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Precision and accuracy of nannofossil biostratigraphic correlation

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Calcareous nannofossils are widely recognized to be a powerful tool for regional and worldwide biostratigraphic correlations. Recently, nannofossil biostratigraphy has been advanced by expanding the nannofossil database using a quantitative analytical approach, and by testing the reliability of bioevents in different time-intervals. Efforts to improve nannofossil biostratigraphy have resulted in a set of reliable 'biohorizons' (biostratigraphic datums), which are correlatable across wide distances. Where dating tools such as cyclostratigraphy and magnetostratigraphy are available, calcareous nannofossil biohorizons can be used as control points for the identification of cycle numbers and polarity zones. For the Cenozoic, nannofossil biochronology can provide a basis for age models, which can then be developed into orbitally tuned cyclostratigraphies, or used for chronological revision of polarity time-scales.

Keywords: calcareous nannofossils; biostratigraphy; stratigraphic correlation; reliability; Late Cenozoic; Oligocene–Miocene transition

1. Introduction

The biostratigraphic correlation and dating provided by the study of the calcareous plankton groups are essential for studies of marine sedimentary sections. This has been demonstrated by, for example, the numerous papers published in the last three decades on material obtained by ocean drilling, beginning with the first Deep Sea Drilling Project (DSDP) cruises in the late 1960s. A decisive advance towards consistently successful biostratigraphy was achieved in the last decade. Before that, a period of decreased interest in (and decrease in demand for) the work of micropalaeontologists and biostratigraphers by geologists, especially those related to the hydrocarbon industry, led to a decrease in the number of positions for micropalaeontologists in academic and industrial environments (see the editorial of Simmons (1998)). This deteriorating situation was mitigated by an increase in the collection of biostratigraphic data, involving studies on a great variety and quantity of sedimentary sequences from all over the world, and, perhaps most importantly, a remarkable change in the character of the biostratigraphic data collected.

This change in the character of data collected is due, firstly, to the increased tendency of biostratigraphers to favour a quantitative approach to data acquisition, aimed at increasing the resolution and describing a greater range of biostratigraphic signals in addition to the classical markers; and secondly, to biostratigraphers increasingly comparing their diverse data, integrating data from different microfossil groups, and correlating them to other stratigraphic data, in an effort to improve the temporal resolution provided by isolated biostratigraphic data-sets. Among calcareous

plankton, calcareous nannofossils have acquired an excellent reputation as powerful biostratigraphic and dating tools, thanks to a series of classic, detailed studies (see the summaries of Bukry (1981) and Haq (1984)). These have progressively confirmed the biostratigraphic potential of nannofossils, which was already emphasized in the pioneering paper of Bramlette & Riedel (1954). More recently, nannofossil biostratigraphy has been correlated with different types of stratigraphic data—magnetostratigraphy, isotope stratigraphy, litho-(cyclo)stratigraphy—with the principal purpose of obtaining biochronologic data (nannofossil calibration) for different settings and locations. These integrated procedures permit an evaluation of the degree of synchrony (isochrony or diachrony) of biohorizons (biostratigraphic events) when data from different areas and environments are compared.

This effort has generated excellent results for different intervals of geological time. An example is the nannofossil biochronology for the Late Neogene (see a summary in Berggren *et al.* 1995), which is now precisely established on account of studies carried out on numerous sedimentary sequences with independent age controls straddling this time-interval. These include the best sequences recovered so far in terms of the completeness and quality (richness of microfossil assemblages) of the sediments. Other examples are the detailed biochronologic studies of nannofossils performed on Palaeogene and Mesozoic sections (e.g. Backman 1986, 1987; Herbert *et al.* 1995; Bralower 1988; Channell *et al.* 1995).

This paper illustrates the quality and pivotal role of calcareous nannofossils as biostratigraphic and biochronologic tools, in particular for some time-intervals. Stratigraphic correlations supported by such data, in most instances, result in particularly accurate and precise correlations, and often represent the key to the interpretation of other stratigraphic records. This supports the contention that the effort involved in such procedures is worthwhile.

2. Calcareous nannofossils as biostratigraphic and dating tools

The special role of nannofossils in biostratigraphy, and their importance in dating marine sediments, is due to some distinctive aspects of this group of fossils. In well-preserved planktonic assemblages (from sediments recovered away from upwelling areas) nannofossils are usually abundant. They tend to be ubiquitous, and are generally absent only in sediments from very deep sites, where corrosive bottom waters dissolve calcium carbonate. Nannofossils are generally more resistant to diagenetic changes (dissolution and overgrowth) than are foraminifers. Analyses of nannofossil assemblages do not require laborious processing of the samples. A very small quantity of material is needed, so that these microfossils are ideal for obtaining high-resolution biostratigraphy. Moreover, calcareous nannofossils represent an extremely diverse group of microfossils, characterized by varied morphologies. Despite their very small size, such distinct morphologic features facilitate the recognition of the majority of the species within the group. However, it should be acknowledged that nannofossils lack a rigorous taxonomy, that is, one that consistently follows the established rules of classification. This anomaly does not seem to affect the usefulness of their biostratigraphic signal, which benefits from fast evolutionary changes within the group, associated with great diversity.

(a) *Improving nannofossil biostratigraphy*

Since DSDP cores became available, biostratigraphic zonal schemes based on calcareous nannofossils have been established. The detailed calcareous nannofossil biostratigraphies available for the Mesozoic and Cenozoic intervals are the results of the intense work done on these microfossils over the last few decades. Some of these biozonations, recognizable over wide areas, are regarded as standards for biostratigraphic dating (Martini 1971; Okada & Bukry 1980). More recently, a major effort has been made to improve biostratigraphic resolution. Consequently, new data and results have been obtained in numerous sedimentary successions worldwide. Standard or regional biostratigraphic schemes are continuously refined. Part of the biostratigraphic work has been focused on testing the reliability of the nannofossil datums, including both the well-known biostratigraphic markers and also the secondary markers, which provide standard and additional biohorizons (e.g. Wei 1993; Raffi *et al.* 1993, 1995; Rio *et al.* 1990*a, b*; Fornaciari & Rio 1996; Fornaciari *et al.* 1996; Backman & Raffi 1997).

Refinements of the biostratigraphic schemes are obtained both by extending the database through the study of increasing numbers of suitable sedimentary successions, and also by introducing new methodologies for biostratigraphic analysis, which allow the recognition of new biohorizons.

(i) *Extending the database*

Following improvements in drilling technologies, which provide sediment cores characterized by complete and undisturbed recovery in most of the intervals within the Cenozoic, high-quality deep-sea sedimentary successions are available to biostratigraphers. The sediments are representative of different environments from different latitudes in various ocean basins. Examples include the sediments recovered from low- and mid-latitudes by the Ocean Drilling Program (ODP), such as those recovered during ODP Leg 115 in the tropical Indian ocean (Backman *et al.* 1988), ODP Leg 130 in the western equatorial Pacific (Kroenke *et al.* 1991), ODP Leg 138 in the eastern equatorial Pacific (Mayer *et al.* 1992), and ODP Leg 154 in the Western Equatorial Atlantic (Curry *et al.* 1995). The detailed biostratigraphic and biochronologic studies made on these sediments in the recent past (e.g. Rio *et al.* 1990*b*; Fornaciari *et al.* 1993; Raffi & Flores 1995; Raffi *et al.* 1995; Backman & Raffi 1997) demonstrate the importance of having such high-quality material available.

(ii) *Refining the methodology*

Beyond the sheer increase of biostratigraphic data (and zonal schemes) from widely distant areas, an important recent innovation in nannofossil biostratigraphy is the introduction of new analytical approaches to data acquisition. Backman & Shackleton (1983) showed, for the first time, how the precision of the nannofossil population changes used in biostratigraphy can be improved by applying a semi-quantitative approach to biostratigraphic analyses.

The data obtained using the quantitative methodology provide important information for refining biostratigraphic resolution. With these techniques, it is possible to document in detail changes in nannofossil assemblages through time. Such changes

were caused by the evolutionary appearances and extinctions of taxa and by environmental changes, which control migrations and fluctuations in presence and abundance (temporary absence, increase, acme, dominance) of taxa in different biogeographical areas. Such floral changes, if demonstrably distinct and correlatable, can serve as biostratigraphic events.

With a rigorous analytical approach it is possible also to capture subtle biostratigraphic signals that, although difficult to determine, may serve to further improve biostratigraphic resolution and correlations. In addition, this approach permits the consideration of problems that can influence the reproducibility of the detection of an event, such as problems in operational procedures (i.e. drilling disturbances, field and laboratory contamination) or in the stratigraphic record (sediment mixing, reworking).

The use of the semi-quantitative methodology overcomes the problem of subjectivity inherent in the 'qualitative' analytical approach. This is based on the presence/absence method, which, although it can provide an accurate biostratigraphy, excludes types of information useful for enhanced biostratigraphic resolution. Quantitative data gathering allows criteria to become established which can 'standardize' the recognition of biostratigraphic events, and which can be consistently applied by other biostratigraphers. Hence, the practice of proposing operating definitions of quantitatively detected bioevents (e.g. Thierstein *et al.* 1977; Rio *et al.* 1990a) has proved to be very useful.

However, extreme details in biostratigraphic observations are not always useful for enhancing the reproducibility of datums and can lead to excessively detailed biozonations, difficult to apply in practical biostratigraphic and routine analyses. This can happen, for instance, when marker events are recognized and defined on the basis of a subtle morphologic difference recorded in nannofossil assemblages, or on the basis of small-scale biometric observations, quantitatively meaningless, which the analyst uses to recognize a larger number of bioevents (see De Kaenel *et al.* 1999). With this procedure, an extremely detailed set of biohorizons can be provided. These biohorizons are, however, difficult to reproduce elsewhere, less trustworthy, and of little relevance to routine work (e.g. the routine biostratigraphic work performed during an ODP drilling leg).

Another important aspect of improving biostratigraphic resolution is the number of samples and the depth interval between samples analysed for biostratigraphy. The degree of accuracy typical of palaeoceanographic analyses based on palaeoenvironmental proxies should represent a goal for the improvement of biostratigraphic information (see the discussion in Backman & Raffi (1997)). Analyses using closely spaced samples, which parallel those on palaeoenvironmental proxies, permit the depiction in detail of the evolutionary appearances or extinction of species and, more importantly, enhance the precision of the biostratigraphic estimate associated with these events (figure 1). In addition, comparisons between biostratigraphic information of this type and palaeoenvironmental proxies may provide insights into the influence of changing environmental conditions on evolutionary developments.

Optimizing the analytical methodologies by gathering quantitative data and using closely spaced sampling helps to minimize the problems outlined above, and clearly represents a critical factor for testing and possibly improving the reliability of biostratigraphic events as stratigraphic markers. To do this, the reproducibility and traceability of an event must be evaluated. Subsequently, its precision and accu-

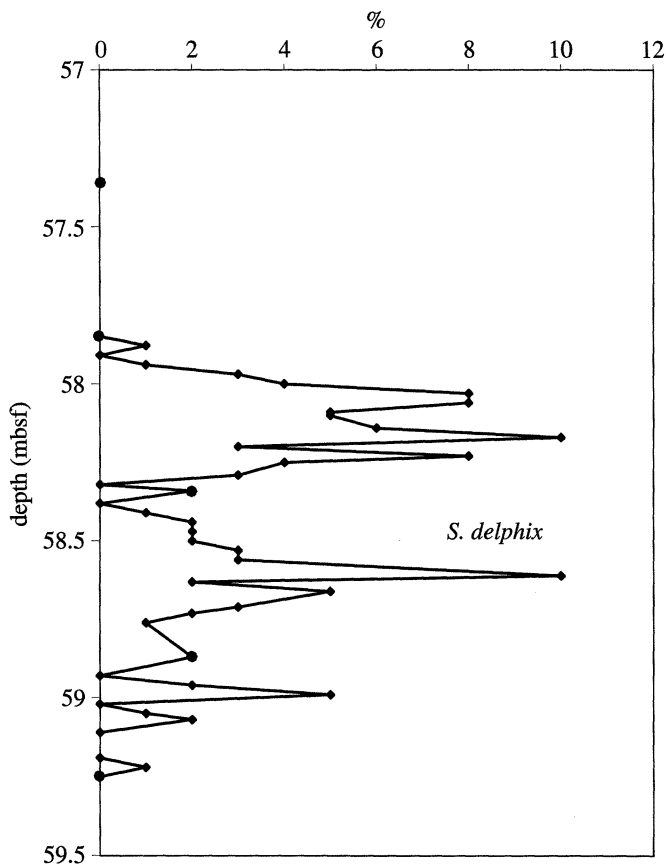


Figure 1. Example of the influence of sampling intervals and counting methods on the quality of biostratigraphic information. The distribution pattern of the nannofossil species *S. delphix* at DSDP Site 522, obtained at a 0.03 m sampling interval, shows high-frequency variations in abundance and a precise biostratigraphic signal. Much less precise information is obtained at a sampling interval (black dots) of ca. 0.5 m (three samples per section).

racy as a means of biostratigraphic correlation should be established, as discussed below.

(b) Reliability of nannofossil biohorizons

Accurate and precise biostratigraphic correlations are obtained by using biohorizons (biostratigraphic datums) representing reliable bioevents. There have been discussions of the reliability of biostratigraphic events (i.e. Gradstein *et al.* 1985; Hills & Thierstein 1989), and there have been tentative attempts to quantify the 'degree of reliability' of datums in absolute terms, including the introduction of the 'reliability index' (Bralower *et al.* 1989). Referring in particular to calcareous nannofossils, some authors consider the evaluation of synchrony of events as the critical aspect for estimates of reliability. Reliability is tested by comparison of different bio-magnetostratigraphic data from different deep-sea sections (Wei & Wise 1989; Spencer-Cervato *et al.* 1994). This procedure can easily produce misleading evalua-

tions of synchrony, and hence reliability, because of the varied sources of information and differing quality of the data used and compared.

Other authors have focused on the problem of evaluation of biostratigraphic reliability from the point of view of other considerations, such as the importance of provable synchrony in first and last appearances (Rio *et al.* 1990a; Olafsson 1991). They considered biostratigraphic reliability to be dependent also on (1) the distinctiveness of the abundance change that defines the event—a function of productivity in the living assemblage and also of the preservation of the signal in the fossil assemblage; and (2) the correlatability between distant sites. Only biostratigraphic events defined by evaluating the factors mentioned above are suitable for deriving a confident and useful biostratigraphy.

Building on these convictions, numerous studies have established that many nanofossil events (biohorizons) are recognizable in different oceanic areas and in different facies, and that they maintain the same characteristics in distribution patterns, and the same stratigraphic ranking (*sensu* Gradstein *et al.* 1985). They are therefore considered demonstrably reliable. To be precise, nanofossil biostratigraphic events can be referred to as reliable when they have the critical requisites of reproducibility and traceability, being well defined and easily recognizable in different sequences and among different researchers. As discussed above, their reproducibility primarily derives from unambiguous taxonomic definitions of the index species involved, and clear ‘morphology’ of the relative event, in terms of the mode of occurrence (abrupt, subtle, etc.) of the change in distribution pattern of the index species (e.g. appearance and extinction patterns, continuity and abundance variations along the range).

(i) *Clarity in taxonomy*

Uncertainties in taxonomic assignments do not represent a major problem for the identification of nanofossil species. For the Cenozoic, for example, most of the key species are clearly described and easily identified by experienced biostratigraphers.

Taxonomic problems certainly affect nanofossil stratigraphy to a lesser extent than the taxonomic difficulties associated with planktonic foraminifers affect foraminiferal stratigraphy. Nanofossil micropalaeontologists very rarely face what is a rather common problem in planktonic foraminiferal biostratigraphy, namely the ambiguity, or uncertainty, of taxonomic assignments of marker species which are generated by gradual evolutionary transition. As discussed by Pearson & Chaisson (1997), in planktonic foraminifer biostratigraphy, different workers may use different (sometimes subjective) criteria to discriminate morphospecies in an evolutionary lineage, when the morphospecies intergrades between an ancestral form and a descendant form. This uncertainty contributes to the uncertainty associated with first/last occurrence datums and therefore to uncertainty in correlations and age assignments.

Among calcareous nanofossils, evolving lineages with gradual transitions between morphotypes are theoretically described but very rarely documented. The relatively rapid rate of evolutionary change that calcareous nanofossils show through geological time is documented in rapid changes in the assemblages, and sudden appearances and disappearances of taxa from the stratigraphic record. These bioevents seem to be evolutionary episodes that occur relatively rapidly, are therefore less likely to be preserved in the fossil record, and are seldom documented at ‘standard’ stratigraphic

resolution. When evolutionary trends in nannofossil key species can be documented (e.g. in the Middle–Late Miocene (Raffi *et al.* 1998)), observations indicate that the time-interval involved in the evolutionary event is only a few thousand years, confirming a very high rate of evolutionary appearance (speciation) of nannofossil species. Therefore, the theoretical concept that biostratigraphic datums represent geological instantaneous events seems to be acceptable for many calcareous nannofossil markers. It is still important to document and evaluate how distinctive ('instantaneous') each particular event is, and this can be achieved only through a precise characterization using high-resolution sampling.

(ii) '*Morphology*' of biostratigraphic events

As stated above, the determination of occurrence patterns of index species is a strategy that, in turn, characterizes the related datums (biohorizons) in terms of reproducibility. Quantitative investigations of extinction, evolutionary emergence, total abundance behaviour of species makes it possible to obtain important biostratigraphic informations. When this is done in several (possibly many) stratigraphic sections in different geographical areas, and the biohorizons retain the same stratigraphic position in relation to each other (that is, they possess the quality of 'being traceable'), their reliability is demonstrated. Biohorizons with such characteristics constitute biostratigraphic successions correlatable among distant areas.

In summary, a rigorous analytical approach to nannofossil studies permits an evaluation of biohorizons (biostratigraphic datums) in terms of reliability and calibrates their potential correlatability. Rigorous methodology involves the application of stringent event definition and the use of high-resolution procedures for sample collection and data collection.

(c) *Nannofossil biohorizons as dating tools*

Once a set of 'reliable' biohorizons is available, an important further goal is to obtain a reliable biochronology; that is, to assign a chronological significance to these biohorizons. High-quality biostratigraphic data, gathered using rigorous analytical techniques, provide the potential for high-resolution calibration between nannofossil biohorizons and other records used for dating, such as magnetostratigraphy, stable isotopic stratigraphy and orbitally tuned cyclostratigraphy. Some examples of such data are: in the Pleistocene and Pliocene, $\delta^{18}\text{O}$ records (e.g. Thierstein *et al.* 1977; Backman & Shackleton 1983; Raffi *et al.* 1993; Wei 1993; Lourens *et al.* 1996), in the Late Neogene, astronomically tuned polarity records (Shackleton *et al.* 1995*a, b*), in the Middle–Late Miocene, orbitally tuned cyclostratigraphies (e.g. Backman & Raffi 1997). In this way, the accurate time resolution which distinguishes these data sequences is transferred to the biohorizons. It is clear that the introduction of orbitally tuned time-scales is crucial for the improvement of the age calibrations for biostratigraphic events, in terms of chronological precision. What was expressed as a hope in the 1980s for the improvement of biostratigraphy (Haq & Worsley 1982), namely, the possibility of 'a major breakthrough in the development of refined and accurate time-scales based on marine microbiochronologies' (Haq & Worsley 1982, p. 31) seems now to be taking place.

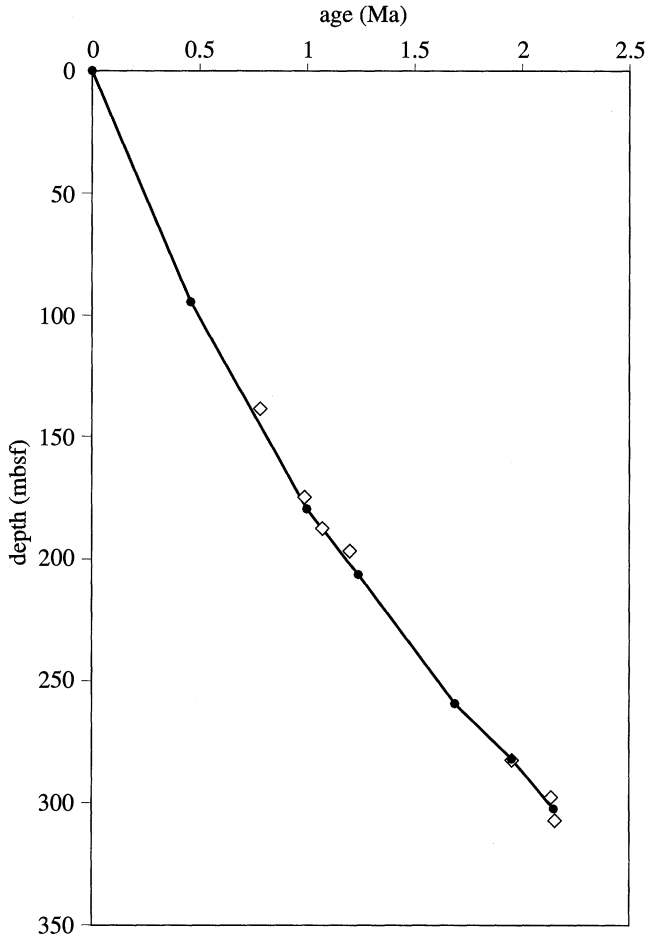


Figure 2. Age–depth plots for ODP Hole 1063A (Leg 172, Bermuda Rise) based on biostratigraphic (calcareous nannofossils) tie-points (black dots) and magnetostratigraphic reversal boundaries (open diamonds) (modified from Keigwin *et al.* (1998)).

(d) *Biostratigraphic correlations based on calcareous nannofossils*

Several cases can be cited as examples of the usefulness of nannofossil biostratigraphic and dating correlations, relying on the precision and accuracy of the technique. Within the diverse range of uses of nannofossil data for dating and correlation purposes, the examples described below are noteworthy.

Figure 2 shows that high-quality biostratigraphy and magnetostratigraphy have a comparable potential for generating refined sedimentation rate histories for sedimentary successions. The construction of composite depth sections from adjacent holes in multiply cored sites, and the site-by-site correlation of composite sections, depends on precise biostratigraphic data (e.g. the ODP sites from Legs 138 and 154; Mayer *et al.* 1992; Curry *et al.* 1995). That is, the construction of composite sections can benefit from a set of nannofossil biostratigraphic datums as control points, when these datums are accurately detected with sufficiently rigorous methods. The

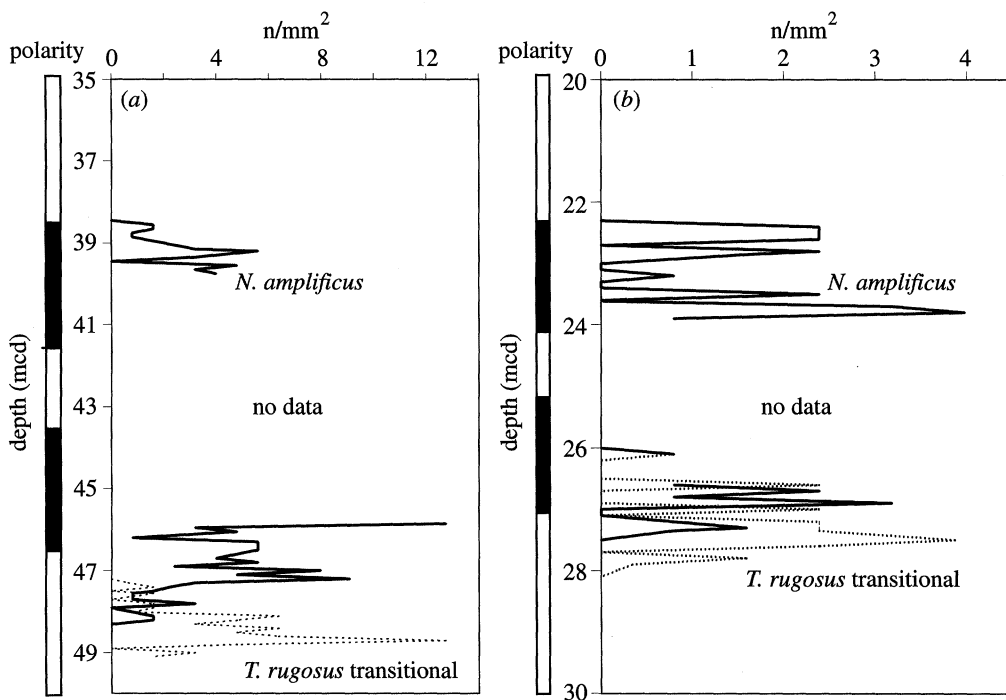


Figure 3. Distribution patterns of *Nicklithus amplificus* and related forms (transitional morphotypes between *Triquetrorhabdulus rugosus* and *N. amplificus*) at ODP Site 853 ((a) Leg 138, eastern equatorial Pacific) and ODP Hole 711B ((b) Leg 115, equatorial Indian Ocean). Data refer to the lower and uppermost parts of *N. amplificus* range. Abundance of index species expressed relative to unit area of smear-slide (number of specimens per square millimetre). Palaeomagnetic data from Schneider & Kent (1990) for ODP Hole 711B, and from Mayer *et al.* (1992) for ODP Hole 853B.

examples quoted above demonstrate that this can be achieved, even where analyses were performed largely during shipboard work.

Another example, from the Late Miocene, of the precision and utility of nannofossils as a correlation tool is shown in figure 3, which shows detailed distribution patterns (at the appearance and extinction levels) of *Nicklithus* (= *Amaurolithus*) *amplificus* and related forms. These biostratigraphic datums can be shown to be isochronous among distant sections, as illustrated in the equatorial Indian and Pacific oceans (at ODP Site 711 and ODP Site 853). The evolutionary appearance of *N. amplificus* occurred simultaneously close to the base of chron C3An, and the extinction of the same group occurred simultaneously in correspondence with the top of chron C3An (Rio *et al.* 1990b; Raffi *et al.* 1995; present paper). The distribution patterns of *N. amplificus* and related forms (the morphotypes transitional between *Triquetrorhabdulus* and *Nicklithus*) are the same as are observed, at the appearance and extinction level, in sediments recovered from the western equatorial Atlantic at ODP Site 926 (fig. 5 of Backman & Raffi 1997). The documentation of this evolutionary appearance in this oceanic area, together with the similarity of distribution patterns, confirms the reliability of the events for biostratigraphy. In the same Site, ODP 926, the two biohorizons were astronomically calibrated as occurring at 6.84 Ma

and 5.99 Ma (Backman & Raffi 1997). These ages differed, by *ca.* 100–120 ka, from the ages obtained at Site 853 by extrapolation from chron C3An, using the Leg 138 time-scale (Shackleton *et al.* 1995a). However, applying a more recent age model (using the magnetic reversal ages based on the astronomically tuned Late Miocene time-scale of Hilgen *et al.* (1995)) to the critical interval at Site 853, the age calibration of these two biohorizons conforms with the astronomical chronology developed for Site 926 (see Backman & Raffi 1997). This means that precise biostratigraphy can be used for chronologic revision, and can help to test the validity of newly proposed age models.

A final example, which may further clarify and summarize what was discussed in previous sections as regards the precision and accuracy of nannofossils as correlation tools, comes from the nannofossil biostratigraphy from around the Oligocene–Miocene (O–M) boundary. Specifically, it relates to a study performed on reference sedimentary sequences, including the internationally ratified ‘global stratotype section and point’ for the boundary.

(i) *Calcareous nannofossils in the Oligocene–Miocene time*

As with most chronostratigraphic boundaries, the O–M boundary has been, and still is, the subject of discussions and controversies. The main reason for this dispute is the condition of the historically accepted Upper Oligocene and Lower Miocene stratotypes, which clearly do not conform to the modern concept of ‘global stratotype section and point’ (GSSP) (see the discussion in Fornaciari & Rio (1996)). A general consensus was recently reached in identifying a new GSSP section for the O–M boundary, namely a Mediterranean section (Lemme–Carrosio) located in northern Italy (Steininger *et al.* 1994). As far as calcareous nannofossil biostratigraphy is concerned, questions have arisen in the past concerning the ‘best’ criteria (biostratigraphic datum/s with coherent geochronological meaning) for approximating the O–M boundary. Consequently, nannofossil palaeontologists recognized the boundary using different datums, most of which turned out to be unreliable (see Fornaciari & Rio 1996).

In the tentative effort to resolve this problem, some authors (Miller *et al.* 1985; Rio *et al.* 1990b; Olafsson 1991; Fornaciari *et al.* 1993) focused attention on a few nannofossil species belonging to the genus *Sphenolithus*, whose stratigraphic ranges were related to the critical time-interval of the O–M transition.

Biostratigraphic events provided by *Sphenolithus ciperoensis* (last occurrence, LO), *S. delphix* and *S. capricornutus* (first and last occurrences, FO and LO), and *S. disbelemnus* (first occurrence, FO), were studied. The aim was to clarify the biostratigraphy, and possibly the biochronology, of this critical interval (Rio *et al.* 1990b; Olafsson 1991; Fornaciari *et al.* 1990, 1993; Fornaciari & Rio 1996; Aubry & Villa 1996).

Varying opinions are held about the reliability of each particular datum, leading to distinct proposals for the biohorizons which serve to locate the O–M boundary worldwide (e.g. Berggren *et al.* 1995; Fornaciari & Rio 1996; Aubry & Villa 1996). It should be noted that for all but one (*S. ciperoensis* LO) of the above-mentioned events, the chronology was uncertain, because the known bio-magnetostratigraphic characterizations were based on unsuitable marine sections (see the discussion in Berggren *et al.* (1995) and Aubry & Villa (1996)). A good opportunity for per-

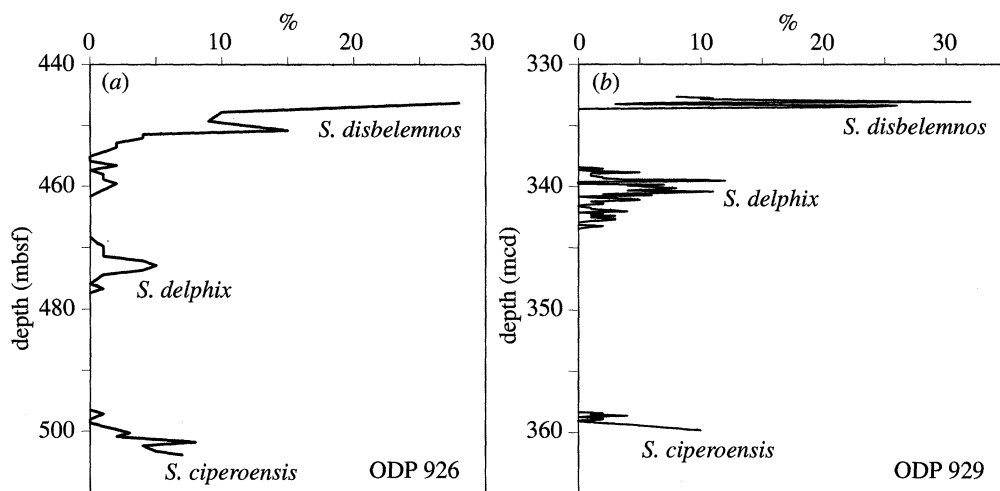


Figure 4. Distribution patterns of selected *Sphenolithus* species in the Oligocene–Miocene interval at ODP Sites (a) 926 and (b) 929 (Leg 154, western equatorial Atlantic). Abundance of the index species expressed relative to 100 sphenoliths. Data of Site 926 from Fornaciari (1996).

forming a detailed study of nannofossil biostratigraphy at the O–M transition was provided by some of the sedimentary sequences recovered during ODP Leg 154 in the western equatorial Atlantic (Curry *et al.* 1995). The study was planned firstly to obtain preliminary control points to reflect the astronomical tuning of the sequences (Shackleton *et al.*, this issue). As the tuning was performed and the astronomical calibration acquired, a precise calibration has been obtained of the relationship of the bioevents to the time-scale.

In figure 4 the distribution patterns of *S. ciperoensis* close to its LO, and of *S. disbelemnos*, close to its FO and of *S. delphix*, along its range, in ODP Sites 929 and 926 are shown. Comparison of the plotted abundance data indicates an evident correlation between the two data-sets, although they were obtained by different researchers (I. Raffi and E. Fornaciari) with different analytical methods. In fact, although in both sites semi-quantitative analyses were performed on the index species, data at ODP Site 929 were obtained at 10 cm sample resolution (averaging 6–9 ka), whereas data at ODP Site 926 were obtained at an average sample resolution of 80 cm. The results partly confirmed the observations already known from the literature on the mode of occurrence of the index species. The total range of *S. delphix* was limited to a short interval, as was observed in the equatorial Indian and Pacific oceans (Rio *et al.* 1990b; Fornaciari *et al.* 1990, 1993), and in the mid-latitude Mediterranean (Fornaciari & Rio 1996) and Atlantic (Miller *et al.* 1985). At ODP Site 929, *S. capricornutus* was present with scattered single specimens within the range of *S. delphix*, whereas it is unrecorded in the (fewer) samples examined from ODP Site 926. However, *S. capricornutus* shows variable ranges in different areas, and it is therefore considered an unreliable datum. The calibration of the considered events to the astronomical time-scale in this interval (Shackleton *et al.*, this issue) indicates the following ages (table 1): *S. ciperoensis* LO at 24.141 ± 0.003 Ma; *S. delphix* FO at 23.270 ± 0.003 Ma; *S. delphix* LO at 22.980 ± 0.003 Ma; *S. disbelemnos* FO at 22.671 ± 0.003 Ma.

Table 1. Calibration of Oligocene–Miocene *Sphenolithus* biohorizons

(Astronomical ages at ODP Site 929 from Shackleton *et al.* (this issue). Age calibrations at DSDP Site 522, using the time-scale of Cande & Kent (1995) (CK95), are based on biomagnetostratigraphic positions from the present study and: (A) palaeomagnetic interpretation by Shackleton *et al.* (1999); (B) palaeomagnetic interpretation of Tauxe & Hartl (1997). Age uncertainties refer to sampling interval, not to overall uncertainty.)

biohorizon	ODP Site 929 astronomical ages	DSDP Site 522 (A) CK95 ages	DSDP Site 522 (B) CK95 ages
FO <i>S. disbelemnos</i>	22.671 ± 0.003 Ma	23.539 ± 0.002 Ma	23.078 ± 0.006 Ma
LO <i>S. delphix</i>	22.980 ± 0.003 Ma	23.866 ± 0.003 Ma	23.582 ± 0.002 Ma
FO <i>S. delphix</i>	23.270 ± 0.003 Ma	24.129 ± 0.002 Ma	23.817 ± 0.005 Ma
LO <i>S. ciproensis</i>	24.141 ± 0.003 Ma	24.836 ± 0.002 Ma	24.839 ± 0.006 Ma

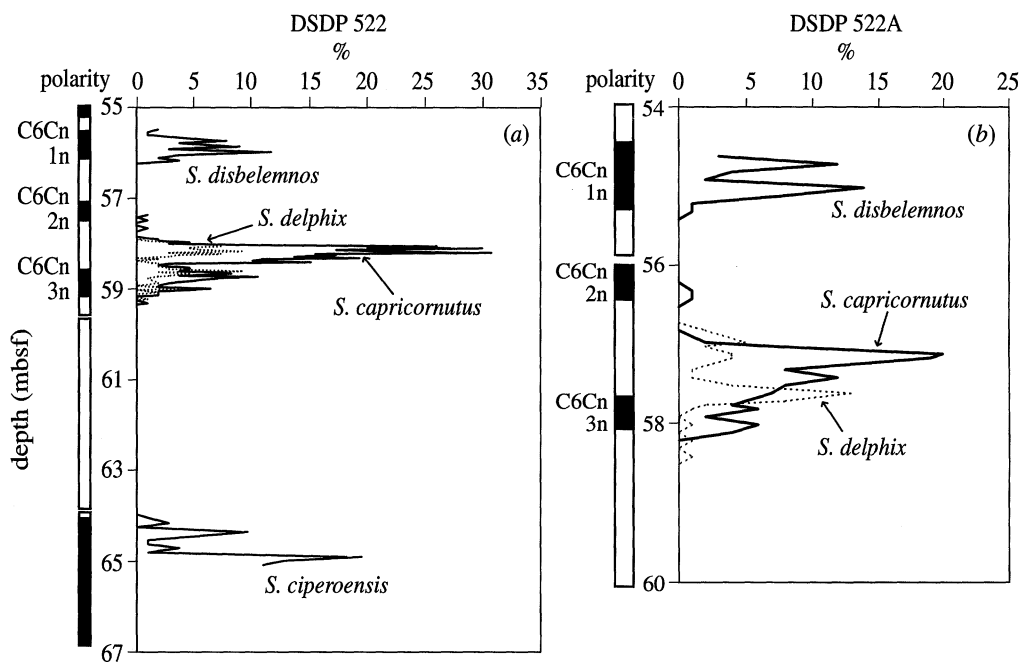


Figure 5. Distribution patterns of selected *Sphenolithus* species in the Oligocene–Miocene interval at DSDP Site 522 (Holes 522 and 522A, Leg 73, southern Atlantic). Abundance of the index species expressed relative to 100 sphenoliths. *S. delphix* = dashed line. Palaeomagnetic data from Tauxe *et al.* (1984). Magnetostratigraphic interpretation from Shackleton *et al.* (1999).

Due to the lack of magnetostratigraphic data at Leg 154 Sites with which to compare the nannofossil data obtained, the biostratigraphic study has been extended to another reference section which has reliable magnetostratigraphy in the interval of the O–M transition. The analyses of the nannofossil assemblages were carried out on a sedimentary succession from DSDP Site 522 (Holes 522 and 522A) located in the southeastern Atlantic (Hsü *et al.* 1984). The data obtained assisted the correlation and reinterpretation of the palaeomagnetic records of Tauxe *et al.* (1984) and Tauxe

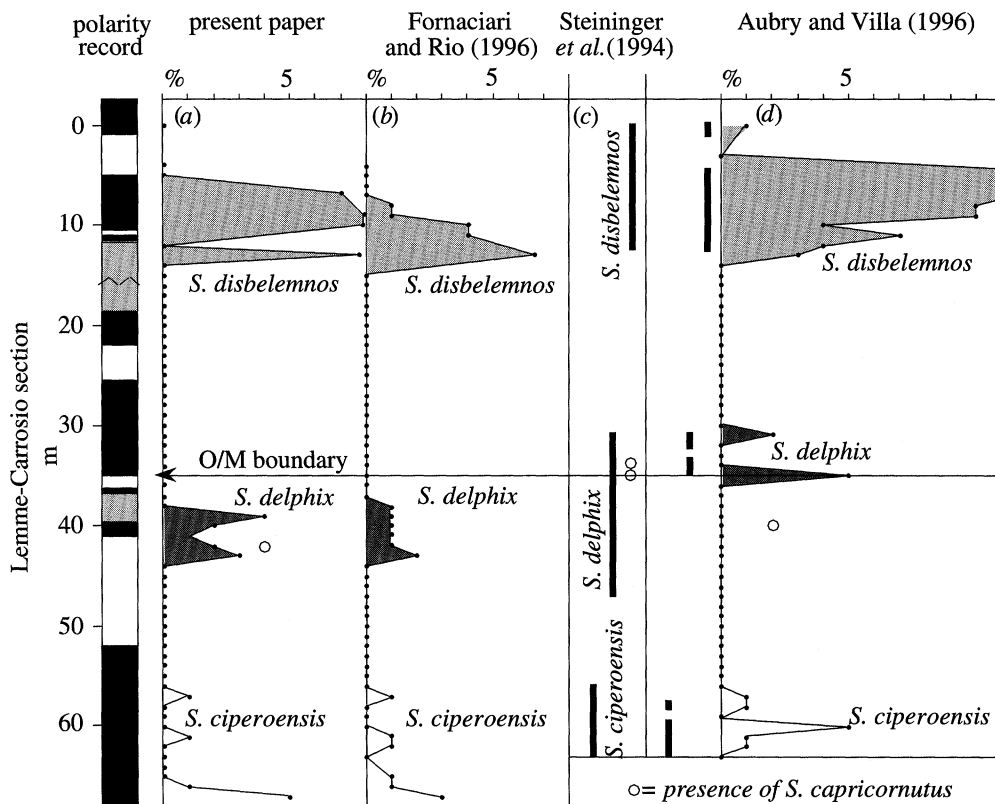


Figure 6. Distribution patterns of selected *Sphenolithus* species in the GSSP of the Oligocene–Miocene boundary (Lemme–Carrosio Section). Data from different authors are compared. Palaeomagnetic data from Napoleone *et al.* (1996).

& Hartl (1997) from the two holes (Shackleton *et al.* 1999) (figure 5), and permitted the determination of the position of the bioevents relative to magnetic reversals, as follows.

1. *S. ciproensis* LO occurs at the top of chron C7n.2n (in accordance with Olafsson & Villa 1992) and the biohorizon is confirmed as reliable over distant areas (Wei & Wise 1989; Fornaciari *et al.* 1990; Olafsson & Villa 1992).
2. The consistency of *S. delphix* biohorizons is reaffirmed, although its short range can be difficult to recognize when the species is particularly rare. The range of *S. delphix* is associated with the lower part of chron C6Cn. Its FO is recorded just below a normal polarity interval interpreted as chron C6Cn.3n, and the LO is recorded within the reversed polarity interval above this. This result modifies the calibration previously suggested (see Berggren *et al.* 1995) which indicated the extension of the *S. delphix* range within chron 6Cn.2n. The relative abundance of *S. capricornutus*, associated with *S. delphix*, at Site 522 is remarkable in contrast to that at Sites 926 and 929 (figure 4). This observation reaffirms the inconsistency of the marker *S. capricornutus*, which shows different distributions in the different areas.

Table 2. Comparison among the positions of selected nannofossil biohorizons in the Oligocene–Miocene Lemme–Carrosio Section as recorded by different authors

biohorizon	present paper	Fornaciari & Rio (1996)
FO <i>S. disbelemnus</i>	between 14 and 13 m	between 15 and 13 m
LO <i>S. delphix</i>	between 39 and 38 m	between 38 and 37 m
FO <i>S. delphix</i>	between 44 and 43 m	between 44 and 43 m
LO <i>S. ciperoensis</i>	between 57 and 56 m	between 57 and 56 m
biohorizon	Steininger <i>et al.</i> (1994)	Aubry & Villa (1996)
FO <i>S. disbelemnus</i>	between 13 and 12 m	between 14 and 13 m
LO <i>S. delphix</i>	between 31 and 30 m	between 31 and 30 m
FO <i>S. delphix</i>	between 47 and 46 m	between 36 and 35 m
LO <i>S. ciperoensis</i>	between 56 and 55 m	between 57 and 56 m

3. *S. disbelemnus* FO is associated with the base of a normal polarity interval (well represented in Holes 522 and 522A) which corresponds to chron C6Cn.1n. This finding modifies the calibration of the event as occurring at the base of chron C6Bn.2n, proposed by Fornaciari & Rio (1996).

Additional information on the reliability of the Oligocene–Miocene biostratigraphic events considered was generated by comparing the data from the deep-sea sequence of Site 522 with the biostratigraphies obtained in the proposed GSSP section of Lemme–Carrosio, from different sources. In figure 6, the data presented here from the Lemme–Carrosio Section are plotted with the biostratigraphic data on nannofossils previously obtained in the same set of samples by other authors (Fornaciari & Rio 1996; Steininger *et al.* 1994; Aubry & Villa 1996) (table 2). This comparison also suggests interesting observations on the methodology of gathering biostratigraphic data which, as already and repeatedly stressed above, can strongly influence the validity of the results.

The nannofossil biostratigraphy from the proposed site of the Oligocene–Miocene GSSP is reported in figure 6*c, d*. These data refer to two successive studies (Steininger *et al.* 1994; Aubry & Villa 1996) on the same set of samples (by the same biostratigraphers), but reflect unexplained contradictions as regards some bioevents. The use of different methods of analysis in the two successive studies (presence/absence method versus quantitative method) does not account for the discrepancy in the stratigraphic position of *S. delphix* range. Discrepancies exist even between these data (figure 6*d*) and the data on *S. delphix* gathered for the present work and acquired by Fornaciari & Rio (1996) (figure 6*a, b*). In addition, the latter two data-sets (figure 6*a, b*) are notably in agreement between each other, and partly correlate with the previous versions of nannofossil data from the Lemme–Carrosio Section (figure 6*c*) (from Steininger *et al.* 1994).

On the basis of the updated biostratigraphy of the Lemme–Carrosio Section, Aubry & Villa (1996) discussed the criteria for recognizing the O–M boundary (defined in the section as coincident with the base of subchron C6Cn.2n) and proposed a calibration of the bioevents by comparison with the magnetostratigraphic record in the section (Napoleone *et al.* 1996). The conclusions that they reached are obviously influenced by the biostratigraphic distributions presented. The authors indicated a

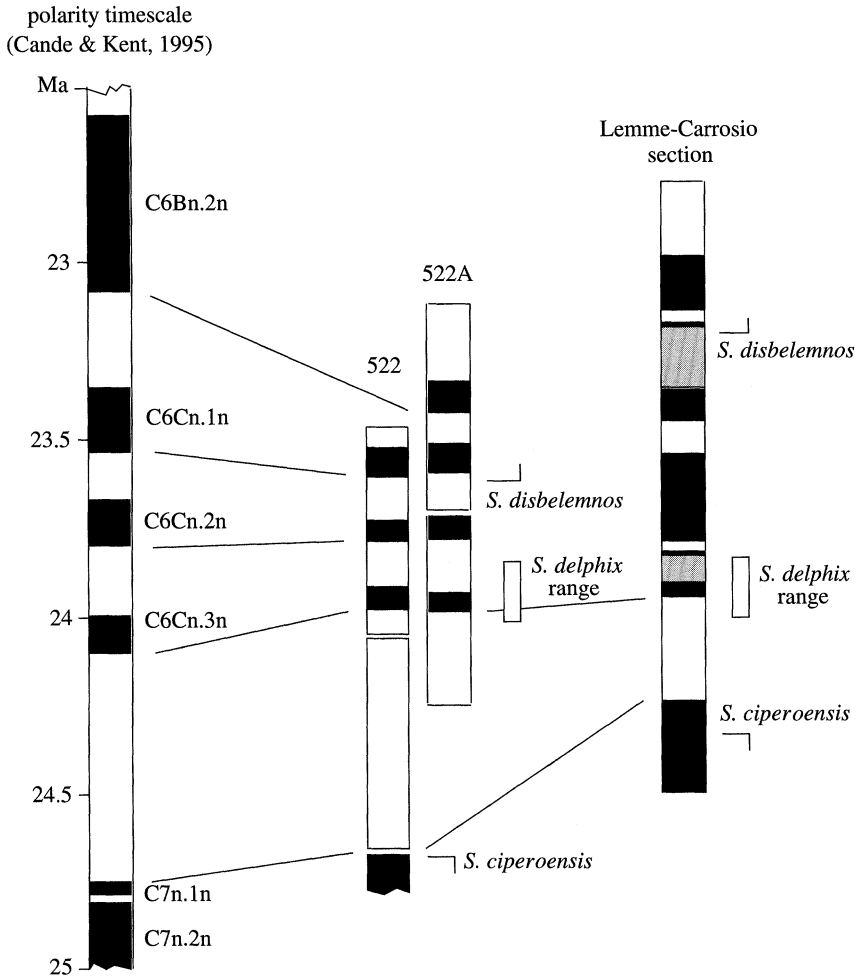


Figure 7. Correlation based on magnetostratigraphy and biostratigraphy between DSDP Site 522 and Oligocene-Miocene GSSP Lemme-Carrosio Section. Magnetostratigraphic interpretation of DSDP Site 522 from Shackleton *et al.* (1999).

magnetostratigraphic position for the *S. delphix* range close to chron C6Cn.2n; they stressed the unreliability of the *S. delphix* biohorizons as correlation tools outside the Mediterranean, and suggested the use of *S. capricornutus* LO as a marker for recognizing the O-M boundary.

The partly different results presented here from the Lemme-Carrosio Section, and the comparison with the data from deep-sea Site 522 (figure 7; table 1), suggest the following.

1. The position of *S. ciproensis* LO in the O-M GSSP section is consistent with the known magnetobiochronology derived from the ocean basins, and correlates with the topmost part of chron C7n.2n.
2. There is a good correlation between the range of *S. delphix* from the O-M GSSP section and outside the Mediterranean, confirmed by their similar mag-

netostratigraphic position (across the lower normal polarity interval of chron C6Cn) (this paper; Fornaciari & Rio 1996).

3. *S. capricornutus* is not useful for biostratigraphic correlations, since its distribution varies in different areas. The species is associated with *S. delphia*, but it was subordinate in the Indian Ocean, very rare or absent in the Mediterranean area and in the equatorial Atlantic, and was abundant in the South Atlantic (Rio *et al.* 1990b; Fornaciari *et al.* 1990; Fornaciari & Rio 1996; Aubry & Villa 1996; present paper).
4. Considering the biomagnetostratigraphic position of *S. disbelemnus* FO at Site 522 and its position in the Lemme–Carrosio Section, it is evident that, assuming the isochrony of this biohorizon, the published interpretations of the magnetostratigraphic record of the O–M GSSP section (Napoleone *et al.* 1996; Aubry & Villa 1996) should be partly reinterpreted. In addition, the astronomical ages obtained for the nannofossil index species at ODP Site 929, and their comparison with data from DSDP Site 522 and with the O–M GSSP section (table 2), suggest that the current age model for the Oligocene–Miocene transition needs to be revised.

3. Conclusions

Calcareous nannofossils are demonstrably useful as biostratigraphic tools. To improve the quality of nannofossil biostratigraphy it is crucial to improve the quality of the database and to test the reliability of biohorizons. This can be achieved by applying a strategy that combines quantitative data-gathering techniques with high-resolution sampling (small depth intervals between samples). A set of reliable nannofossil biohorizons is transformed into an accurate biochronology when it is correlated to magnetostratigraphy, isotope stratigraphy and orbitally tuned time-scales. This approach has provided an accurate chronologic framework in, for example, various intervals of the Cenozoic. The large number of reliable nannofossil datums permits accurate biostratigraphic correlation on both regional and global scales. Nannofossil biostratigraphy can be used to provide preliminary control points for the astronomical tuning of cyclostratigraphic records. In this study, another example of the potential of nannofossil correlation is shown, which relates to the Oligocene–Miocene time-interval. Results such as this confirm the importance of rigorous and detailed analyses for improving nannofossil biostratigraphy and its correlation potential. They also underline the importance of integrating high-quality biostratigraphic data with the other high-resolution stratigraphic signals.

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