Integrated chronostratigraphic calibration of the Oligocene-Miocene boundary at 24.0 ± 0.1 Ma from the CRP-2A drill core, Ross Sea, Antarctica

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ABSTRACT

An expanded Oligocene-Miocene boundary interval recovered in the Cape Roberts Project CRP-2A core from beneath the Ross Sea, Antarctica, has yielded a high-resolution integrated chronostratigraphy that has, in turn, enabled a new, more direct, calibration of magnetic polarity and biostratigraphic events. The Oligocene-Miocene boundary interval in the CRP-2A core comprises three ~60-m-thick, rapidly deposited (>0.5 m/k.y.) sedimentary sequences (sequences 9, 10, and 11). In sequences 10 and 11, single-crystal, laser-fusion $^{40}Ar/^{39}Ar$ analyses of anorthoclase phenocrysts from two tephra horizons independently calibrate the CRP-2A magnetic-polarity stratigraphy and age model. Sequences 10 and 11 encompass subchron C6Cn.3n, which is dated as 24.3 ± 0.1 to 24.16 ± 0.1 Ma. Sequence 9 is interpreted to encompass subchron C6Cn.2n and the Oligocene-Miocene boundary, which is dated as 24.0 ± 0.1 Ma. These ages are ~0.2 m.y. older than those of the geomagnetic polarity time scale calibrated from seafloor-spreading ridges and ~0.9–1.3 m.y. older than the newly proposed astronomically calibrated ages. We contend that the discrepancy with the astronomically calibrated ages arises from a mismatch of three 406 k.y. eccentricity cycles or a 1.2 m.y. modulation of obliquity amplitude in the astronomical calibration of the Oligocene–Miocene time scale.

Keywords: chronostratigraphy, isotope dating, Antarctica, biostratigraphy, Cape Roberts Project.

INTRODUCTION

Dating and correlation of the Oligocene-Miocene boundary in stratigraphic sequences has proved historically difficult and has been compounded by changes in the criteria for identification of the Oligocene-Miocene boundary. Berggren et al. (1985) defined it at the last occurrence (LO) of the nannofossil *Dictyococcites bisectus* in Deep Sea Drilling Project (DSDP) Site 522, where it occurs in the middle of chron C6Cn. When Cande and Kent (1992) revised the geomagnetic polarity time scale (GPTS), they assigned the Oligocene-Miocene boundary to the base of subchron C6Cn.2n, which slightly preceded the LO of *D. bisectus*.

Shackleton et al. (2000) proposed an astronomical calibration of the Oligocene-Miocene boundary in cores from Ocean Drilling Program (ODP) Site 929 and DSDP Site 522, where it is 0.9 m.y. younger than the boundary of Cande and Kent (1995). Despite the lack of a reliable magnetic polarity stratigraphy for Site 929, Shackleton et al. (1999) were able to match the composite magnetic susceptibility record with the orbital data of Laskar et al. (1993) by relying on the 406 k.y. and 100 k.y. eccentricity cycles. The result suggested that Oligocene biostratigraphic datums in Site 929 cores were much younger than their previously accepted ages (e.g., Berggren et al., 1995). Shackleton et al. (2000) used key biostratigraphic and carbon isotopic data in the vicinity of the Oligocene-Miocene boundary to correlate Sites 929 and 522 and to retune the Site 522 magnetostratigraphy (Tauxe et al., 1983) to the Site 929 astronomical time scale. The resulting age model suggested that the paleomagnetic subchrons within chrons C6 and C7 at Site 522 were also 0.9 m.y. younger than the conventionally calibrated GPTS (Cande and Kent, 1995).

CRP-2A CORE

In the Austral spring of 1998, an Oligocene-Miocene succession was recovered in the Cape Roberts Project CRP-2A core from offshore Cape Roberts, Antarctica (Fig. 1; Cape Roberts Science Team, 1999). Fielding et al. (2000) subdivided the CRP-2A succession into stratigraphic sequences on the basis of recurrent sedimentary lithofacies that are interpreted to represent cycles of glacial advance and retreat with associated changes in relative sea level. Between 130.27 and 306.65 mbsf (below seafloor) in the core, sequences 9, 10, and 11 represent an expanded Oligocene to Miocene succession with sediment accumulation rates of >1000 m/m.y. The chronology of the succession is well defined by diatom (Scherer et al., 2000) and calcareous nannofossil (Watkins and Villa, 2000) biostratigraphy and by $^{87}Sr/^{86}Sr$ (Lavelle, 2000) and $^{40}Ar/^{39}Ar$ (McIntosh, 2000) ages on mollusk fragments and ash horizons and volcanic clasts, respectively (Fig. 2). A magnetic polarity stratigraphy correlation (Wilson et al., 2000a; Fig. 2) and development of an age model demonstrate sedimentary sequence durations comparable to orbital frequencies of obliquity (40 k.y.) and eccentricity (100 k.y.; Naish et al., 2001).

CHRONOSTRATIGRAPHIC DATA
Diatom and Calcareous Nannofossil Biostratigraphy

Scherer et al. (2000) defined three diatom zones within sequences 9, 10, and 11 of the CRP-2A core as part of a new Antarctic conti-
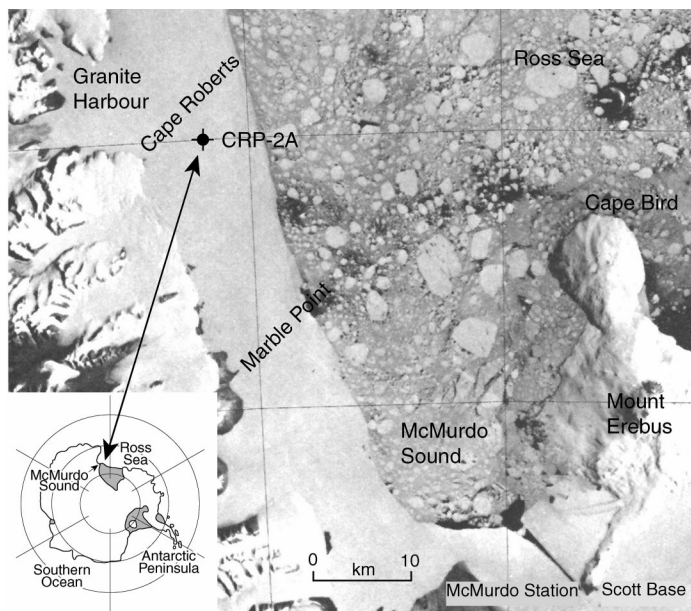
quences 9, 10, and 11 of the CRP-2A core with more detailed sampling (Table 1; Fig. 2). The boundary between the *Hemiaulus* sp. A zone and the *Pterotheca reticulata* partial range zone is defined by the LO of *Lisitzinia ornata* and occurs between samples at 256.92 and 259.20 mbsf within an interval of increased diatom abundances (Fig. 2). *L. ornata* ranges from chron C9r to chron C6Cr in the Southern Ocean. Its LO is best defined in cores recovered from the Kerguelen Plateau (ODP Leg 120). In Hole 748B, *L. ornata* last occurs in sample 748B-9H-3-47-48 cm beneath a short unconformity that is interpreted to be within chron C6Cr (Harwood and Maruyama, 1992). However, the LO of *L. ornata* may be as young as subchron C6Cn.2r. In Hole 747A, its LO is higher, within normal-polarity strata interpreted to be chron C6Cn and possibly subchron C6Cn.2n. Consequently, the LO of *L. ornata* cannot be reported to better than 24.1 ± 0.2 Ma (Table 1; Fig. 2). The boundary between the *P. reticulata* partial range zone and the *Kisseleviella* sp. A zone is defined by the LO of *P. reticulata* and coincides with the sequence-bounding unconformity that separates sequences 9 and 10 at 185.96 mbsf in CRP-2A.

Watkins and Villa (2000) identified the LO of *D. bisectus* and hence the top of the *D. bisectus* zone (Wei and Wise, 1992) at 149.28 mbsf within sequence 9 in CRP-2A (Fig. 2). Wei and Wise (1989) used the LO of *D. bisectus* at DSDP Sites 516, 522 (Poore et al., 1983), 558, and 563 (Miller et al., 1985) to define the Oligocene-Miocene boundary at 24.0 Ma. Unfortunately, however, the LO of *D. bisectus* at Site 516 is truncated by a hiatus as long as 0.6 m.y. in duration, and only two normal-polarity subchrons were recognized within chron C6Cn at Sites 558 and 563 (Miller et al., 1985; Berggren et al., 1995). The paleomagnetic record at Site 522 is, however, more complete (Tauxe et al., 1983), and it allowed Poore et al. (1983) and Hsü et al.

nental-shelf diatom zonation that is tied to magnetostratigraphically calibrated Southern Ocean diatom zonations (Baldauf and Barron, 1991; Harwood and Maruyama, 1992). We have been able to refine the position of individual diatom datums and zonal boundaries in se-

Figure 1. Map of southwest Ross Sea, showing location of Cape Roberts Project CRP-2/2A core.
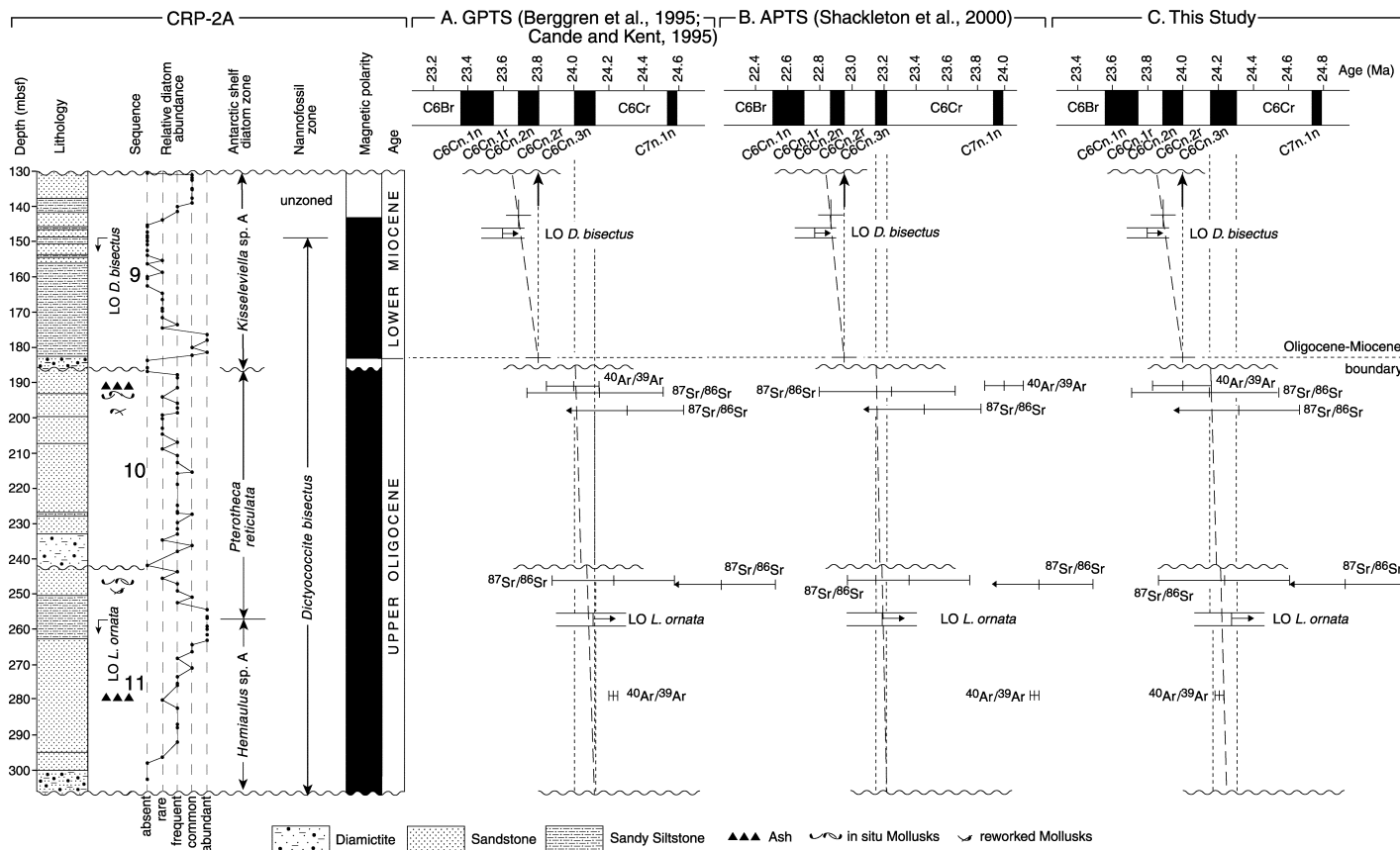

Figure 2. Stratigraphy of sequences 9, 10, and 11 of CRP-2A core and comparison of chronostratigraphic data and age model for CRP-2A sequences 9, 10, and 11 using (A) geomagnetic polarity time scale (GPTS) of Berggren et al. (1995) and Cande and Kent (1995), (B) astronomical polarity time scale (APTS) of Shackleton et al. (2000), and (C) time scale calibrated by [40]Ar/[39]Ar ages discussed in this study. Chronostratigraphic data are listed in Table 1. LO—last occurrence; mbsf—meters below seafloor.

Datum	Previously published age (Ma)*	This paper	
		CRP-2A depth (mbsf)	CRP-2 age (Ma)
Sequence 9			
LO *Kisseleviella* sp. A[†]		130.61 ± 0.29	<23.84 ± 0.1
C6Cn.1r/C6Cn.2n	23.677	143.71	23.87 ± 0.1
LO *Dictyococcites bisectus*	23.6 ± 0.1[§]	146.86 ± 2.42	23.87 ± 0.1
Oligocene-Miocene boundary	23.800	183.7	24 ± 0.1
C6Cn.2n to C6Cn.2r transition	23.800	183.7	24 ± 0.1
Sequence 9-10 boundary		185.96	>24.0 <24.16
Sequence 10			
C6Cn.2r/C6Cn.3n transition	23.999	185.96[#]	24.16 ± 0.1
LO *Pterotheca reticulata*[†]		188.13 ± 0.45	>24.98 <24.16
[40]Ar/[39]Ar age** on pumice		193.42 ± 0.05	23.98 ± 0.13
[87]Sr/[86]Sr age[††] on bivalve frag.[§§]	23.95 ± 0.45	194.89	24.13 ± 0.45
[87]Sr/[86]Sr age[††] on bivalve frag.[##]	24.10 ± 0.35	198.75	24.30 ± 0.35
Sequence 10-11 boundary		242.7	>24.2 <24.23
Sequence 11			
[87]Sr/[86]Sr age[††] on bivalve frag.[§§]	24.02 ± 0.35	246.97	24.23 ± 0.35
[87]Sr/[86]Sr age[††] on bivalve frag.[##]	24.81 ± 0.32	247.67	24.86 ± 0.32
LO *Lisitzinia ornata*	24.1 ± 0.2***	258.06 ± 1.14	24.3 ± 0.1
[40]Ar/[39]Ar age** on pumice		280.03 ± 0.11	24.22 ± 0.03
FO *Hemiaulus* sp. A[†]		297.24 ± 0.85	24.25 ± 0.1
C6Cn.2r/C6Cn.3n transition		306.65[#]	24.3 ± 0.1

*With respect to the geomagnetic polarity time scale (Cande and Kent, 1995; Berggren et al., 1995).
[†]New Antarctic shelf datums (this study).
[§]Southern Ocean age (Poore et al., 1983; Hsü et al., 1983).
[#]Transition occurs within a hiatus in the CRP-2A core.
**[40]Ar/[39]Ar ages were determined relative to the interlaboratory standard Fish Canyon Tuff sanadine with an assigned age of 27.84 Ma (Deino and Potts, 1990). Mean ages were calculated using the variance weighting method of Samson and Alexander (1987). Errors were calculated using the method of Taylor (1982).
[††][87]Sr/[86]Sr age error include a 2σ measurement error, a 2σ long-term laboratory error for standard determination and error in the LOWESS fit to the marine Sr curve of McArthur et al. (2001).
[§§]In situ.
[##]Provenance uncertain.
***Southern Ocean age (Harwood and Maruyama, 1992).

(1983) to place the LO of *D. bisectus* within subchron C6Cn.1r (23.6 ± 0.1 Ma). We have adopted this age for the LO of *D. bisectus* (Fig. 2).

[87]Sr/[86]Sr Stratigraphy

Lavelle (2000) reported four ages from [87]Sr/[86]Sr analyses of mollusk fragments recovered from CRP-2A sequences 9, 10, and 11 (Table 1; Fig. 2). We have improved the analytical error on the sample from 194.89 mbsf. The [87]Sr/[86]Sr values were normalized to NIST-987 ([87]Sr/[86]Sr = 0.708 249, $n = 55$, $2\sigma = 0.000\,015$) and converted to best-fit age and error by using the LOWESS fit to the marine Sr curve of McArthur et al. (2001). Shell taphonomy indicates that shells at 194.89 mbsf (sequence 10) and 246.97 mbsf (sequence 11) are in situ. They have [87]Sr/[86]Sr ages of 23.95 ± 0.45 Ma and 24.02 ± 0.35 Ma, respectively (Table 1; Fig. 2). Shells at 198.75 mbsf (sequence 10) and 247.67 mbsf (sequence 11) cannot be confidently identified as in situ, but afford maximum ages of 24.10 ± 0.35 Ma and 24.81 ± 0.34 Ma, respectively (Table 1; Fig. 2).

Paleomagnetism

A magnetic-polarity zonation for CRP-2A sequences 9, 10, and 11 was reported by Wilson et al. (2000b) and is shown in Figure 2. Discrete paleomagnetic samples were taken, on average, at 0.5 m stratigraphic intervals and characteristic remanent magnetization (ChRM) directions were determined using principal component analysis of detailed stepwise demagnetization data. A conglomerate test in an intra-

formational breccia at 311–315.6 mbsf and a reversals test were used to infer that the ChRM directions are ancient and primary.

[40]Ar/[39]Ar Ages

Single-crystal laser-fusion analyses of anorthoclase phenocrysts from two tephra layers provide ages for sequences 10 and 11 of the CRP-2A core. Weighted mean ages of 23.98 ± 0.13 Ma ($n = 19$) and 24.22 ± 0.03 Ma ($n = 52$) were calculated from multiple analyses of pumice clasts in the tephras at 193.34–193.37 mbsf and 279.92–280.13 mbsf, respectively (McIntosh, 2000; Table 1; Fig. 2).

AGE MODEL

The [87]Sr/[86]Sr ages are consistent with nannofossil and diatom biostratigraphy for the CRP-2A core. Along with the LO of *L. ornata*, they define the age of sequences 10 and 11 as the latest Oligocene and indicate the correlation of the normal polarity of sequences 10 and 11 with subchron C6Cn.3n of the GPTS. Wilson et al. (2000a, 2000b) took the LO of *D. bisectus* to mark the Oligocene-Miocene boundary and reported two possible age models for sequence 9. In the first model, the reversed-normal-reversed polarity pattern in sequence 9 was correlated with subchrons C6Cn.2r-C6Cn.2n-C6Cn.1r of the GPTS, which required *D. bisectus* to last occur within C6Cn.2n (the lowermost Miocene). The second age model involved correlation of both the interval of normal polarity in sequences 10 and 11 and the normal polarity of sequence 9 with subchron C6Cn.3n of the GPTS. This correlation left the thin reversed-polarity interval at the base of sequence 9 with no equivalent in the GPTS.

Following our more recent reevaluation of the occurrence of *D. bisectus* in the Southern Ocean and our refinement of the diatom zonation of sequences 9, 10, and 11 of the CRP-2A core, we prefer the first age model, which was also adopted by Naish et al. (2001). In this age model, the Oligocene-Miocene boundary is placed within sequence 9 at the base of subchron C6Cn.2n at 183.70 mbsf, which suggests that much of subchron C6Cn.2r is missing in the sequence-bounding unconformity that separates sequences 9 and 10. This interpretation also suggests that (1) sequence 9 represents a duration of ~120 k.y. because it encompasses subchron C6Cn.2n in its entirety and (2) sequences 10 and 11 combined represent a duration of ~120 k.y. because they both correlate with subchron C6Cn.3n (Fig. 2).

Calibration of Subchron C6Cn.3n

The tephra at 279.92–280.13 mbsf in sequence 11 occurs within normal-polarity subchron C6Cn.3n, yet its [40]Ar/[39]Ar age (24.22 ± 0.03 Ma) suggests that it should be within reversed-polarity chron C6Cr (Fig. 2A) of the conventionally calibrated GPTS. Given the low error on this age, we conclude that the age of the C6Cr to C6Cn.3n transition in the CRP-2A core is 0.1–0.2 m.y. older than the 24.118 Ma age reported by Cande and Kent (1995). It is not possible to define the difference more exactly because the base of C6Cn.3n is truncated in a hiatus in the CRP-2A core. The [40]Ar/[39]Ar age (23.98 ± 0.13 Ma) of the tephra at 193.37–193.47 mbsf has a higher error, but it does not preclude the possibility that the C6Cn.3n to C6Cn.2r transition in the CRP-2A core is also 0.1–0.2 m.y. older. Accordingly, we propose an age of 24.16 ± 0.1 to 24.3 ± 0.1 Ma for subchron C6Cn.3n in the CRP-2A core (Fig. 2C).

Comparison with the Astronomical Calibration of C6Cn.3n

Shackleton et al. (2000), in their astronomical calibration of the Oligocene-Miocene boundary, suggested not only that this boundary is 0.9 m.y. younger than the age reported by Cande and Kent (1995), but also that the GPTS in the vicinity of the boundary (subchrons C6Cn.1n to C7n.2n) is 0.9 m.y. younger than reported by Cande and Kent (1995). Because the discrepancy between these age estimates is so large, our ability to test the astronomically calibrated age does not rely on our ability to date the Oligocene-Miocene boundary. It hinges

on our ability to date any number of the subchrons in the vicinity of the boundary. Our ability to identify and date subchron C6Cn.3n in the CRP-2A core is robust, and it is within 0.2 m.y. of the Oligocene-Miocene boundary. Our proposed age of 24.16 ± 0.1 to 24.3 ± 0.1 Ma for subchron C6Cn.3n is 0.9–1.3 m.y. younger than the astronomically calibrated age of 23.13 ± 0.05 to 23.21 ± 0.05 Ma proposed by Shackleton et al. (2000).

To test their calibration, Shackleton et al. (1999) conducted a cross-spectral analysis of eccentricity versus the amplitude of the variability in magnetic susceptibility and noted high coherency at periods of 406 k.y. and 1.2 m.y. This result, they concluded, suggested that either their time scale was broadly correct or it should be shifted by a multiple of 406 k.y. eccentricity cycles. We contend that Shackleton et al. (1999) were three 406 k.y. eccentricity cycles or a 1.2 m.y. modulation of obliquity amplitude too young in their match and that the ages of the Oligocene-Miocene boundary at Sites 929 and 522 and of subchron C6Cn.3n at Site 522 should be astronomically calibrated to ca. 24.0 ± 0.1 Ma and 24.3 ± 0.1 to 24.16 ± 0.1 m.y., respectively. With this calibration, the astronomical age of subchron C6Cn.3n is within error of the $^{40}Ar/^{39}Ar$ calibrated age (24.3 ± 0.1 to 24.16 ± 0.1 m.y.) that we have obtained for the CRP-2A core.

CONCLUSIONS

Despite the generally coarse-grained nature of the sediments and the presence of multiple stratigraphic hiatuses in the CRP-2A record, we have, for the first time, been able to integrate biostratigraphy and magnetic-polarity stratigraphy with $^{87}Sr/^{86}Sr$ and $^{40}Ar/^{39}Ar$ ages to date Oligocene–Miocene strata from the Antarctic margin with a resolution and precision of <100 k.y. Our integrated chronostratigraphy provides a well-defined age model for strata around the Oligocene-Miocene boundary in the CRP-2A core. Correlation of a high-resolution magnetic-polarity record with subchrons C6Cn.3n–C6Cn.1r is determined by diatom and nannofossil biostratigraphy and $^{87}Sr/^{86}Sr$ ages. Subchron C6Cn.3n is, in turn, independently calibrated at 24.3 ± 0.1 to 24.16 ± 0.1 Ma by $^{40}Ar/^{39}Ar$ ages on pumice from two tephra horizons in CRP-2A sequences 10 and 11, respectively. We conclude that the Oligocene-Miocene boundary occurs at ~186 mbsf in CRP-2A sequence 9, at the base of subchron C6Cn.2n, and that it is 24.0 ± 0.1 Ma in age or 0.2 m.y. older than in the conventionally calibrated GPTS (Cande and Kent, 1995).

Our new calibration does not affect the duration of the magnetic polarity subchrons in the vicinity of the Oligocene-Miocene boundary (chrons C6Cn.1r, C6Cn.2n, C6Cn.2r, and C6Cn.3n), because we contend that the entire time scale in the vicinity of the Oligocene-Miocene boundary is ~200 k.y. older than in the conventionally calibrated GPTS (Cande and Kent, 1995). Nor does our new calibration affect the conclusions of duration of the sedimentary cycles in CRP-2A and their relationship to the Oligocene-Miocene boundary (Naish et al., 2001). However, our $^{40}Ar/^{39}Ar$ calibrated ages for the Oligocene-Miocene boundary and subchrons C6Cn.3n–C6Cn.1r contrast markedly with the astronomically calibrated ages of Shackleton et al. (2000). The astronomically derived ages are 0.9 m.y. younger than in the conventionally calibrated GPTS (Cande and Kent, 1995) and 0.9–1.3 m.y. younger than the $^{40}Ar/^{39}Ar$ calibrated ages from the CRP-2A core. We contend that Shackleton et al. (1999, 2000) are three 406 k.y. eccentricity cycles or a 1.2 m.y. modulation of obliquity amplitude too young in their astronomical calibration.

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