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The role of calcareous nannofossils in building age models for Cenozoic marine sediments: a review

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Abstract
This review paper has been thought to emphasize the role of Biostratigraphy in Geosciences and, specifically, of calcareous nannofossils as dating tool. This group of calcareous plankton occurs in Mesozoic and Cenozoic carbonate-bearing marine sediments in all depositional settings and is routinely used for stratigraphic purposes. The importance of calcareous nannofossils in relative dating of marine sediments is due to their abundance, taxonomic diversity, rapid evolution and wide distribution in marine environments. Nannofossil biostratigraphy improved over the last few decades due to the use of accurate methods for data gathering, including acquisition of semiquantitative census data on high-resolution samples. These microfossils contribute to obtain reliable biostratigraphic classification in various time-intervals in the last 66 m.y. and often provide the key to the interpretation of other stratigraphic records. Nannofossil biohorizons can be used as control points for constructing cyclostratigraphic composite sections, and for identification of magnetostratigraphic intervals, and have provided a basis for age models subsequently developed into orbitally tuned cyclostratigraphies or used for chronological revision of polarity timescale.
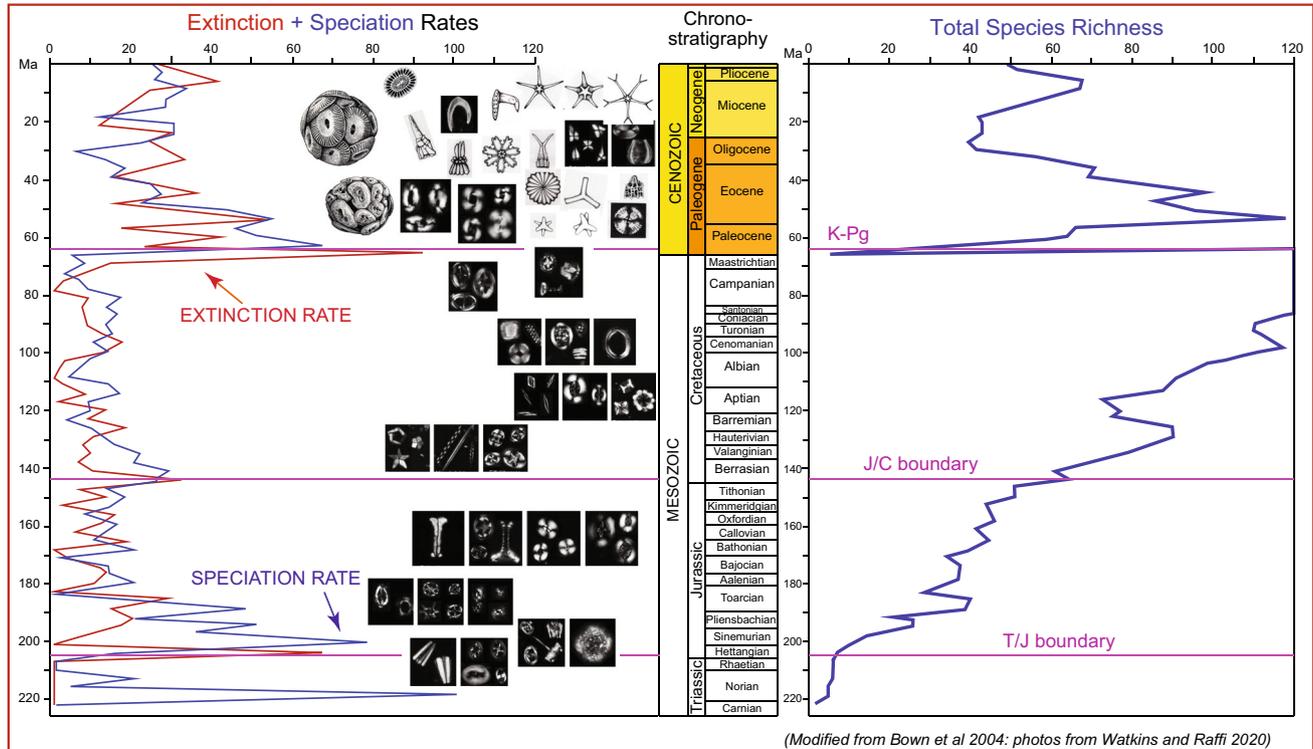
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Graphic abstract

(Modified from Bown et al 2004: photos from Watkins and Raffi 2020)

CALCAREOUS NANNOFOSSILS THROUGH TIME

Keywords Calcareous nannofossils · Biostratigraphy · Biochronology · Age models

1 Introduction

"Despite advances in magnetostratigraphy, stable isotope stratigraphy and various manifestations of cyclostratigraphy, it is still true that biostratigraphy is the essential tool by which the geological evidence for environmental change is put into a temporal framework."

N.J. Shackleton (1995).[1]

Over four billion years of Earth history is portrayed by the Geologic Time Scale (GTS), which synthesizes the many various means available to provide age of geological strata, the latest effort being that of Gradstein et al. (2020). Radioisotopic dating is a key method in this effort, in providing absolute ages that are based on radioactive decay of unstable atoms in geological materials throughout Earth's long history.

During the youngest ca. 0.01% of Earth's history (the past 66 million years, the Cenozoic), which is the interest of our study as this refers to our experience, radioisotopic dating provides necessary absolute age tie points for seafloor marine magnetic anomaly boundaries, a crucial component for subdivision of Cenozoic time (Hiertzler et al. 1968; Cande and Kent 1992). Throughout the past 3 decades, absolute age determinations derived through astronomical tuning of Cenozoic sediments have grown in importance (Westerhold et al. 2020), based on cyclic behaviour driven by climate caused by the periodicity of celestial objects and expressed, for example, by oxygen isotopes and lithostratigraphic properties (Emiliani 1966; Hays et al. 1976; Hilgen 1991a).

Among geosciences, Stratigraphy (layer description) is the science of rock strata, their composition, distribution, succession and age relations. In our experience, there is a set of tools in the Cenozoic marine stratigraphy "toolbox" that stands out: biostratigraphy, paleomagnetic stratigraphy, stable isotope stratigraphy and various other cyclostratigraphies.

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[1] From p. 517 in Shackleton et al. (1995).

Biostratigraphy employs paleontological methods, referring to the irreversible continuum of organic evolution as preserved in the fossil record which contributes to arrange rock units into relative order and to correlate them over geographic distance. Marine microfossil shells of Protista, as a result of their diverse and rapid evolution, are widely used for relative dating of marine sedimentary sequences through their biostratigraphic content. Marine calcareous plankton predominantly involves planktonic foraminifera and calcareous nannofossils that represent two key groups for providing biostratigraphic classification of carbonate-bearing Cenozoic rocks/sediments, both those cropping out on land and those recovered by coring of marine sediments and scientific ocean drilling.

This review paper deals with calcareous nannofossils and aims to illustrate their quality as biostratigraphic and biochronologic tools and their role in the construction of age models of Cenozoic marine sedimentary sequences. The intent is also to emphasize how calcareous nannofossil biostratigraphy contributes to the Geologic Time Scale, in providing guidance for identification of cycle numbers and magnetic polarity intervals.

2 About calcareous nannofossils

Calcareous nannofossils refer to coccolithophores, a group of single-celled algae (haptophyte protists) belonging to the phytoplankton that produce calcareous elements through biomineralization. These microfossils were first described back in the mid-nineteenth century when the terms 'coccoliths' 'coccosphere' were introduced (Huxley 1868; Wallich 1861). This group includes also morphogroups with uncertain biological affinity, but their small size (1–40 μm), composition (low magnesium calcite), abundance and distribution in marine environments make it reasonable to assume that these morphogroups were coccolithophores. See Young et al. (1997) for coccolith and calcareous nannofossil terminology.

The importance of calcareous nannofossils in relative dating of marine sediments is due to their abundance (millions of specimens per gram carbonate-bearing sediment), taxonomic diversity, rapid evolution, wide distribution in marine environments and preservation potential (slightly less susceptible to dissolution than planktonic foraminifers).

Calcareous nannofossils occur in Mesozoic and Cenozoic carbonate-bearing marine sediments in all depositional settings that are not covered by sea-ice. Despite the small size of these fossils, their abundance, distinct morphology and optical behaviour facilitate the recognition of species using standard polarizing light microscopy. The history of calcareous nannofossils began with their initial radiation during the Late Triassic (Norian Age) at ca. 220 Ma (von Salis

1998; Bown 1998). Widespread adaptive radiation and species turnovers followed for about 154 million years in the Mesozoic Era, ending with the catastrophic extinction at the Cretaceous-Paleogene (K-Pg) boundary at 66 Ma when, in the oceans, ca. 75% of species and ca. 40% of genera became extinct (Sepkoski 1996), including calcareous plankton (Schulte et al. 2010, and references therein). Although over 90% of latest Cretaceous calcareous nannofossils species disappeared during the K-Pg boundary mass extinction (Bown et al. 2004), a rapid adaptive radiation followed during the early Paleocene, when species richness and establishment of new orders and families increased (Perch-Nielsen 1985). Evolutionary changes continued with variable intensity through the Cenozoic Era, resulting in numerous appearance and extinction events (biohorizons) which thus provided a rich set of biohorizons available for biostratigraphy.

A few words about taxonomy. We confess to being "lumpers" rather than "splitters". This means that our taxonomic concepts permit some intra-specific morphologic variability rather than describing a "new" species for a morphology that deviates only marginally from the original description of the species. The question about how to define the morphological limits of a morphospecies remains a relatively poorly investigated and ditto understood character among marine microplankton shells (including those of calcareous nannofossils), which typically are described qualitatively rather than being based on detailed morphometrics. However, errors in taxonomy are probably distributed both among lumper and splitter micropaleontologists and when it comes to key Cenozoic biohorizons, taxonomic problems based on morphospecies concepts exist but are considered to be few.

3 Early efforts to employ calcareous nannofossils in biostratigraphy

Efforts to organize calcareous nannofossils into their proper (bio-)stratigraphic order began less than 70 years ago: Bramlette and Riedel (1954), Stradner (1959) and Bramlette and Sullivan (1961) pioneered the earliest investigations about Cenozoic calcareous nannofossil biostratigraphy, whereas Stradner (1961) pioneered biostratigraphic work among Jurassic and Cretaceous calcareous nannofossils. The focus of this paper is on the Cenozoic, in harmony with our expertise.

In less than 2 decades after Bramlette's pioneering work, two independent and subsequently widely used Cenozoic calcareous nannofossil biostratigraphic schemes were established (Martini 1971; Bukry 1973): the former mainly used marine sections exposed on land, often at middle latitude settings, whereas the latter relied on low-latitude sediment successions, retrieved by the Deep Sea Drilling Project (DSDP) a mere five years after its start. During the late

60ies and 70ies several other biozonations were established for various parts of the Cenozoic, some of which aimed for specific regions (Bramlette and Wilcoxon 1967; Hay et al. 1967; Ellis 1979; Raffi and Rio 1979). About 40 years after Martini's and Bukry's biozonations, we were involved with two revised calcareous nannofossil zonations, one for the Neogene and Quaternary (Backman et al. 2012) and the other for the Paleogene (Agnini et al. 2014), both taking into account improvements made during these 4 decades with a focus on the reliability and applicability of individual biohorizons.

4 Calibration of calcareous nannofossil biohorizons to independent time scales

There are a few main strategies at hand to convert evolutionary appearances or extinctions of marine plankton taxa onto an accurate geologic timeline. First, providing age estimates of calcareous nannofossils from numerous deep-sea sediment sequences via direct radioisotopic measurements is a difficult task. Reasons involve analytical costs and, more importantly, the rare presence of radioactive elements and their decay products in most marine pelagic sediments, except for the interval corresponding to the most recent 0.0008% of Cenozoic history, which can be organized in terms of time by carbon-14 dating. Hence other means are needed to progress.

Two key tools emerged during a formative decade that helped convert, or calibrate, positions of biohorizons in marine sediment sequences into age estimates: (1) the development of the Geomagnetic Polarity Time Scale (GPTS) and (2) cyclostratigraphy. The first portrays the polarity sequence as derived from marine magnetic anomaly analysis combined with selected radiometric age tie points, and the latter portrays the astronomically forced paleoclimatic change as preserved in the sediment stratigraphy, a strategy also known as astrochronology. Two of the most commonly applied tools in astrochronology are stable isotopes of carbon and oxygen (in essence geochemistry) and lithologic properties (in essence geology, that is, biological, chemical and physical properties of marine sediments).

4.1 The GPTS and Cenozoic calcareous nannofossil calibrations

Soon after geophysical measurements began to establish the occurrence of alternating switches between normal and reversed remanent magnetizations among stratigraphically layered volcanic rocks on land (Cox et al. 1963), the corresponding "geomagnetic polarity reversals" were observed to be preserved also in deep-sea sediment cores. This was a major eye-opener indicating that any given polarity reversal

in a deep-sea sediment core should represent a globally synchronous single point in geologic time. It follows that a potential tool to hinge biostratigraphic data onto magnetostratigraphic polarity records was discovered, the first published by Harrison and Funnell (1964), soon followed by Opdyke et al. (1966). Their work was followed by numerous other similar studies (e.g., Saito et al. 1975) over just a decade after the initial pioneering efforts, which genuinely improved age determinations of marine biohorizons. Moreover, during that decade of geoscientific development, Heirtzler et al. (1968) published the first marine magnetic anomaly time scale, or GPTS, that encompassed the entire Cenozoic. Amazingly, this first Cenozoic GPTS from 1968 was based on only two age tie points: spreading center at 0.00 Ma and base of the polarity Chron C2An.1n (base Gauss), at the time 3.35 Ma, and was linearly extrapolated to nearly 80 Ma, into the Late Cretaceous. In retrospect, Heirtzler's GPTS remains surprisingly close to present data.

A comprehensive synthesis of the early developments of marine magnetic anomaly time scales was provided by Ness et al. (1980). Not far after, Glen (1982) wrote his book "*The Road to Jaramillo: Critical years of the Revolution in Earth Science*", an inspiring historical piece about how the theory of plate tectonics emerged and got manifested among geoscientists as well as a much broader general audience. Magnetostratigraphy and, by implication, bio-magnetostratigraphy, are intertwined with this history.

The earliest effort to match marine plankton biostratigraphic data with a complete Cenozoic GPTS is that of Berggren (1969), depicting Heirtzler's GPTS,[2] saying that "Palaeomagnetic reversals are plotted at their assumed age interval. The relationship of palaeomagnetic stratigraphy to the biostratigraphic zonation based upon planktonic foraminifera remains to be verified but is accurate down to about 5 million years on the basis of present data". Subsequently, Berggren et al. (1985, 1995) published two widely used Cenozoic time scales, using the evolving marine magnetic anomaly time scales for calibration with an abundance of new biostratigraphic data of planktonic foraminifera, calcareous nannofossils (and radiolaria in the 1985 opus), from deep-sea sediment cores retrieved by the DSDP and the Ocean Drilling Program (ODP).

Over the past 60 years bio-magnetostratigraphic data have been, and remain, a powerful tool in establishing Cenozoic age estimates of calcareous nannofossils in marine sediments (e.g., Backman and Shackleton 1983; Backman 1986; Olafsson 1991; Gartner 1992; Agnini et al. 2007). Once calibrated to magnetostratigraphy, biostratigraphic data are commonly and successfully applied to generate age models in marine

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[2] No reference given but Heirtzler's was the only GPTS available in 1969 that encompassed the entire Cenozoic.

sediments lacking magnetostratigraphy (e.g., Kroenke et al. 1991; Curry et al. 1995). In contrast, interpreting magnetostratigraphic data without guidance from biostratigraphy may result in huge discrepancies: an example being the result from ODP Site 690 in which, at the identical level, biostratigraphy suggested an age of 57.8 Ma whereas magnetostratigraphy suggested an age of 44.66 Ma, "constructed without recourse to biostratigraphic data" (Shipboard Scientific Party 1988).

A problem inherent in bio-magnetostratigraphic data, however, pertains to resolution. An individual age estimate of a biohorizon calibrated to magnetostratigraphy rarely falls precisely on a reversal boundary in continuously deposited sediments but is typically located within an interval of variable length/duration of either normal or reversed polarity. Standard procedure is to derive an age estimate of the biohorizon via linear interpolation between the two nearest reversal boundaries, often expressed in terms of percentage of time distance from the established age of nearest reversal boundary (Agnini et al. 2007, 2014). The age uncertainty of the biohorizon thus partly depends on the duration of the polarity zone, an uncertainty that can be several hundred thousand years if the sedimentation rate varies within a polarity zone of longer duration.

Cyclostratigraphy is the answer to this bio-magnetostratigraphic resolution problem because astronomical tuning of cyclic behaviour of some property (biological, chemical, physical) can accurately subdivide time into shorter aliquots within longer polarity zones.

4.2 Cyclostratigraphy and calcareous nannofossils

Below follows a brief historical account about the initial merging of cyclostratigraphy and calcareous nannofossil biochronology.

Harold Urey (1948) rightfully exclaimed to have found a "geological thermometer" when analysing isotopes of oxygen (see excellent review by Pearson 2012, on theory and use of foraminiferal oxygen isotopes). A few years after, Urey's student Cesare Emiliani began to publish his pioneering work (1954, 1955) about reconstructing ocean paleotemperatures by means of measurements of oxygen isotopes in marine benthic and planktonic foraminifers. In his Fig. 1 in the 1954 paper, Emiliani reported three (3) data points, assumed to show an 8 °C temperature cooling of abyssal waters from the Oligocene to the Pliocene (Fig. 1). A good figure to keep in mind, to use in teaching and to compare knowledge from the pioneering days with the development over the following 50 years—when thousands of similar data points were used to depict evolving paleoclimatic and paleoceanographic conditions (Zachos et al. 2001) (Fig. 2). Regardless, one of Emiliani's key colleagues in the field, N.J.
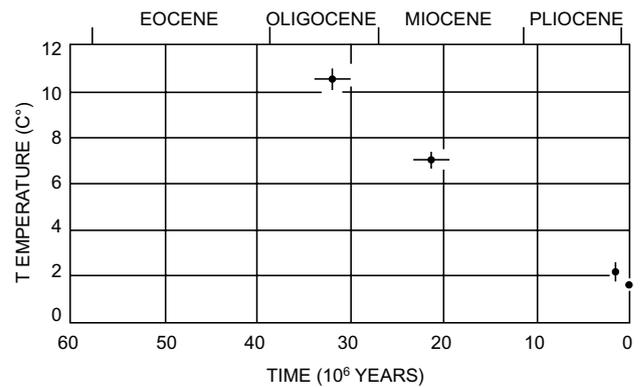

Fig. 1 Replication of Fig. 1 from Emiliani (1954) in which he reconstructed ocean paleotemperatures through measurements of oxygen isotopes in marine benthic and planktonic foraminifers

Shackleton, once remarked to us that Emiliani clearly was ten years ahead "of the rest of us".

In a synthesis paper on Pleistocene paleotemperatures, Emiliani (1966) noticed that "the correlation coefficient between the astronomically calculated ages of the summer insolation minima at 65°N and the stratigraphic position of the temperature minima in the 'average core' previously mentioned is 0.997", concluding that insolation variations drive the Pleistocene oscillations in climate. Three major advances followed: first, a year later, Shackleton (1967) established that oxygen isotopes represent both paleotemperature and global ice volume; second, ten years after Emiliani's synthesis paper, Hays et al. (1976) published a landmark paper on "Variations in the Earth's orbit: Pacemaker of the Ice Ages", which ended "four decades of controversy" of the Milankovitch model (Gribbin 1976) and opened the field of astrochronology. Third, in another landmark paper, Shackleton and Opdyke (1973) presented magnetostratigraphic and foraminiferal oxygen isotope data from a deep-sea core (V28-238) raised from the Ontong-Java Plateau. They managed to subdivide the Brunhes (polarity Chron C1n) into 19 distinct oxygen isotope stages and, based on linear interpolation, listed age estimates for all 19 oxygen isotope stage boundaries. Oxygen isotope stages thus provided a tool to subdivide time in longer geomagnetic polarity zones, thus permitting improved resolution of age estimates of marine biohorizons.

The first such astro-biochronological work was published by Thierstein et al. (1977), a year after Hays et al. (1976), providing calibration of calcareous nannofossil biohorizons to oxygen isotope stratigraphies from several deep-sea piston cores. They also introduced a new concept in calcareous nannofossil biostratigraphy, based on a shift in relative abundance between two key taxa, of which one dominant species (in terms of relative abundance) was replaced by another dominant species: this kind of biohorizon was used

Fig. 2 Comparison of data (**A**) from the pioneering Emiliani's publication (Fig. 1 in Emiliani 1954) with data (**B**) from deep-sea core sediments (Zachos et al. 2001, modified), that depict the evolving paleoclimatic and paleoceanographic conditions in the Cenozoic
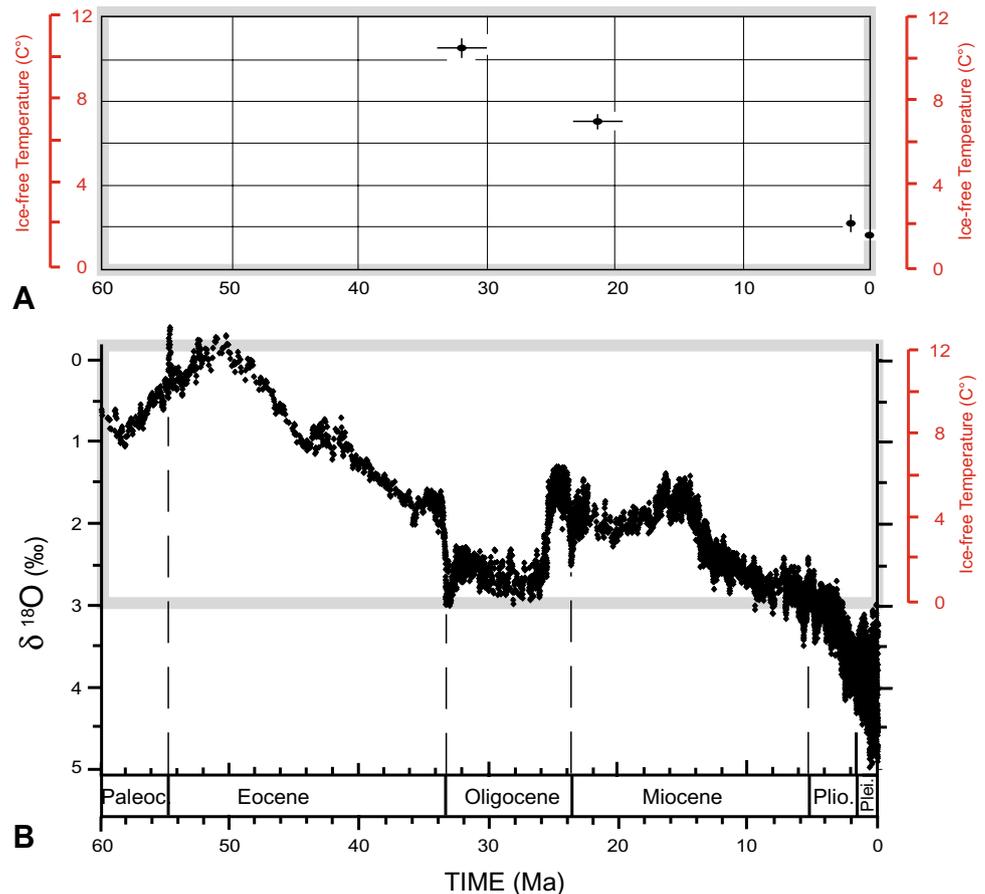
as biostratigraphic and biochronologic marker. For us, Thierstein et alii's paper became a source of much inspiration.

Different expressions of sedimentary rhythms have since long been observed in the geological record, for example fluctuating carbonate contents (Arrhenius 1952) and sapropels (Kidd et al. 1978). A series of studies began to emerge over a decade from the late 70ies to late 80ies, leading up to the pioneering work of Hilgen (1987, 1991a) on the usefulness of rhythmical bedding in Mediterranean Plio-Pleistocene marine strata, uplifted and presently exposed on land, for improvements of the geologic time scale. Hilgen's work contributed to improve calcareous nannofossil biochronology (Hilgen 1991b) and provided a tool for comparison and correlation with corresponding open ocean biochronologies derived from astrochronology (e.g., Raymo et al. 1988; Shackleton et al. 1990).

During the 90ies we further developed Pleistocene through late Miocene calcareous nannofossil biochronology based on astrochronology (Raffi et al. 1993; Backman and Raffi 1997) and, subsequently, Raffi et al. (2006) synthesized calcareous nannofossil astrobiochronology over the past 25 million years. In this synthesis, biohorizons have been placed into the combined chronological framework of

magnetostratigraphy and astrocyclostratigraphy, as exemplified in Fig. 3 (from Raffi et al. 2006).

In addition to its importance for the relative chronology of marine sediments, another relevant result derived from the improvement of nannofossil biostratigraphy has been the quality of the database acquired, in terms of accuracy and reliability (Rio et al. 1990; Raffi 1999). This is related to the approach of acquiring (semi) quantitative biostratigraphic data (see discussion in subchapter 4.3). The direct comparison of these detailed data with cyclic variation of other paleoenvironmental proxies (i.e., magnetic susceptibility, carbonate concentration, stable isotope ratios) led to new discoveries on the abundance behaviour of the species: a direct response by several nannofossil taxa, as *Discoaster* and *Sphenolithus*, to orbitally forced climatic variation was pointed out, as shown by fluctuations in abundances which are in the frequency range of earth orbital variations (e.g., Backman and Pestiaux 1987; Chepstow-Lusty et al 1989; Gibbs et al. 2004). An example from ODP Site 926 is shown in Fig. 4, showing cycles in the sediment cores and abundance of *Discoaster kugleri* plotted vs. magnetic susceptibility (darker areas = higher susceptibility and vice versa).
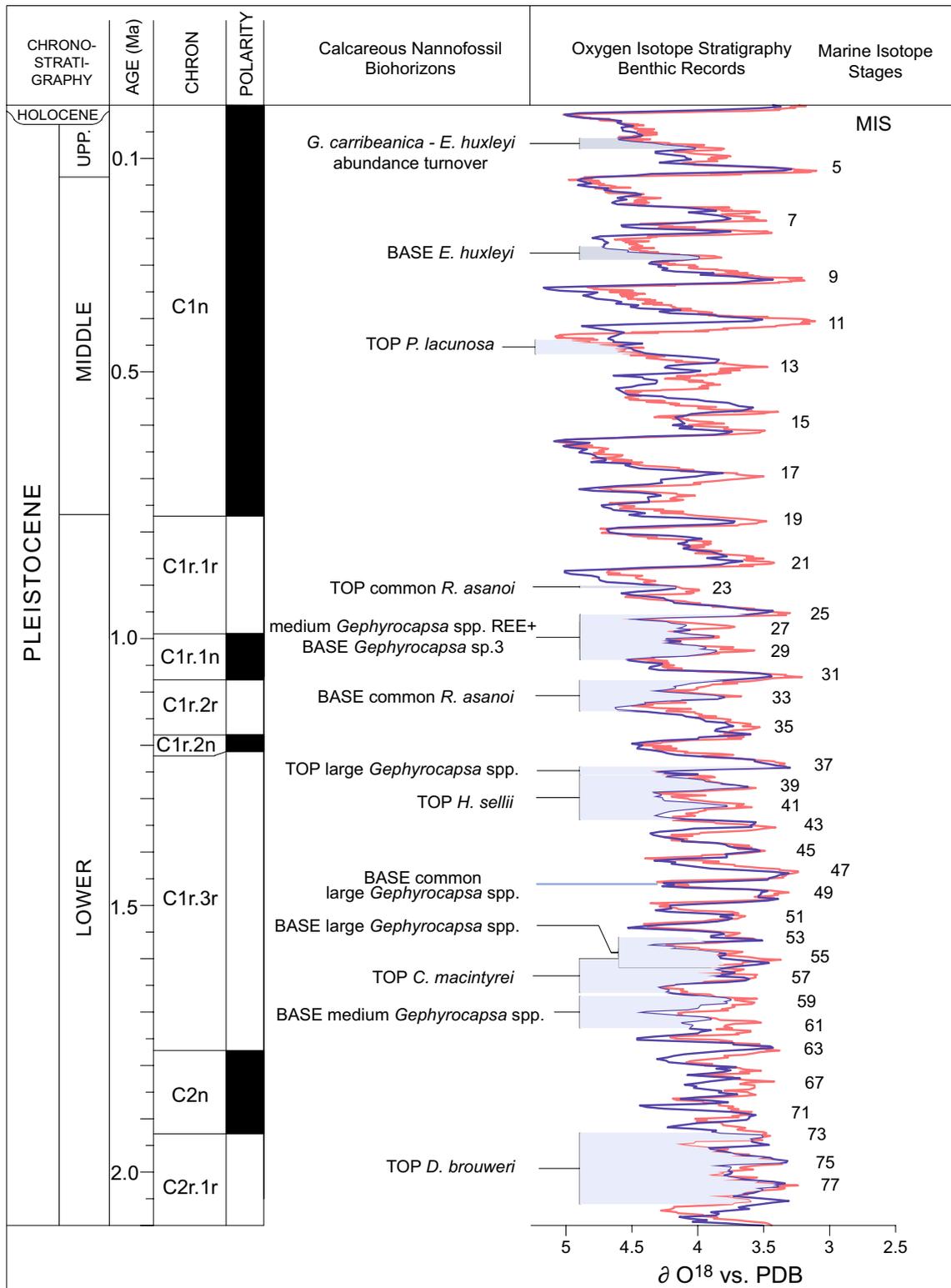
Fig. 3 Calcareous nannofossil biohorizons vs. framework of astronomically calibrated magnetic reversal records and stable isotope stratigraphies for the last 2.0 m.y. (modified from Raffi et al. 2006)
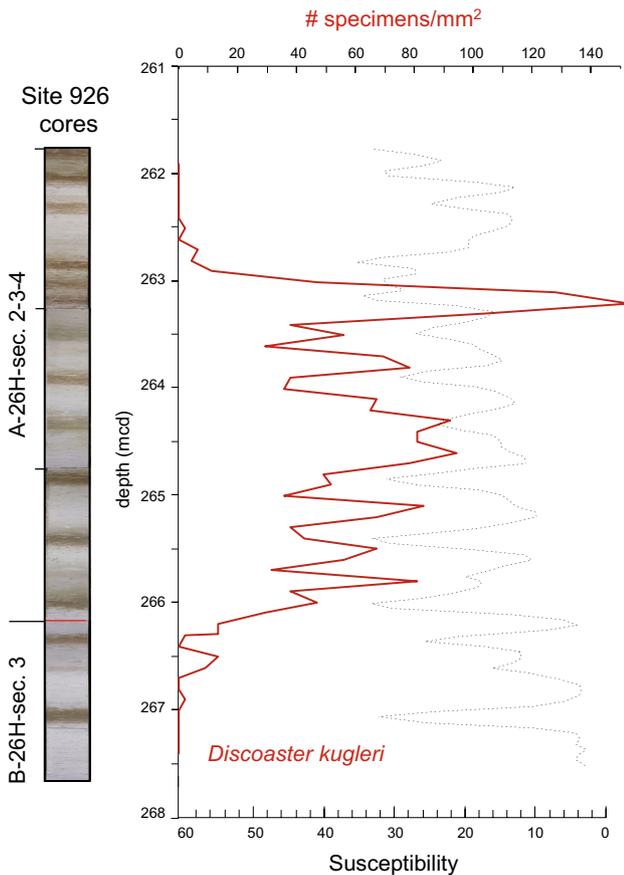
Fig. 4 Abundance record of *Discoaster kugleri* at ODP Site 926 sediment cores showing cycles (https://web.iodp.tamu.edu/janus web/imaging/photo.cgi). Abundance fluctuations are compared with magnetic susceptibility record, in which darker layers correspond to higher susceptibility/higher clay content and, vice versa, lighter layers to low susceptibility/higher carbonate content

4.3 Calcareous nannofossil biostratigraphy: problems and solutions

Biostratigraphic analyses using calcareous nannofossils commonly rely on the presence/absence data of species together with qualifiers such as "barren" "rare" "few" "common" "abundant", i.e., in range charts. We, and most other colleagues, have employed this method onboard during numerous DSDP/ODP/IODP expeditions. This method more or less represents a black box containing information that is virtually impossible to judge and evaluate independently by non-biostratigraphers, although most biostratigraphers provide information that can be reproduced by other experts in the field.

During several of these scientific ocean drilling expeditions, in biostratigraphic analyses we partly abandoned the range chart method, which is to list every species observed with one of the above qualifiers in each sample investigated. We applied the range chart method only to analyse

core catcher samples, using much time to what we refer to as "biohorizon chasing". To put it simply, in delineating a biohorizon between two core-catcher samples, how could it be further constrained in terms of core depth via additional within-core samples? Chasing an appearance or extinction of a species in a 9.5 m long core is readily done if your smear-slide production line is quick, permitting at least ten smear-slides to be produced in an hour from raw samples. In shipboard analyses during ODP Leg 154, for example, we constrained most critical calcareous nannofossil biohorizons to within 40–80 cm, collecting 12–14 (or more) samples per core. This reduced depth uncertainties of most age indicative biohorizons, from the traditional ± 450 cm if using only core catcher samples, to ± 20–40 cm; that is, 11–20 times more precise depths of age tie points of the biohorizons (Fig. 5).

We have previously discussed the biostratigraphic resolution problem (Backman and Raffi 1997): "Several analytical fields in paleoceanography [...] routinely use sampling intervals that are close enough to capture the finest details of the records of environmental change that are preserved in cores. Marine biostratigraphic work, in contrast, has rarely adopted the smallest meaningful sampling interval to acquire its basic information about the evolutionary emergence or extinction of species." Thus, a problem of calcareous nannofossil biostratigraphy refers to resolution, which can only be solved by analysing additional samples, at similar sample frequency used for proxy records, so that depth positions of individual biohorizons are narrowed.

Another problem in biostratigraphy refers to the difficulty to independently evaluate the reliability of data, which preferably should be resolved using census data showing the abundance behaviour (relative or semiquantitative) of individual taxa. We have since long employed a semiquantitative approach (Backman and Shackleton, 1993) to solve this biostratigraphic "black box" problem. In fact, the use of the semiquantitative methodology overcomes the problem of subjectivity inherent in the 'qualitative' analytical approach based on the presence/absence method. Although the 'qualitative' approach can result in an accurate biostratigraphy, it relies on a combination of subjective judgements involving taxonomic identification and assessment of relative abundance (e.g., "rare", "common") and excludes types of information useful for enhanced biostratigraphic resolution. We use the label 'semiquantitative' in terms of representing an estimate of nannofossil census data that have less than quantitative precision, yet graphically manages to depict true abundance variability on the order of ± 10–15%.

The resolution problem can be addressed as a precision problem: how precise can biostratigraphers determine positions of evolutionary appearances and extinctions in the stratigraphic column? And, how to determine the smallest meaningful sample interval for determinations of biohorizons? The abundance behaviour problem can be addressed

Fig. 5 Effects of different sample resolution and data gathering. The stratigraphic range (lower part) of *Discoaster broweri* at ODP Site 926 is depicted at different sampling intervals with different abundance evaluation: (**1**) 5.0-m sampling interval (1 sample/400 k.y.); (**2**) 2.5-m sampling interval (1 sample/200 k.y.); (**3**) 0.1-m sampling intervals (1 sample/8 k.y.). Comparison of presence/absence data (**1**) to semiquantitative abundance data of the taxon (**2** and **3**) is shown. C = common specimens; F = few specimens; R = rare specimens. The plot showing high-resolution data (**3**) displays considerable details (short-term variations in abundance)
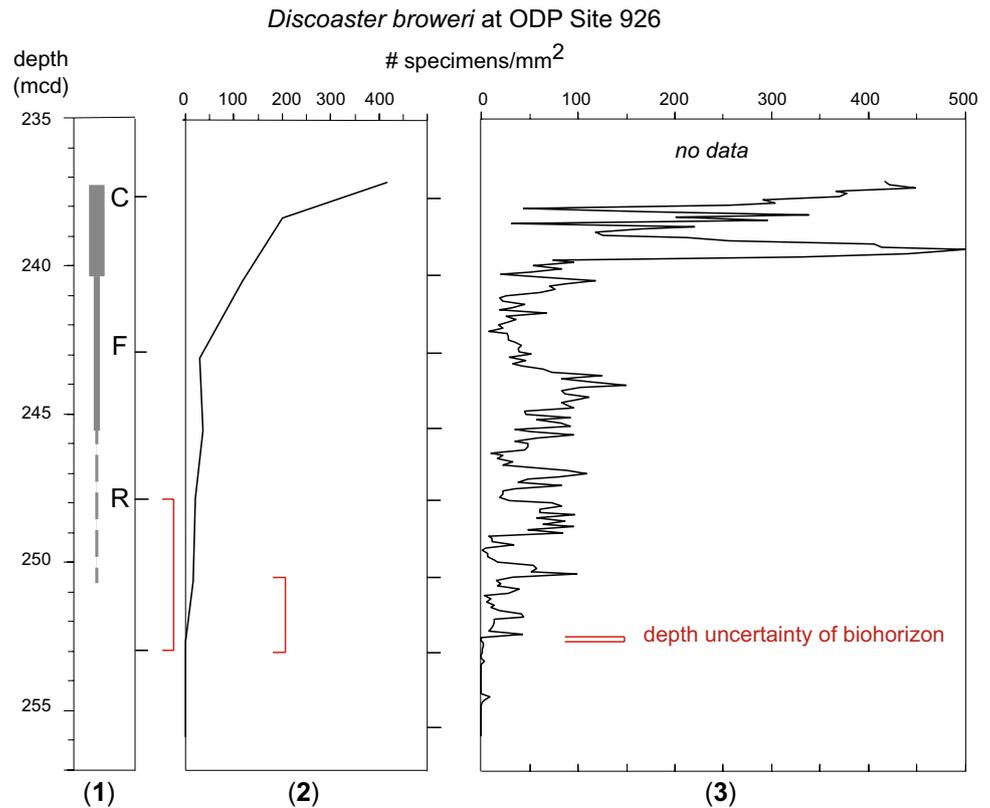
as an accuracy problem: how accurate can we determine evolutionary appearances and extinctions in the stratigraphic column? Biostratigraphers often experience low and sporadic occurrences of critical taxa prior to evolutionary appearances or after extinctions. Again, the solution, which opens the "black box", lies in a combination of narrowing sample spacing intervals with semiquantitative analyses, permitting independent judgements.

5 Precision of calcareous nannofossil biochronology for accurate correlation

The precision of age estimates of individual calcareous nannofossil biohorizons has been steadily improved over several decades due to the use of semiquantitative analyses and decreasing sample-space intervals, in combination with calibration of individual biohorizons directly to magnetostratigraphy and astronomically tuned cyclostratigraphy. Concomitantly, the construction of the Cenozoic time scale has been an ongoing process through the past 4–5 decades in which calcareous nannofossils have played a role (see overviews in GTS2020 chapters by Raffi et al. 2020; Speijer et al. 2020). This multifaceted development has resulted in precise age determinations of numerous Cenozoic biohorizons, often within a few 10^3–10^4 years. Below, a few examples serve

to illustrate different uses of calcareous nannofossil data for correlation purposes and dating.

When sedimentary cycles are exposed in sedimentary sections outcropping on land, but no continuous succession could be logged and sampled along a single trajectory, or when ODP scientific drilling recovers sediment from multiple holes cored from single sites, the construction of composite sections is essential for building cyclostratigraphic records that could be correlated to astronomical target curves and calibrated for constructing age models. In the absence of magnetostratigraphic data, biostratigraphy provides necessary correlation: an example is shown in Fig. 6, in which composite depth sections from adjacent holes and site-by-site correlation of the same composite sections (Shipboard Scientific Party 1995) depend on precise biostratigraphic data, given the lack of reliable magnetostratigraphic records in those sediment cores.

Likewise, the synchroneity of calcareous nannofossil biohorizons can be relevant for discussing the validity of timescales. In Fig. 7, it is shown that the nannofossil biostratigraphic data, obtained in two sedimentary sections with rhythmic bedding, are in line, although the two cyclostratigraphic records are from different geographic areas and latitudes, one in the Mediterranean (Monte Gibliscemi, Sicily; Hilgen et al. 2000), the other in the tropical Atlantic Ocean (Ceara Rise; Backman and Raffi 1997). Most importantly, the estimated astronomical ages for the biohorizons agree
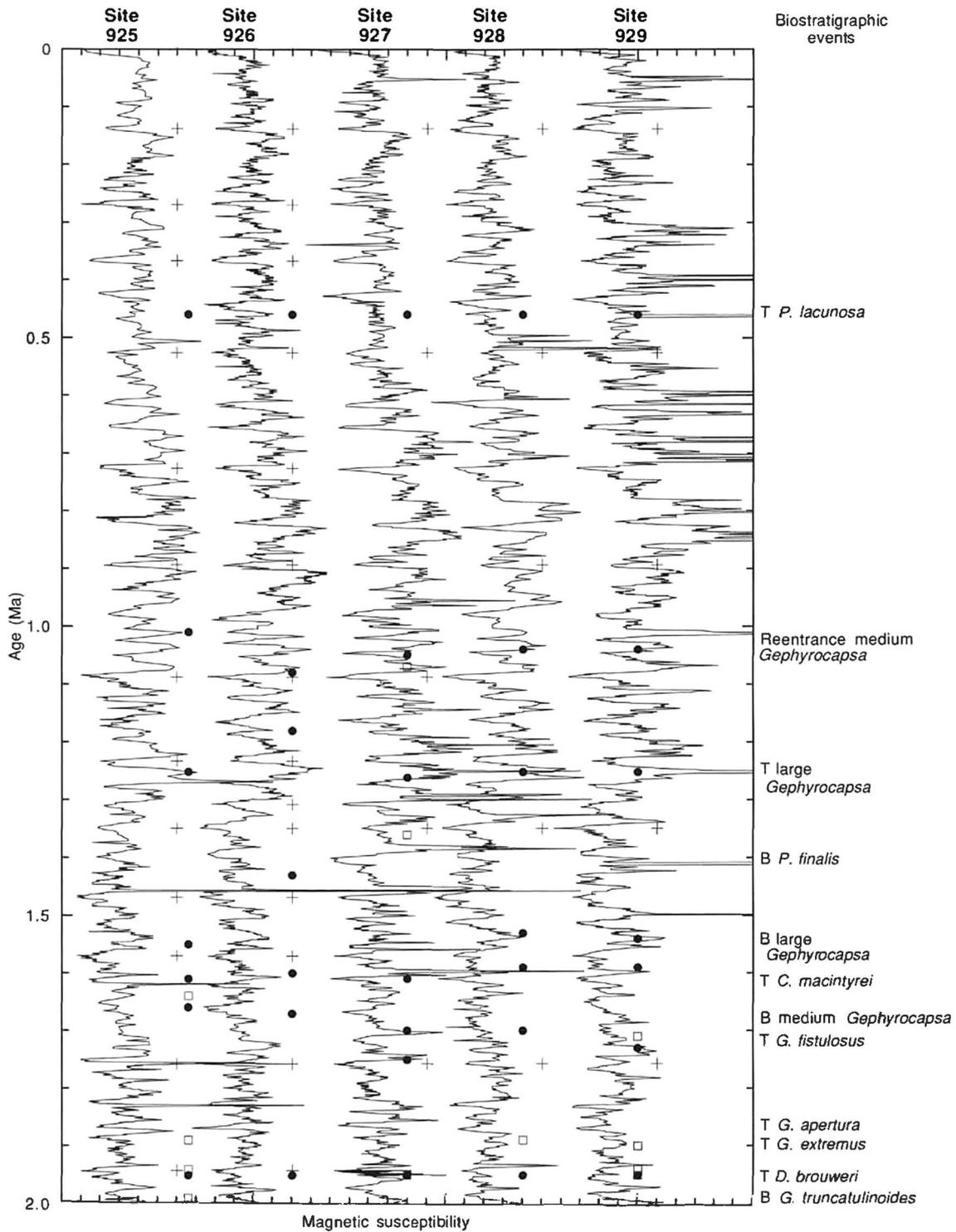
Fig. 6 Composite magnetic susceptibility records of ODP Sites 925, 926, 927, 928 and 929 vs. age for the last 2 m.y. Correlation among sites was based on the graphic correlation tie points (plus signs), and confirmed by the sequence of calcareous plankton biohorizons, listed to the left and including mostly nannofossil biohorizons (black dots). Note that the ages for the tie points were obtained from selected nannofossil events of Site 926. (Reproduction of Fig. 8 published in Shipboard Scientific Party 1995)
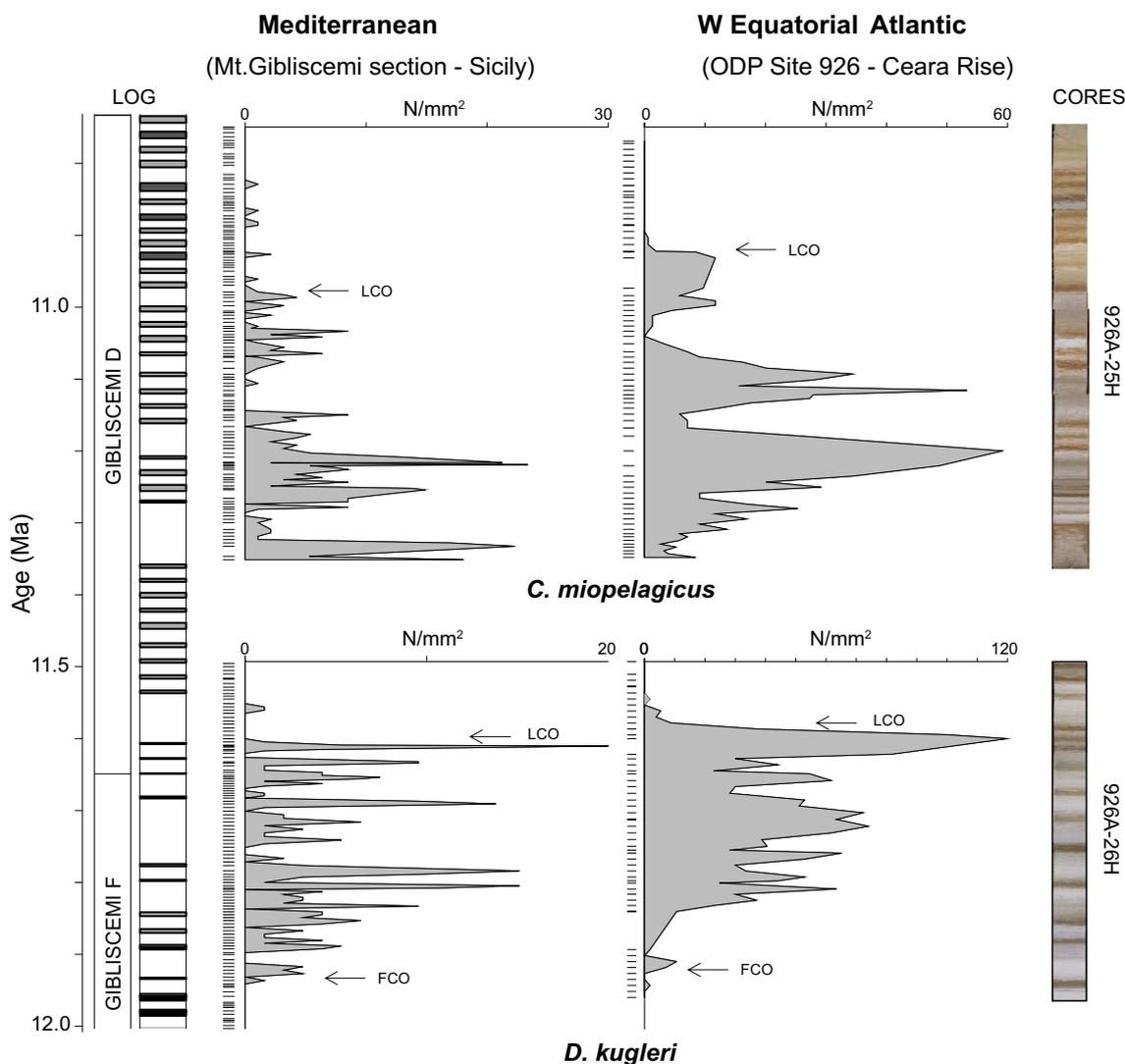
Fig. 7 Comparison of (semi)quantitative distribution patterns of *Coccolithus miopelagicus* and *Discoaster kugleri* in sedimentary sections with cyclic patterns in the equatorial Atlantic (at Ceara Rise) and in the Mediterranean (Mt. Gibliscemi). Time series based on the independently established astronomical chronologies for Ceara Rise (Shackleton and Crowhurst 1997) and Monte Gibliscemi (Hilgen et al. 2000). FCO = First Common/continuous Occurrence; LCO = Last Common/continuous Occurrence

with each other even though resulting from two independently established astronomical timescales, by Shackleton and Crowhurst (1997) for low latitude Atlantic and by Hilgen et al. (2000) for Mediterranean. In our opinion, this correspondence expresses the mutual consistency of the two timescales (with a possible difference of only one or two precession cycles) and the indubitable biochronological value of these nannofossil biohorizons, an example among many others in the Cenozoic nannofossil biochronology.

6 Conclusion

The usefulness of calcareous nannofossils for stratigraphic purposes, via biostratigraphy and biochronology, and their role in the construction of age models for the Cenozoic have been highlighted during the last 6 decades through a rich literature based on studies on suitable marine sedimentary sequences, applying rigorous and detailed methods of analysis. The attributes of this microfossil group, functional to biostratigraphic classification, lead to improvement of their correlation potential and achievement of a high degree of reliability in various time-intervals in the last 66 million years. These results underline the importance of integrating high quality biostratigrahic data with the other

high-resolution stratigraphic signals. Calcareous nannofossil biohorizons are used as control points of dating tools such as cyclostratigraphy and magnetostratigraphy, namely for the identification of cycle numbers and polarity zones and represent powerful means for regional and worldwide correlations.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethical statement This paper has not been published elsewhere and we have no conflicts of interest to disclose. Results are presented clearly, honestly, and without inappropriate data manipulation (including image-based manipulation). No data, text, or theories by others are presented as if they were the author's own ('plagiarism').

Availability of data and material Not applicable.

Code availability Not applicable.

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