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

Gary S. Wilson  Geology Department, University of Otago, PO Box 56, Dunedin, New Zealand
Mark Lavelle  British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK, and Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK
William C. McIntosh  New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801, USA
Andrew P. Roberts  School of Ocean and Earth Science, University of Southampton, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK
David M. Harwood  Department of Geosciences, University of Nebraska, Lincoln, Nebraska 68588-0340, USA
David K. Watkins  Department of Geosciences, University of Nebraska, Lincoln, Nebraska 68588-0340, USA
Giuliana Villa  Dipartimento di Scienze della Terra, Università di Parma, Parco Area delle Scienze 157A, 43100 Parma, Italy
Steven M. Bohaty  Earth Sciences Department, University of California, 1156 High Street, Santa Cruz, California 95064, USA
Chris R. Fielding  Department of Earth Sciences, University of Queensland, Brisbane, QLD 4072, Australia
Fabio Florindo  Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, I-00143 Rome, Italy
Leonardo Sagnotti  Dipartimento di Scienze della Terra, Università di Parma, Parco Area delle Scienze 157A, 43100 Parma, Italy
Timothy R. Naish  Institute of Geological and Nuclear Sciences Ltd, P.O. Box 30-368, Lower Hutt, New Zealand
Reed P. Scherer  Department of Geology and Environmental Geosciences, Northern Illinois University, De Kalb, Illinois 60115, USA
Kenneth L. Verosub  Department of Geology, University of California, Davis, California 95616, USA

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 40Ar/39Ar 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.2n, 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 Dictyococcosites bissectus 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. bissectus.

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 magnetostatigraphy (Tauxe et al., 1983) to the Site 929 astronomical time scale. The resulting age model suggested that the paleomagnetic subchrons within chron 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 87Sr/86Sr (Lavelle, 2000) and 40Ar/39Ar (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-
continental-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 sequences 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 Hsiü et al.
TABLE 1. CHRONOSTRATIGRAPHIC DATA FOR SEQUENCES 9, 10, AND 11 OF THE CRP-2A CORE

<table>
<thead>
<tr>
<th>Datum</th>
<th>Previously published age (Ma)*</th>
<th>This paper</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRP-2A depth (mbsf)</td>
<td>CRP-2 Age (Ma)</td>
</tr>
<tr>
<td>Sequence 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LO Kisselievia sp. A</td>
<td>130.61 ± 0.29</td>
<td>&lt;23.84 ± 0.1</td>
</tr>
<tr>
<td>C6Cn.1n/C6Cn.2n</td>
<td>23.67 ± 0.15</td>
<td>143.71</td>
</tr>
<tr>
<td>LO Dictyococcales bisectus</td>
<td>23.8 ± 0.1</td>
<td>148.66 ± 2.42</td>
</tr>
<tr>
<td>Oligocene-Miocene boundary</td>
<td>C6Cn.2n/C6Cn.2r</td>
<td>183.7</td>
</tr>
<tr>
<td>Sequence 9-10 boundary</td>
<td>23.80</td>
<td>183.7</td>
</tr>
<tr>
<td>Sequence 9-10 boundary</td>
<td>185.96</td>
<td>&gt;24.0 &lt;24.16</td>
</tr>
<tr>
<td>C6Cn.2n/C6Cn.3n transition</td>
<td>23.999</td>
<td>185.96</td>
</tr>
<tr>
<td>LO Pterotheca reticulata</td>
<td>188.1</td>
<td>249.04 ± 0.45</td>
</tr>
<tr>
<td>40Ar/39Ar age** on pumice</td>
<td>193.42 ± 0.05</td>
<td>23.88 ± 0.13</td>
</tr>
<tr>
<td>87Sr/86Sr age* on bivalve</td>
<td>23.95 ± 0.45</td>
<td>194.89</td>
</tr>
<tr>
<td>87Sr/86Sr age* on bivalve</td>
<td>24.10 ± 0.35</td>
<td>198.75</td>
</tr>
<tr>
<td>Sequence 10-11 boundary</td>
<td>247.2</td>
<td>&gt;24.2 &lt;24.23</td>
</tr>
<tr>
<td>Sequence 11</td>
<td>244.20 ± 0.35</td>
<td>246.97</td>
</tr>
<tr>
<td>87Sr/86Sr age* on bivalve</td>
<td>24.11 ± 0.35</td>
<td>247.67</td>
</tr>
<tr>
<td>87Sr/86Sr age* on bivalve</td>
<td>24.81 ± 0.32</td>
<td>247.67</td>
</tr>
<tr>
<td>LO Liatinitzina ornata</td>
<td>24.1 ± 0.2</td>
<td>258.06 ± 1.14</td>
</tr>
<tr>
<td>40Ar/39Ar age** on pumice</td>
<td>280.03 ± 0.1</td>
<td>24.22 ± 0.03</td>
</tr>
<tr>
<td>FO Hemipentopatus sp. A</td>
<td>297.24 ± 0.85</td>
<td>24.25 ± 0.1</td>
</tr>
<tr>
<td>C6Cn.2n/C6Cn.3n transition</td>
<td>306.65</td>
<td>24.3 ± 0.1</td>
</tr>
</tbody>
</table>

* 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.
** 40Ar/39Ar ages were determined relative to the interlaboratory standard Fish Canyon Tuff sanidine with an assigned age of 27.84 Ma (Deino and Potts, 1990).
*** 87Sr/86Sr 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).
†† Southern Ocean age (Harwood and Maruyama, 1992).
§§ Provenance uncertain.

(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).

87Sr/86Sr Stratigraphy
Lavelle (2000) reported four ages from 87Sr/86Sr analyses of mullusk 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 87Sr/86Sr values were normalized to NIST-987 (87Sr/86Sr = 0.708 ± 0.002, n = 55, 2σ = 0.00016) and converted to best-fit age and error 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 87Sr/86Sr 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 intraformational breccia at 311–315.6 mbsf and a reversal test were used to infer that the ChRM directions are ancient and primary.

40Ar/39Ar 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 87Sr/86Sr ages are consistent with nanofossil and diatom stratigraphy 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 40Ar/39Ar 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 40Ar/39Ar 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.
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