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Glaciation across the Oligocene–Miocene boundary in southern McMurdo Sound, Antarctica: new chronology from the CIROS-1 drill hole

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Abstract

Few Palaeogene and Neogene sediment cores from the Antarctic continental margin have been dated with sufficient precision to enable establishment of direct linkages between glacial events on the Antarctic continent and marked events in deep-sea δ^{18}O records. As a result, much of our knowledge of the gradual, but stepwise, shift from 'greenhouse' climates of the Cretaceous to the 'ice-house' climates of the Quaternary is inferred from well-dated and more continuously deposited deep-sea sediments. In this study, we present new magnetostratigraphic results from the CIROS-1 drill core from McMurdo Sound, Antarctica, along with a reinterpretation of a published diatom biostratigraphic zonation that is constrained by correlation to a high-precision age model from the nearby CRP-2/2A drill core. Our results suggest that most of the upper 350 m of the CIROS-1 drill core represents rapid sediment accumulation during a short time interval spanning the Oligocene–Miocene boundary. Chronostratigraphic control is precise enough to enable correlation of this interval of glacimarine sedimentation with the Mi-1 deep-sea δ^{18}O event, which confirms that the Mi-1 event was related to a major expansion of Antarctic ice. A major unconformity at 366 m in the CIROS-1 drill core, which is widely observed in regional seismic reflection studies, represents 9 Myr of missing time. This unconformity can be traced offshore into the Ross Sea using seismic stratigraphy and is interpreted to indicate significant East Antarctic ice sheet development during the Mi-1 glaciation. The stratigraphic expression of this ~400-kyr glacial event is evidently multiphase and complex in the Victoria Land Basin, probably because it was punctuated by higher-frequency orbitally induced glacial oscillations. The presence of *Nothofagidites* pollen throughout the CIROS-1 drill core and the presence of a *Nothofagus* (Southern beech) leaf within the early Miocene portion of the core indicate that Antarctic mean summer temperatures did not decrease below 5°C throughout the Mi-1 glaciation. These temperatures are significantly warmer than present-day mean summer temperatures at sea level in McMurdo Sound. The persistence of a *Nothofagus* forest in coastal southern Victoria Land throughout this time interval suggests that the present state of deep refrigeration was not reached until some time after the Mi-1 glaciation.

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1. Introduction

Global compilations of deep-sea oxygen and carbon isotope records (e.g., Zachos et al., 2001a) suggest significant and extensive glaciation of the Antarctic continent since the Oi-1 glaciation (Miller et al., 1991) at the Eocene–Oligocene boundary. Oligocene glacigene strata recovered in Ocean Drilling Program drill holes from Prydz Bay (Hambrey et al., 1991; Florindo et al., 2003) and from Cape Roberts Project (CRP) drill holes from McMurdo Sound (Cape Roberts Science Team, 1999, 2000) confirm the presence of ice on the Antarctic craton since the earliest Oligocene. However, studies of the CIROS-1 drill core from McMurdo Sound, Ross Sea, Antarctica, suggested that glaciers did not advance and ground across the Ross Sea continental shelf until a mid-Oligocene (Barrett et al., 1989; Rieck, 1989; Harwood et al., 1989) glacioeustatic draw-down of sea level (Haq et al., 1987; Wilson et al., 1998). New data from McMurdo Sound, offshore of Cape Roberts (Cape Roberts Science Team, 1999), indicate a dynamic ice sheet history (Naish et al., 2001), with significant cooling, glacial intensification and Antarctic ice sheet expansion that was coincident with the Mi-1 glaciation (Miller et al., 1991) at the Oligocene–Miocene boundary.

The CIROS-1 core is an important record for constraining interpretations of Cenozoic Antarctic ice sheet development. Wilson et al. (1998) reported a magnetic polarity stratigraphy for the lower 336 m of the CIROS-1 drill core. Their interpretation indicated that strata directly underlying an unconformity at 366 m below sea floor (mbsf) span an interval from the late Eocene to the Eocene–Oligocene boundary, which is slightly older than previously reported by Harwood et al. (1989). Wilson et al. (1998) adopted the age interpretation of Rieck (1989) and Harwood et al. (1989) for the upper part of the core and concluded that glaciers did not advance and ground across the CIROS-1 site until after the mid-Oligocene unconformity at 366 mbsf. ^{40}Ar/^{39}Ar dating of two ash horizons near the Oligocene–Miocene boundary in the CRP-2/2A drill core enabled Wilson et al. (2002) to independently calibrate the Oligocene–Miocene boundary magnetic polarity stratigraphy and palaeontological datums for the Antarctic shelf. The upper part of the CIROS-1 drill core contains the same Antarctic continental shelf diatom zones (Harwood, 1989) as the Oligocene–Miocene boundary interval of the CRP-2/2A drill core (Scherer et al., 2000), which suggested that the recent age calibration of the diatom zones requires a revision of the age interpretations for the upper part of the CIROS-1 drill core.

In this paper, we reassess the age of the CIROS-1 succession above the unconformity at 366 mbsf in an effort to better resolve the temporal link between ice-proximal glacimarine sedimentation and interpretations of Cenozoic Antarctic ice sheet development based on deep-sea δ^{18}O events. In order to test whether the upper part of the CIROS-1 drill core correlates with the Oligocene–Miocene boundary interval of the nearby CRP-2/2A drill core (Fig. 1), we present a new magnetic polarity stratigraphy that was developed using more modern techniques and equipment than the original study by Rieck (1989). We also investigate the environmental magnetic signal of the upper sequence of the CIROS-1 drill core to test whether the magnetic signature associated with climatic variability in the lower sequence (Sagnotti et al., 1998a) persisted above the unconformity at 366 mbsf.

2. Geological setting and stratigraphy of the CIROS-1 core

Cenozoic Investigations in the western Ross Sea hole 1 (CIROS-1) was drilled in 197 m of water beneath McMurdo Sound (Fig. 1) and penetrated to a depth of 702 mbsf, with 98% core recovery

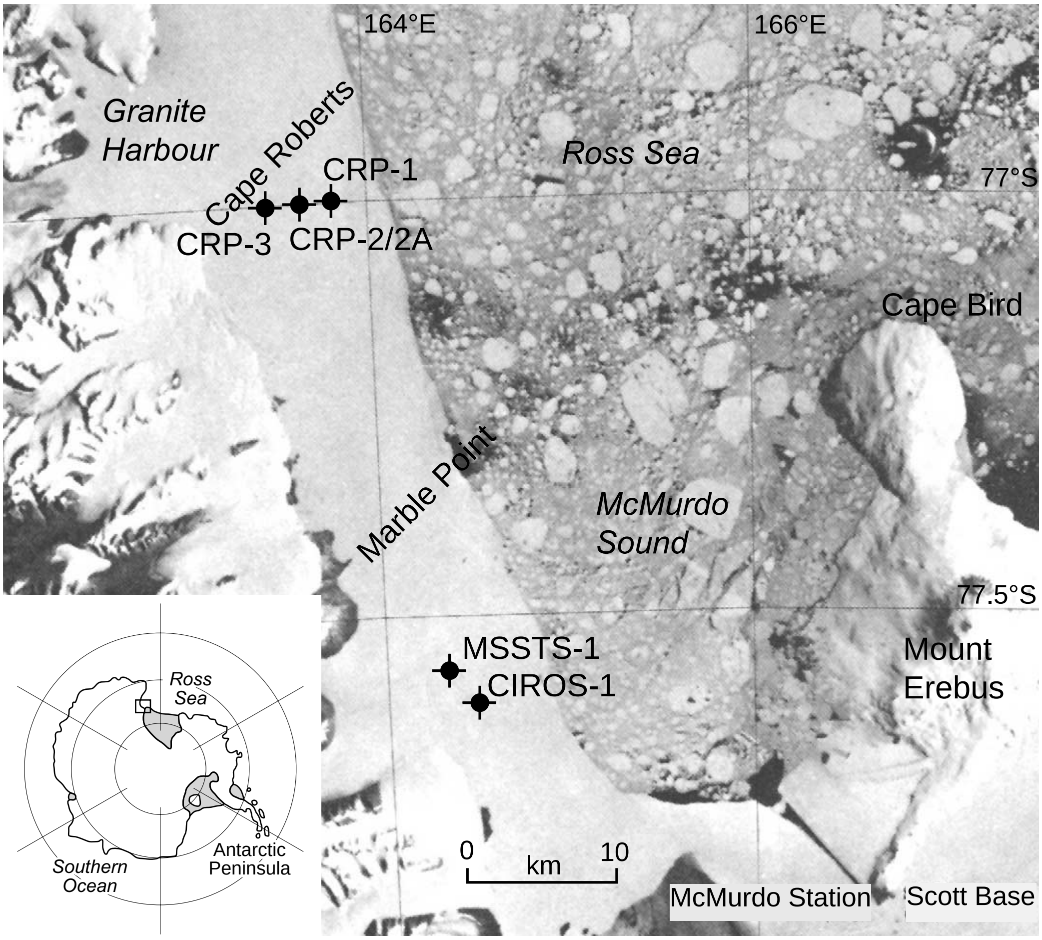


Fig. 1. Satellite image of the southwestern Ross Sea, with the location of relevant drill holes in McMurdo Sound. The box on the inset map indicates the location of the satellite image.

(Barrett, 1989). Robinson et al. (1987) logged the CIROS-1 drill core in detail and subdivided the recovered strata into 22 lithostratigraphic units. Subsequently, Hambrey et al. (1989) made a detailed analysis of the facies and depositional environments recorded in the core. A major unconformity at 366 mbsf separates the recovered sequence into two parts. A glacial influence is present throughout the drill core, but it is much more pronounced in the upper sequence (units 1–17) above the major unconformity (Fig. 2). The lower sequence (units 18–22), between 366 and 702 mbsf, is finer-grained and was only intermittently influenced by glacial activity (Hambrey et al., 1989). The unconformity at 366 mbsf occurs at the base of a 23-m-thick succession of graded conglomeratic sandstone beds (unit 17) that were interpreted to have a fluvial origin with deposition occurring in proximity to a terrestrial glacier (Hambrey et al., 1989). This unconformity has been correlated with a seismic reflector that is interpreted to represent significant glacial erosion and ice grounding across the Ross Sea (Anderson and Bartek, 1992; Barrett et al., 1995; Bartek et al., 1996) and is thought to represent a major event in the development of the East Antarctic Ice Sheet (EAIS).

Mildenhall (1989) recovered a sparse in situ assemblage of *Nothofagidites* pollen throughout the glacigene succession recovered in the CIROS-1

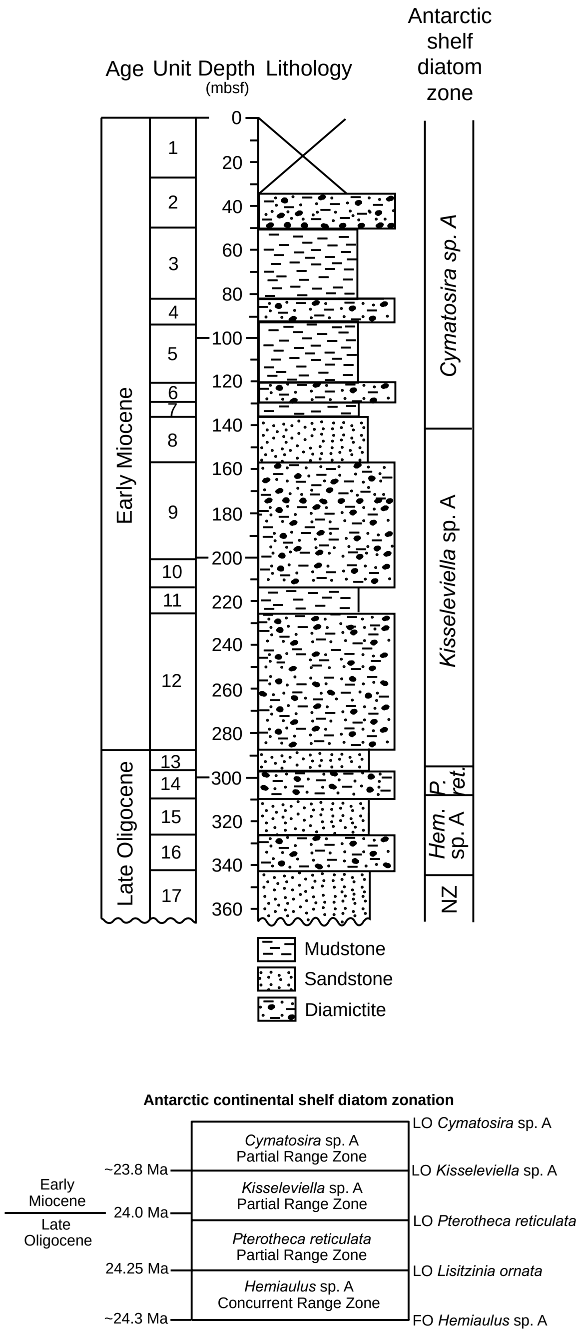


Fig. 2. Lithological column and diatom zonation for the upper 366 mbsf of the CIROS-1 drill core. The lithological units are from Hambrey et al. (1989). The diatom zonation is based on application of the diatom biostratigraphic zonation of Scherer et al. (2000) (bottom of figure) to the diatom biostratigraphic data of Harwood (1989). The calibration of the zonation of Scherer et al. (2000) is from Wilson et al. (2002). NZ = not zoned because the interval is barren of diatoms.

Fig. 3. Upper cast of a fossil leaf from 215.5 mbsf in the CIROS-1 drill core. Hill (1989) concluded that the leaf is closest in affinity to the Tasmanian *Nothofagus gunnii* (photograph: P.J. Barrett).

drill core. He interpreted this, along with the occurrence of a *Nothofagus* leaf at 215.5 mbsf (Hill, 1989) (Fig. 3), to indicate temperate to warm temperate conditions with forests occurring along the Antarctic coastline throughout the period of time represented by the CIROS-1 drill core.

The original chronological interpretation of the CIROS-1 succession was reported by Harwood et al. (1989). A combination of diatom, foraminiferal, calcareous nannofossil and palynological biostratigraphic datums, along with a single strontium isotope date, indicated that the lower sequence was early Oligocene in age. Rieck (1989) presented a palaeomagnetic interpretation for the CIROS-1 drill core, which was interpreted to indicate a late Oligocene age for the upper sequence. The disconformity that separates the lower (less glacial) and upper (glacial) sequences at 366 mbsf was interpreted to have had a duration of 4 Myr. Rieck (1989) did not carry out detailed demagnetisation for samples below 366 mbsf. Wilson et al. (1998) therefore undertook a more detailed palaeomagnetic investigation of the lower 336 m of the CIROS-1 drill core, to extend the magnetic polarity stratigraphy of Rieck (1989) to the base of the drill hole. Wilson et al. (1998) also reassessed the biostratigraphic and isotopic data presented by Harwood et al. (1989). They concluded that the lower part of the CIROS-1 succession is late Eocene in age, with the Eocene–Oligocene boundary being recorded at about

410–420 mbsf, within a 20-m-thick interval of mudstone. The numerical ages of the lower CIROS-1 succession provided by Wilson et al. (1998) are similar to those of Harwood et al. (1989); the change in designation from lower Oligocene to Eocene age is a result of redefinition of the Eocene–Oligocene boundary in the timescale of Cande and Kent (1995). As part of our reanalysis of the CIROS-1 drill core, we resampled the upper 366 mbsf of the drill core and subjected the samples to detailed palaeomagnetic analysis.

3. Methods

Two-hundred and thirty-one samples were obtained from the interval between 77.04 and 346.03 mbsf in the CIROS-1 drill core, which is housed at the Antarctic Research Facility core repository at Florida State University, Tallahassee, FL, USA. Cylindrical samples (25 mm diameter) were drilled from the core at approximately 0.5–1-m stratigraphic intervals. Sand grains, granules and pebbles in coarse-grained lithologies pose a problem for palaeomagnetic analysis because the deposition of such particles would be controlled by gravitational rather than magnetic forces. However, glacigene sediments from the Victoria Land Basin have polymodal particle size distributions with a significant mud component. Our palaeomagnetic sampling was restricted to the fine-grained sedimentary matrix; pebbly and deformed intervals were avoided. Based on our investigations of a number of cores from the Victoria Land Basin, it is evident that the palaeomagnetic signal is carried by fine-grained (pseudo-single domain) magnetite in the sediment matrix, even in dominantly coarse-grained lithologies (Roberts et al., 1998; Sagnotti et al., 1998a,b, 2001; Wilson et al., 1998, 2000; Verosub et al., 2000; Florindo et al., 2001). The characteristic remanent magnetisation (ChRM) directions identified in these studies have consistently steep inclinations with bimodal normal and reversed polarity distributions that pass palaeomagnetic field tests for stability, including a conglomerate test, and an inclination-only reversal test. Thus, even in diamictites, it is possible to sample the fine-grained sedimentary matrix and identify reliable palaeomagnetic directions. Samples were oriented with respect to vertical (i.e., in the up-core direction). Azimuthal orientation of the cores was not preserved during drilling, but this does not preclude magnetostratigraphic studies at high latitudes because the geomagnetic field has steep inclinations and palaeomagnetic polarity can be determined from inclination data only.

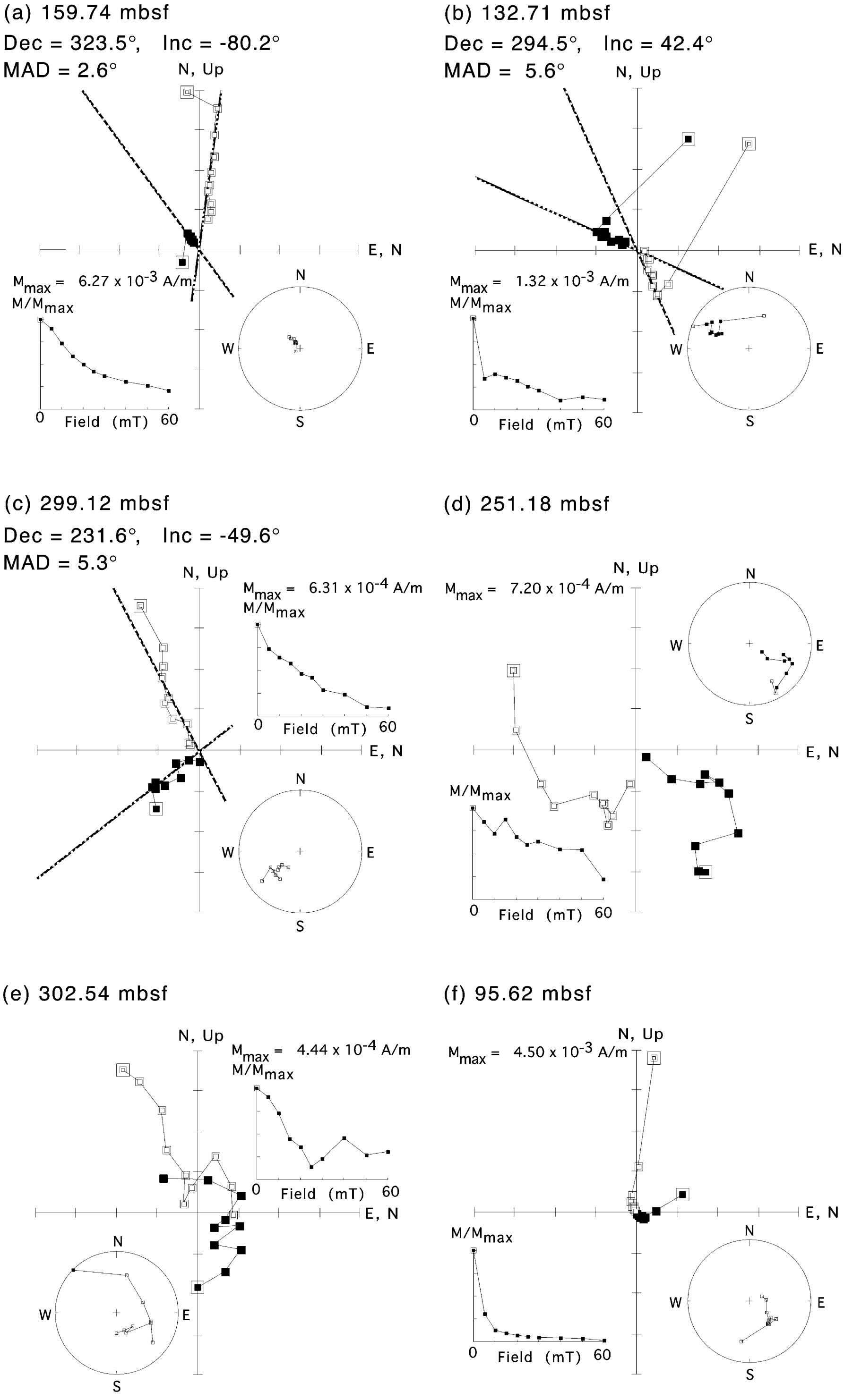
Measurements of the natural remanent magnetisation (NRM) were made using a 2G-Enterprises cryogenic magnetometer at the University of California, Davis (UCD), CA, USA. Static alternating field (AF) demagnetisation was performed using a system arranged in-line with the magnetometer. Vector component plots were inspected for all samples, and, if the magnetisation of the sample was stable, the ChRM was determined using principal component analysis (Kirschvink, 1980) with a minimum of three data points at different stepwise demagnetisation levels.

Magnetic susceptibility (κ) and anhysteretic remanent magnetisation (ARM) measurements were also made at UCD. κ was measured using a Bartington Instruments MS2 magnetic susceptibility meter. ARMs were imparted using a DC bias field of 0.05 mT and an AF of 100 mT. Magnetic hysteresis measurements were made at UCD using a Princeton Measurements Corporation alternating gradient magnetometer up to maximum fields of 1 T. Measured hysteresis parameters include the saturation remanence (M_r), saturation magnetisation (M_s), coercive force (B_c) and coercivity of remanence (B_{cr}).

4. Results

4.1. CIROS-1 magnetostratigraphy

As is the case for the lower part of the CIROS-1 drill core (Wilson et al., 1998), samples from the upper part of the CIROS-1 drill core are affected to variable extents by a near-vertical, normal polarity drilling-induced overprint (Fig. 4). The overprint is usually removed at peak AFs of 5–10 mT (Fig. 4a–c), although higher fields are often required to enable separation of the ChRM and


(a) 159.74 mbsf
Dec = 323.5°, Inc = -80.2°
MAD = 2.6°
N, Up
E, N
M$_{max}$ = 6.27 x 10^{-3} A/m
M/M$_{max}$
0 Field (mT) 60
N
W
E
S
(b) 132.71 mbsf
Dec = 294.5°, Inc = 42.4°
MAD = 5.6°
N, Up
E, N
M$_{max}$ = 1.32 x 10^{-3} A/m
M/M$_{max}$
0 Field (mT) 60
N
W
E
S
(c) 299.12 mbsf
Dec = 231.6°, Inc = -49.6°
MAD = 5.3°
N, Up
E, N
M$_{max}$ = 6.31 x 10^{-4} A/m
M/M$_{max}$
0 Field (mT) 60
N
W
E
S
(d) 251.18 mbsf
N, Up
M$_{max}$ = 7.20 x 10^{-4} A/m
E, N
M/M$_{max}$
0 Field (mT) 60
N
W
E
S
(e) 302.54 mbsf
N, Up
M$_{max}$ = 4.44 x 10^{-4} A/m
M/M$_{max}$
0 Field (mT) 60
E, N
N
W
E
S
(f) 95.62 mbsf
N, Up
M$_{max}$ = 4.50 x 10^{-3} A/m
E, N
M/M$_{max}$
0 Field (mT) 60
N
W
E
S

secondary overprints (Fig. 4d). Stable palaeomagnetic behaviour was evident in vector component diagrams for 70% of the samples, where the ChRM generally tended toward the origin of the diagrams. The remaining samples were either unstably magnetised with no systematic behaviour on demagnetisation (Fig. 4e) or were dominated by low-coercivity components so that no stable ChRM could be identified (Fig. 4f).

Most of the studied interval is dominated by normal polarity (Fig. 5). Three intervals with clear reversed polarity are evident at 92–111 mbsf, 247–256 mbsf and 338–342 mbsf. Reversed polarity is also recorded by a single sample at 263.00 mbsf, but we do not consider it to represent a real geomagnetic polarity interval because it is only indicated by a single sample. Similarly, a transitional interval at 281–284 mbsf is not considered to represent a real polarity interval because the two samples do not reach fully reversed polarity directions. Interpretation of the magnetic polarity zonation is discussed below.

4.2. CIROS-1 environmental magnetism

For the lower part of the CIROS-1 drill core (below 366 mbsf), Sagnotti et al. (1998a) reported alternations between zones of high magnetic mineral concentration ($\kappa > 50 \times 10^{-5}$ SI; NRM $> 10^{-2}$ A/m) and zones of low magnetic mineral concentration ($\kappa \approx 10 \times 10^{-5}$ SI; NRM $\approx 10^{-3}$ A/m). These zones with alternating magnetic properties provide a record of palaeoclimatically controlled variations in the weathering regime on the Antarctic craton, as suggested by concomitant variations in smectite concentration and crystallinity (Ehrmann, 1998). Environmental magnetic analyses were carried out for the upper part of the CIROS-1 drill core to test whether it contains similar evidence for palaeoclimatic control of the magnetic properties. The upper part of the CIROS-1 drill core has magnetic properties that are consistent with the zones of low magnetic mineral concentration from the lower part of the core (Figs. 6 and 7). Hysteresis parameters indicate a progressive up-core decrease in magnetic grain size (Fig. 7). The significance of these results is discussed below.

4.3. CIROS-1 diatom biostratigraphy

Marine diatoms are the most abundant, best-preserved and most age-diagnostic microfossil group in sediment cores from the Victoria Land Basin. The stratigraphic ranges of key diatom taxa of Harwood (1989) are summarised, following the biostratigraphic zonal scheme of Scherer et al. (2000), alongside a lithological log of the CIROS-1 drill core in Fig. 2. The sandstones in the vicinity of, and immediately above, the major unconformity at 366 mbsf are interpreted to represent fluvial deposits (Hambrey et al., 1989) and are almost barren of marine diatoms. The first diamictite above this interval falls within the *Hemiaulus* sp. A Zone, based on the first occurrence of the nominative taxon. The boundary between the *Hemiaulus* sp. A Zone and the *Pterotheca reticulata* Zone occurs just above an unconformity (Fielding et al., 1997) between samples at 309.38 and 304.95 mbsf, and is identified by the last occurrence (LO) of *Lisitzinia ornata*. The *Pterotheca reticulata* Zone appears to be thin in the CIROS-1 drill core, where the LO of *P. reticulata*, which marks the upper boundary of this zone, is identified between samples at 296.68 and 290.79 mbsf (Fig. 2). This position

Fig. 4. Representative vector component diagrams from the upper 350 mbsf of the CIROS-1 drill core. Open (closed) symbols represent projections onto the vertical (horizontal) plane. The dashed lines represent linear regression fits that indicate the ChRM direction for respective samples. (a) Example of stable palaeomagnetic behaviour for a normal polarity sample from 159.74 mbsf. (b) Reversed polarity sample from 132.71 mbsf. (c) Normal polarity sample from 299.12 mbsf. (d) Quasi-stable reversed polarity palaeomagnetic behaviour for a sample from 251.18 mbsf, where the polarity of the ChRM component is clear, but where an accurate principal component analysis cannot be made because of the noisy data. (e) Sample with unstable magnetisation from 302.54 mbsf. (f) Sample from a coarse-grained lithology (95.62 mbsf), which is dominated by a low-coercivity magnetisation. Samples such as those shown in panels e and f were not used for constructing a magnetic polarity zonation for the CIROS-1 drill core.

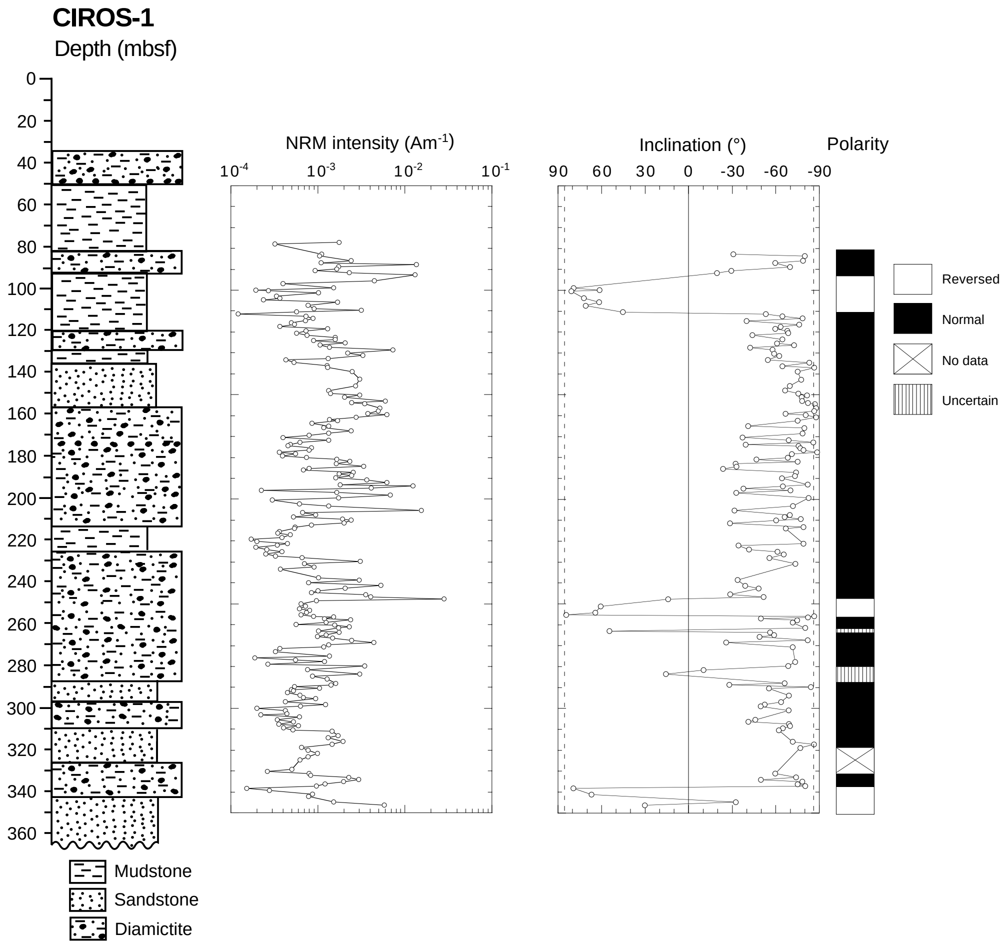


Fig. 5. Lithological log and down-core variations of the NRM intensity and inclination of the ChRM (identified from stepwise AF demagnetisation data) for the upper 350 mbsf of the CIROS-1 drill core. The magnetic polarity zonation is shown on the right-hand side of the diagram. Dashed vertical lines indicate the expected palaeomagnetic inclination at the site latitude. This revised interpretation is substantially different from that of Rieck (1989). See text for discussion. NB: The NRM intensities are consistent with those of Sagnotti et al. (1998a), whereas those reported by Wilson et al. (1998) were too high by a factor of 10.

for the LO of *P. reticulata* may be related to the coarse-grained lithofacies, which is poorly suited to documenting deposition of diatoms. The *Kisseleviella* sp. A Zone extends from the top of the *P. reticulata* Zone between 296.68 and 290.70 mbsf to a position between samples at 145.21 and 139.35 mbsf, where the LO of the nominative taxon was documented by Harwood (1989). The base of the overlying *Cymatosira* sp. A Zone is coincident with the top of the *Kisseleviella* sp. A Zone, but the top of the *Cymatosira* sp. A Zone is not well defined in the CIROS-1 drill core. The upper portion of this zone contains an interval with sparse diatom occurrences, which prevents resolution of the upper boundary of the *Cymatosira* sp. A Zone. Based on the calibration of the diatom zonation of Scherer et al. (2000) by Wilson et al. (2002), most of the upper 350 m of the CIROS-1 drill core represents a relatively short interval of time that extends from the latest Oligocene to the earliest Miocene (Fig. 2). This contrasts with the interpretations of Harwood et al. (1989) who concluded that the upper part of the CIROS-1 drill core, based on the palaeomagnetic

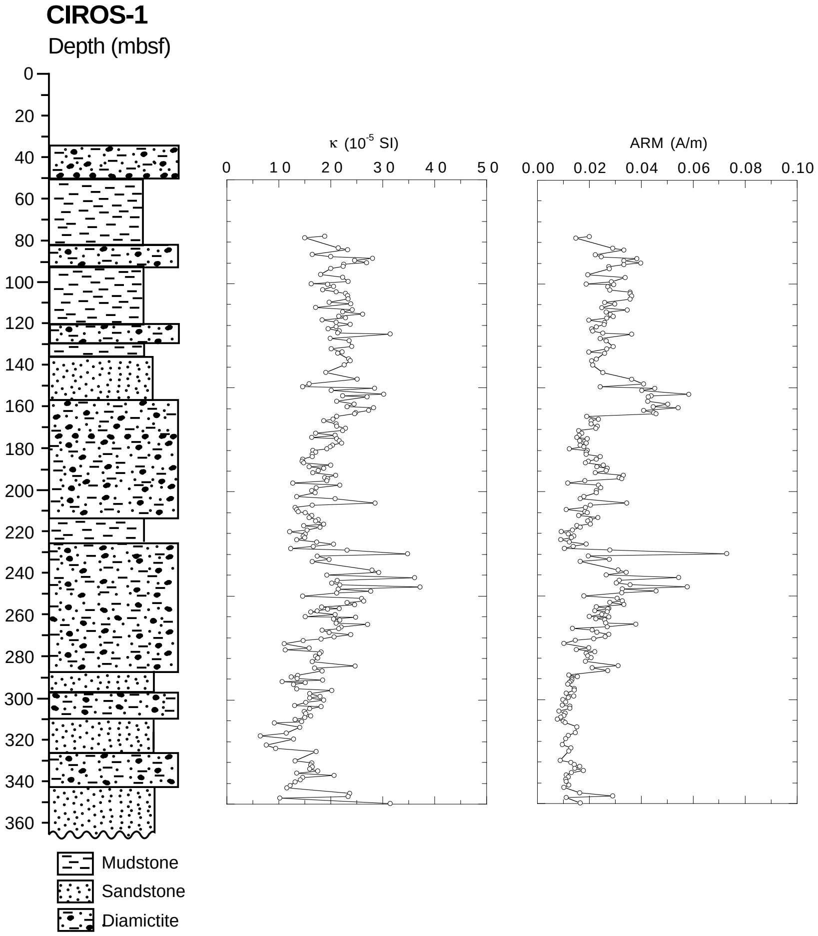


Fig. 6. Lithological log and down-core variations in volumetric magnetic susceptibility (κ) and ARM for the upper part of the CIROS-1 drill core.

polarity data of Rieck (1989), represents deposition during a broader age interval through the late Oligocene.

5. Discussion

5.1. Magnetostratigraphic interpretation for the CIROS-1 drill core above 366 mbsf

There are substantial differences between our new magnetostratigraphic results (Fig. 5) and those of the earlier magnetostratigraphic study of the upper part of the CIROS-1 drill core by Rieck (1989). The upper two reversed polarity intervals between 92 and 111 mbsf and between 247 and 256 mbsf were also identified by Rieck (1989), but they are both much thinner in our study. Rieck (1989) also reported more reversed polarity intervals within the long normal polarity interval that we document between 111 and 247 mbsf (Fig. 5). It may seem surprising that spurious reversed polarity directions have been reported in a core where there are normal polarity drilling-induced overprints. However, in this part of the CIROS-1 drill core, many samples (up to 30%) have unstable magnetisations (e.g., Fig. 4e) and it is not unusual for the noisy directions to have reversed polarity at some demagnetisation steps. Thus, if each sample is not treated with

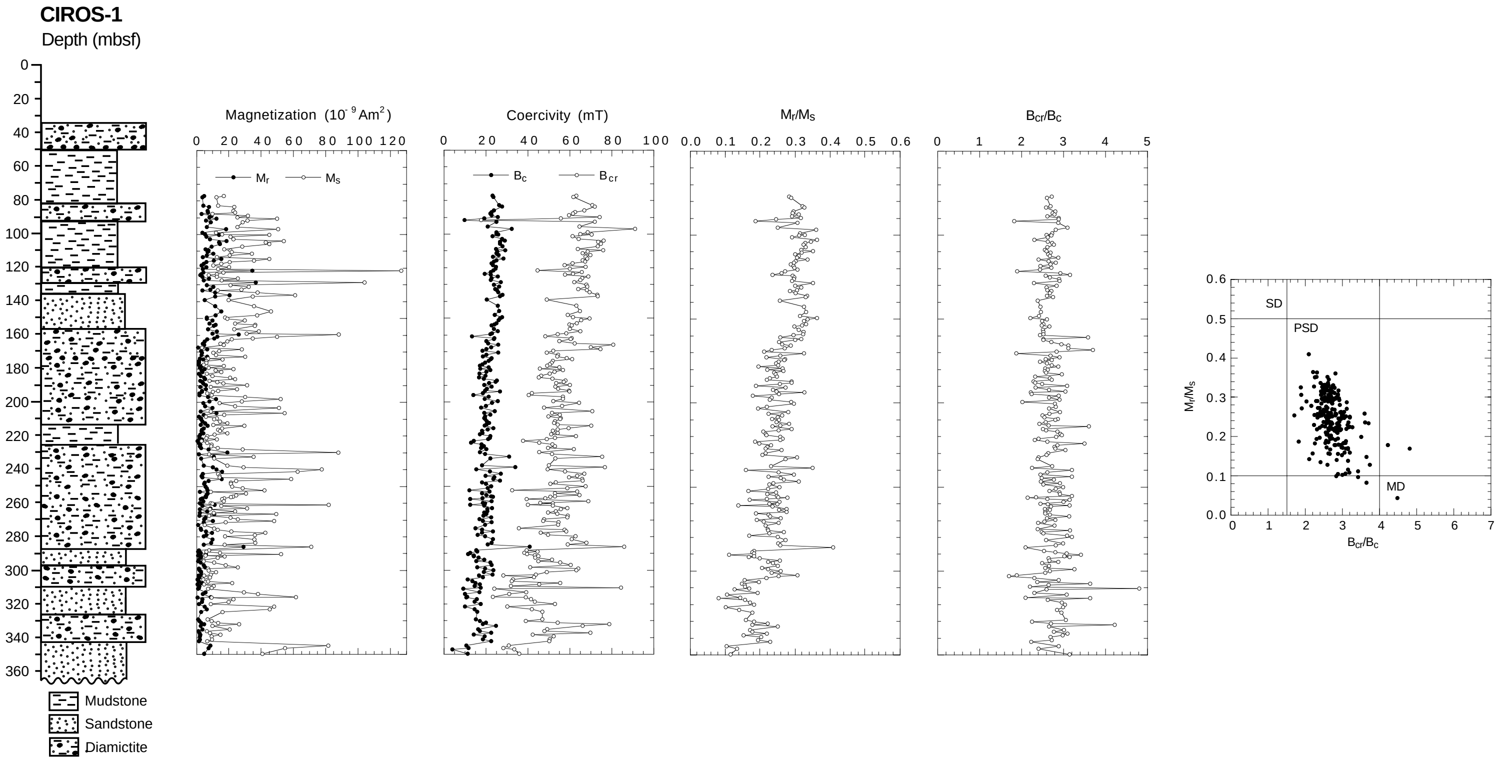


Fig. 7. Lithological log and down-core variations of magnetic hysteresis parameters for the upper 350 mbsf of the CIROS-1 drill core. The plot on the right-hand side indicates that the majority of the data fall in the PSD field of Day et al. (1977). SD = single domain, PSD = pseudo-single domain, and MD = multi-domain.

detailed stepwise demagnetisation, as seems to have been the case in the study by Rieck (1989), it is possible that spurious reversed polarity directions were preferentially selected because they were considered less likely to be affected by the secondary overprint. In many cases, reversed polarity directions were clear in stepwise demagnetisation data (Fig. 4b). In other cases, strong normal polarity overprints are clearly superposed on a reversed polarity ChRM (Fig. 4d). We only interpret reversed polarity ChRM directions in similar cases where it is clear that there is a systematic trend toward reversed polarity throughout the demagnetisation sequence. The polarity sequence obtained in our new analysis for the upper part of the CIROS-1 drill core is much simpler, with far fewer polarity intervals, than that reported by Rieck (1989). This, along with application of the updated Antarctic continental shelf diatom biostratigraphic zonation of Scherer et al. (2000), requires substantial changes to previous interpretations of the chronology of the upper portion of the CIROS-1 drill core.

Our chronostratigraphic interpretation of the CIROS-1 drill core is shown in Fig. 8. As is the case for the CRP-2/2A drill core (Wilson et al., 2000, 2002), the majority of the *Hemiaulus* sp. A Zone has normal polarity, although the lower part of this zone in the CIROS-1 drill core has reversed polarity. This suggests that the lower part of the studied interval in the CIROS-1 drill core represents the upper part of Chron C6Cr and Chron C6Cn.3n. By analogy with the CRP-2/2A drill core (Wilson et al., 2002), the reversed polarity interval in the *Kisseleviella* sp. A Zone is interpreted to represent part of Chron C6Cn.2r. It should be noted that there are numerous sharp sedimentary contacts in the CIROS-1 drill core that may represent unconformities within this reversed polarity interval. It is possible that much of Chron C6Cn.2r is missing at an unconformity and that the normal–reversed polarity transition at 256 mbsf and the reversed–normal polarity transition at 247 mbsf represent the chron C6Cn.3n–C6Cn.2r and C6Cn.2r–C6Cn.2n transitions, respectively. The reversed polarity interval between 92 and 111 mbsf probably represents Chron C6Cn.1r. The overlying normal polarity interval is unconstrained by diatom biostratigraphy, so correlation with Chron C6Cn.1n is uncertain. Overall, this interpretation of our new magnetic polarity stratigraphy and of the diatom biostratigraphic data of Harwood (1989), using the diatom zonal framework for the Antarctic shelf (Scherer et al., 2000), is consistent with the well-constrained chronology from the CRP-2/2A drill core (Wilson et al., 2002).

5.2. *Glacigene sedimentation at the Oligocene–Miocene boundary and the Mi-1 $\delta^{18}O$ event*

Our revised age interpretation for the upper part of the CIROS-1 drill core suggests that a significant glacial advance occurred close to the Oligocene–Miocene boundary in McMurdo Sound, as recorded by both the CIROS-1 and CRP-2/2A drill cores (Naish et al., 2001; Wilson et al., 2002). Deep-sea benthic foraminiferal δ^{18}O records for the Oligocene and Miocene are marked by events with increased δ^{18}O values (Oi-1 and Oi-2 in the Oligocene and Mi-1 to Mi-7 in the Miocene). Many of these events are interpreted to represent times of substantially increased ice volume at high latitudes and lower glacioeustatic sea levels (Miller et al., 1991). The peak of the Mi-1 δ^{18}O event occurred within Chron C6Cn.2r (Billups et al., 2002), which is coeval with increased glacigene sedimentation identified in the CIROS-1 and CRP-2/2A drill cores (Fig. 8). This ~400-kyr period of substantial glacigene sedimentation in the Victoria Land Basin suggests a marked increase in Antarctic ice volume in association with the Mi-1 δ^{18}O event, which confirms the suggestions of Naish et al. (2001) and Zachos et al. (2001b). However, the stratigraphic signature of glacigene sedimentation on the Antarctic continental shelf across the Oligocene–Miocene boundary is complex and does not represent a single pulse of sedimentation. Three distinct unconformity-bounded sequences are recognised in this interval of the CRP-2/2A core (Naish et al., 2001). This is consistent with evidence from deep-sea δ^{18}O records which indicates that the Mi-1 event spanned a period of ~400 kyr and that it was punctuated by higher-frequency orbitally induced (e.g., 40-kyr obliquity) glacial oscillations (e.g., Paul et al., 2000). The stratigraphic expression of such a multiphase glacial event at any given site will therefore depend on a number of factors including the extent of erosion associated with a single glacial advance. If the glaciers that feed from the EAIS to the Victoria Land Basin waxed and waned during successive 40-kyr cycles, it is likely that several erosion surfaces will be present and that these surfaces may sometimes amalgamate depending on the amount of erosion in a single glacial advance. Naish et al. (2001) interpreted the hiatus that removed most of Chron C6Cn.2r in the CRP-2/2A drill core to represent erosion during a period of expansion of the EAIS and sea level fall during the Mi-1 $\delta^{18}O$ event. However, the stratigraphic expression of the Mi-1 event is likely to have varied across the Victoria Land Basin and more work is required to unravel the complexities of glacigene sedimentary response to EAIS fluctuations in continental shelf environments during multiphase glacial events like the Mi-1 event.

Finally, it should also be noted that our revised chronology and correlation with the Mi-1 event also contrasts with the interpretation of Miller et al. (1991) who linked glacimarine sedimentation in the upper part of the CIROS-1 drill core to the Oi-2 $\delta^{18}O$ event.

5.3. The unconformity at 366 mbsf in the CIROS-1 drill core

An important question raised by our new chronology relates to the period of time represented by the unconformity at 366 mbsf in the CIROS-1 drill core. Using the geomagnetic polarity timescale of Cande and Kent (1995), Wilson et al. (1998) provided evidence that the lower part of the CIROS-1 drill core (366–702 mbsf) was deposited between 36.5 and 33 Ma (late Eocene to earliest Oligocene). Wilson et al. (1998) accepted the interpretation of Rieck (1989) and Harwood et al. (1989) for the interval above 366 mbsf, which suggested that the oldest sediments above 366 mbsf were deposited near the early–late Oligocene boundary at ~29 Ma and that the unconformity represents a hiatus of 4 Myr. The revised chronology presented here suggests that the unconformity at 366 mbsf represents a total duration of 9 Myr, with sediment accumulation beginning again near the Oligocene–Miocene boundary at 24.3 Ma (Fig. 8).

This revised age interpretation for the CIROS-1 drill core has important implications for the interpretation of regional seismic lines. Bartek et al. (1996) traced the major unconformity in the CIROS-1 drill core on seismic lines (base of seismic unit Q) across McMurdo Sound. Our revised estimates for the age of sediments on either side of the unconformity and the duration of the hiatus should help with reinterpretation of glacial history from seismic lines, at least in the vicinity of the CIROS-1 drill site. The incorrect original chronology for the portion of the CIROS-1 drill core above 366 mbsf (Harwood et al., 1989; Rieck, 1989) might explain why Bartek et al. (1996) were unable to see any convincing relationship between the seismic stratigraphic signature of the Ross Sea sediments and the sea level curve of Haq et al. (1987), and why such substantial thicknesses of upper Oligocene and lower Miocene sediments were unexpectedly recovered in the CRP drill holes offshore of Cape Roberts (Cape Roberts Science Team, 1998, 1999, 2000) (Fig. 1). It should also be noted that, while this unconformity appears to have had a major effect in the vicinity of the CIROS-1 drill core, a substantial thickness of sediment deposited between 33 and 24 Ma was recovered in the CRP-2/2A and CRP-3 drill holes (Cape Roberts Science Team, 1999, 2000; Wilson et al., 2000; Florindo et al., 2001). This observation suggests that variations in basinal accommodation space and glacial erosion can produce substantial local variations in the amount of sediment preserved in the stratigraphic record. Thus, to accurately understand glacial history in an ice-proximal setting, it is clear that numerous drill holes are necessary to avoid bias caused by local variations in erosion or sediment accumulation. Overall, sea levels appear to have been low throughout the late Oligocene (e.g., Billups and Schrag, 2002), and the CIROS-1 drill site appears to have been above sea level (Hambrey et al., 1989), which might partially explain the long duration of the hiatus represented by the uncon-

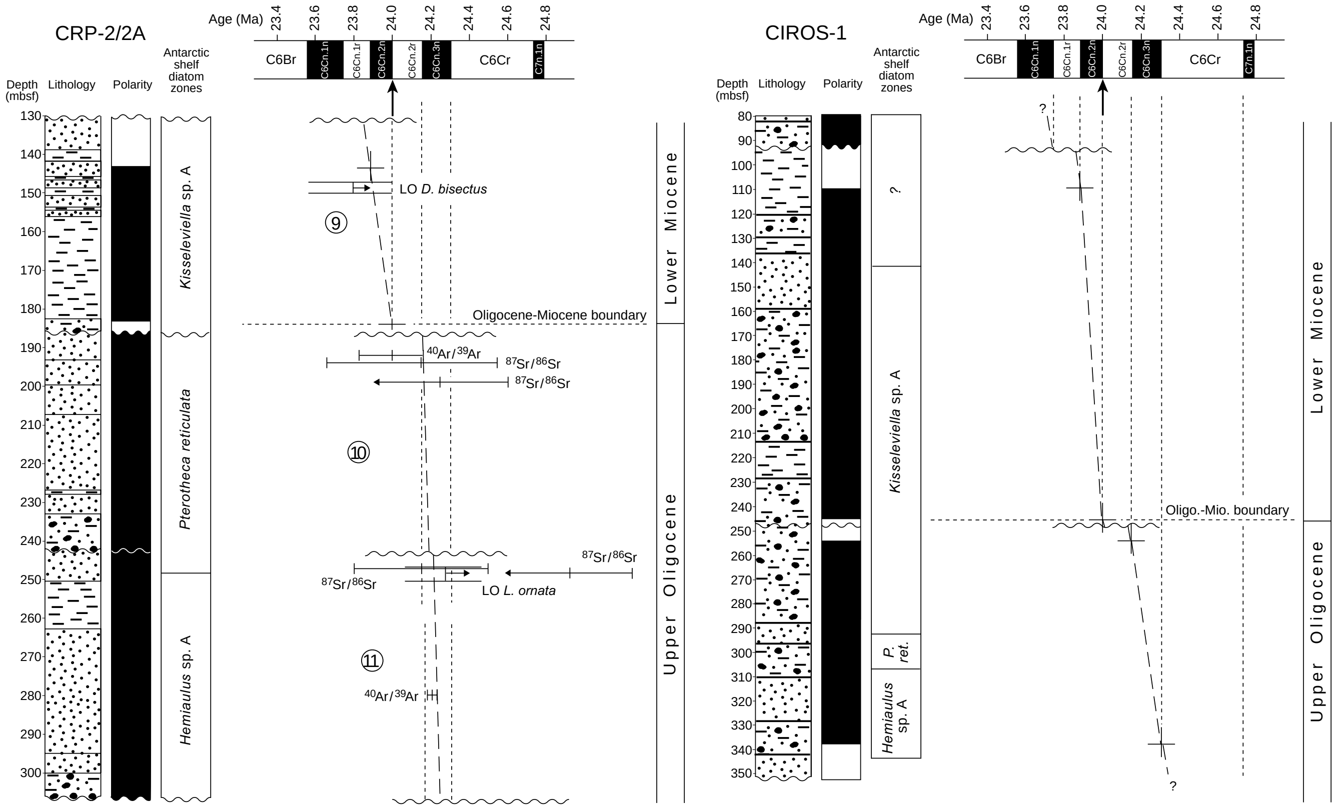


Fig. 8. Chronostratigraphic interpretation for the CIROS-1 drill core across the Oligocene–Miocene boundary interval. The interpretation for the CRP-2 drill core is from Wilson et al. (2000, 2002). The combination of high-precision $^{40}Ar/^{39}Ar$ dates, and $^{87}Sr/^{86}Sr$ dates, biostratigraphy and magnetostratigraphy provide an unusually high-precision chronology for Antarctic margin continental shelf sediments across the Oligocene–Miocene boundary. These age constraints are used to interpret the chronology for the CIROS-1 drill core. See text for discussion. The geomagnetic polarity timescale of Cande and Kent (1995) is used, but the dates follow the Oligocene–Miocene boundary calibration of Wilson et al. (2002). The peak of the Mi-1 glaciation occurred in Chron C6Cn.2r (Billups et al., 2002). It should be noted that placement of the Oligocene–Miocene boundary (arrow) at the base of Chron C6Cn.2n (Cande and Kent, 1995) means that the peak of the Mi-1 event occurred in the uppermost Oligocene rather than in the lowermost Miocene as defined by Miller et al. (1991).

formity at 366 mbsf in the CIROS-1 drill core compared to other drill holes in the Victoria Land Basin.

5.4. Environmental magnetism across the Oligocene–Miocene boundary in the Victoria Land Basin

Magnetic mineral concentrations are generally low in the studied interval of the CIROS-1 drill core. Sagnotti et al. (1998a) reported alternations between zones with high and low magnetic mineral concentrations in the upper Eocene to lower Oligocene portion of the CIROS-1 drill core. Zones with higher concentrations of fine-grained magnetite coincide with increased smectite contents, which have been attributed to increased chemical weathering of the Ferrar Dolerite under warmer, more humid climatic conditions (Ehrmann, 1998; Sagnotti et al., 1998a). In contrast, the low magnetic mineral concentrations in the upper part of the CIROS-1 drill core (above 366 mbsf) are consistent with decreased chemical weathering (Ehrmann, 1998; Sagnotti et al., 1998a). The presence of glacigene lithofacies throughout the upper part of the drill core suggests that physical weathering was dominant over chemical weathering under cooler climatic conditions.

Ehrmann (1998) noted increased smectite concentrations between 110 and 170 mbsf and between 233 and 285 mbsf in the CIROS-1 drill core, although these smectite concentrations are considerably less than in the lower part of the core (below 366 mbsf) where increased chemical weathering was inferred. These two intervals with elevated smectite concentrations also have the greatest concentrations of fine magnetic particles (Fig. 6) and increased contributions from basaltic sands derived from the McMurdo Volcanic Group (George, 1989). Rocks of the McMurdo Volcanic Group mainly crop out to the south of the CIROS-1 drill site. Thus, it appears that the CIROS-1 drill core records significant changes in source terrain, with local ice eroding McMurdo Volcanic Group rocks in the south at some time intervals. At other times, glaciers must have fed from the main EAIS through the Transantarctic Mountains and transported Beacon Supergroup, basement and early Palaeozoic rocks, as well as Ferrar Dolerites to the drill site. This variable provenance was also reported for the nearby MSSTS-1 drill core (Barrett et al., 1986).

The progressive upward fining of magnetite grain size observed in the CIROS-1 drill core (Fig. 7) probably reflects a progressive change in grain size of magnetic grains from the McMurdo Volcanic Group. Fining-upward trends were also observed in the CRP-2/2A (Verosub et al., 2000) and CRP-3 (Sagnotti et al., 2001) drill cores, although McMurdo Volcanic Group material is not present below 307 mbsf in the CRP-2/2A drill core (Smellie, 2000; Armienti et al., 2001). This fining-upward trend may therefore be controlled by changes in grain size of material eroding from the Ferrar Dolerite.

While magnetite concentrations vary in concert with smectite contents (both are derived from basic igneous rocks), the smectite in the Victoria Land Basin cores has variable origins (McMurdo Volcanic Group and Ferrar Dolerite) and cannot be simply interpreted in terms of variations in weathering regime and palaeoclimate. Nevertheless, magnetic properties, along with clay mineralogy, appear to be sensitive indicators of variation in sediment provenance in the Victoria Land Basin.

5.5. Indicators of Oligocene–Miocene climate and glaciation in the CIROS-1 core

Terrestrial palynology of the CIROS-1 and CRP-2/2A drill cores provides important constraints on climatic conditions of coastal southern Victoria Land across the Oligocene–Miocene boundary. In situ palynomorphs are dominated by *Nothofagidites* pollen that persist throughout much of the CIROS-1 succession (Mildenhall, 1989). The occurrence of *Nothofagidites* pollen in clumps and the occurrence of part of a beech leaf at 215.5 mbsf in the CIROS-1 drill core (Fig. 3) indicate the persistence of coastal forests until early Miocene times. This conclusion is supported by results of recent CRP drilling in southern Victoria Land (Raine, 1998; Askin and Raine, 2000). It is significant that this vegetation persisted beyond the Mi-1 glaciation. Hill (1989) concluded that the beech leaf at 215.5 mbsf was closest in affinity to the Tasmanian *Nothofagus gunnii*, which is adapted to a role as a coloniser in cold, disturbed habitats. Its presence in a mudstone unit in the CIROS-1 drill core suggests that it was growing in an interglacial period during the early Miocene. Webb and Harwood (1993) and Hill et al. (1996) undertook a comprehensive assessment of the phytogeography of high-latitude *Nothofagus* following its discovery in the Meyer Desert Formation (Sirius Group) from the Beardmore Glacier region (see also Francis and Hill, 1996; Ashworth et al., 1997). The evidence compiled by Hill et al. (1996) suggests that no extant *Nothofagus* species can survive temperatures below −22°C in winter and that summer air temperatures of the order of 5°C are required over periods of several weeks for *Nothofagus* to reproduce. This is significantly warmer than current conditions: mean annual temperatures of −20°C are recorded at sea level for McMurdo Sound and summer temperatures do not persist above 0°C for weeks on end. Therefore, the occurrence of *Nothofagidites* pollen in early Miocene strata of the CIROS-1, CRP-1 and CRP-2/2A drill cores indicates the persistence of cold interglacial conditions between the Oligocene and Oligocene–Miocene glaciations of the Antarctic continent, much like those of present-day high-altitude Tasmania and Patagonia (Hill, 1989). Based on this evidence, the Oi-1, Oi-2 and Mi-1 glacial events identified by Miller et al. (1991) and Zachos et al. (2001a) could not have been as cold as the present-day Antarctic climate. On the contrary, these glacials must have been significantly warmer than at present. Thus, while seismic stratigraphic evidence (e.g., Bartek et al., 1996) indicates that the unconformity at 366 mbsf in the CIROS-1 drill core extends well out into the Ross Sea, which suggests a major late Oligocene expansion of the EAIS, mean annual temperatures were warmer than today. This is consistent with the conclusion of Zachos et al. (2001b) who stated that the magnitude of the Mi-1 δ^{18}O excursion suggests the brief appearance of a full-scale ice sheet on east Antarctica coupled with a few degrees of deep-sea cooling.

6. Conclusions

New magnetostratigraphic results and the diatom biostratigraphy of Harwood (1989) from the upper part of the CIROS-1 drill core from McMurdo Sound, Antarctica, are interpreted here in light of a precise age calibration of the Antarctic continental shelf diatom biostratigraphic zonation (Scherer et al., 2000) for the Oligocene–Miocene boundary interval (Wilson et al., 2002). These results suggest that it is necessary to substantially revise published age interpretations for the sediments recovered above a major unconformity at 366 mbsf in the CIROS-1 drill core. This upper part of the CIROS-1 drill core records glacimarine sedimentation that is coeval with the Mi-1 δ^{18}O event recorded in deep-sea sediments. Our results, and those from the nearby CRP-2/2A drill core (Naish et al., 2001), therefore confirm that this δ^{18}O event was related to a major expansion of Antarctic ice. The unconformity at 366 mbsf is interpreted to represent erosion during expansion of the EAIS which extended well offshore into the Ross Sea (e.g., Bartek et al., 1996). In our interpretation of the age of the CIROS-1 drill core, this unconformity represents a hiatus of 9 Myr, which is substantially longer than previously estimated. Use of an incorrect age model for the upper part of the CIROS-1 drill core may explain why Bartek et al. (1996) did not observe a clear relationship between the seismic stratigraphic signature of Ross Sea sediments and the global sea level curve of Haq et al. (1987) and why coring near Cape Roberts recovered an unexpectedly thick Oligocene and Miocene record (Cape Roberts Science Team, 1998, 1999, 2000).

The presence of *Nothofagidites* pollen throughout the CIROS-1 drill core (Mildenhall, 1989) and a *Nothofagus* leaf in lower Miocene strata (Hill, 1989) suggests that mean annual temperatures were significantly warmer than present conditions in coastal McMurdo Sound during the late Oligocene and early Miocene. Thus, while seismic reflection data (Bartek et al., 1996) indicate that the extent of continental ice was at least as large as the present day, Antarctica did not reach the present level of deep refrigeration until some time after the Mi-1 glaciation. It therefore appears that relatively warm conditions, with dynamic ice sheets, persisted into the Miocene and that the Antarctic 'ice-house' was not fully developed during the Oi-1, Oi-2 and Mi-1 glaciations. The exact timing of the onset of 'ice-house' conditions is a matter of ongoing debate (e.g., Miller and Mabin, 1998). Further chronostratigraphically well-constrained records are required from events younger than the Mi-1 glaciation in order to resolve this debate.

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