Evidence for orbitally controlled size variations of the East Antarctic Ice Sheet during the late Miocene

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ABSTRACT

Ocean Drilling Program Site 1165 penetrated drift sediments on the East Antarctic continental rise and recovered sediments from a low-energy depositional environment. The sediments are characterized by prominent alternations between a green to greenish-gray diatom-bearing hemipelagic facies and gray to dark gray hemiturbiditic facies. Our investigation of an upper Miocene section, using high-resolution color spectra, multisensor core logs, and X-ray fluorescence scans, reveals that sedimentation changes occur at Milankovitch orbital frequencies of obliquity and precession. We use this finding to derive an astronomical calibrated time scale and to calculate iron mass-accumulation rates, as a proxy for sediment-accumulation rates. Terrigenous iron fluxes change by as much as 100% during each obliquity cycle. This change and an episodic pattern of enhanced ice-rafted debris deposition during times of deglaciation provide evidence for a dynamic and likely wet-based late Miocene East Antarctic Ice Sheet (EAIS) that underwent large size variations at orbital time scales. The dynamic behavior of the EAIS implies that a significant proportion of the variability seen in oxygen isotope records of the late Miocene reflects Antarctic ice-volume changes.

Keywords: paleoclimatology, Ocean Drilling Program, Antarctic Ice Sheet, Prydz Bay, Milankovitch theory, Miocene.

INTRODUCTION

It has been proposed that the East Antarctic Ice Sheet (EAIS) was relatively stable during the past 14 m.y. (see summary by Barker et al., 1999). However, low-resolution studies that cover long time intervals of the Neogene have presented evidence of a dynamic EAIS with sliding glaciers carrying large amounts of basal and supraglacial debris to the continental margin (Hambrey and McKelvey, 2000). Furthermore, Joseph et al. (2002) interpreted pulses of fine-grained sediment delivery to the ocean basins as representing times of retreating warm-based ice sheets.

Proximal Antarctic high-resolution records that could document size fluctuations of the EAIS before 3 Ma on orbital time scales are rare because of low core recovery, discontinuities, and scarcity of biostratigraphic constraints. Furthermore, carbonate dissolution by corrosive bottom waters prevented the construction of oxygen isotope records. Low-latitude benthic isotope records show that Milankovitch cycles are superimposed on the general climate trend (Shackleton and Hall, 1997), but the amplitude and period of ice-sheet variations remain undefined in these data sets because the $\delta^{18}O$ changes reflect a combined effect of ice volume and temperature. The first direct evidence for significant size fluctuations of the EAIS on orbital time scales was found at the Ross Sea continental margin (Naish et al., 2001). The observed lithologic changes occurred at the Oligocene-Miocene boundary, a time when global temperatures are estimated to have been 3–4 °C warmer than at present.

Here we present a high-resolution study of a cyclic upper Miocene depositional sequence from the East Antarctic continental rise. At this time, global ice volume was likely larger than today (Kennett and Barker, 1990). Our investigation is based on high-resolution core-logging measurements that illustrate orbitally controlled fluctuations in terrigenous and ice-rafted debris (IRD) accumulation on orbital time scales that indicate the existence of an EAIS with a more dynamic behavior than previously inferred.

MATERIAL AND METHODS

Site 1165 is in a water depth of 3357 m on the Prydz Bay continental rise offshore from the Lambert glacier system (Fig. 1) that today drains ~22% of East Antarctica and acts as a focused sediment outlet to the sea (Anderson et al., 1991). The site was drilled into the central Wild Drift, an elongate sediment body formed of sediment that is supplied from the shelf and redistributed by westward-flowing currents (Kuvaas and Leitchenkov, 1992).

The 999-m-deep drill hole recovered a fine-grained sedimentary sequence that is characterized by alternations between (1) a generally gray to dark gray terrigenous facies interpreted as contourites mainly deposited during ice-growth phases and (2) a green to greenish-gray hemipelagic facies reflecting warmer climate conditions during deglaciations and interglacials. The greenish facies layers are structureless diatom-bearing clays with common bioturbation and larger amounts (>15%–20%) of biogenic silica, dispersed clasts, and lonestones compared to the layers of the dark gray facies, which are mostly less bioturbated clay with some silt laminations (Shipboard Scientific Party, 2001). The green and gray sediment colors may be related to the oxidation state of iron (Fe^{2+}, green) and organic carbon content (>0.3 wt%, gray) (Potter et al., 1980).

Upper Miocene sections drilled at Site 1165 were at relatively shallow burial depth. We here focus on a detailed investigation of cores 1165B-10H and 1165B-11H, spanning the depth interval from 82.90 to 99.40 m below seafloor (bsf) and covering the age range 7.00–7.49 Ma. Sediment loss at the break between the two cores is estimated to be in the range of 0.5–2.0 m (Hagelberg et al., 1995). Good magnetostratigraphic age control is available for this interval.

Color-reflectance measurements were made every 5 cm at the surface of split cores. The CM-2002 photospectrometer was used to measure the reflected visible light (ranging from 400 to 700 nm) in 31 bands, each 10 nm wide. In order to construct a parameter that best reflects the visible impression of color changes in the cores, we calculated the green/gray color ratio by dividing the average re-

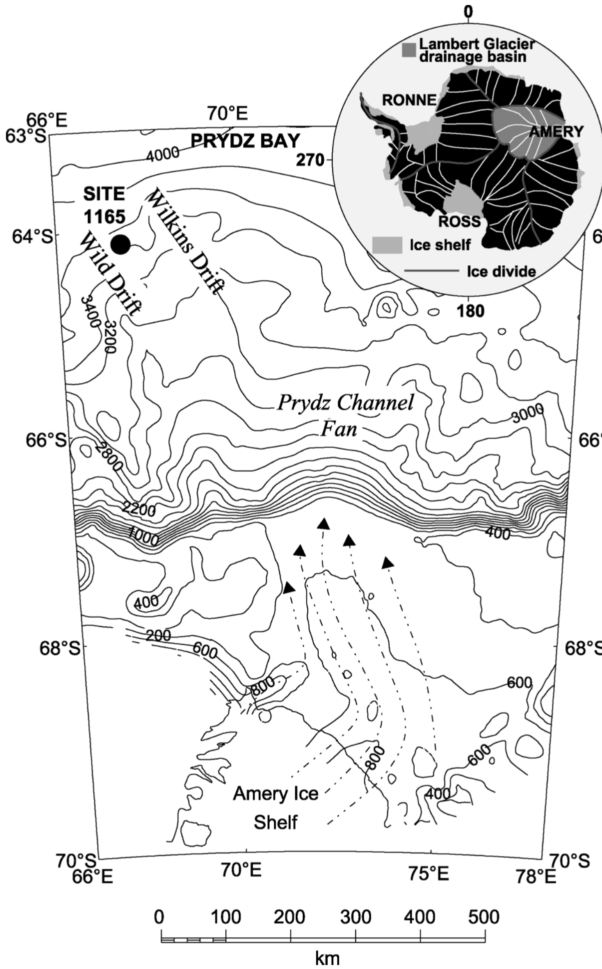

Figure 1. Location maps for Prydz bay region. Arrows indicate flow lines of Lambert Glacier during major late Neogene ice advances. Inset shows present ice-sheet flow lines.

flectivity in the 500–590 nm bands (green) by the average reflectivity of all spectral bands (gray).

Geochemical core logging was performed at a resolution of 1 cm with an X-ray fluorescence (XRF) core scanner, a nondestructive analysis system for scanning the surface of archive halves of cores (Norris and Röhl, 1999). Here we use the iron (Fe) record because this element is primarily deposited with the siliciclastic sediment component and the Fe intensity shows very pronounced amplitude changes. Measurements of titanium (Ti), which is redox insensitive, show an identical downcore pattern. Hence, Fe variations at Site 1165 within the studied interval are not diagenetically controlled. The Fe-intensity counts were calibrated with inductively coupled plasma emission spectrometry (ICP-ES) analyses on discrete samples (Murray et al., 2000) to derive Fe concentrations. Accumulation rates of Fe (R_{Fe}, in g·cm^{-2}·k.y.$^{-1}$) were calculated by using the equation $R_{Fe} = (R_{LS} \times \rho_{DB} \times [Fe])/100$, where R_{LS} is the linear sedimentation rate (in cm/k.y.), ρ_{DB} is the dry bulk density (in g/cm^3) derived from gamma-ray attenuation bulk-density values (2 cm sampling interval), and [Fe] is the weight percentage concentration of Fe.

Sediment samples at 30 cm spacing were analyzed to determine the percentage of coarse grains. By comparing the IRD record (grain size > 250 μm) and magnetic susceptibility measurements (MS, 4 cm sampling interval), we found that every IRD peak ($>$10%) is reflected by a sharp positive spike in the MS record, and hence MS can be used as an IRD predictor (Robinson et al., 1995). We infer that other sharp spikes observed in the MS data also represent IRD layers that were missed by the 30 cm spacing of the grain-size samples.

RESULTS AND DISCUSSION

Orbital Forcing

The biogenic- and terrigenous-facies alternations appear as lightness variations in black and white core photographs (Fig. 2), but are more apparent as alternations in the green/gray color ratio (Figs. 2 and 3A) and as cyclic variations in other core-logging parameters (Fig. 3A). Greenish facies generally have lower bulk density, magnetic susceptibility, and Fe values than the darker facies.

To further evaluate the nature of the facies alternations we performed cross-spectral analyses (algorithm of Schulz and Stattegger, 1997) in the depth domain by using the green/gray ratio and the Fe record. Significant spectral density maxima in Fe and green/gray ratio are found at wavelengths of 3.11, 1.55, 0.74, and 0.62 m (Fig. 3B), and the coherencies between Fe and color at these periods are mostly high (Fig. 3B). Magnetostratigraphic reversals C3An.2n to C3Ar (6.677 Ma, Hilgen et al., 1995) at 73.52 mbsf and C3Ar to C3Bn (7.101 Ma) at 89.20 mbsf yield an average sedimentation rate of ~3.7 cm/k.y. for the investigated interval. On the basis of this rate, the previously listed wavelengths in the depth domain are equal to cycles of 84.1, 41.9, 20.0, and 16.8 k.y. duration. The concurrence of the coherent spectral amplitude maxima at 1.55 and 0.74 m wavelength with astronomical cycles of obliquity (41 k.y.) and precession (19–23 k.y.) suggests an orbital origin for the observed color and Fe changes.

We used the 1.55 m cycle, which reflects a 41 k.y. time interval, to calculate a refined average sedimentation rate of 3.78 cm/k.y. for the investigated cores. The longer wavelength of 3.11 m is equivalent to a period of 82 k.y. and likely reflects an amplitude modulation within the obliquity band.

Our spectral results indicate that the cyclic biogenic-terrigenous sedimentation pattern was largely controlled by variations in solar insolation. On the basis of these results we derived a high-resolution chronology by using astronomical tuning (Shackleton et al., 1990). We interpret the prominent 1.55 m cycles in the interval 83–100 mbsf (Fig. 3B) as an orbital obliquity signal, and we correlate the

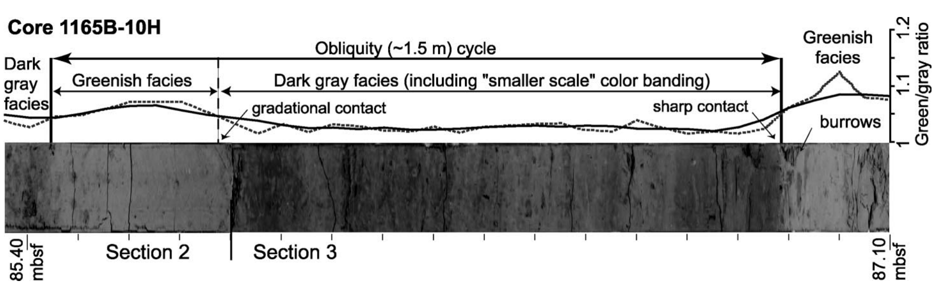

Figure 2. Core photograph and green/gray color ratio (dotted line = 5 cm record, solid line = 25 cm average) of sections 1165B-10-H and 1165B-10H-3, illustrating observed color and facies alternations at Site 1165; (mbsf—m below seafloor).

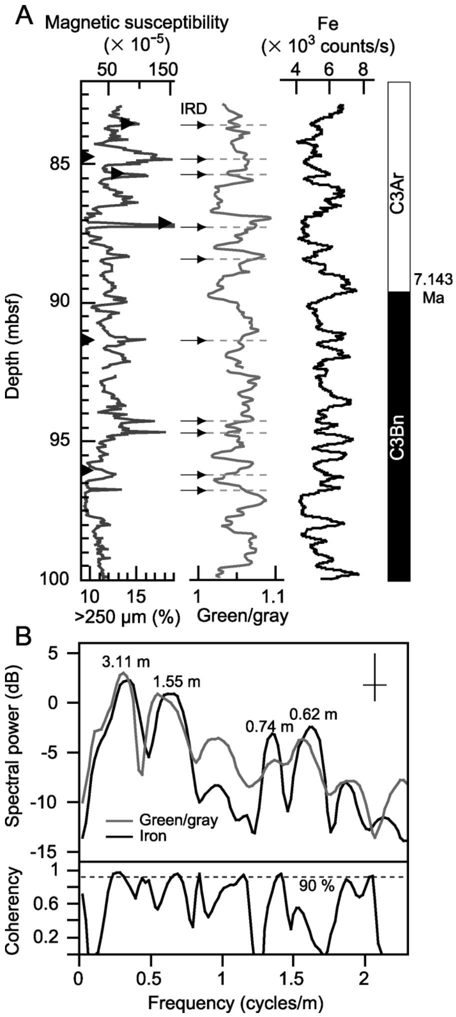

Figure 3. A: Magnetic susceptibility, green/gray color ratio, and Fe intensity measured for cores 1165B–10H and 1165B–11H. Triangles: samples with >10% sand-sized particles (i.e., >250 μm). Arrows—susceptibility spikes indicating ice-rafted debris (IRD) layers. Magnetostratigraphic age control is shown at right (mbsf—m below seafloor). B: Cross-spectral analyses of green/gray ratios and Fe records (normalized to unit variance) in depth domain. Cross gives 6 dB bandwidth and 90% confidence interval. Dashed horizontal line indicates 90% confidence level of coherency.

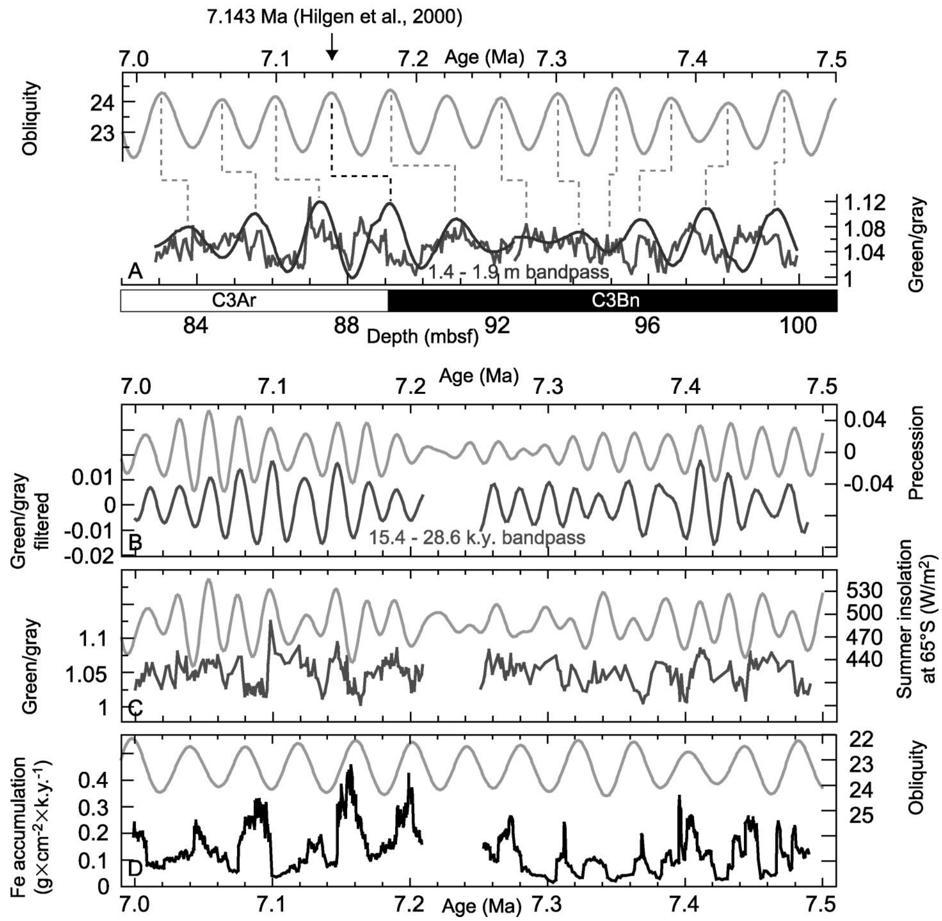

Figure 4. Astronomical calibrated age model for interval 82–100 m below seafloor (mbsf) at Ocean Drilling Program Site 1165. A: Preliminary depth to age conversion is based on correlation of orbital obliquity (Laskar, 1990) and filtered (bandpass centered at 1.55 m) color (green/gray ratio) record. Unfiltered data set is shown in background. B: Fine tuning was accomplished by filtering resulting (obliquity tuned) time series at 20 k.y. and correlating output to orbital precession. C: Resulting green/gray time series in comparison to solar insolation at 65°S. D: Time series for Fe accumulation (black) in comparison to obliquity.

bandpass-filtered (window from 1.38–1.90 m) green/gray ratio record to obliquity (Laskar, 1990) (Fig. 4A). Absolute age control is based on a magnetostratigraphic datum (top of chron C3Bn) found at 89.20 mbsf. According to the geomagnetic polarity time scale (GPTS) of Cande and Kent (1995), this reversal dates to 6.94 Ma, but the GPTS has been considerably modified by astronomical tuning of cyclic variations in geologic records. We here use the astronomical calibrated time scale of Hilgen et al. (2000) that dates the C3Bn reversal between 7.141 and 7.146 Ma. To further increase the resolution of our age model, we bandpass-filtered the resulting (obliquity tuned) time series at 20 k.y. (window from 15.4 to 28.6 k.y.) and correlated the output to orbital precession (Fig. 4B). The resulting (precession tuned) green/gray time series is in good agreement with summer insolation at 65°S (Fig. 4C). A time gap of one obliquity cycle (41 k.y.) between the cores was estimated.

Ice-Volume Changes

We postulate that fluctuations in continental-erosion rates in areas around Prydz Bay strongly controlled the observed cyclicity pattern and hence indicate that the size of the East Antarctic cryosphere varied on orbital time scales. We present two lines of evidence.

First, the Wild Drift received sediment directly from the adjacent glaciated continent, and drift growth was dominated by downslope sediment processes related to Lambert glacier advances to the shelf edge (Kuvaas and Leitchenkov, 1992). The drift is south of the Antarctic Circumpolar Current, and sedimentary structures are mostly absent in the study interval (Fig. 2); both these facts are consistent with a low-energy depositional environment in which along-slope water-mass movement is a minor component in the sediment-transportation process. Recurring IRD deposition (Fig. 3A) by floating icebergs suggests that ice cover was extensive, but the location of the glacier grounding line was possibly variable (e.g., Powell, 1984). IRD peaks occur just below maxima in the green/gray ratio. Because the green/gray ratio mimics biogenic silica content and correlates inversely with terrigenous supply, we think that IRD transport by floating icebergs was high during deglaciation and prior to maximum biogenic silica deposition, whereas IRD transport was reduced during times of maximum ice expansion (minimum opal deposition and likely complete ice cover). Hence IRD, terrigenous, and biogenic components appear to be controlled by ice-sheet size variations.

The second line of evidence is based on changes in Fe mass-accumulation rates (R_{Fe}). The R_{Fe} time series (Fig. 4D) is characterized by cyclic changes with maxima that occur about every 41 k.y. and correlate with lows in orbital obliquity. Changes in bottom-current transport patterns and hemipelagic processes may partly contribute to the R_{Fe} fluctuations. However, the large amplitude of the R_{Fe} variations (>100% during each obliquity cycle) indicates that large changes in sediment delivery from the Antarctic continent were occurring and that these changes are the likely explanation for changes in sediment accumulation at the continental rise. Records of sedimentological data from the continental shelf indicate that grounded ice advanced to the shelf edge during the late Miocene (Hambrey et al., 1991). From our data sets, we conclude that shifts to more extensive ice coverage—probably to the shelf edge—occurred during every 41 k.y. obliquity cycle.

Previous work in the nearby Kerguelen Plateau area (Joseph et al., 2002) identified Neogene time intervals of significantly enhanced sediment transport and IRD input to the Southern Ocean, indicating an active and wet-based EAIS. However, the relatively low time resolution of their studies did not allow determination of the frequency of ice advances. Our detailed results indicate that during late Miocene time, the EAIS was likely wet based with greater meltwater production and glacial sediment erosion than would occur with a stable, cold-based ice sheet such as today. Our inference agrees with the concept of Harwood and Webb (1998) and Hambrey and McKelvey (2000) that the transition to a more stable, cold ice sheet took place in late Pliocene or early Pleistocene time rather than in middle Miocene (Stroeven et al., 1998) time. Further, we conclude that the observed cyclicity mimics oscillations in the size of the EAIS ca. 7 Ma caused by orbital forcing. Therefore the Milankovitch variability seen in global oxygen isotope records of that time interval likely reflects significant EAIS ice-volume changes.

CONCLUSIONS

1. At Site 1165, pronounced alternations between a biogenic (green) and a more terrigenous (gray) facies have been observed. Spectral analyses on physical and chemical proxy records from selected sediment sections of late Miocene age indicate that variance is dominated by orbital frequencies of obliquity and precession.

2. A high-resolution time series of Fe accumulation rate based on our new tuned age scale reveals obliquity-controlled fluctuations in terrigenous delivery to the continental rise. The large magnitude of these fluctuations (100% change in Fe accumulation during one cycle) and the episodic recurring IRD input (during deglaciation and just prior to biogenic silica maxima) suggest that the EAIS was likely wet based and dynamic in late Miocene time.

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