and Burrell, 1977; Barker and Thomas, 2004). Other recent estimates place this opening at approximately 24 Ma, near the time of the Oligocene–Miocene boundary (Pfuhl and McCave, 2005; Lyle et al., 2007).

The ACC is the only current on Earth extending from the sea surface to the sea floor, flowing from west to east and unimpeded by any landmasses. Although mainly wind-driven, two jets carry the majority of the flow (130 Sv) (Barker and Thomas, 2004). Closer to the Antarctic Peninsula, the Antarctic Counter Current flows northeast to southwest forming, a sub-polar gyre (Camerlenghi et al., 1997a; Giorgetti et al., 2003). Bathymetrically guided currents along the ocean bottom often carry sediments and deposit them in the form of sediment drifts that extend along the flanks of topographic highs. These drift deposits accumulate at relatively high rates and commonly provide a continuous history of sedimentation, including records of changes in current intensity (Joseph et al., 1998; Hall et al., 2001; Joseph et al., 2002). Two sediment drifts along the Pacific continental slope of the Antarctic Peninsula were drilled as part of Leg 178 of the Ocean Drilling Program (ODP) to study the glacial history of Antarctica and the Southern Ocean (Fig. 1; Barker and Camerlenghi, 1999). Here we examine the record found at ODP Site 1095 which provides a direct, semi-quantitative record of current flow for the past 9.5 million years.

Our primary tool in this reconstruction is magnetic fabric analysis, the anisotropy of magnetic susceptibility (AMS). Magnetic fabric reflects the degree to which sediment grains are aligned by currents and therefore is a proxy for current strength as demonstrated by the work of Ellwood and Ledbetter three decades ago (Ellwood and Ledbetter, 1977; 1979; Ellwood et al., 1979). In the past several years

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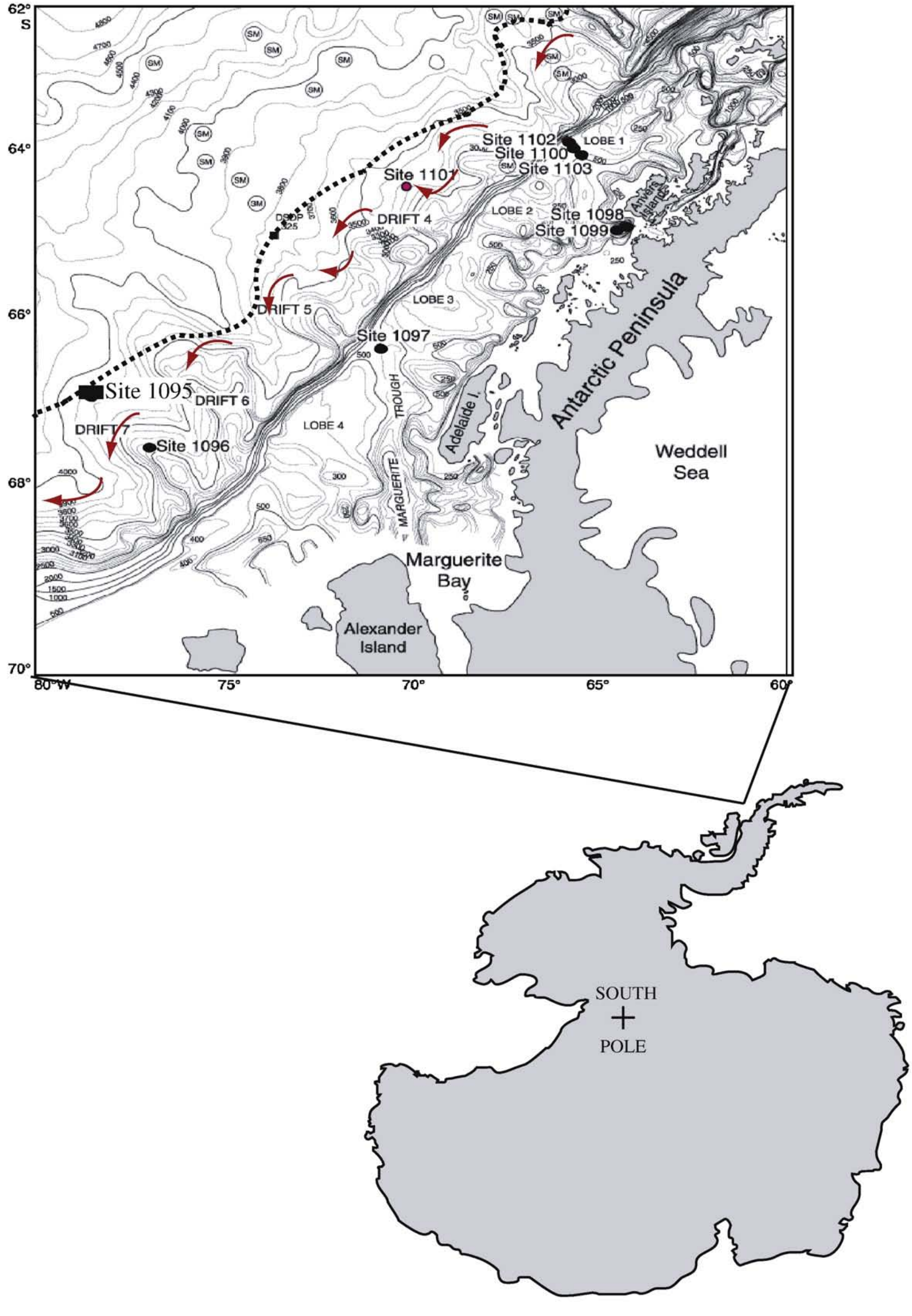

Fig. 1. Location of Site 1095. Dotted line shows southern ACC front, arrows show the path of the bottom current (from Uenzelmann-Neben, 2006).

we have refined this technique (Joseph et al., 1998) and applied it to drift deposits on the Kerguelen Plateau, southern Indian Ocean (Joseph et al., 2002) and in the North Atlantic Ocean (Hassold et al., 2006). These previous studies indicate a slowing of abyssal circulation since late Miocene time.

2. Setting, sediments, and methods

The Antarctic Peninsula is a long, narrow plateau, extending from 63° S to 74° and merging into West Antarctica (Fig. 1). Elevation varies from roughly 900 m in the north to 1750 m or higher southward of

65° S. Currently, the peninsula receives almost 4 times the average continental snowfall, and most of the climate is polar (Barker and Camerlenghi, 2002).

The input of terrigenous sediment to the ocean from the Antarctic Peninsula is dominated by the action of glaciers and ice streams. Hallet et al. (1996) studied erosion rates for mountain glaciers from different environments (temperate and polar) and on different types of bedrock. They found that erosion rates varied over orders of magnitude, depending especially upon the basal conditions. Warm, wet-based glaciers tend to have copious amounts of melt water at the base and are associated with significant erosion. Cold-based glaciers are frozen to the ground and tend to move slowly; any melt water is surficial and erosion is much less. Erosion is almost non-existent from glaciers with basal temperatures below the pressure melting point. In Antarctica, sediment transport to the shelf-slope break occurs via ice streams during grounding events (Barker and Camerlenghi, 1999). Instability of the deposited sediments, due to the steep continental slope, has resulted in turbidity current flows, which transport the sediments down onto the continental rise, where bottom currents distribute the fine-grained component laterally forming large drift deposits. Bart and Anderson (2000) suggested that the smaller Antarctic Peninsula Ice Cap (APIC) might have been more sensitive to climate changes and, therefore, more dynamic than either the East Antarctic Ice Sheet (EAIS) or the West Antarctic Ice Sheet (WAIS). They also speculated that APIC behavior is independent of that of the other Ice sheets during the late Neogene.

Ocean Drilling Program (ODP) Leg 178 Site 1095 (66°59′S, 78°29′W, 3840 m) was drilled on a sediment drift (Drift 7, Fig. 1; Barker et al., 1999) located along the Pacific margin of the Antarctic Peninsula. This site, bathed by the southwest-flowing bottom current (Camerlenghi et al., 1997a,b; Giorgetti et al., 2003), was the most distal from the continental shelf of the drift deposits that were drilled during the cruise. Results of current meter studies at Drift 7 show a generally southwestward flowing current, conforming to the bathymetry in this area, with average velocities of 6 cm/sec and never exceeding 20 cm/sec (Camerlenghi et al., 1997a; Giorgetti et al., 2003). Further, the flow patterns at Drift 7 mimic those of the ACC, suggesting that these sediments may serve as a paleocurrent meter for that great current (Camerlenghi et al., 1997a).

Four holes were drilled at Site 1095 to a total depth of 570 m below sea floor (mbsf) (Barker et al., 1999). The sediments of the Antarctic Peninsula drifts are a two component mixture of siliceous material, dominantly diatom ooze, and terrigenous silts. The clay mineralogy of the terrigenous component is dominated by smectite, illite and chlorite along the Peninsula, with cyclic changes suggesting glacial–interglacial effects (high chlorite during glacials and high smectite during interglacials) (Hillenbrand and Fütterer, 2000; Hillenbrand and Ehrmann, 2001, 2005; Hillenbrand et al., 2003). We sampled sediments downcore to a depth of 512 mbsf, with an age of 9.6 Ma, below which sediment recovery fell to very low values.

We analyzed 325 sediment samples from Site 1095 for composition and grain size of the terrigenous component. To isolate the terrigenous component, approximately 1 g of each sample was freeze-dried and treated chemically to remove carbonates, oxides and hydroxides, and biogenic opal using the method developed by Rea and Janecek (1981) and modified by Hovan (1995). Prior to the opal removal step, the samples were sieved and the >63 μm fraction, which consisted of mineral and rock fragments, was isolated, dried and weighed. After the opal removal, the sediments were dried, reweighed, and the weight percent terrigenous component was determined. The initial sediment description (Barker et al., 1999) and a factor analysis of geochemical data provided by Kyte and Vakulenko (2001) documented the two component system consisting of terrigenous material and biogenic silica, and so the weight percent silica component was determined by difference from 100% using the weight percent of the terrigenous component. Weight percentage values are accurate to ±3% of the values.

Grain size distributions of the terrigenous component were determined using a Coulter Multisizer 3, which apportions the sediment into 256 channels and records the volume percent (weight percent at constant grain density) in each channel. The median grain size (φ_{50}) ($\varphi = -\log_2$ (diameter$_{mm}$)) was calculated from the distribution data (Folk, 1974; Prothero and Schwab, 1996). The standard deviation of φ_{50} is ±0.1. We also calculated the inclusive graphic standard deviation (IGSD = (($\varphi_{84} - \varphi_{16}$)/4 + ($\varphi_{95} - \varphi_5$)/6.5)) (Folk, 1974) which is a measure of the sorting and has been used in conjunction with the median grain size to define depositional energy fields (Joseph et al., 1998).

Down hole magnetic reversal data from Acton et al. (2002) and the Geomagnetic Polarity Time Scale of Cande and Kent (1995) provided the age model for this study. Resulting linear sedimentation rates (LSR), calculated using these data, were somewhat variable and were slightly smoothed by removing short-interval, extreme-rate variations and combining intervals of less than 100 ky with an adjacent longer time interval. The resulting intervals range from 100 ky to 1 my (Fig. 2). Mass accumulation rates (MAR) were calculated using these smoothed LSRs and the dry bulk densities (DBD) determined by the Shipboard Scientific Party (Barker et al., 1999). The sediment component MARs were calculated using the % component and the flux: MAR component (g/cm^2/ky) = LSR (cm/ky) × DBD (g/cm^3) × % component.

Ten samples of the extracted terrigenous grains from Site 1095 were analyzed for Nd–Sr radiogenic isotope geochemistry with the goal of constraining provenance. Samples were prepared using methods described in (Stancin et al., 2006). Isotopic ratios of Nd and Sr were determined at the University of Michigan on a Finnigan 262 Thermal Ionization Mass Spectrometer equipped with 8 collectors using static mode analysis (Stancin et al., 2006). The La Jolla Nd and NBS 987 Sr standards gave mean values of $^{143}Nd/^{144}Nd = 0.511820 \pm 0.000008$ (and $^{87}Sr/^{86}Sr = 0.710225 \pm 0.000014$ (over the course of this study. The Nd data were corrected to $^{143}Nd/^{144}Nd = 0.511850$ (old Michigan La Jolla value), a shift of 0.6 epsilon units (Table 7).

The two parameters that define the magnetic fabric are calculated from anisotropy of magnetic susceptibility measurements: P' is the measure of the magnitude of the fabric strength, and T is a geometric factor describing the shape of the magnetic ellipsoid whether oblate ($0 < T \leq 1$) or prolate ($-1 \leq T < 0$) (Tarling and Hrouda, 1993). Three hundred twenty-two 8-cm^3 paleomagnetic cube samples from Site 1095 were analyzed for the anisotropy of magnetic susceptibility (AMS), using standard techniques to characterize the fabric (Parés and van der Pluijm, 2002). Samples were measured on a KLY-2 Kappa-Bridge at the University of Michigan to determine the bulk susceptibility and the P' and T parameters of the susceptibility ellipsoid.

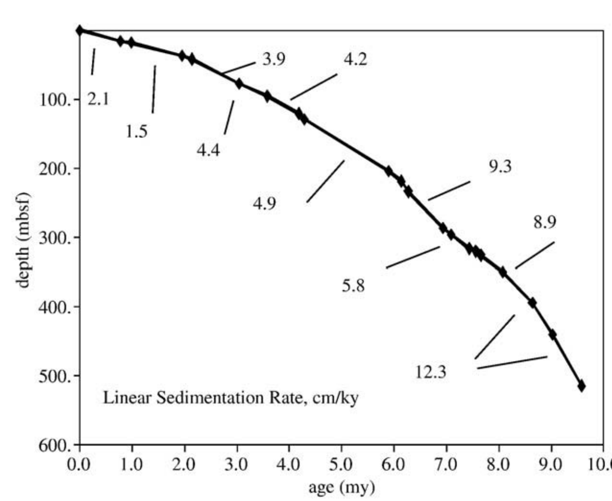

Fig. 2. Age model used for Site 1095.

Low-temperature studies were conducted on selected samples from Site 1095 to determine the dominant magnetic carrier of the fabric signal and whether this magnetic mineralogy remains constant throughout the core. We performed comparisons of sample susceptibility at high (298 K) and low (77 K) temperatures, measured susceptibility as samples warmed to room temperature from 77 K, and conducted isothermal remnant magnetism analyses (Parés and van der Pluijm, 2002; Richter and van der Pluijm, 1994). Results all showed a ferromagnetic carrier of the signal. Details of this work can be found in (Hassold, 2006). Our results agree with those of Acton et al. (2002) who performed rock magnetic analyses on samples from Sites 1095, 1096, and 1101 and showed that the main remanence carrying mineral was consistent with pseudo-single domain magnetite.

3. The sedimentary record at Site 1095

The weight percent of biogenic silica and terrigenous components remains fairly constant over the time span studied, fluctuating around 45% for opal and 55% for terrigenous material (Fig. 3). Both components show an increase in mass accumulation rate (from 1 to 2.2 g/cm^2/ky for terrigenous and 0.9 to 1.6 g/cm^2/ky for silica) between 2.5 and 3.0 Ma, another increase (from 2.2 to 4.1 g/cm^2/ky for terrigenous and 1.6 to 3.2 g/cm^2/ky for silica) between 6.0 and 6.5 my and a large increase starting around 8.5 Ma (to >7 g/cm^2/ky for terrigenous and to 5.8 g/cm^2/ky for silica) (Fig. 4).

All the indicators of provenance show that the terrigenous material has a constant source throughout the record provided by the Site 1095 sediments. Radiogenic isotope analyses on several samples across the 4.5 to 6.4 Ma time span indicate no change in provenance (Fig. 5). The magnetic carrier is unchanging throughout the core (Fig. 6), our factor analysis of the geochemical data of Kyte and Vakulenko (2001) shows the mineral component to be uniform throughout, and the clay mineralogy varies within well understood values (Hillenbrand and Ehrmann, 2001). These data confirm that the decrease in magnetic fabric strength between 5 and 5.5 Ma (see below) is current-related and not composition-related. Further, the Nd and Sr isotopic values reflect an Antarctic Peninsula provenance for the terrigenous component (see: Flowerdew et al. (2005); Riley et al. (2001)).

The degree of magnetic anisotropy, P', which is a measure of fabric strength (Fig. 7), is a proxy for current strength (Ellwood and

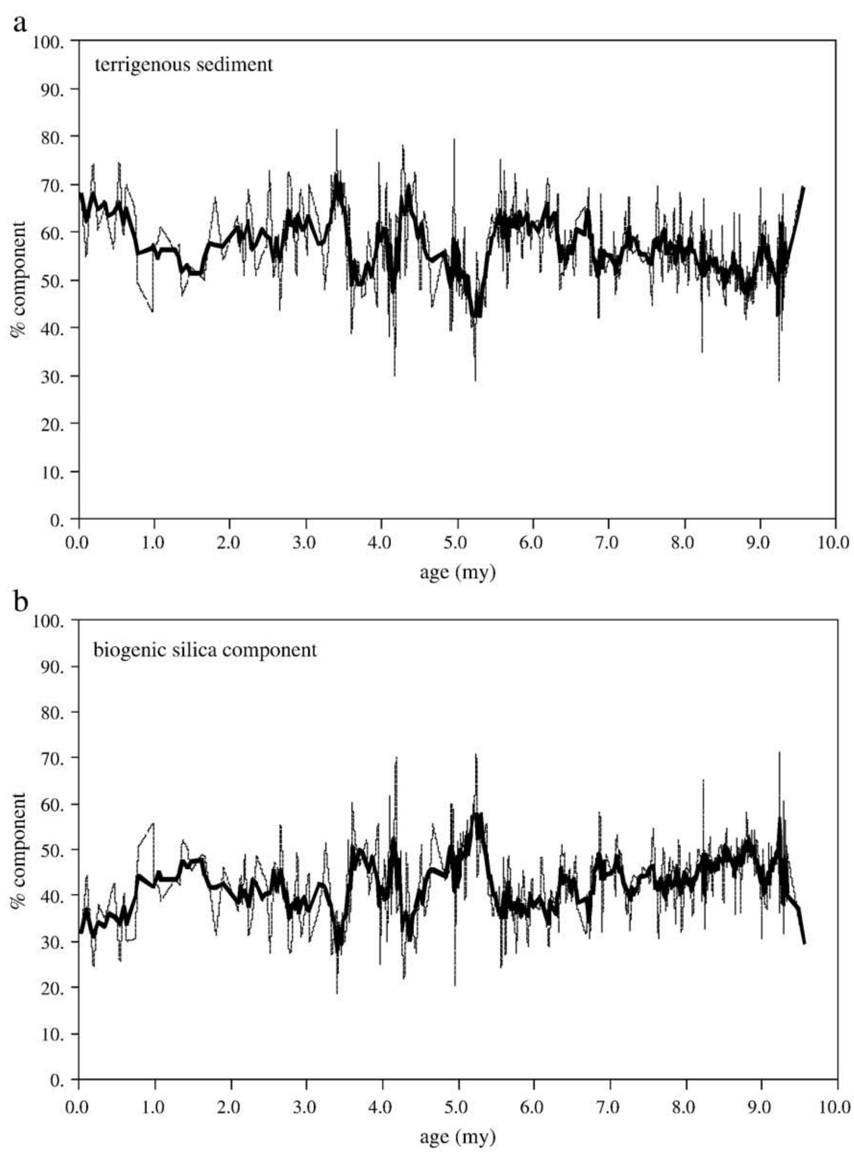

Fig. 3. Component weight percent. Weight percent values remain fairly constant for both components, varying around 45% for biogenic silica and 55% for terrigenous sediment. Gray line is actual data, heavy black line is nine-point smoothing.

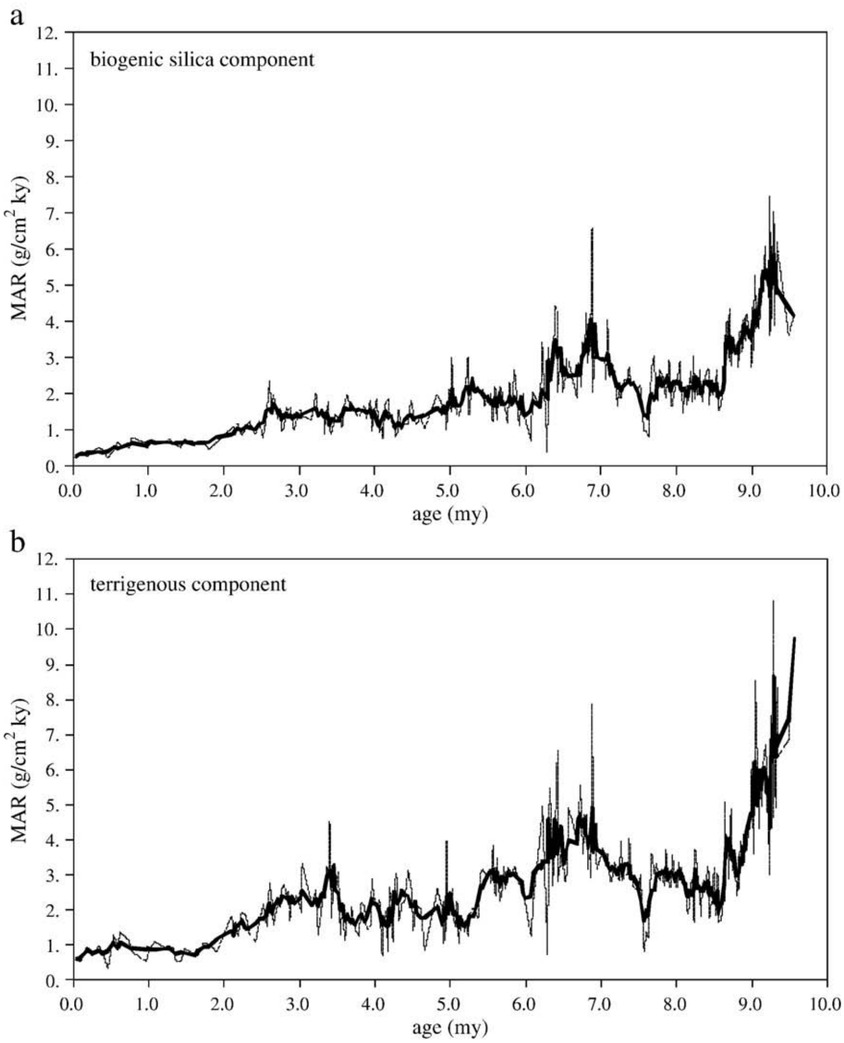

Fig. 4. Mass accumulation rates for samples from Site 1095. A large change in the MAR for both components occurs around 8.5 Ma. Another change, not as large, occurs at 2.5 Ma. Gray line is actual data, heavy black line is nine-point smoothing.

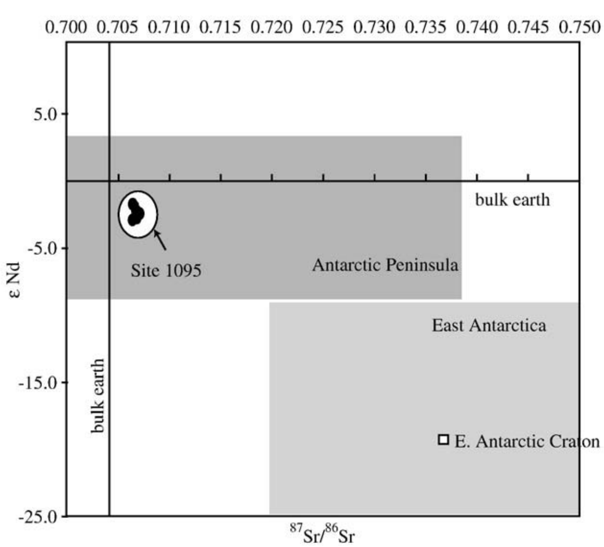

Fig. 5. Radioisotopic analysis of selected samples from Site 1095. These samples were chosen to span the 5 to 5.5 Ma period when a dramatic change in the magnetic fabric strength is seen. Results are consistent with an Antarctic Peninsula provenance. (values for E. Antarctica and Antarctic Peninsula from Joseph et al., 2002).

Ledbetter, 1977, 1979; Joseph et al., 1998). It shows a general increase back to 2.8 Ma followed by a decrease to 5.0 Ma and then a pronounced reduction between 5.0 and 5.5 Ma. Older sediment shows an increase at 5.5 Ma to P' values that are clearly higher than the younger values, with a brief decrease between 6.5 and 7.0 Ma. Fig. 8 is a plot of the shape factor, T vs. P' and indicates that the fabric is mostly oblate (disk-shaped) rather than prolate (cigar-shaped), which is in common with other drift deposits (Joseph et al., 1998; Hassold et al., 2006). This result, along with the low temperature results, show that K_{max} (the maximum magnetic anisotropy axis) is in the bedding plane and parallel to current flow (Pares et al., 2007).

Grain size of the terrigenous component increases downcore to a relative maximum between about 3.5 and 5.0 my ago. A relative low in grain size occurs at about 5.5 Ma; older values have an average median value of 6.8 φ (9.0 µm) (Fig. 9). The average median grain size over the entire interval is 7.0 φ (7.8 µm).

4. Paleoceanography of the eastern-most South Pacific and the ACC

Opal fluxes generally decline throughout the record at Site 1095 (Fig. 4). Oldest values, older than about 8.6 Ma, are in excess of 3.5 to 4 g/cm^2/ky; remaining late Miocene and Pliocene values average 2.0 g/cm^2/ky or less, with a modest maxima exceeding 3.0 g/cm^2/ky that occurred between about 7 and 6 Ma. Late Pliocene and

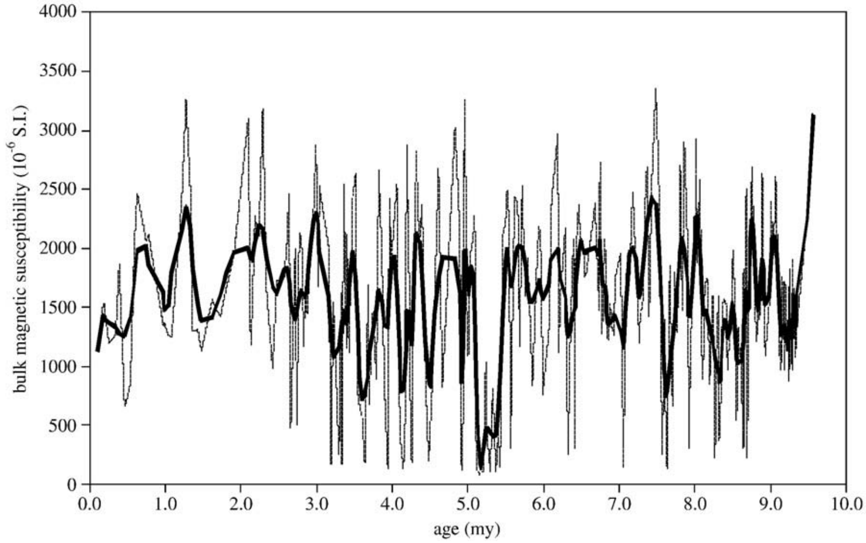

Fig. 6. Bulk magnetic susceptibility for the entire last 9.5 my. Other than the sharp change between 5 and 5.5 Ma, the susceptibility varies around a fairly constant value, implying no change in the magnetic carrier. Gray line is actual data, heavy black line is a nine-point smoothing.

Pleistocene opal fluxes decline to less than 0.5 g/cm^2/ky, with a step down at about 2.5 Ma. Our record (Fig. 4) agrees well with that determined by the Leg 178 shipboard scientists (Hillenbrand and Fütterer, 2000 (their Fig. 4)).

In pelagic and hemipelagic sedimentary systems, sediment fluxes are interpreted as a more or less direct function of the supply of that component, hence biogenic fluxes are usually interpreted as general indicators of paleoproductivity. The results of sedimentary processes associated with drift deposits, especially these along the Antarctic Peninsula that may be supplied in part by distal turbidites, may not have such a straightforward interpretation. Hillenbrand and his coworkers (Grutzner et al., 2005; Hillenbrand and Ehrmann, 2005; Hillenbrand and Fütterer, 2000) interpret opal fluxes as a reflection of sea–ice coverage of the region, increased ice coverage reduces sea-surface productivity and thus the supply of diatoms. Following that reasoning we would interpret enhanced sea ice coverage since about 2.6 Ma, which is also the time of onset of major northern hemisphere glaciation. Other, high-resolution studies have shown a sudden decrease in opal accumulation at this time in the North Pacific (Haug et al., 1999, 2005) and at nearby Site 1096 (Sigman et al., 2004).

The MAR of terrigenous materials, derived from the Antarctic Peninsula, is very high, in excess of 7 g/cm^2/ky, between 9.5 and 8.5 Ma, declining rapidly by about 8.5 Ma to values around 3 g/cm^2/ky. Successive declines in terrigenous flux occur about 5.5 Ma, and again between 2 and 3 Ma. We interpret this record as reflecting the later stages of ice sheet growth on the Antarctic Peninsula, likely beginning about 13 Ma as suggested by the oxygen-isotope record of ice volume (Zachos et al., 2001; Handwerger and Jarrard, 2003). Fluxes of sediment issuing from beneath glaciers would have been significantly reduced once the glacier became stabilized and, eventually, frozen to the ground (Hallet et al., 1996). There is no significant increase of terrigenous input in this record that might correspond to a meltback associated with any middle Pliocene warming, an observation similar to that made from sediment fluxes on the Kerguelen Plateau in the southern Indian Ocean (Joseph et al.,

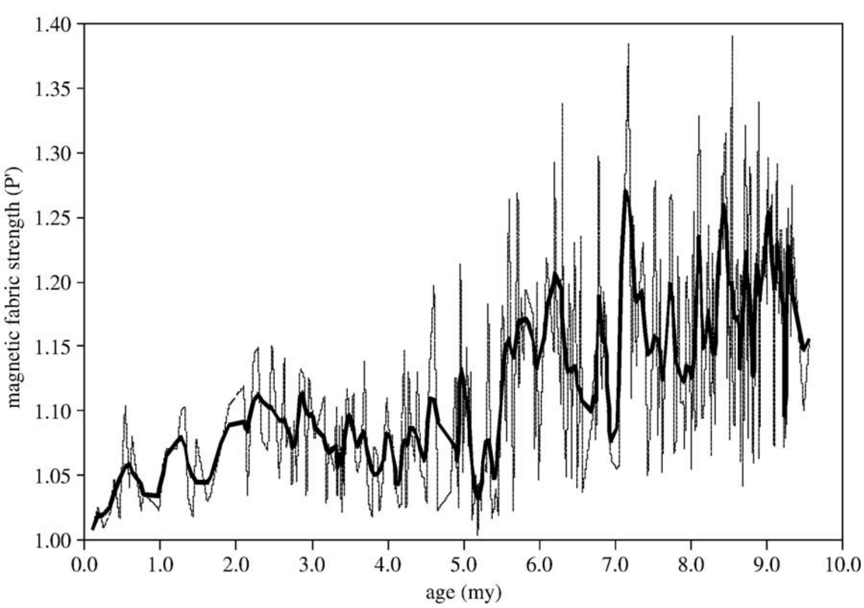

Fig. 7. Magnetic fabric strength. The magnetic fabric strength show a distinct change at 5.5 Ma. Prior to this, fabric strength is high, implying a stronger current. After 5 Ma, the fabric strength, and, by proxy, current strength, is greatly reduced. Gray line is actual data, heavy black line is a nine-point smoothing.

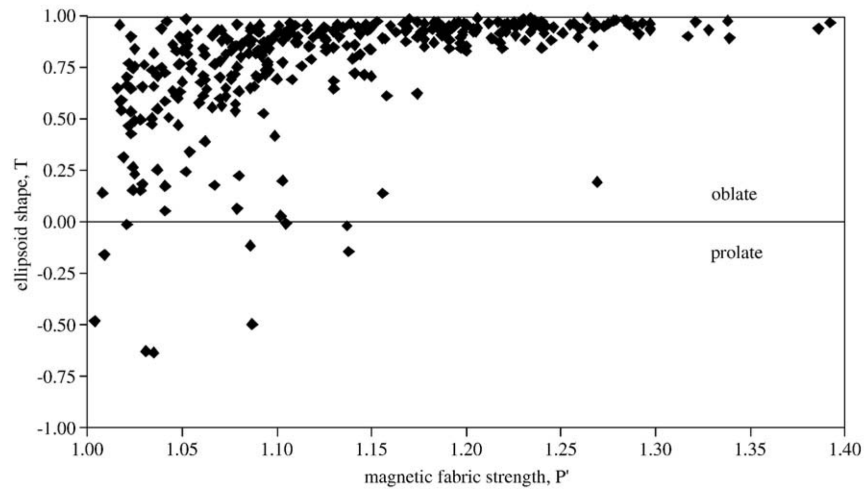

Fig. 8. *T* vs. *P*′. The shape of the magnetic ellipsoid is predominantly oblate.

2002). The MAR results, coupled with the magnetic fabric results, support our interpretation of stabilization of the ice sheet resulting in decreased sediment supply, rather than changes in the current strength.

The paleocurrent record provided by the AMS data from Site 1095 depicts a slowing of abyssal flow since the late Miocene (Fig. 6). A distinct step down from higher, older values to lower younger values occurs 5.5 to 5.0 my ago. Older AMS values indicate strong, somewhat varying flows from 9.5 to 7 my ago, and a less pronounced step down to somewhat lower values at about 7 my ago. Fabric strength increased somewhat from about 5.0 Ma to 2.5 Ma, but never again reaching previous highs. The youngest 2.5 my is characterized by a general decline in fabric strength.

These data showing greater magnetic fabric strength, thus stronger currents, before the 5.0 to 5.5 Ma transition, are consistent with interpretations of the seismic reflection records obtained in the vicinity of the Antarctic Peninsula drifts. Those surveys indicate a shift from processes of "drift growth," which show a definite influence of bottom currents on the drift development, to those of "drift maintenance," which show a more diminished influence of bottom currents, at about 5 Ma (Rebesco et al., 1997).

There are a number of other studies that all indicate a slowing of abyssal circulation since the late Miocene. Magnetic fabric studies of the Kerguelen Drift in the southern Indian Ocean (Joseph et al., 2002) show a continuing decline in current strength over the last 6.5 Ma at ODP Site 745. Examination of the Feni and Gardar Drifts of the North Atlantic Ocean revealed a two-stage reduction in flow. At the deeper Gardar Drift (DSDP Site 611) magnetic fabric strength began to decline about 5.2 Ma, while at the shallower Feni Drift (DSDP Site 610), this reduction happened at about 2.5 Ma (Hassold et al., 2006). In the northwest Pacific, Kerr et al. (2005) infer a slowing of the Meiji drift current strength beginning about 5.7 Ma based upon their studies of seismic reflection profiles from Detroit Seamount.

Geochemical studies of manganese crusts and nodules have shown that the composition of North Atlantic and Southern Ocean deep waters began to diverge at the end of Miocene time, suggesting lower

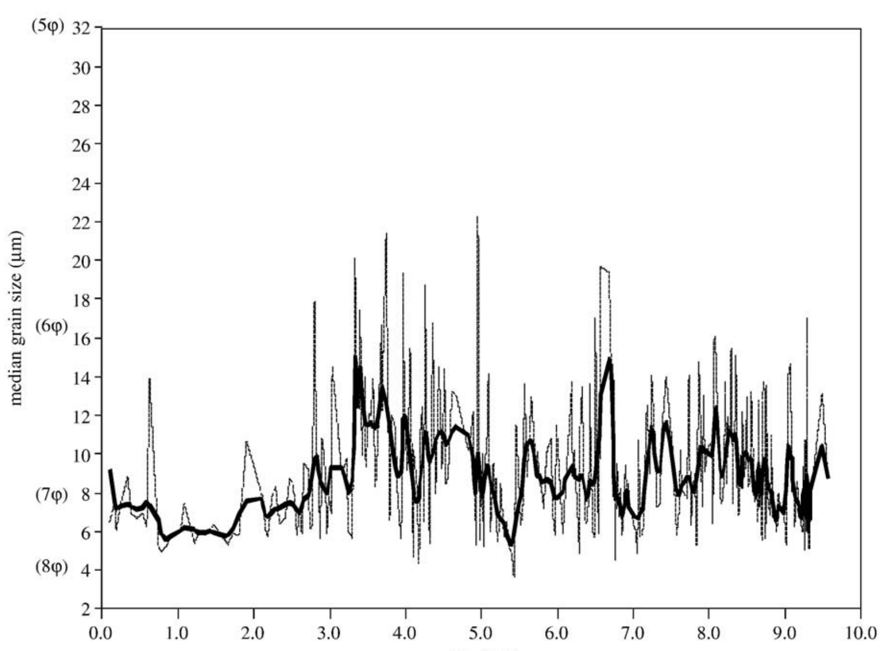

Fig. 9. Median grain size. Prior to 3 Ma, values vary around an average of 6.8 φ (9 μm). After 3 Ma, the median grain size decreases. Gray line is actual data, heavy black line is a nine-point smoothing.

interoceanic flow rates (Frank et al., 2002). Benthic $\delta^{13}C$ values reflect the age of deep waters and can be used as a measure of interoceanic hydrologic communication. These studies also indicate a reduction in deep-water flow rates since the middle or late Miocene, although the reported timing of the flow reductions varies somewhat. All studies indicate a reduction in North Atlantic deep outflow at the time of Northern Hemisphere glaciation onset in the late Pliocene (Hodell and Venz, 1992; Raymo et al., 1992; Ravelo and Andreasen, 2000).

5. Summary

Our work at ODP Site 1095 provides new insights into the paleoceanographic and paleoclimatic conditions of the Antarctic Peninsula since 9.5 Ma. A physical record of abyssal flow, the strength of magnetic fabric of sediment, documents a decline in current strength of Southern Ocean waters since the late Miocene.

The mass accumulation rate of the terrigenous component of the sediments, derived from the Antarctic Peninsula, suggests that the Antarctic Peninsula Ice Cap was in place by about 9 Ma, after which the input of terrigenous materials declined by a factor of 2 or more. A sharp change in current strength occurs between 5.5 and 5.0 Ma, which seems to correspond to the change in drift morphology reported by Rebesco et al. (1997) The influx of this material further declined 2.5 to 3.0 Ma to its present relatively low value of about 1 $g/cm^2/ky$.

These results indicate a general decoupling of land-surface, ice-sheet related responses to climate change most pronounced at 9 Ma, and the phenomenon of abyssal flow which undergoes a marked reduction nearly 4 million years later. There is little change at the Antarctic Peninsula site that might be related to the onset of major Northern Hemisphere glaciation at about 2.6 Ma, perhaps just a modest decline in the terrigenous and biogenic component flux rates.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.palaeo.2009.01.011.

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