2000

Chronostratigraphy of CRP-2/2A, Victoria Land Basin, Antarctica

G S. Wilson
University of Oxford, gary.wilson@earth.ox.ac.uk

S M. Bohaty
University of Nebraska, Lincoln

Christopher R. Fielding
University of Nebraska-Lincoln, cfielding2@unl.edu

F Florindo
Istituto Nazionale di Geofisica, University of Southampton

M J. Hannah
Victoria University of Wellington

See next page for additional authors

Authors
G S. Wilson, S M. Bohaty, Christopher R. Fielding, F Florindo, M J. Hannah, David M. Harwood, W C. Mcintosh, T R. Naish, A P. Roberts, L Sagnotti, R P. Scherer, C P. Strong, K L. Verosub, G Villa, David K. Watkins, P N. Webb, and K J. Woolfe

Terra Antartica
2000, 7(4), 647-654

TERRA ANTARTICA
AN ANTARCTIC EARTH SCIENCE JOURNAL

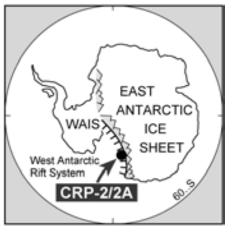
Chronostratigraphy of CRP-2/2A, Victoria Land Basin, Antarctica

G.S. Wilson[1*], S.M. Bohaty[2], C.R. Fielding[3], F. Florindo[4, 8], M.J. Hannah[5], D.M. Harwood[2], W.C. McIntosh[6], T.R. Naish[7], A.P. Roberts[8], L. Sagnotti[4], R.P. Scherer[9], C.P. Strong[7], K.L. Verosub[10], G. Villa[11], D.K. Watkins[2], P.-N. Webb[12] & K.J. Woolfe[13†]

[1]Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR - United Kingdom
[2]Department of Geosciences, University of Nebraska, Lincoln NE 68588-0340 - USA
[3]Department of Earth Sciences, University of Queensland, Brisbane Qld 4072 - Australia
[4]Istituto Nazionale di Geofisica, Via di Vigna Murata 605, 00143 Roma - Italy
[5]School of Earth Sciences, Victoria University of Wellington, PO Box 600, Wellington - New Zealand
[6]New Mexico Institute of Mining and Technology, Socorro NM 87801 - USA
[7]Institute of Geological and Nuclear Sciences, PO Box 30-368, Lower Hutt - New Zealand
[8]School of Ocean and Earth Science, University of Southampton, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH - United Kingdom
[9]Department of Geology and Environmental Sciences, Northern Illinois University, De Kalb IL 60115 - USA
[10]Department of Geology, University of California, Davis CA 95616 - USA
[11]Dipartimento di Scienze della Terra, Università degli Studi di Parma, Parco Area della Scienze 157A, 43100 Parma - Italy
[12]Byrd Polar Research Center and Department of Earth Sciences, The Ohio State University, Columbus, OH 43210 - USA
[13]School of Earth Sciences, James Cook University, Townsville Qld 4811 - Australia (†deceased)

**Corresponding author* (gary.wilson@earth.ox.ac.uk)

Received 28 January 1999*; accepted in revised form* 23 May 2000



Abstract - The 624.15 m glaciomarine sedimentary succession recovered in the CRP-2/2A drillcore comprises lower Oligocene (< *c*. 31 Ma) to lower Miocene (18.5 Ma) strata that are overlain by a thin succession of Pliocene and Pleistocene strata. The age model for the CRP-2/2A drillhole, as presented in this paper, is based on combined microfossil biostratigraphy, $^{40}Ar/^{39}Ar$ ages on volcanic material, $^{87}Sr/^{86}Sr$ analyses on mollusc shells, and correlation of a magnetic polarity zonation to the magnetic polarity time scale (MPTS). Between 25.92 and 109.05 metres below sea floor (mbsf), several alternative correlations to the MPTS are possible, all of which suggest that sediment accumulation rates averaged ~180 m/m.y. between unconformities, although actual sedimentation rates may have been higher. Between 109.05 and 306.65 mbsf, the age model is straightforward and average sedimentation rates were much higher (≥1000 m/m.y.). Between 306.65 mbsf and the bottom of the drillcore (624.15 mbsf), fewer datums are available to constrain the age model and unique correlation with the MPTS is not possible, although high average sediment accumulation rates are likely. A significant unconformity is identified at 306.65 mbsf, which may represent as much as 5 m.y. of missing time. Additional unconformities at 25.92 and 130.27 mbsf account for *c*. 16 and 2.5 m.y. of missing time, respectively. The Oligocene - lower Miocene interval documented in the CRP-2/2A drillcore spans about 13 million years, however, it is possible that more time is missing in sequence-bounding unconformities than is represented in the stratigraphic record recovered in the CRP-2/2A drillcore.

INTRODUCTION

A 624.15 m sequence of glaciomarine strata was recovered at the CRP-2/2A drillsite on the Antarctic continental shelf in the western Ross Sea. The CRP-2 drillhole was cored to a depth of 57.43 metres below sea floor (mbsf), with a deviation in drilling resulting in the CRP-2A drillhole being cored at the same site to a depth of 624.15 mbsf. The record from these two drillholes is referred to as the CRP-2/2A drillcore. It comprises a 597 m succession of lower Oligocene through lower Miocene alternating glacial and interglacial strata that is overlain by a *c*. 27 m succession of mainly glacial Pliocene - Quaternary sediments (Cape Roberts Science Team, 1999).

A preliminary age model for the CRP-2/2A drillcore was reported immediately after drilling and initial drillcore characterization was completed at McMurdo Station (Cape Roberts Science Team, 1999). At that time, chronostratigraphic data were available from an initial biostratigraphic survey, $^{40}Ar/^{39}Ar$ ages on two volcanic ash layers, and a partial magnetic polarity stratigraphy. At the same time, twenty-four depositional cycles, each bounded by unconformities, were identified through sequence stratigraphic analysis. The initial age data suggested that at least four of these sequence boundaries (at 25.92, 130.27, 306.65, and 442.96 mbsf) reflect significant hiatuses. Diatom and foraminiferal biostratigraphic analysis indicated that the strata above 25.92 mbsf are Pliocene and Quaternary in age. The interval between 25.92 and 306.65 mbsf was assigned to the lower Miocene and upper Oligocene and the age model was well constrained by $^{40}Ar/^{39}Ar$ ages and diatom and calcareous nannofossil biostratigraphy. A correlation of the magnetic polarity stratigraphy to the magnetic polarity time scale (MPTS; Cande & Kent, 1995; Berggren et al., 1995) was also possible for this interval. Below 306.65 mbsf, the age was poorly constrained. Apparent truncation of diatom assemblages at 306.65 and 442.96 mbsf indicated that the sequence-bounding unconformities identified at these levels represented significant hiatuses. The interval below 442.96 mbsf was interpreted initially to be early Oligocene, or latest Eocene, in age.

Subsequent post-drilling research has resulted in additional geochronologic constraints that significantly improve the age model for the CRP-2/2A drillcore. New data include additional $^{40}Ar/^{39}Ar$ ages on a third volcanic ash and three volcanic clasts (McIntosh, this volume), new $^{87}Sr/^{86}Sr$ analyses of mollusc shell material (Lavelle, this volume), a refined microfossil biostratigraphy (Scherer et al., this volume; Watkins & Villa, this volume), and additional palaeomagnetic analyses that have resulted in a refined magnetic polarity stratigraphy (Wilson, Florindo et al., this volume). Sequence stratigraphic analysis of the CRP-2/2A drillcore has also been refined (Fielding et. al., this volume) and now includes correlation of some sequence boundaries with the seismic reflectors of Henrys et al. (this volume).

In this paper, we consider all available age data and present a revised age model for the CRP-2/2A drillcore. Because of the many unconformities encountered in the CRP-2/2A succession and paucity of age data within some of the unconformity-bounded sequences, construction of a robust age model is often difficult. Our aim, in this paper, is to present a consensus age model where it exists, and where that is not possible, to present the range of possibilities from existing chronostratigraphic data. Because of changing Cenozoic time scale calibrations (Shackleton et al., 1999; Kent, 1999) and evolving individual biostratigraphic zonations (*e.g.*, Scherer et al., this volume), even existing chronostratigraphic controls might require future refinement. The age implications of individual data sets are discussed in the primary papers (Fielding et al., this volume; Hannah et al., this volume; Lavelle, this volume; McIntosh, this volume; Scherer et al., this volume; Watkins and Villa, this volume; Webb and Strong, this volume; Wilson et al., this volume).

With the integrated age model, as presented in this paper, we can delineate the chronostratigraphic subdivisions, estimate the amount of time missing in unconformities and estimate the average sediment accumulation rates for the CRP-2/2A drillcore. The age model presented for the interval above 306.65 mbsf is relatively straightforward. Below 306.65 mbsf, biostratigraphic datums (Hannah et al., this volume; Scherer et al., this volume; Watkins & Villa, this volume) and strontium isotope ages (Lavelle, this volume) provide age control, but the magnetic polarity stratigraphy for this interval (Wilson et al., this volume) is ambiguous and difficult to correlate to the MPTS within these other constraints.

CHRONOSTRATIGRAPHIC DATA

The age model, which is constrained by $^{40}Ar/^{39}Ar$ and $^{87}Sr/^{86}Sr$ ages, and by biostratigraphic (Tab. 1) and palaeomagnetic data, is presented in figure 1. These data are summarised below and are then integrated in our discussion of the age model. Hiatuses are interpreted to coincide with the sequence bounding unconformities discussed by Fielding et al. (this volume).

$^{40}Ar/^{39}Ar$ AGES

Analyses of feldspar crystals from volcanic ashes and clasts provide $^{40}Ar/^{39}Ar$ ages from 6 horizons between 36.02 and 294.22 mbsf (McIntosh, this volume; Tab. 1). All ages were determined relative to the inter-laboratory standard Fish Canyon Tuff sanidine with an assigned age of 27.84 Ma (Deino & Potts, 1990). Multiple analyses of feldspar phenocrysts in pumice lapilli from volcanic ash horizons provide depositional ages of 21.44 ± 0.05 Ma (111-114 mbsf), 23.98 ± 0.13 Ma (*c.* 193 mbsf) and 24.22 ± 0.06 Ma (280.03 mbsf), respectively. The remaining $^{40}Ar/^{39}Ar$ analyses are on feldspars from basaltic and trachytic clasts that provide maximum ages of 19.18 ± 0.26 Ma (36.02 mbsf), 22.56 ± 0.29 Ma (125.92-125.93 mbsf) and 24.98 ± 0.17 Ma (294.22 mbsf) for the strata in which they occur.

$^{87}Sr/^{86}Sr$ AGES

Strontium isotope ratios were measured on fourteen mollusc shell fragments at eleven stratigraphic levels (Lavelle, this volume). When compared with the marine strontium isotope curve of Howarth and McArthur (1997), these ratios provide age data for the interval between *c.* 36 and 483 mbsf (Tab. 1). Taphonomic study of the molluscs suggests that shells at 36.24 (S1), 194.87 (S4), 246.97 (S6), 445.03 (S8), 460.64 (S9), 463.36 (S10) and 483.15 mbsf (S11) are *in situ*. Shells at 54.94 (S2), 126.55 (S3), 198.74 (S5) and 247.67 mbsf (S7) show varying degrees of abrasion and cannot be confidently identified as *in situ*. Two horizons yielded multiple overlapping dates (S2 at 54.94 mbsf and S11 at 483.15 mbsf). The remaining ages are from single mollusc shell fragments.

In addition to the above ages, dating of multiple abraded mollusc shell fragments of uncertain provenance between 10.28 and 23.90 mbsf reveals a mixed assemblage of late Miocene (*c.* 6 Ma) and Plio-Pleistocene (*c.* 1.3 – 3.9 Ma) macrofaunas. These results suggest that the uppermost lithological unit in the CRP-2/2A drillcore is ≤ *c.* 1.3 Ma in age (Lavelle, this volume).

BIOSTRATIGRAPHY

The biostratigraphic framework for the lower Miocene to lower Oligocene succession in the CRP-2/2A drillcore is provided primarily by marine diatoms, and, to a lesser extent, by calcareous nannofossils. There are considerable variations in the distribution, the abundance and the preservation of these microfossils throughout the drillcore. Representation by open-ocean pelagic diatom or nannofossil taxa, which provide direct correlations to Southern Ocean and global biostratigraphic and chronostratigraphic frameworks, is limited. Nine diatom datums (Scherer et al., this volume), two calcareous nannofossil datums (Watkins & Villa, this volume) and a marine palynomorph datum (Hannah et al., this volume) provide age control (Tab.1). Ten diatom zones (Fig. 1)

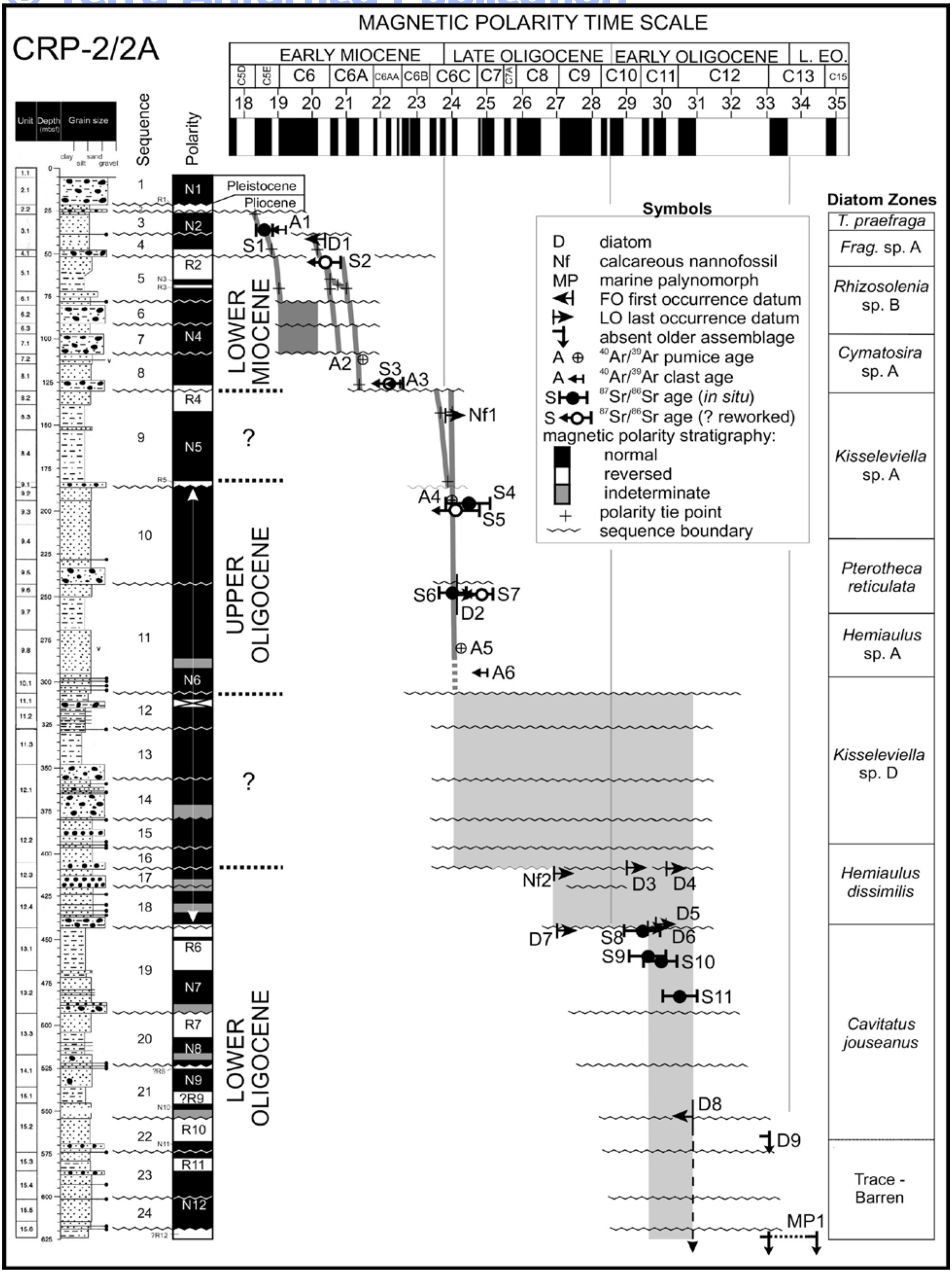


Fig. 1 - Age model for the CRP-2/2A drillcore. The age model is based on biostratigraphy, $^{40}Ar/^{39}Ar$ ages of volcanic material, $^{87}Sr/^{86}Sr$ analyses of mollusc shells and magnetostratigraphy. The stratigraphic column, with lithological units and sequence stratigraphic interpretations, is from Cape Roberts Science Team (1999). Datum events, with alphanumeric indicators that are used to constrain the correlation, are listed in Table 1. The length of vertical bars on biostratigraphic datums indicates the range of error from the respective sampling interval on which the datums are defined. Undulating lines represent sequence bounding unconformitites where time loss is predicted. Above 306.65 mbsf, possible correlations to the MPTS are indicated by dark grey lines. Between 306.65 and 624.15 mbsf, no unique correlation to the MPTS is possible. Above 306.65 mbsf, correlation lines represent average sediment accumulation rates. Actual sedimentation rates may be higher. Palaeomagnetic polarity was not determined for the intraformational breccia between *c*. 311 and 315 mbsf. Light grey shading within the main diagram indicates the range of possible age-depth correlations based on biostratigraphic data.

Tab. 1 - Chronostratigraphic data from the CRP-2/2A drillhole.

Event	Datum	CRP-2/2A Depth (mbsf)	Age (Ma)	Error (+)	Error (-)
A1	Basaltic Clast	36.02	19.18	0.26	0.26
A2	Pumice	111 - 114	21.44	0.05	0.05
A3	Trachyte Clast	125.92 - 125.93	22.56	0.29	0.29
A4	Pumice	*c.* 193	23.98	0.13	0.13
A5	Pumice	280.03	24.22	0.06	0.06
A6	Trachyte Clast	294.22	24.98	0.17	0.17
S1	Solitary coral (*in situ*)	36.24 - 36.27	18.62	0.22	0.21
S2	Bivalve fragment (provenance uncertain)	54.94 - 54.98	20.35	0.38	0.42
S2	Bivalve fragment (provenance uncertain)	54.94 - 54.98	20.29	0.64	0.55
S3	Pectinid fragment (provenance uncertain)	126.55 - 126.56	22.24	0.39	0.39
S4	Bivalve fragment (*in situ*)	194.87 - 194.91	24.52	0.63	0.66
S5	Bivalve fragment (provenance uncertain)	198.74 - 198.75	24.10	0.35	0.36
S6	Bivalve fragment (*in situ*)	246.97 - 247.00	24.02	0.35	0.35
S7	Bivalve fragment (provenance uncertain)	247.67 - 247.71	24.81	0.34	0.34
S8	Modiolid fragment (*in situ*)	445.03 - 445.06	29.41	0.52	0.50
S9	Modiolid fragment (*in situ*)	460.64 - 460.67	29.55	0.52	0.54
S10	Modiolid fragment (*in situ*)	463.36 - 463.38	29.89	0.51	0.52
S11	Modiolid fragment (*in situ*)	483.15 - 483.18	30.67	0.45	0.48
S11	Modiolid fragment (*in situ*)	483.15 - 483.18	30.33	0.48	0.50
S11	Modiolid fragment (*in situ*)	483.15 - 483.18	30.39	0.47	0.51
D1	FO *Thalassiosira praefraga* complex	36.25 – 47.41	20.3 (C6r)		
D2	LO *Lisitzinia ornata*	236.26 – 260.02	24.1 (C6Cr)		
D3	LO *Eurossia irregularis*	405.39 - 412.27	27 to 29 (C9 - C10)		
D4	LO *Pyxilla reticulata*	405.39 - 412.27 (316.48)	30.1 (C11r)		
D5	LO *Rhizosolenia antarctica*	437.37 - 441.85	29.8 (C11n.2n)		
D6	LO *Rhizosolenia oligocaenica*	441.87 - 443.89	29.6 (C11n.1r)		
D7	LO *Asterolampra punctifera*	443.90 - 444.96	27.0 (C9n)		
D8	FO *Cavitatus jouseanus*	543.81 – 564.63 also in CRP-3	30.9 (C12n)		
D9	CIROS-1 "Assemblage B" absent	>564.67	<33 (C13n)		
	LO *Hemiaulus characteristicus* absent	>564.67	<33 (C13n)		
Nf1	LO *Dictycoccites bisectus*	144.44	23.9 (C6Cn.2r)		
Nf2	LO *Chiasmolithus altus*	412.25	26.1 (C8)		
MP1	"Transantarctic assemblage" absent	624.15	(<C13n to C15n)		

divide the interval recovered in the CRP-2/2A drillcore (Scherer et al., this volume).

Foraminiferal and diatom biostratigraphy (Cape Roberts Science Team, 1999; Webb & Strong, this volume) indicate that the upper 25.92 mbsf of the CRP-2/2A drillcore (lithostratigraphic units 2.1 and 2.2) includes Pliocene and Pleistocene sediments. Sequence 1 is Quaternary in age and Sequence 2 is of Pliocene age (Fig. 1).

The interval between 25.92 and 306.65 mbsf in the CRP-2/2A drillcore contains two diatom datums; the FO of the diatom *Thalassiosira praefraga* (D1, 36.25 mbsf, Chron C6r) and the LO of the diatom *Lisitzinia ornata* (D2, 259.21 mbsf, Chron C6Cr). The LO of the calcareous nannofossil *Dictycoccites bisectus* (Nf1, Chron C6Cn.2r) at 144.44 mbsf and its associated assemblage are taken to indicate the Oligocene-Miocene boundary (Wei & Thierstein, 1991; Berggren et al., 1995). The ranges of the diatoms *T. praefraga* and *Fragilariopsis* sp. A in the CRP-1 drillcore (Harwood et al., 1998) and in the CRP-2/2A drillcore (Scherer et al., this volume) indicate an overlap between CRP-1 and CRP-2/2A.

Truncation of a diatom assemblage at the sequence-bounding unconformity at 306.65 mbsf (Scherer et al., this volume) suggests that significant time may be missing in this unconformity. Refinement of the diatom biostratigraphy did not confirm that significant time is missing in the unconformity at 442.96 mbsf, as suggested by the Cape Roberts Science Team (1999). Between 306.65 and 624.15 mbsf, several diatom datums (D3 to D8, Fig. 1) indicate an age within the late part of the early Oligocene. Although microfossil preservation is poor between 306.65 and 409.36 mbsf, diatom assemblages are similar to those that occur more abundantly below 409.36 mbsf. At 412 mbsf, the LO of the calcareous nannofossil *Chiasmolithus altus* (Nf2) suggests a late Oligocene age, but its occurrence at this level may be facies dependent or due to poor preservation above 412 mbsf (Watkins & Villa, this volume). The LO of *Eurossia irregularis* (D3) occurs at about the same depth as Nf2. *E. irregularis* has not previously been reported from the upper Oligocene. The main basis for assigning an early Oligocene age to D3 is that it does not occur in strata above the unconformity at *c*. 366 mbsf in the CIROS-1 drillcore (Harwood, 1989; Harwood et al., 1989). Scherer et al. (this volume) report the LO of *Pyxilla reticulata* (D4) at 412.27 mbsf, but also note that fragments of *P. reticulata* occur as high as 316.48 mbsf which possibly indicates reworking.

The FO of *Cavitatus jouseanus* (D8, Chron C12n; Harwood & Maruyama, 1992) is reported at 543.81 mbsf (Scherer et al., this volume) and provides the strongest biostratigraphic control for the lower 180 m of the CRP-2/2A drillcore. However, *C. jouseanus* is also reported from reversed polarity strata in the upper part of the CRP-3 drillcore (Cape Roberts Science Team, 2000). This suggests that its FO in the CRP-2/2A drillcore results from poor preservation below 543.81 mbsf, that it may first occur within the upper part of C12r (Cape Roberts Science Team, 2000), and that strata in the lower part of the CRP-2/2A drillcore are late early Oligocene in age. This inferred age is supported by the lowermost diatom assemblages recovered from the CRP-2/2A drillcore at 560 mbsf. Biostratigraphically important diatom taxa from "Assemblage B" (such as *Stictodiscus kittonianus, Sphynctolethus pacificus, Stephanopyxis superba*, *Hemiaulus caracteristicus,* and the chrysophycean cyst *Archaeosphaeridium australense*), which are recovered from below 366 mbsf in the CIROS-1 drillcore (Harwood, 1989), are absent in the CRP-2/2A drillcore (Scherer et al., this volume). The absence of these diatoms and other members of "Assemblage B" (D9, Fig. 1) indicates that sediments from above *c*. 560 mbsf in the CRP-2/2A drillcore are no older than early Oligocene in age. Upper Eocene marine palynomorphs (MP1) of the "Transantarctic Flora" (Hannah, 1997) are also absent in the CRP-2/2A drillcore (Hannah et al., this volume). The youngest age of this marine palynomorph assemblage, as inferred from the CIROS-1 drillcore by Hannah et al. (1997) and Wilson et al. (1998), is between Chron C13n and C15n. Thus, the lowermost 318 m (306 - 624 mbsf) of the CRP-2/2A drillcore represents, at least in part, the stratigraphic interval that is missing in an unconformity at 366 mbsf in the CIROS-1 drillcore (see Fig. 3 of Scherer et al., this volume).

MAGNETOSTRATIGRAPHY

In conjunction with the above-described geochronological data, additional age constraints are provided by correlation of a detailed palaeomagnetic reversal stratigraphy (Wilson et al., this volume) with the MPTS of Cande & Kent (1992, 1995) and Berggren et al. (1995). Characteristic remanence directions were identified throughout the CRP-2/2A succession by examination of vector component demagnetisation diagrams. These characteristic remanence directions pass an inclination-only reversals test and a conglomerate test, which indicates that the polarity zonation represents a primary signal. Above 306.65 mbsf, correlation to the MPTS is mostly well constrained by $^{40}Ar/^{39}Ar$ ages, $^{87}Sr/^{86}Sr$ ages, and diatom and calcareous nannofossil datums (Fig. 1). Where unique correlation with the MPTS is possible, rapid average sediment accumulation rates are indicated (200-1000 m/m.y.; Wilson, Florindo et al., this volume). Below 306.65 mbsf, the CRP-2/2A magnetic polarity record is complex. Correlation with the MPTS within the available independent age constraints leaves several magnetozones in the CRP-2/2A polarity record without any correlatives in the MPTS. Wilson, Florindo et al. (this volume) have suggested that this may be due to the preservation of Oligocene cryptochrons (Cande & Kent, 1992), which are short period polarity intervals (<30 k.y.), in the rapidly accumulated CRP-2/2A succession. They also noted that while sedimentological evidence suggests a hiatus at each of the sequence bounding unconformities, palaeomagnetic evidence suggests that several of these hiatuses are relatively short in duration (<50 k.y.). This makes them difficult to resolve within the age model presented in figure 1, and, therefore, each sequence bounding unconformity is drawn to indicate a break in deposition.

CORRELATION TO THE MPTS

Poor fossil preservation, coarse lithofacies, numerous disconformities and variable palaeoenvironmental conditions make it difficult to interpret the biostratigraphic record in the pre-Pliocene interval of the CRP-2/2A drillcore (26.75 - 624.15 mbsf). However, integration with $^{40}Ar/^{39}Ar$, $^{87}Sr/^{86}Sr$ and palaeomagnetic data allow identification of three major pre-Pliocene chronostratigraphic intervals (Fig. 1), as described below.

SEQUENCES 3 - 8

The interval between 25.92 and 130.27 mbsf contains several datums that help to constrain correlation of the magnetic polarity stratigraphy with the MPTS. An $^{40}Ar/^{39}Ar$ age on a volcanic clast (A1) at 36.02 mbsf and a $^{87}Sr/^{86}Sr$ age on a solitary *in situ* coral (S1) at 36.24 mbsf indicate that this interval is *c*. 18.5 - 19.0 Ma in age, and that the normal-reversed polarity pattern represented by the upper part of magnetozone N2 and the lower part of magnetozone R1 correlates with chrons C5En and C5Dr.

Interpretation of the palaeomagnetic stratigraphy between 37.80 and 109.05 mbsf (sequences 4-7) is ambiguous. Correlation with the MPTS is constrained by the FO of *T. praefraga* complex (D1) between 36.25 and 47.41 mbsf and by the $^{87}Sr/^{86}Sr$ age at 54.94 mbsf (S2). These datums suggest that most of magnetozone N4, magnetozones R3 and N3 and the lower part of magnetozone R2 correlate with chrons C6An.2n – C6r. However, it is also possible that they correlate with chrons C6n-C5Er and that significant time is lost at one or several of the sequence bounding unconformities. In this latter interpretation, magnetozone R3 would have no correlative in the MPTS.

The age of Sequence 8 is well constrained by the high precision $^{40}Ar/^{39}Ar$ age (A2; 21. 44 ± 0.05 Ma) on a pumice horizon at *c*. 113 mbsf and the R-N magnetic polarity sequence (magnetozones R4-N4) is correlated with chrons C6Ar-C6An.2n. The 21.44 Ma age should occur within reversed polarity Chron C6Ar. However, the pumice horizon (A2) falls toward the base of a thick normal polarity magnetozone (N4; 71.89 - 127.72 mbsf). It is unlikely that this ash was significantly reworked (McIntosh, this volume). The preferred explanation for this discrepancy is that, given uncertainties in numerical ages assigned to $^{40}Ar/^{39}Ar$ standards (Renne et al., 1998) and uncertainties in calibration of the MPTS in the early Miocene, the ash actually fell within the nearest normal polarity Chron (C6An.2n). The volcanic clast from which A3 was obtained and the pectinid shell fragment from which S3 was obtained (both at *c*. 126 mbsf; Tab. 1) are both considered to have been reworked.

In all of the above-described correlations, average sediment accumulation rates were *c*. 180 m/m.y. between 25.92 and 130.27 mbsf. Average sediment accumulation rates may have reduced to *c*. 15 m/m.y. in the more muddy and sandy strata between 61.94 and 72.84 mbsf. As much as 2.5 m.y. may have been lost in sequence bounding unconformities, however, with the existing data, it is not possible to determine what percentage of time is represented by each of these hiatuses. The *c*. 2.5 m.y. unconformity at 130.27 mbsf is marked by a change in diatom assemblages, but these assemblages are not age-diagnostic (Scherer et al., this volume).

SEQUENCES 9 - 11

Correlation of the magnetic polarity stratigraphy to the MPTS is largely robust for the interval between 130.27 and 306.65 mbsf; the correlation is constrained by $^{40}Ar/^{39}Ar$ and $^{87}Sr/^{86}Sr$ ages and by nannofossil and diatom datums (Fig. 1). Within sequence 9, the last occurrence of *Dictycoccites bisectus* (Nf1; at 144.44 mbsf) is widely taken to be indicative of the Oligocene-Miocene boundary (*e.g*., Wei & Thierstein 1991; Berggren et al., 1995). Correlation of magnetozone N5 with Chron C6Cn.2n suggests that Nf1 is slightly younger here, alternatively magnetozone R5 may have no correlative in the MPTS and the LO of Nf1 may be slightly older and occur within the upper part of Chron C6Cn.3n. The LO of *L. ornata* (D2) at 259.21 mbsf should, accordingly, be extended slightly from C6Cr to C6Cn.3n. The $^{40}Ar/^{39}Ar$ pumice age (A5; 24.22 ± 0.06) at 280.03 mbsf should lie within a zone of reversed polarity (Chron C6Cr). Based on the measured normal polarity between *c*. 186 and 307 mbsf, the rapid sedimentation rate (see below), and the lack of physical evidence for a hiatus within Sequence 11, and using the same calibration argument as for datum A2, it is likely that the pumice fell within the lower part of Chron C6Cn.3n. Correlation to the MPTS between *c*. 287 and 306.65 mbsf is shown as a dashed line in figure 1, to allow for uncertainty associated with the short zone of indeterminate polarity within Sequence 11. The volcanic clast from which datum A6 was obtained (at 294.22 mbsf) is assumed to have been reworked.

This correlation to the MPTS suggests average sediment accumulation rates greater than 1000 m/m.y. in sequences 9 - 11 (130.27 - 306.65 mbsf), and that the entire 176-m-thick succession of sandstone, sandy mudstone and minor diamictite was deposited in as little as 120 k.y. The exact position of the Oligocene-Miocene boundary is difficult to locate with the existing data. It may occur within the rapidly deposited Sequence 9 or, alternatively, it may be lost within the sequence bounding unconformity at 130.27 mbsf.

SEQUENCES 12 - 25

The unconformity at 306.65 mbsf is identified on the basis of petrological, palaeontological, lithostratigraphic, seismic and palaeomagnetic data (Cape Roberts Science Team, 1999), which suggests that it represents a significant hiatus. However, existing data prevent assessment of how much time is lost at this horizon or how much time is distributed through several other disconformities between 306.65 and 409.36 mbsf. The presence of only normal (or indeterminate) palaeomagnetic polarity between 306.65 and 441.22 mbsf suggests that sedimentation was rapid (200 - 1000 m/m.y.), and that only one or two polarity chrons are represented. With the existing dating constraints, it is possible that the unconformity at 306.65 mbsf may encompass up to 5 m.y. of lost time. However, the time represented within the individual hiatuses that separate sequences 12 to 16 cannot be determined with the existing data. It is therefore not possible to suggest a correlation to the MPTS between 306.65 and 409.36 mbsf (Fig. 1).

The age at the base of the CRP-2/2A drillcore is constrained by the absence of earliest Oligocene and latest Eocene diatom (D9) and marine palynomorph (MP1) assemblages, which are present in the CIROS-1 drillcore below 366 mbsf. Their absence in basal sediments of the CRP-2/2A drillcore indicates that the drillhole terminated within the lower Oligocene, or possibly in the uppermost Eocene. However, the FO of *C. jouseanus* (D8, Chron C12n) in CRP-3 in strata that lie beneath the lowermost part of CRP-2/2A provides the strongest biostratigraphic control and indicates a middle early Oligocene age (Chron C12n, Harwood & Maruyama, 1992) for the base of the CRP-2/2A drillcore (Fig. 1). It should be noted that the Cape Roberts Science Team (2000) suggest that *C. jouseanus'* first occurrence is slightly older, within Chron C12r, in the CRP-3 drillcore.

Development of an age model that is consistent with all available data for the lowermost 215 m (409 - 624 mbsf) of the CRP-2/2A drillcore is problematical. While $^{87}Sr/^{86}Sr$

ratios, diatom and marine palynomorph assemblages provide useful age constraints, no unique interpretation of the magnetic polarity stratigraphy can accommodate all of these data. We therefore refrain from showing an age-depth correlation line for the lower part of the drillcore. If a correlation was drawn between the palaeomagnetic polarity zonation and the MPTS in a way that best fits the diatom biostratigraphy and strontium data below 441 mbsf (Fig. 1), this would suggest that sediments at the base of the drillcore are late Eocene in age. However, this interpretation is inconsistent with the diatom (D8 and D9) and marine palynomorph data (MP1) in the lower 60 m of the drillcore, which suggest that the strata at the base of the hole are early Oligocene in age. It is possible to accommodate all of the palaeomagnetic data by drawing a younger correlation, but such a correlation suggests that the interval between 409 and 483 mbsf is younger than suggested by the diatom (D3-D6) and $^{87}Sr/^{86}Sr$ data (Fig. 1). At the time of writing, an additional several hundred metres of Oligocene strata has been recovered in the CRP-3 drillcore (Cape Roberts Science Team, 2000) from a succession that lies stratigraphically below the CRP-2/2A drillcore. This demonstrates that the CRP-2/2A drillhole probably terminated well within the lower Oligocene.

RECONCILING THE CONFLICTS

Recovery of the rapidly deposited Oligocene-Miocene glaciomarine succession in the CRP-2/2A drillcore from the Antarctic continental shelf highlights several limitations of existing late Palaeogene – early Neogene time scales (Berggren et al., 1995; Cande & Kent, 1995). The MPTS is constructed from interpolation of composite marine magnetic anomalies on profiles from oceanic crust of the appropriate ages (Cande & Kent, 1992). The late Neogene MPTS (Cande & Kent, 1992, 1995) is well calibrated by astronomical tuning of high-resolution marine sedimentary records (Hilgen et al., 1995; Shackleton et al., 1995). However, prior to 5.23 Ma, the MPTS is calibrated by interpolation of a cubic spline curve that joins calibration points from radiometric ages at ~10 m.y. intervals (Cande & Kent, 1995). Future astronomical calibration of the pre-late Neogene time scale may result in a refinement of at least 100 k.y. in the age of the early Miocene time scale (Kent, 1999).

Mis-calibration of the present MPTS adequately explains the discrepancy between $^{40}Ar/^{39}Ar$ ages and our correlation to the MPTS in sequences 8 and 11 (Fig. 1). It does not, however, explain discrepancies between magnetic polarity and the biostratigraphic and strontium age data that are calibrated against the MPTS. The Southern Ocean diatom biostratigraphy zonation is still evolving (Scherer et al., this volume) and we may, therefore, expect refinement of datums with new data such as those obtained by Cape Roberts Project drilling. Also, in CRP-2/2A preservation of microfossils is a problem (Cape Roberts Science Team, 1999) and this may have resulted in discrepancies in the location of first and last occurrences. *Dictyococcites bisectus* (Nf1) co-occurs with a more extensive nannofossil assemblage in the CRP-2/2A drillcore, which suggests that its last occurrence, taken to mark the Oligocene-Miocene boundary, is faithfully recorded in the CRP-2/2A drillcore. However, Steininger (1994) changed the criteria for recognition of the Oligocene-Miocene boundary to palaeomagnetic criteria rather than biostratigraphic criteria and this may account for the slight discrepancy seen in the CRP-2/2A record.

Cande & Kent (1992) recognised short period, low amplitude anomalies (cryptochrons) in the ocean floor profiles used to construct the Eocene-Oligocene MPTS. The duration of these cryptochrons is inferred to be 30 k.y. or less and they may represent short-lived polarity intervals (*e.g.*, Blakely & Cox, 1972). The lower succession of CRP-2/2A represents a high-resolution Oligocene record that may contain several cryptochrons. If this is the case, some of the magnetozones in the lower *c*. 180 m of the CRP-2/2A succession may not have correlatives in the MPTS. Cande & Kent (1992) did not recognise any cryptochrons in the early – middle Miocene MPTS, so this would not explain discrepancies between magnetic polarity and other data above 306.65 mbsf in the CRP-2/2A record. It is still possible, however, to record short period geomagnetic field fluctuations, such as geomagnetic excursions, which could make it difficult to interpret polarity records from environments with high sedimentation rates. Also, several shear zones in the lower 317.5 m of the CRP-2/2A drillcore may have contributed to repetition of strata, which would further complicate the age model.

CONCLUSIONS

The strata recovered in the CRP-2/2A drillcore comprise a thin interval of Pleistocene and Pliocene sediments that are underlain by a thick succession of lower Miocene (*c*. 18.3 Ma at 36.24 mbsf) and lower Oligocene strata (*c*. 31 Ma at the base of the drillhole at 624.15 mbsf). An age model based on biostratigraphy, $^{40}Ar/^{39}Ar$ ages of volcanic material, $^{87}Sr/^{86}Sr$ analyses of mollusc shells and magnetostratigraphy is presented in figure 1. For sequences 3 - 8 (between 25.92 and 130.27 mbsf), the age model is not well constrained and a single line of correlation to the MPTS can only be defined for sequences 3 and 8. For sequences 4-7 (51.94-109.05 mbsf), multiple correlations are possible. Average sediment accumulation rates for this interval were *c*. 180 m/m.y., but actual sedimentation rates were probably much higher because significant amounts of time are missing at the numerous disconformities identified in the CRP-2/2A succession. Correlation to the MPTS is largely robust for the interval between 130.27 and 306.65 mbsf (sequences 9-11) and high average sediment accumulation rates are suggested (> 1000 m/m.y.). Between 306.65 and 624.15 mbsf, the age model is less robust and no unique correlation to the MPTS can accommodate all of the biostratigraphic, strontium and palaeomagnetic data (Fig. 1). Biostratigraphic data demonstrate that CRP-2/2A terminated within the lower Oligocene. Average sediment accumulation rates for this interval were greater than *c*. 150 m/m.y., but again, actual sedimentation rates were probably much higher and significant amounts of time are missing in numerous disconformities.

Three significant unconformities are identified in the CRP-2/2A drillcore. A disconformity at 25.92 mbsf separates Plio-Pleistocene sediments from lower Miocene sediments, with the hiatus representing *c*. 16 m.y. An unconformity at 130.27 mbsf represents a *c*. 2.5 m.y. hiatus within which much of the earliest Miocene was lost. This unconformity may also contain the Oligocene-Miocene boundary. Up to *c*. 5 m.y. is potentially missing in an unconformity at 306.65 mbsf. Other unconformities representing short hiatuses are identified at sequence boundaries, but the duration of these hiatuses is unresolved in the present age model. Although the pre-Pliocene succession recovered in the CRP-2/2A drillcore represents an interval spanning *c*. 13 million years of early Miocene and Oligocene time, it is possible that more time is missing in unconformities than is represented in the stratigraphic record. The lower Oligocene interval that is missing in an unconformity at *c*. 366 mbsf in the CIROS-1 drillcore (Harwood et al., 1989; Wilson et al., 1998) is represented, in part, in the CRP-2/2A drillcore by the interval between the unconformity at 306.65 mbsf and the base of the drillcore (624.15 mbsf).

The CRP-2/2A drillcore represents a significant stratigraphic sequence from the western Ross Sea. A composite record, drawing upon information from the MSSTS-1, CIROS-1, CRP-1, CRP-2/2A and CRP-3 drillcores, will provide an important reference for stratigraphic correlation on the Antarctic continental shelf.

ACKNOWLEDGEMENTS

We are grateful to our colleagues on the Cape Roberts Project Science Team for access to data and for discussions. The manuscript was improved by reviews from John Barron and Mark Lavelle. We are also grateful to the Australian Research Council (CRF, KJW), New Zealand Foundation for Research (MJH, TRN, CPS, GSW), United States National Science Foundation – Office of Polar Programs (SMB, DMH, WCM, APR, RPS, KLV, DKW, PNW, GSW) , and the Italian Programma di Recerche in Antartide (FF, LS, GV) who have provided financial support for this work. The Cape Roberts Project is a joint venture of the Antarctic programmes of Australia, Germany, Italy, New Zealand, the United Kingdom, and the United States of America.

REFERENCES

Berggren W.A., Kent D.V., Swisher C.C. & Aubrey M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren W.A., Kent D.V., Aubrey M.-P. & Hardenbol J. (eds.), *Geochronology, Time Scales and Global Stratigraphic Correlation*, *Society of Economic Paleontologists and Mineralogists, Special Publication*, **54**, 129-212.

Blakely R.J. & Cox A., 1972. Evidence for short geomagnetic polarity intervals in the early Cenozoic. *Journal of Geophysical Research*, **77**, 7065-7072.

Cape Roberts Science Team, 1999. Studies from the Cape Roberts Project, Ross Sea, Antarctica: Initial Report on CRP-2/2A. *Terra Antartica*, **6**(1/2), 1-173.

Cape Roberts Science Team, 2000. Studies from the Cape Roberts Project, Ross Sea, Antarctica: Initial Report on CRP-3. *Terra Antartica*, **7**(1/2), 1-209.

Cande S.C. & Kent D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, **97**, 13917-13951.

Cande S.C. & Kent D.V., 1995. Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, **100**, 6093-6095.

Deino A. & Potts R., 1990. Age probability spectra for examination of single crystal $^{40}Ar/^{39}Ar$ dating results: Examples from Olorgesailie Formation, Southern Kenya Rift. *Quaternary International*, **13/14**, 47-53.

Hannah M.J., 1997. Climate Controlled Dinoflagellate Distribution in Late Eocene-Earliest Oligocene Strata from CIROS-1 Drillhole, McMurdo Sound, Antarctica. *Terra Antartica*, **4**(2), 73-78.

Hannah M.J., Cita M.B., Coccioni R., & Monechi S., 1997. The Eocene/Oligocene Boundary at 70° South, McMurdo Sound, Antarctica. *Terra Antartica*, **4**(2), 79-87.

Harwood D.M., 1989. Siliceous microfossils. In: Barrett P.J. (ed.), *Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound*. *DSIR Bulletin*, **245**, Science Information Publishing Centre, Wellington, 67-97.

Harwood D.M. & Maruyama T., 1992. Middle Eocene to Pleistocene diatom biostratigraphy of Southern Ocean sediments from the Kerguelen Plateau, Leg 120. In: Wise S.W. Jr., Schlich R., et al. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX, Ocean Drilling Program, **120**(2), 683-733.

Harwood D.M., Barrett P.J., Edwards A.R., Rieck H.J. & Webb P.-N., 1989. Biostratigraphy and chronology. In: Barrett P.J. (ed.), *Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound*. *DSIR Bulletin*, **245**, Science Information Publishing Centre, Wellington, 499-514.

Harwood D.M., Bohaty S.M. & Scherer R.P., 1998. Lower Miocene Diatom Biostratigraphy of the CRP-1 Drillcore, McMurdo Sound, Antarctica. *Terra Antartica*, **5**(3), 499-514.

Hilgen F.J., Krijgsman W., Langereis C.G., Lourens L.J., Santarelli A. & Zachariasse W.J., 1995. Extending the astronomical (polarity) time scale into the Miocene. *Earth and Planetary Science Letters*, **136**, 495-510.

Howarth R.J. & McArthur J.M., 1997. Statistics for strontium isotope stratigraphy: A robust LOWESS fit to the marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. *Journal of Geology*, **105**, 441-456.

Kent D.V., 1999. Orbital tuning of geomagnetic polarity time-scales. *Philosophical Transactions of the Royal Society of London, Series A*, **357**, 1995-2007.

Renne P.R., Swisher C.C., Deino A.L., Karner D.B., Owens T.L. & DePaolo D.J., 1998. Intercalibration of standards, absolute ages and uncertainties in $^{40}Ar/^{39}Ar$ dating. *Chemical Geology*, **149**, 259.

Shackleton N.J., Crowhurst S.J., Hagelberg T., Pisias N.G. & Schneider D.A., 1995. A new Late Neogene time scale: Application to Leg 138 sites. In: Pisias N.G., Mayer L., Janecek T.R., Palmer-Julson A. & Andel T.H. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX, Ocean Drilling Program, **138**, 73-101.

Shackleton N.J., Crowhurst S.J., Weedon G.P. & Laskar J., 1999. Astronomical calibration of Oligocene-Miocene time. *Philosophical Transactions of the Royal Society of London, Series A*, **357**, 1907-1929.

Steininger F.F., 1994. Proposal for the Global Stratotype Section and Point (GSSP) for the Base of the Neogene (the Palaeogene/Neogene boundary), *International Commission on Stratigraphy, Subcommission on Neogene Stratigraphy; Working Group on the Palaeogene/Neogene Boundary*: Vienna, Institute for Paleontology, University of Vienna 41p.

Wei W. & Thierstein H.R., 1991. Upper Cretaceous and Cenozoic calcareous nannofossils of the Kerguelen Plateau (Southern Indian Ocean) and Prydz Bay (East Antarctica). In: Barron J., Larsen B., et al. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX, Ocean Drilling Program, **119**, 467-493.

Wilson G.S., Roberts A.P., Verosub K.L., Florindo F. & Sagnotti L., 1998. Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in the CIROS-1 core, Victoria Land margin, Antarctica: Implications for Antarctic glacial history. *Geological Society of America Bulletin*, **110**, 35-47.