Astronomical calibration age for the Oligocene-Miocene boundary

Nicholas J. Shackleton
Michael A. Hall — Department of Earth Sciences, University of Cambridge, The Godwin Laboratory, Pembroke Street, Cambridge CB2 3SA, UK
Isabella Raffi — Dipartimento di Scienze della Terra, Università "G. D'Annunzio," Campus Universitario, via dei Vestini 31, 66013 Chieti Scalo, Italy
Lisa Tauxe — Scripps Institution of Oceanography, La Jolla, California 92093-0220, USA
James Zachos — Earth Sciences Department, University of California, Santa Cruz, California 95064, USA

ABSTRACT

The stratotype section for the base of the Miocene is at a reversed (below) to normal (above) magnetic transition that is claimed to represent magnetic chron C6Cn.2n (o). Deep Sea Drilling Project (DSDP) Site 522 is the only location we are aware of that unambiguously records the three normal events of C6Cn. We have quantitatively determined the range of the short-lived nannofossil *Sphenolithus delphix* and the lower limit of *S. disbelemnos* in DSDP Holes 522 and 522A in order to calibrate their precise relationship to the magnetostratigraphy and to confirm the completeness of the record at this site. Astronomical tuning of Ocean Drilling Program (ODP) Sites 926, 928, and 929 shows that *S. disbelemnos* appears at 22.67 Ma and that the entire range of *S. delphix* is from about 22.98 Ma to 23.24 Ma. Using these ages, linear interpolation in DSDP Site 522 suggests that the age of C6Cn.2n (o) and of the Oligocene-Miocene boundary is 22.92 ± 0.04 Ma. Our value, conservatively expressed as 22.9 ± 0.1 Ma, is 0.9 m.y. younger than the currently accepted age of the Oligocene-Miocene boundary and of C6Cn.2n (o), which was assigned an age of 23.8 Ma, based on an estimate of 23.8 ± 1 Ma for the Oligocene-Miocene boundary. The bulk-sediment carbon isotope data from DSDP Site 522 is correlated to the record from benthic foraminifera at ODP Site 929 to refine the calibration of magnetic reversals from C6Cn.1n (o) to C7n.2n (o) at DSDP Site 522 on the astronomical time scale.

Keywords: magnetostratigraphy, Oligocene-Miocene boundary, carbon isotopes, nannofossil biostratigraphy, astronomical calibration.

INTRODUCTION

The Oligocene-Miocene boundary has long been recognized as being difficult to identify, correlate, and date. Berggren (1969) gave an age of 22.5 Ma for the boundary, then recognized globally by the first appearance of *Globigerinoides* sp., and depicted it correlated approximately to C6An. Berggren et al. (1985b) reviewed the criteria for correlating the boundary and gave an age of 23.7 Ma on the basis of the first appearances of *Reticulofenestra bisectus*, *R. abisectus*, and *R. scrippsae* in Deep Sea Drilling Project (DSDP) Site 522 in mid-C6Cn, and of foraminiferal events that also linked the boundary to C6Cn. The numerical age given by Berggren et al. (1985a) was derived by linear interpolation on a seafloor-spreading magnetic anomaly profile between C5 (o) and C24 (o), so that their boundary age was determined from the seafloor spreading model.

In their reevaluation of the seafloor spreading time scale, Cande and Kent (1992, 1995) inserted an age-control point at the Oligocene-Miocene boundary, assuming for convenience that the boundary was precisely at C6Cn.2n (o) and assigning an age of 23.8 Ma. They cited Harland et al. (1990) for this figure; Harland et al. (p. 155 and 198) gave an uncertainty of ±1 m.y.

Berggren et al. (1995) updated the Cenozoic time scale using Cande and Kent (1995); as they anticipated, a boundary stratotype for the base of

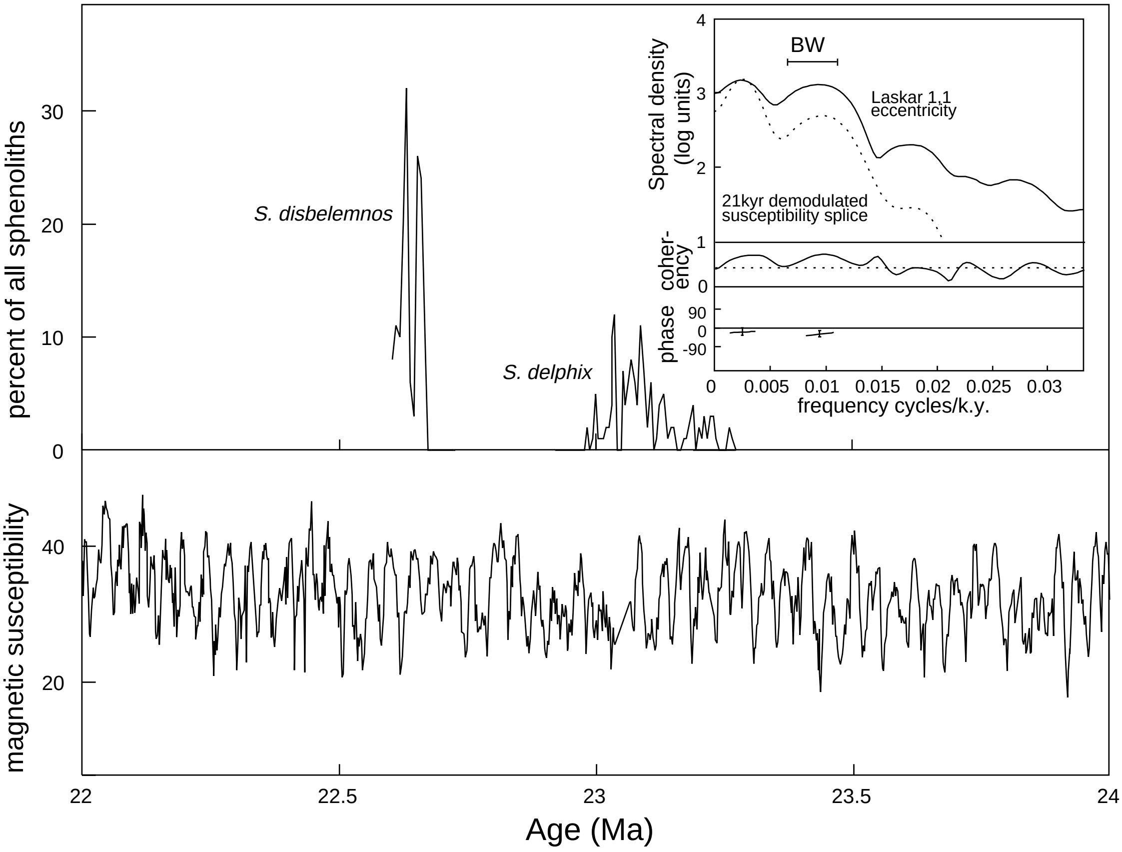

Figure 1. Tuned high-resolution magnetic susceptibility splice data for Ocean Drilling Program Leg 154 sites either side of Oligocene-Miocene boundary (i.e., 22–24 Ma), and relative abundance of *Sphenolithus disbelemnos* and *S. delphix* in Site 929 (upper limit of *S. ciperoensis* was also determined quantitatively but is outside range of figure). Inset: Cross-spectral analysis of 21 k.y. demodulation of data against calculated orbital eccentricity for solution (Laskar et al., 1993) to which they are tuned. Uncertainty of phase estimates forms basis for assessing uncertainty in absolute ages in interval depicted.

the Miocene has been ratified at the Lemme-Carrosio section (Steininger et al., 1997). The boundary is positioned so as to coincide with a reported magnetic polarity transition identified as C6Cn.2n (o). In this paper we address the correlation and astronomically calibrated age of this global stratotype section and point.

ASTRONOMICAL CALIBRATION

Astronomical time-scale calibration for the Oligocene-Miocene boundary interval was carried out by Shackleton et al. (1999) using sediments from Ocean Drilling Program (ODP) Leg 154 (Curry et al., 1995). Shackleton et al. (1999) correlated each successive core at Sites 925, 926, 928, and 929 to an orbital template (from Laskar et al., 1993) on a cycle by cycle basis. Site to site correlation was verified at the scale of individual cycles both by the character of the individual cycles and by high-precision biostratigraphy. Figure 1 shows a magnetic susceptibility splice based on ODP Site 926B with the small intercore gaps covered by data from overlapping sites. In the interval shown, the size of these gaps was verified using downhole logs. The astronomical calibration of Shackleton et al. (1999) is verified over a 10 m.y. interval. Over this long interval, the 1.2 m.y. amplitude modulation of the obliquity cycle provides an important constraint on the time scale. However, it is possible to verify the tuning at a smaller scale. Figure 1 shows the tuned data for about 1 m.y. either side of the boundary, and the inset shows a cross-spectral analysis versus eccentricity of the amplitude of the precession signal in the same data. The phase uncertainty implies an age uncertainty well below ±0.1 m.y. based on both the 406 k.y. and the 100 k.y. components. The phase relationships to obliquity and precession do not provide additional constraints on the accuracy of the estimated ages, because of uncertainties in the orbital calculations (Laskar, 1999).

BIOSTRATIGRAPHY AND MAGNETOSTRATIGRAPHY

The biostratigraphic marker most relevant for correlating the Oligocene-Miocene boundary is the short-ranging nannofossil *Sphenolithus delphix*. In ODP Site 926 the astronomically calibrated range of *S. delphix* (determined by E. Fornaciari, *in* Shackleton et al., 1999) is 23.30–22.99 Ma, and in ODP Site 929 the range of *S. delphix* (determined by Raffi, 1999) is 23.34–22.98 Ma. Above the boundary, the first appearance of *S. disbelemnos* is the next useful nannofossil biostratigraphic datum; its astronomical calibration in both ODP Sites 926 and 929 is 22.67 Ma. Below the boundary the upper limit of *S. ciperoensis*, widely used as a rough approximation to the boundary itself, is astronomically calibrated to 24.14 Ma (astronomically calibrated ages all from Shackleton et al., 1999).

The only site we know that preserves an unambiguous record of the three normal events that make up C6Cn is DSDP Site 522 (Shipboard Scientific Party, 1984). The first paleomagnetic data were published by Tauxe et al. (1984). Hole 522 was sampled at ~20 cm intervals, while the relevant part of Hole 522A was studied continuously using U-channels. In Hole 522 Tauxe et al. (1984) recognized C6Cn.3n by two normally magnetized samples in 522 core 15 section 3, and C6Cn.2n by two normally magnetized samples in 522 core 15 section 2. Tauxe and Hartl (1997) made a detailed study of Hole 522, sampling every 3 cm. Finding normal magnetization in a single sample at 522 16H/1/97 beneath almost 1 m of drilling debris, Tauxe and Hartl (1997) assumed that this represented C6Cn.3n and reassigned the normal event in core 15 section 3 from C6Cn.3n to C6Cn.2n, and that in section 2 from C6Cn.2n to C6Cn.1n.

In order to document the exact correlation between cores from the two holes, we carried out stable isotope stratigraphy in bulk sediment and counted *S. delphix* every 3 cm in Hole 522, and every 5 cm in Hole 522A.

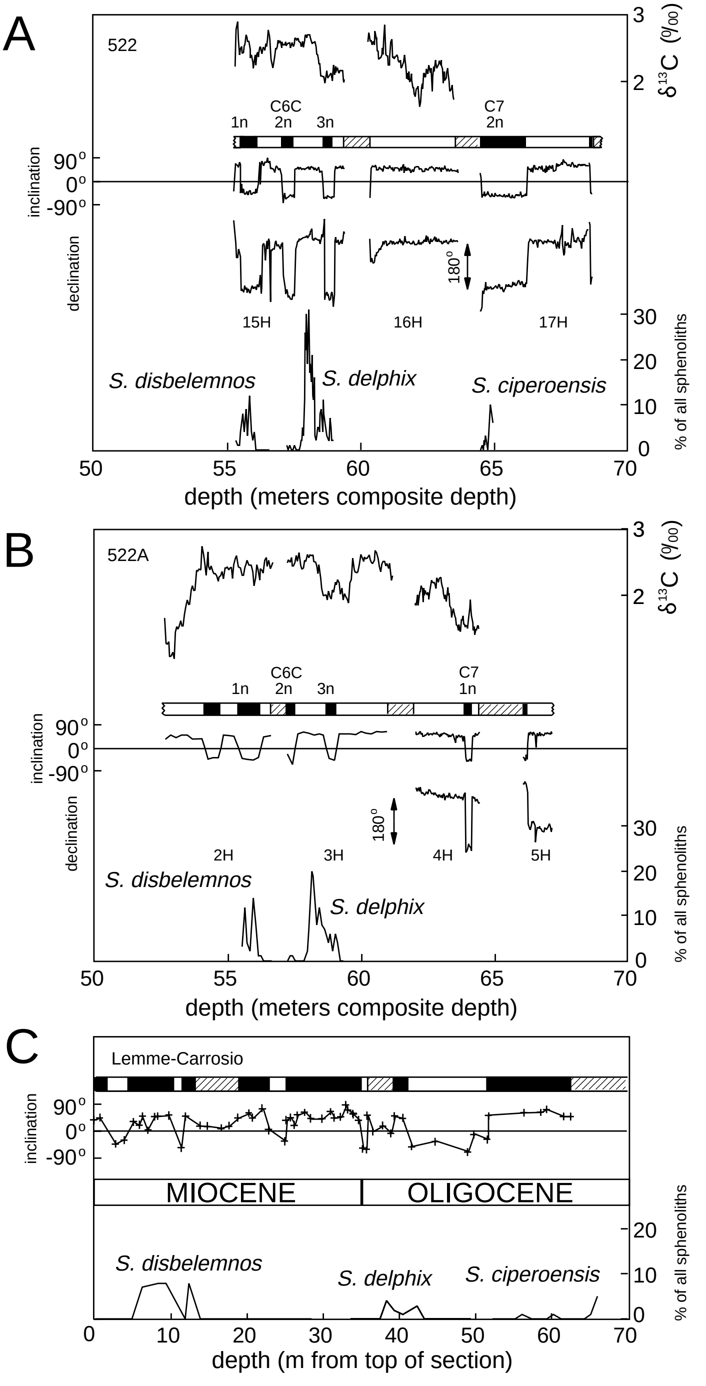

Figure 2. Paleomagnetic, stable carbon isotope, and nannofossil data from Deep Sea Drilling Project (DSDP) Holes 522 (A) and 522A (B) plotted on composite depth scale (see Table 1); DSDP core numbers are indicated. C: Published magnetostratigraphic data from Lemme-Carrosio section from Steininger et al. (1997), and our biostratigraphic data. Marker for base of Miocene is at 35 m; we consider magnetostratigraphy uninterpretable.

TABLE 1. DEPTH OFFSETS APPLIED TO CREATE A COMPOSITE DEPTH SCALE FOR DSDP SITE 522

Core	Offset (m)	Basis
522-15H	0.0	Reference
522A-2H	0.9	C6Cn.1n(o); see also base *S. disbelemnos*
522A-3H	1.0	C6Cn.2n(o); C6Cn.3n(y); C6Cn.3n(o)
522-16H	−0.15	$\delta^{13}C$
522A-4H	0.65	$\delta^{13}C$
522-17H	0.5	No overlap (see text)
522A-5H	0.65	C7n.2n(o)

Note: Within each recovered core, depth mcd equals depth mbsf plus offset. DSDP is Deep Sea Drilling Project; mbsf is meters below sea floor; mcd is meters composite depth.

The new assignation by Tauxe and Hartl (1997) was incorrect; the single apparently normally magnetized sample mentioned was probably from disturbed material. The data are plotted on a composite depth scale (Hagelberg et al., 1992) in Figure 2 after making the depth adjustments shown in Table 1. Figure 2 shows that the three normal events of C6Cn can be identified unambiguously and that *S. delphix* is present between 59.22 m composite depth (mcd), just below C6Cn.3n, to 57.88 mcd, above C6Cn.3n in Hole 522. We have also reanalyzed the magnetostratigraphy of DSDP Site 522A cores 4 and 5 using the sampling method of Tauxe and Hartl (1997). Contrary to the data shown by Mead et al. (1986) (but as suggested by a reexamination of their raw data), chron C7n.1n is unambiguously present between 63.885 ± 0.015 and 64.125 ± 0.015 mcd. This confirms that the upper limit of *S. ciperoensis* reported by Olafsson and Villa (1992) in Hole 522 is within C7n.2n (this was not previously known because the upper limit had never been observed in a site where C7n.1r was reported). Although we slightly refined the upper limit of *S. ciperoensis* reported by Olafsson and Villa (1992) for Site 522, note that the data of Tauxe and Hartl (1997) do not unambiguously support the existence of C7n.2n (y) within the top 10 cm of this core at 60.32 mcd. All the reversals that are at a distance from the ends of the cores show a declination shift of about 180°, whereas this one (as well as the spurious reversal at the top of core 522-16H at 55.23 mcd) does not; moreover, the core description reports disturbance at this point. Thus the extinction of *S. ciperoensis* is not yet directly calibrated to the younger end of C7n.2n.

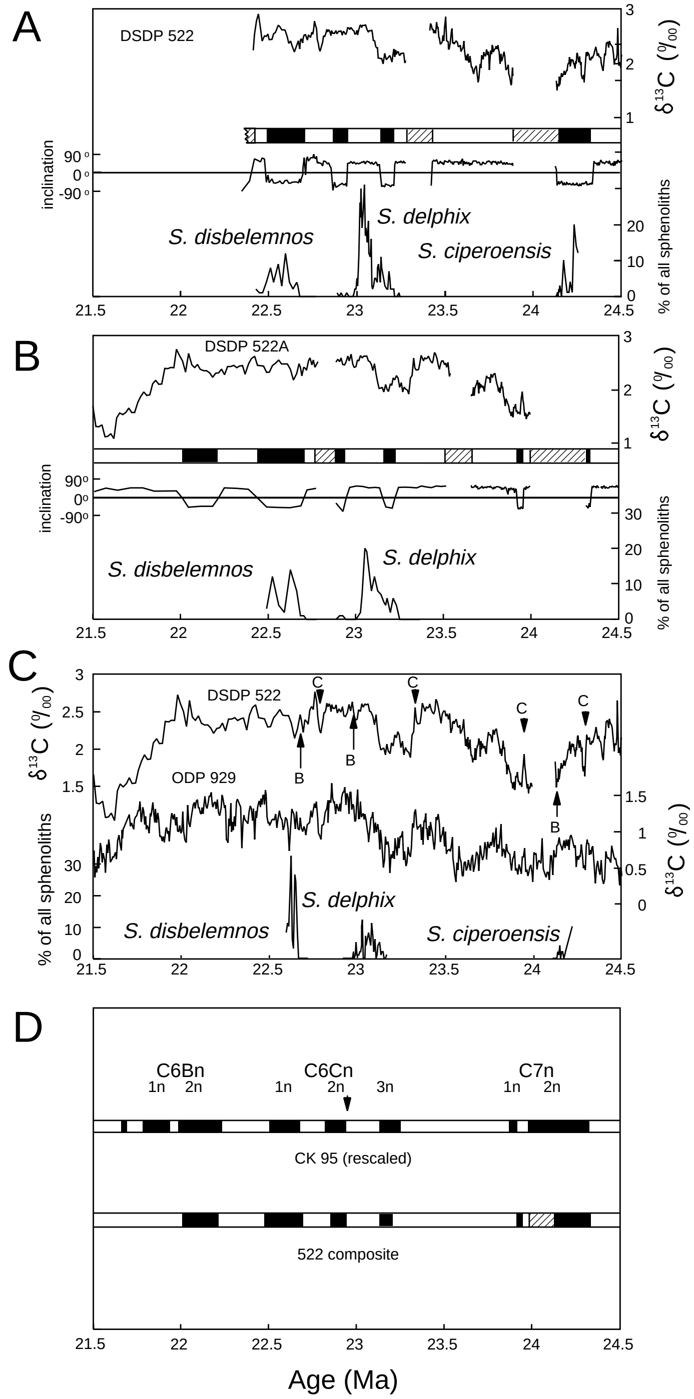

Figure 3. Stable carbon isotope, paleomagnetic, and nannofossil data from Deep Sea Drilling Program (DSDP) Holes 522 (A) and 522A (B) plotted on our age scale. C: Composite carbon isotope record of DSDP Site 522 and carbon isotope record and biostratigraphy of Ocean Drilling Program 929A. Downward arrows marked C show carbon isotope age controls, upward arrows marked B show biostratigraphic age controls. D: Composite magnetostratigraphy of DSDP Site 522 compared with rescaled version of magnetic polarity time scale of Cande and Kent (1995).

CARBON ISOTOPE STRATIGRAPHY

Carbon isotope analyses in bulk sediment from DSDP Sites 522 and 522A were made using an Analytical Precision continuous flow mass spectrometer. Reproducibility for single ^{13}C measurements is about ±0.08‰. Because this is the first set of measurements from the new instrument, every sample was analyzed at least twice.

Figure 3 shows stable isotope analyses of benthonic foraminifera from ODP Site 929 (Zachos et al., 1997, and new data), using the Shackleton et al. (1999) time scale. Between 22.5 Ma and 24.5 Ma there is variability in common between the carbon isotope records of benthic foraminifera in ODP Site 929 and of bulk sediment in DSDP Site 522. This implies that the two records are dominated by the effect of variability in the carbon isotopic composition of dissolved CO_2 in the global ocean. Thus the carbon isotope record may be used to improve the precision with which the two records are correlated.

To transfer the time scale of ODP Site 929 to DSDP Site 522 we first used the four biostratigraphic datums, and then refined the age model by introducing four correlation points based on carbon isotope events and relaxing one biostratigraphic control (Table 2). In Figure 3 the carbon isotope controls are marked by downward-pointing arrows marked C and the remaining biostratigraphic controls are marked B. Relaxing the age control at the first appearance of *Sphenolithus delphix* makes this 0.05 m.y. younger in DSDP Site 522 than in ODP Site 929, a negligible difference considering the rarity of the species at its first appearance. The control at 23.993 Ma provides a secure correlation for C7n.1n in 522A; C7n.2n (y) is not recovered but the ^{13}C data around C7n.2n (o) justify estimating its age.

DISCUSSION AND CONCLUSIONS

Figure 3 shows the DSDP Site 522 data versus age. Within the range of the six datums discussed here, we estimate reversal ages. We do not attempt

TABLE 2. AGE CONTROLS USED TO DERIVE A TIME SCALE FOR DSDP SITE 522

Depth (mcd)	Age (Ma)	Basis
52.62	21.5	Arbitrary fix
56.05	22.671	Base *S. disbelemnos*
56.71	22.791	Carbon isotope low
57.715	22.98	Top *S. delphix*
59.67	23.328	Carbon isotope peak
64.08	23.947	Carbon isotope peak
64.41	23.993	Fix base of core
64.45	24.124	Fix top of core
64.51	24.131	Top *S. ciperoensis*
65.97	24.302	Carbon isotope peak
67.37	24.532	Carbon isotope peak (outside range of Fig. 3)

Note: mcd is meters composite depth; DSDP is Deep Sea Drilling Project.

to obtain ages younger than C6Cn.1n (o). Using linear interpolation between the astronomically calibrated control points yields: C6Cn.1n (o), 22.693 Ma; C6Cn.2n (y), 22.855 Ma; C6Cn.2n (o), 22.944 Ma; C6Cn.3n (y), 23.130 Ma; C6Cn.3n (o), 23.210 Ma; C7n.1n (y), 23.919 Ma; C7n.1n (o), 23.953 Ma; C7n.2n (o), 24.338 Ma. These ages are younger than in Cande and Kent (1995) by 0.85 ± 0.03 m.y.

Figure 3 shows the time scale of Cande and Kent (1995) rescaled on the basis of our age for C6Cn.2n (o), shown by an arrow. Our reconstruction and the rescaled version of Cande and Kent (1995) are so similar it is unlikely that direct tuning of each reversal will make a difference of more than about 0.05 m.y. Ultimately, each reversal should be directly calibrated to the astronomical template, as has already been done for the late Neogene, but this will not significantly improve the absolute ages until the astronomical calculations are further refined.

The stratigraphic range of *S. delphix* in the Lemme-Carrosio type section has been reported variously. Steininger et al. (1997, Fig. 7) defined the base of the Miocene at 35 m and showed a range from 47 m to 31 m. Aubry and Villa (1996) reported a shorter range, from about 35 m to 31 m. Fornaciari and Rio (1996) showed a range equivalent to 43 to 37 m in Steininger et al. (1997, Fig. 7), entirely below the base of the Miocene. We (Raffi, 1999) have reexamined the slides used by Fornaciari and Rio (1996) and find precisely the same range for *S. delphix* as they reported. We found one specimen of *S. capricornutus,* within the range of *S. delphix* as is observed in ODP Sites 926 and 929, but it is too rare in this section to be of value.

The lower limit of the foraminifer *Paragloborotalia kugleri* is reported in the Lemme-Carrosio section at 33 m, 2 m above the boundary (Steininger et al., 1997, Fig. 7). This is consistent with ODP Site 926, where the event is recorded about 0.1 m.y. younger than the upper limit of *S. delphix*.

We also reexamined the range of *S. disbelemnos* in the Lemme-Carrosio section, finding a range similar to that reported in the other investigations. This suggests that the upper part of the section is still within C6Cn.1n. Although at a descriptive level the magnetostratigraphy seems plausible, the distribution of inclination measurements (Fig. 2C) is not sufficient to contribute to the stratigraphic understanding of the boundary stratotype. Langereis (1999, personal commun.) attempted to generate a magnetostratigraphy for the Lemme-Carrosio section and considers that the sediments do not preserve a useful signal.

We conclude that although far from ideal, the Lemme-Carrosio section constitutes a useable boundary stratotype that can be fairly precisely correlated to continuous deep-sea sections by nannofossil biostratigraphy. The defined boundary is probably close to C6Cn.2n (o), although the magnetic data are not of suitable quality to predicate the position of the boundary marker. The absolute age of this reversal is 22.91 Ma. The internal consistency of the nannofossil data suggests that the correlation from orbitally tuned Site 929 to DSDP Site 522, which has excellent magnetostratigraphy, has an uncertainty better than ±0.05 m.y. It is important to note that the accuracy of the astronomical tuning does not depend on counting precession or obliquity cycles back from the present, but on counting eccentricity cycles (Shackleton et al., 1999). The 406 k.y. eccentricity cycle should provide a secure basis for extended geological age calibration.

ACKNOWLEDGMENTS

This work was supported by National Environment Research Council grant GR3/11461 to Shackleton. We thank Simon Crowhurst for assistance, and Heiko Pälike, Steven Clemens, and an anonymous reviewer for helpful comments on the manuscript.

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Manuscript received October 25, 1999
Revised manuscript received February 4, 2000
Manuscript accepted February 16, 2000