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Do magnetic fabrics of marine deposits preserve orbital forcing? A test case in the Southern Ocean, Antarctic Peninsula

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ABSTRACT

The anisotropy of magnetic susceptibility (AMS), or magnetic fabric, of marine sediments is related to depositional current strength; higher AMS values indicate stronger currents. We have collected a 3.1 m.y. record of AMS data from the abyssal silts of Drift 4 (Ocean Drilling Program Site 1101) on the Pacific margin of the Antarctic Peninsula. Spectral analyses of these data show strong, uniform, 100 k.y. and 400 k.y. power in-phase with minima in Earth's eccentricity throughout the long record. However, significant variability related to the 40 k.y. period of obliquity is absent. The unchanging strong 100 k.y. power and the apparent absence of 40 k.y. variability in the AMS record are in contrast to the behavior of most other paleoclimatic proxies for late Pliocene and Pleistocene time.

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INTRODUCTION

Terrigenous material, mineral grains derived from continents, makes up three-quarters of all deep-sea sediment by volume, and about one-half by area of coverage. As part of our efforts to determine uniquely which process (eolian, ice rafting, hemipelagic, turbidity current, drift current) may have been responsible for the ultimate deposition of any given sample, we have been investigating both grain-size distribution of the terrigenous component (Rea and Hovan, 1995) and the anisotropy of magnetic susceptibility (AMS), or magnetic fabric, of sediment (Joseph et al., 1998). AMS data are particularly useful for discriminating between hemipelagic and drift current deposits: these sediments have similar grain-size distributions, but hemipelagic grains are randomly oriented, whereas drift deposits have oriented grains and thus a distinct fabric (Rea and Hovan, 1995; Joseph et al., 1998). The initial studies of the magnetic fabric of deep-sea sediments by Ellwood and Ledbetter (1977; Ellwood et al., 1979; Ledbetter and Ellwood, 1980) demonstrated that stronger currents result in more pronounced fabrics. We have previously completed AMS studies of drift deposits from the Kerguelen Plateau (Joseph et al., 2002), east of northern New Zealand (Joseph et al., 2004), the North Atlantic Ocean (Hassold et al., 2006), and the Antarctic Peninsula (Hassold et al., 2009a), all of which indicate a general slowing of deep-ocean circulation since the late Miocene.

Ocean Drilling Program (ODP) Leg 178 drilled a series of sites located on drift deposits along the Pacific continental margin of the Antarctic Peninsula (Barker et al., 1999, 2002; Fig. 1). These drifts are deposited by a southwest-directed, contour-following flow along the Antarctic Peninsula: a subpolar gyre sometimes termed the East Wind Drift. Current meter moorings along the South Shetland Islands (Nowlin and Zenk, 1988) and atop one of the Antarctic Peninsula drifts (Camerlenghi et al., 1997) document the southwesterly flow averaging 6 cm/s and not exceeding 20 cm/s. The water in this current derives from outflow from the Weddell Sea (Nowlin and Zenk, 1988; Camerlenghi et al., 1997). In prior studies we examined the overall paleoceanographic record from ODP Site 1101 (Hassold et al., 2009b) and quantified the paleoflow directions at the Site 1101 drift deposit based on the directional data in the AMS measurements (Parés et al., 2007). Here we examine the spectral characteristics of the magnetic fabric record from ODP Site 1101 to provide a detailed look at the variability that characterized the past 3.1 m.y. of abyssal flow along the Antarctic Peninsula continental margin.

SEDIMENTS

ODP Site 1101, Antarctic Peninsula

ODP Site 1101 (64°22.3′S, 70°15.6′W, 3280 m) was drilled during ODP Leg 178 on Drift 4 of the sequence of drift deposits on the Pacific margin of the Antarctic Peninsula (Fig. 1). This site is more proximal than the other drift sites and has an accordingly higher sedimentation rate, ~7 cm/k.y. The sediment is predominantly diatomaceous silt or diatomaceous clayey silt with occasional ice-rafted grains (Barker et al., 1999; Hassold et al., 2009b). Because of constraints on ship time, the site was only single cored, so it is not possible to construct a complete and continuous section at Site 110. Although the average recovery of this section was 99.1% (Barker et al., 1999), unresolved core gaps remain and these may be significant, especially when using the extended core barrel (XCB, below 142 m below seafloor, mbsf). In addition, core disturbance and turbidites made some intervals in the cores unsuitable for sampling.

We took paleomagnetic cube samples from all the cores 1101A-1H through –24X, 0–217.7 mbsf. This resulted in an overall average sample

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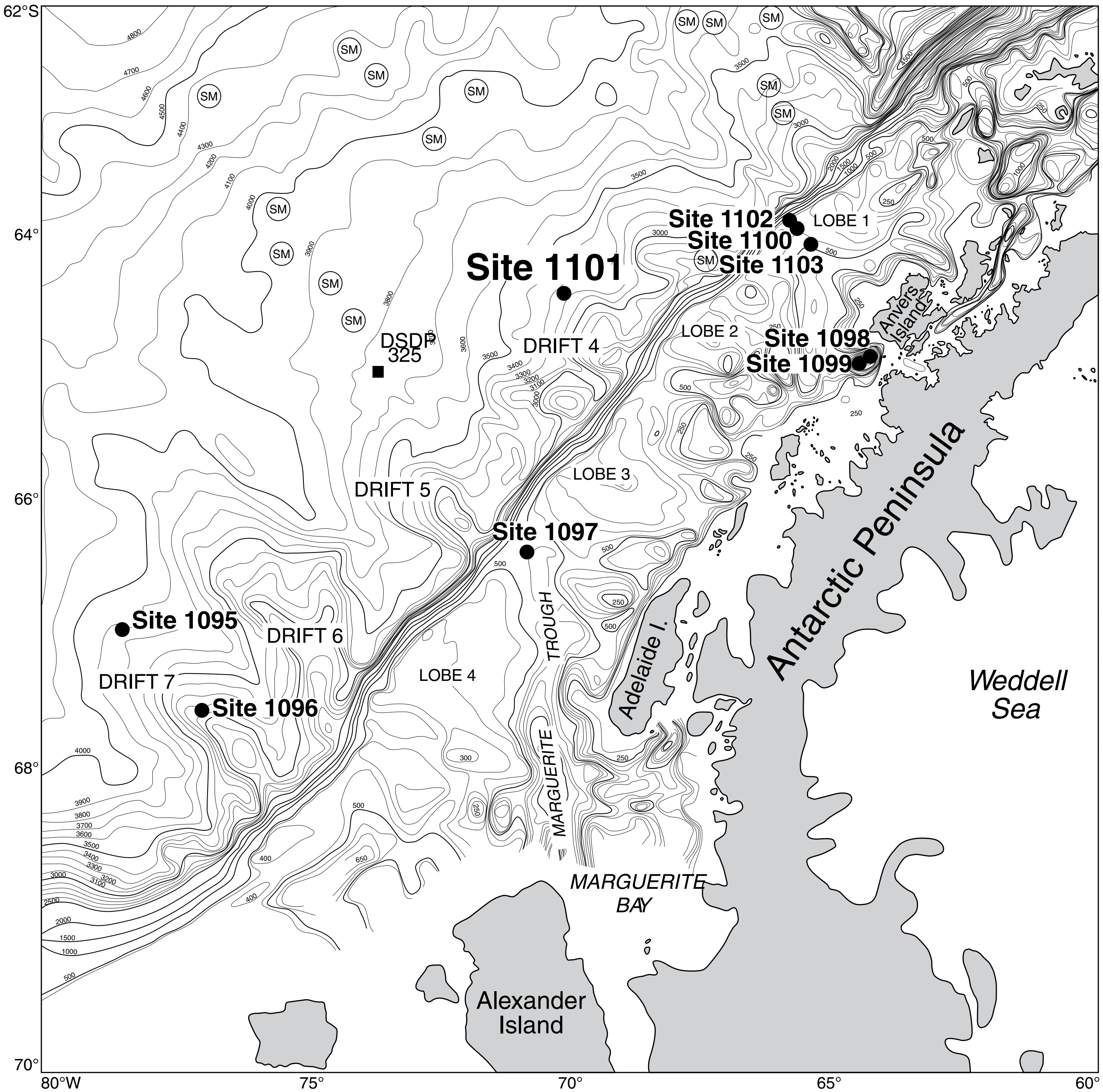

Figure 1. Locations of Ocean Drilling Program Leg 178 drill sites along the Antarctic Peninsula (after Barker et al., 1999). DSDP—Deep Sea Drilling Project; SM—Seamount.

spacing of 1 m, with an average within-core sample spacing of 76 cm down to 142 mbsf and a within-core sample spacing of 1.52 m below that point. These samples were analyzed for AMS using the methods outlined in Joseph et al. (1998), Parés and van der Pluijm (2002), Hassold et al. (2006), and Parés et al. (2007). Turbidites are present within the section recovered at Site 1101 (Barker et al., 2002; Lucchi and Rebesco, 2007). In a study focused on drift current flow, turbidites give an unwanted signal. To obviate this concern we avoided sampling those turbidites we could identify visually. Furthermore, because they are deposited by rapidly moving downslope flows, turbidites have a very strong magnetic fabric (high P′ value; Joseph et al., 1998). Turbidites are also characterized by a distinct grain-size distribution (Joseph et al., 1998). Samples showing strong P′ values were subjected to grain-size analysis using the techniques outlined in Rea and Hovan (1995) and Joseph et al. (1998); samples showing a turbidite-like size distribution were removed from the data set. The results of the paleocurrent direction study based on this sample set from which turbidite samples were removed show contour-parallel flow at the Antarctic Peninsula drifts (Parés et al., 2007), so we are confident that the record shown here represents drift current deposition and not turbidites.

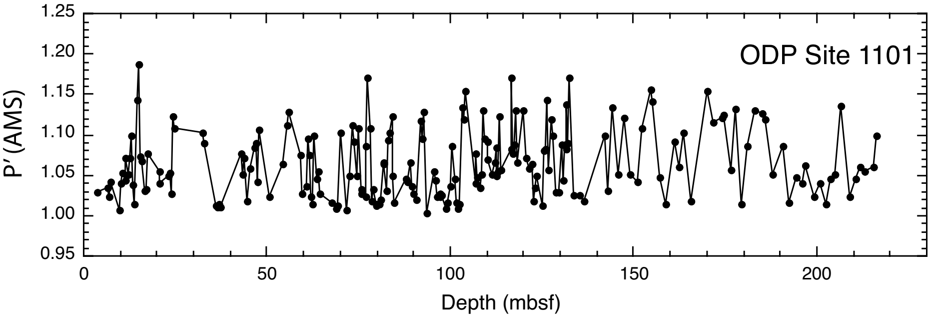

Figure 2. Anisotropy of magnetic susceptibility (AMS) values (P′—magnetic fabric shape) from sediments of Drift 4, Ocean Drilling Program (ODP) Site 1101 (mbsf—meters below seafloor).

The resulting data set of 211 AMS measurements is from samples spaced through the 3.11-m.y.-long record at an average interval of 14.7 k.y. We have used the Site 1101 chronostratigraphy of Acton et al. (2002), which is based on the Cande and Kent (1995) magnetic reversal time scale, to assign the initial ages to these samples.

SPECTRAL ANALYSIS

The AMS data at Site 1101 show 3.1 m.y. of uniform variability (Fig. 2). Supporting data (samples and tuned ages) can be found in the GSA Data Repository Item[1]. There is no increase in the amplitude of variation of this proxy associated with the time of the onset of major Northern Hemisphere glaciation ca. 2.65 Ma, or at 1.8 or 0.9 Ma when the amplitudes of many other proxies, most notably the oxygen-isotope record of changing ice volume, increase. These data suggest a uniformly varying flow since the late Pliocene.

Here we assemble evidence for orbital control of the Antarctic Peninsula drift current, conducting a spectral analysis of the AMS paleocurrent proxy (using the AnalySeries program of Paillard et al., 1996). The average sample interval of 14.7 k.y., along with the likely recovery gaps between successive cores, means that we do not expect to capture variability at the shorter periods of precession, but with a 3.1-m.y.-long record we should be able to evaluate both obliquity and eccentricity frequencies to the degree that they are present in the record.

Spectral analysis of geologic data is usually a two-step process. The first step is to determine if there is a concentration of variation at any particular frequency in the primary data set. These frequencies commonly correspond to those determined by Milankovitch and reflect the orbital parameters of precession at periods of 19 and 23 k.y., obliquity at ~40 k.y., and eccentricity at ~100 and 400 k.y. To be real, or worthy of further analysis, the data set must display both power at, and coherence with, one of these orbitally related periods. The first analysis of the Site 1101 AMS data shows significant power at the eccentricity-related peaks of ~120 and 400 k.y., and coherence between the peaks at ~120 k.y. and 400 k.y. and calculated eccentricity (Laskar et al., 1993, 2004) (Figs. 3A, 3B). An intermediate spectral peak at a period of ~200 k.y. (not seen in the eccentricity spectrum) raises caution in the interpretation of this spectrum as purely a reflection of climatic forcing by eccentricity. Clemens and Tiedemann (1997) found periods of 404, 200, 124, and 95 k.y. in a record of benthic oxygen isotopes (1–5 Ma) and proposed a truncated precession as the model of the true climatic signal; they proposed that the 200 k.y. power was associated with both Northern and Southern Hemisphere precession signals. Although the precession frequencies are not resolved in our record, we believe that the apparent eccentricity peaks seen in our record may also be primarily a result of a similar phenomenon. There are small spectral peaks near periods of 80 k.y., 60 k.y., and 40 k.y.; however, the amount of spectral power associated with these periods is minor.

To know how any orbital control of the paleocurrent data might be interpreted, we must define the phase relationship of the fabric data to the eccentricity record. This check is appropriate even if the primary climate forcing is related to precession because it is the eccentricity that modulates the precession signal. Phasing between the P′ and eccentricity records appears to be at 180° (of 360°) or such that low eccentricity values (low-amplitude precession oscillations), indicative of glacial periods, correspond to high P′ values, which are indicative of stronger currents (Fig. 3C). Thus analysis of the primary data set, using the original paleomagnetic time control, shows important power at eccentricity periods, power that is coherent with eccentricity and 180° out of phase. Using this information as a guide, we can tune the primary data set to enhance it for further spectral analysis.

We tuned the record such that largest fabric values correspond to minimum eccentricity values (Fig. 4). This generates a new time scale, or age-depth relationship for the data set. We conducted a reality check on this new time scale by comparing it to magnetostratigraphy to see if the constraints provided by the age and downcore depth of the known reversals is maintained or violated by the new age-depth relationship. The tuned time scale passed this test (Fig. 5), allowing us to continue the analysis.

Spectral analysis of the tuned fabric record (Fig. 3D) reveals peaks at 96 and 126 k.y. periodicities, the 2 components of eccentricity forcing that often combine into one peak at ~100 k.y. in less well-resolved data sets. The 96 k.y. peak has two or three times the amplitude of the 126 k.y. peak, comparable in relative magnitudes to these peaks in the spectrum of eccentricity (Fig. 3D). Furthermore, the eccentricity long-cycle peak at 412 k.y. is also well defined here. There is a peak at ~200 k.y. that again shows up in our data but not in eccentricity (Figs. 3A, 3D). The persistence of this peak in the tuned record reinforces our belief that the true climate forcing of the P′ record may be a truncated precession-driven

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[1] GSA Data Repository Item 2016340, tables with tuned ages and magnetic data, is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

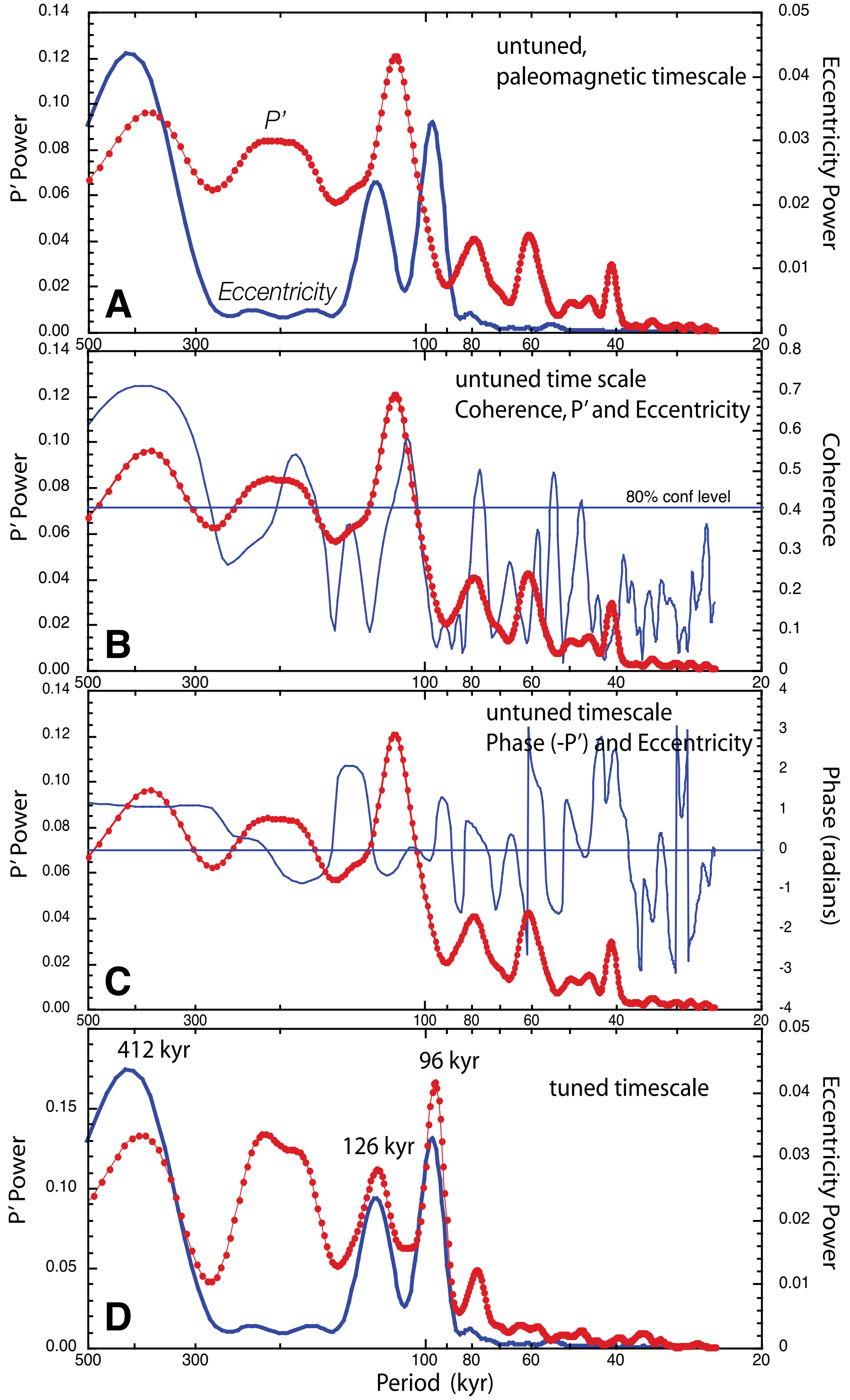

Figure 3. Spectral characteristics of Ocean Drilling Program Site 1101 anisotropy of magnetic susceptibility (AMS) data. (A) Spectral analysis of the AMS data of Figure 2 (dotted line) and of orbital eccentricity (solid line). P′—magnetic fabric. (B) Coherence (light line) between the AMS data (dotted line) and eccentricity is strong at ~120 k.y. and 400 k.y. (C) Phasing (light line) of AMS data (dotted line) shows that values of –P′are in phase, phase angle of 0°, with eccentricity, indicating that P′ is 180° out of phase. (D) Spectral analysis of AMS data using the tuned time scale (dotted line) as described in text and shown in Figure 4. Results show eccentricity-related spectral peaks at 96 k.y., 126 k.y., and 412 k.y., and no spectral peak associated with obliquity at ~40 k.y.

process (Clemens and Tiedemann, 1997). There is a complete absence of any spectral power corresponding to the 40 k.y. periodicity of obliquity. This is an initially curious result, as the 40 k.y. power has been shown to be important in many proxy records of climate change (cf. Raymo and Nisancioglu, 2003). It may be that the quality of the record studied, together with our rather broad sample spacing, obscured the 40 k.y. period of oscillation; however, we would expect that the tuning process would enhance any significant power at higher frequencies. Instead, power at all the periods shorter than 96 k.y. was diminished, with spectral peaks at 60 k.y. and 40 k.y. disappearing completely. Given the quality of the studied record, we are hesitant to draw any definitive conclusions regarding the presence or absence of spectral power at these shorter periods.

IMPLICATIONS FOR ANTARCTIC PALEOCEANOGRAPHY

Demonstration of Milankovitch variability in this AMS data set from the Antarctic Peninsula is further validation of this tool as a robust paleoenvironmental proxy. Magnetic fabric data now joins the few physical proxies, dominantly based on particle size analysis, that record the energetics of oceanic (Robinson and McCave, 1994; Hall et al., 2001) and atmospheric (Pisias and Rea, 1988; Clemens and Prell, 1990) circulation.

The Antarctic Circumpolar Current (ACC) system in its entirety is complex and far reaching, feeding boundary currents in all the major ocean basins. The narrow boundary flow along the Pacific side of the Antarctic Peninsula is part of this system. Supporting this link between the countercurrent and the ACC, Camerlenghi et al. (1997) documented that on synoptic time scales fluctuations in bottom flow at Drift 7 (Fig. 1) are synchronous with those found in the ACC. If this covariance is valid in the past, then the current-controlled deposition of the Antarctic Peninsula drifts would reflect the strength of the ACC. Since the ACC serves as the connection among all three major ocean basins, quantification of its history would provide important information to studies of abyssal circulation and of global climate at all time scales.

Both the primary data (Fig. 2) and results of spectral analyses on 1-m.y.-long subsets of the data (not shown) indicate no change in the nature or amplitude of the variability throughout the 3.1-m.y.-long record. Nearly all other paleoclimatic or paleoceanographic proxy indicators, largely recorders of either ice volume or sediment composition, show increases in the amplitude or periodicity of variation ca. 2.65

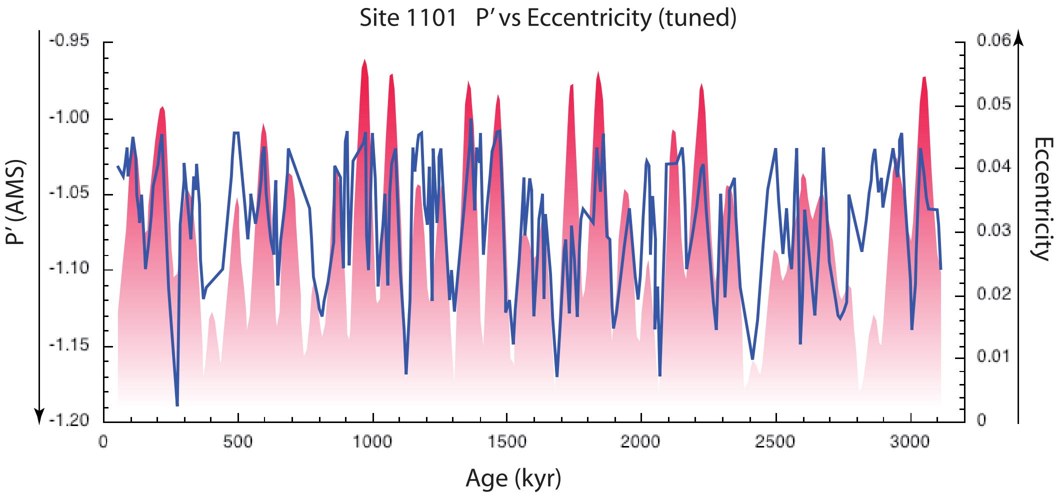

Figure 4. Anisotropy of magnetic susceptibility (AMS) data of Figure 2 tuned to eccentricity (shaded).

Ma, the onset of major Northern Hemisphere glaciation, at 1.8 Ma, and again ca. 0.9 Ma (cf. Mix et al., 1995; deMenocal, 2004). This last increase occurs when 100 k.y. power begins to dominate most younger records. Throughout this time the periodicity and amplitude of eccentricity-related variability in the ACC remains unchanged. Iorio et al. (2004) examined magnetic susceptibility data, a proxy for composition, from the Antarctic Peninsula drift sites and came to a similar conclusion that the 100 k.y. power continues throughout the records with no change in amplitude.

The phasing of the maxima in the P′ fabric strength value with minima in eccentricity suggests that stronger flow of this part of the ACC system occurred during glacial periods of the Pleistocene. However, since this relationship with orbital variability extends back in time to before the buildup of large Northern Hemisphere ice sheets and does not change greatly during the evolution in the variability of global ice volume, it indicates a more direct link with orbital forcing than with changes in ice volume.

The relationship of maximum currents during glacials (minima in eccentricity) in the Pleistocene is similar to that reported from most other studies of boundary currents associated with the ACC system, such as those from the North Atlantic drifts (Robinson and McCave, 1994), the Chatham Rise in the southwest Pacific (Hall et al., 2001), and from the ACC-influenced sediments in the Scotia Sea (Pudsey and Howe, 1998). In the Cape Basin off southern Africa, however, the temporal variation in deep flow may be in the opposite sense (Kuhn and Diekmann, 2002). At present, it is not clear whether the phasing between eccentricity and current strength represents regional differences in oceanography or sediment deposition under different flow regimes.

Even though our sample spacing is just adequate to resolve a 40 k.y. periodicity, particularly in a record with sampling gaps, the apparent absence of any variation at the periods of ~40 k.y. associated with obliquity was still a surprise. This periodicity is common in most records of climate and environmental variability (cf. Imbrie et al., 1992; Raymo and Nisancioglu, 2003). Coupled atmospheric-oceanic circulation models may give a clue to the apparent lack of an obliquity signal in the record studied. We used the Fast Ocean Atmosphere Model (FOAM; Argonne National Laboratory; http://www.mcs.anl.gov/research/projects/foam/) to develop a series of sensitivity tests of the climatic and oceanographic response to a range of obliquity and eccentricity-modulated precessional variations as a way to estimate the importance of orbital variations on current intensity. The results of this modeling indicate that precessional forcing has a pronounced effect on the zonal ocean circulation at 65°S, while obliquity has almost none. These results are consistent with our findings, but a more finely resolved record of AMS variations in deposits strongly influenced by the ACC is needed to verify our hypothesis of precessional and obliquity signals.

It is generally accepted that the insolation response to changes in eccentricity is so small that eccentricity may not, in a linear manner, drive environmental variation; some nonlinear feedback mechanism must be involved (Imbrie et al., 1993; Shackleton, 2000; Berger et al., 2005). Our sampling interval of 14.7 k.y. and the unknown intercore sediment gaps render

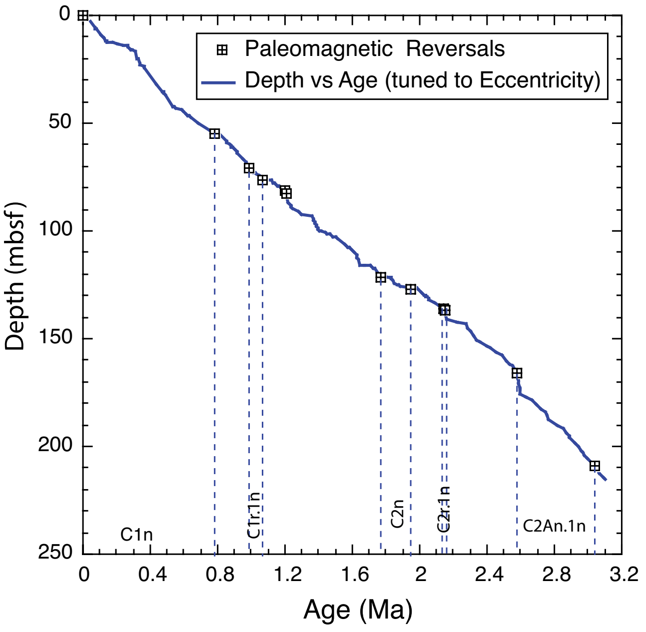

Figure 5. Age versus depth (mbsf—m below seafloor) of the Ocean Drilling Program Site 1101 section tuned to eccentricity (see Fig. 4). Locations of paleomagnetic chron (C) boundaries (Acton et al., 2002) are shown as squares on the plot.

any direct analysis of precession in our fabric data impossible at Site 1101. Iorio et al. (2004) showed that precession-related variability exists in the sediments of the Antarctic Peninsula drifts, so we suggest that the observed eccentricity-related variability is an indirect result of long-period variability induced by precession, rather than of any direct influence of eccentricity (Clemens and Tiedemann, 1997).

CONCLUSION

AMS analyses of sediments in drift deposits provide a relative measure of the strength of past abyssal currents. Our study along the Antarctic Peninsula shows that the abyssal flow there is characterized by fluctuations at the 96, 126, and 400 k.y. periods related to orbital eccentricity throughout the past 3100 k.y. Furthermore, and unlike nearly all other paleoenvironmental proxies, there is no change in the amplitude of the 100 k.y. power.

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