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Pleistocene calcareous nannofossil biochronology at IODP Site U1385 (Expedition 339)

B. Balestra [a,*], J.-A. Flores [b], D.A. Hodell [c], F.J. Hernández-Molina [d], D.A.V. Stow [e]

[a] University of California Santa Cruz, Institute of Marine Science, USA
[b] University of Salamanca, Department of Geology, Spain
[c] Godwin Laboratory for Palaeoclimate Research, University of Cambridge, Department of Earth Sciences, United Kingdom
[d] Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, United Kingdom
[e] Institute of Petroleum Engineering, Heriot-Watt University, United Kingdom

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ABSTRACT

During Integrated Ocean Drilling Program (IODP) Expedition 339, Site U1385 (37°34′N, 10°7′W, 2578 m below sea level) was drilled in the lower slope of the Portuguese margin, to provide a marine reference section of Pleistocene millennial-scale climate variability. Five holes were cored using the Advanced Piston Corer (APC) to a depth of ~151 m below sea floor (mbsf) recovering a continuous stratigraphic record covering the past 1.4 Ma. Here we present results of the succession of standard and unconventional calcareous nannofossil biostratigraphic events. The quantitative study of calcareous nannofossils showed well-preserved and abundant assemblages throughout the core. Most conventional Pleistocene events were recognized and the timing of bioevents were calibrated using correlation to the new oxygen isotope stratigraphy record developed for the Site U1385. The analyses provide further data on the stratigraphic distribution of selected species and genera, such as the large *Emiliania huxleyi* (>4 μm), *Gephyrocapsa caribbeanica*, *Helicosphaera inversa*, *Gephyrocapsa omega* and *Reticulofenestra asanoi* (>6 μm) and other circular–subcircular small reticulofenestrids, resulting in new insights into the environmental control of their stratigraphic patterns. Finally, the comparison between nannofossil datums and oxygen isotope stratigraphy on the same samples has resulted in an accurate revision of timing of the events, providing valuable biochronologic information.

1. Introduction

The availability of temporally calibrated biostratigraphic events is crucial in paleoceanographic investigation, to better interpret proxies commonly used to create age-models, such as $\delta^{18}O$ or paleomagnetic records (Raffi et al., 1993; Wei 1993). Several studies have attempted to directly calibrate calcareous nannofossil and foraminifera biostratigraphic events to the astrochronologic timescale, via oxygen isotope stratigraphy since the late 70s (Thierstein et al., 1977; Shackleton and Hall 1989; Shackleton et al., 1990; Wei, 1993; Raffi et al., 1993; Hilgen, 1991a,b; Langereis and Hilgen, 1991; Lourens et al., 1992; Shackleton et al., 1995a,b; Shackleton et al., 1999; Hilgen et al., 2003). Raffi et al. (2006) gave a detailed review of astrobiochronological calibration of Recent to late Oligocene calcareous nannofossil datum events in mid-latitudes. However, these authors noted that there are still few high-resolution quantitative biostratigraphic analyses of astrochronologically tuned sections in spite of the central role of such studies in addressing fundamental problems such as the tempo and mode of plankton evolution. One of the challenges is identifying continuous sediment records with high-enough sample resolution that can be used for astronomical tuning and biostratigraphic analysis (Raffi et al., 2006).

In order to explore the effects of Mediterranean Outflow Water (MOW) on North Atlantic circulation and climate, IODP Expedition 339 (Mediterranean Outflow) cored a series of sites in the Gulf of Cadiz slope and the continental slope off West Iberia (North East Atlantic). Site U1385 (Fig. 1) was selected on the lower slope of the Portuguese margin, at a location close to the so-called Shackleton Site MD95-2042 (in honor of the late Sir Nicholas Shackleton), to provide a marine reference section of Pleistocene millennial-scale climate variability (Hodell et al., 2015). Five holes were cored at Site U1385 using the Advanced Piston Corer (APC). Site U1385 contains a continuous record of hemipelagic sedimentation from the Holocene to 1.45 Ma (Marine Isotope Stage 47). It is well suitable for calibration of biostratigraphic events to the astrochronologic time scale and well comparable to the Mediterranean cyclostratigraphy derived by tuning sapropel layers to precession (Hodell et al., 2015). The objectives of the present paper are: (1) to produce the first accurate biochronology of the West Iberian Margin for the interval studied; (2) to document the calcareous nannofossil biostratigraphy in mid-latitudes and compare the data to those in the existent literature; (3) to update and improve the

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[*] Corresponding author at: Institute Marine Sciences (IMS), University of California Santa Cruz, USA.
E-mail addresses: balestrabb@gmail.com, balestra@ucsc.edu (B. Balestra).

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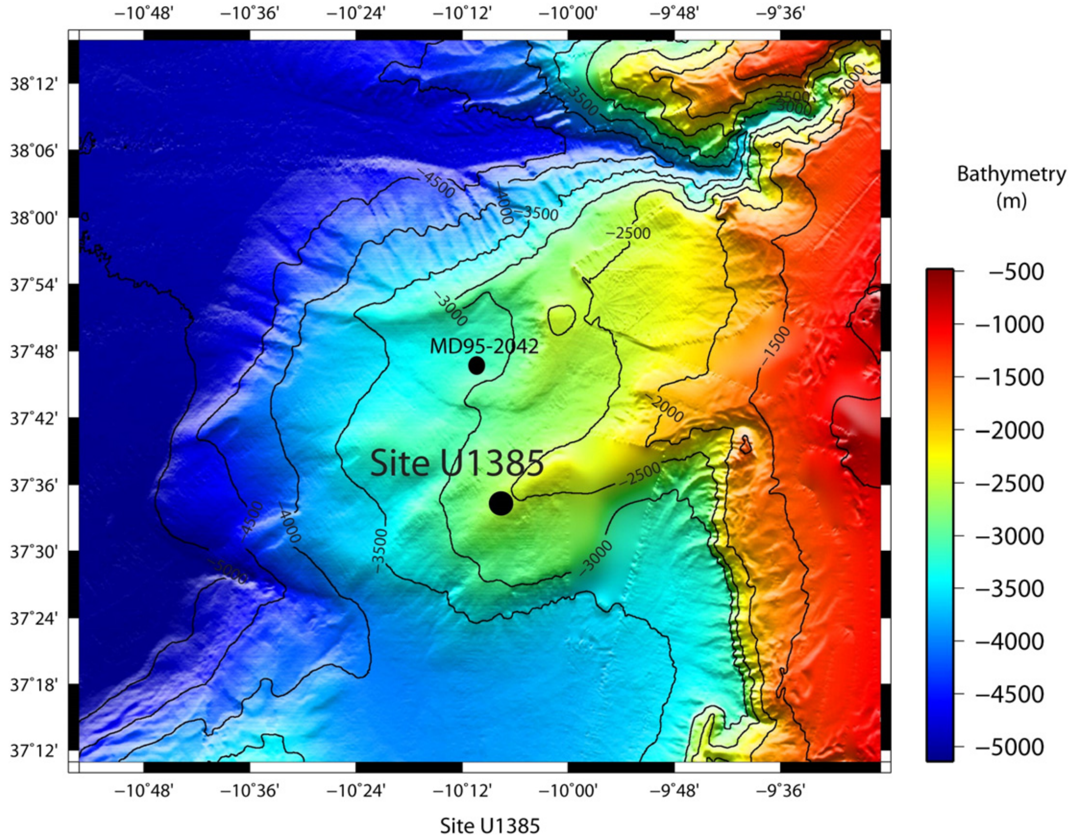

Fig. 1. Map of the west Iberian margin, showing the location of Site U1385 and the so called Shackleton Site MD95-2042 (modified after Hodell et al., 2013).

calcareous nannofossil biostratigraphic framework by means of quantitative evaluation of the abundance patterns of selected taxa, and to detect eventual environmental controls (4) to update the existing calcareous nannofossil biochronology.

2. Oceanographic settings

Site U1385 (37°34′N, 10°7′W, 2578 mbsl, Fig. 1) is under the effect of the Portugal Current (PC) system influenced also by the Canary and Azores Currents (Pérez et al., 2001). The underlying water masses of the PC system originate from a northward moving layer of subtropical origin, from the surface to about 200 m to 300 m. It is underlain by the subtropical Eastern North Atlantic Central Water (ENACW) and, from about 300 m to 400 m, by the subpolar ENACW moving southward (Ambar and Fiuza, 1994; Fiuza et al., 1998; Peliz and Fiuza, 1999). The Mediterranean Outflow Water (MOW) dominates from depths of 400 m to approximately 1300 m (Hernández-Molina et al., 2014). The Northeast Atlantic Deep Water, characterized by a very low temperature and salinity (Bischof et al., 2003), lies beneath the MOW. The core location offers the opportunity to document paleoceanographic changes resulting from both subpolar and subtropical gyre behavior (Hodell et al., 2013 and reference therein).

3. Material and methods

The lithology of IODP Site U1385 mainly consists of nannofossil muds and nannofossil clays, with varying proportions of biogenic carbonate and terrigenous sediment (Expedition 339 Scientists, 2013). The composite sedimentary section of IODP Site U1385 Holes A and B was sampled from 0 to 160.33 crmcd (corrected revised meter composite depth). Sample spacing varied from 30 to 50 cm to obtain approximately one sample per ~5 ky. Occasionally the sample resolution was increased in order to better constrain some of the events. Smear slides were prepared from unprocessed sediment and were examined with a polarizing microscope Zeiss Axiophot and with a polarizing microscope Leica DMRP, at ×1000 and ×1250 magnification. Moreover, ×1600 magnification was also used for the identification of very small specimens as well as characteristics related to the preservation of calcareous nannofossils. Around 3 mm^2 (ca. 300 visual fields at ×1250) were examined to estimate quantitative abundances counting at least 500 coccoliths. Additionally, two to three additional traverses of slides were scanned (between 100 and 150 field of view) to detect the presence of rare or very rare specimens (Marino and Flores, 2002).

For this study, selected bioevents were considered and adopted to define a nannofossil biostratigraphic pattern comparing the standard marker taxa shown in the Martini (1971) and the Okada and Bukry (1980) biozonation schemes (Fig. 2). The selected bioevents were considered also from Raffi and Flores (1995), Bown and Young (1998), Raffi et al. (2006), Sato et al. (2009), and Maiorano et al. (2013a) among others. Additionally, biochronology was developed following the calibrated ages from oxygen isotope stratigraphy reconstructed at this site (Tuned Age Model, Hodell et al., 2015) (Figs. 2, 3). The biohorizons have been defined based on abundance patterns of the index species and recognized as follows: Lowest Occurrence (LO), Lowest Common Occurrence (LcO), Highest Common Occurrence (HcO), Highest Occurrence (HO) and Crossover (CO). List of calcareous nannofossil events, bottom depth of the recognized event (crmcd), correlation to Marine Oxygen Isotope (MIS) and age evaluation are reported in Table 1 and the complete list of all species mentioned in the text is available in Appendix A.

3.1. Taxonomic remarks

Emiliania huxleyi was distinguished in the two morphotypes < and >4 μm (Flores et al., 2010).

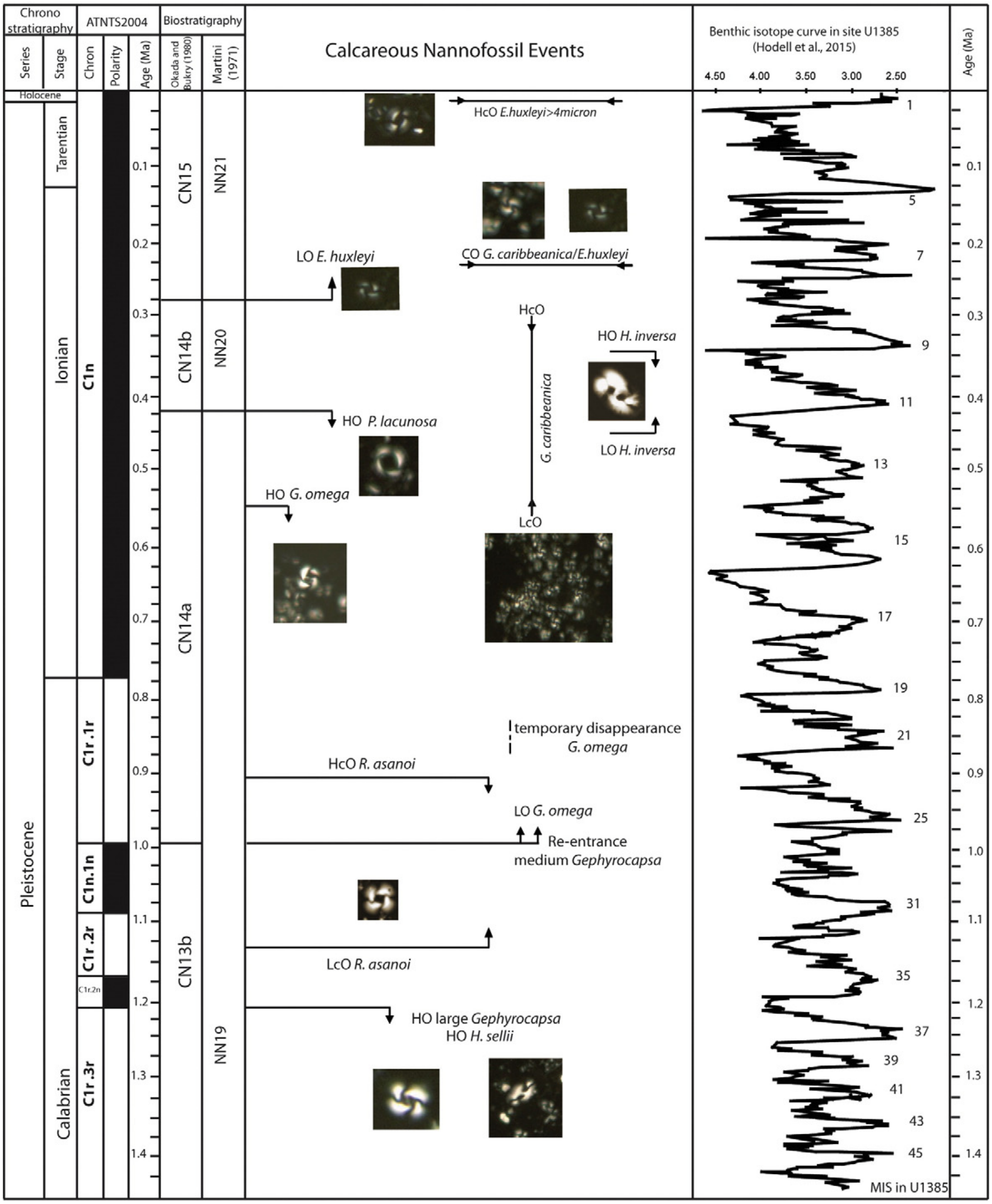

Fig. 2. Biostratigraphic events, recognized in U1385 and comparison with the oxygen isotope stratigraphy of the same core (Hodell et al., 2015). Magnetic reversal and stage boundary ages are based on ATNTS 2004 (Lourens et al., 2004). The age model is discussed in the text.

Gephyrocapsa species were grouped in several size categories, and the classification follows the morphometric criteria adopted in Stow et al. (2013) and Flores et al. (2000). Specimens <3 μm, mainly *Gephyrocapsa ericsonii* and *Gephyrocapsa aperta*, are classified as small *Gephyrocapsa.* Specimens of *Gephyrocapsa muellerae* and *Gephyrocapsa margerelii*, as well as other identified specimens of gephyrocapsids in the 3–5.5 μm size range, are referred to as medium *Gephyrocapsa*. The large *Gephyrocapsa* category includes forms >5.5 μm. We have also distinguished the species *Gephyrocapsa omega* (gephyrocapsids >4 μm and a high angle bridge; synonyms *Gephyrocapsa parallela* Hay and Beaudry, 1973 and *Gephyrocapsa* sp. 3, sensu Rio, 1982) (Maiorano and Marino, 2004; Marino et al., 2003). *Gephyrocapsa caribbeanica* includes mid-sized specimens (3–5.5 μm) with closed central area.

Reticulofenestra specimens were also considered following size concepts by Marino (1996) and Marino et al. (2003). Elliptical forms of <3 μm are called “small *Reticulofenestra*” mainly corresponding to *Reticulofenestra minuta*. *Reticulofenestra haqii* and *Reticulofenestra minutula* are considered “medium *Reticulofenestra*,” ranging between 3 and 5 μm. Occasionally, some elliptical *Reticulofenestra* > 6 μm (referred as “large *Reticulofenestra*”) are observed, but always in low proportion. We have then considered *Reticulofenestra asanoi* > 6 μm. This species has been described by Sato and Takayama (1992) as having a circular to subcircular outline >6 μm, with the presence of a wide, distally protruding collar, and with the opening in the central area with a width of about one-third of the whole coccolith. Specimen of *Reticulofenestra* similar to

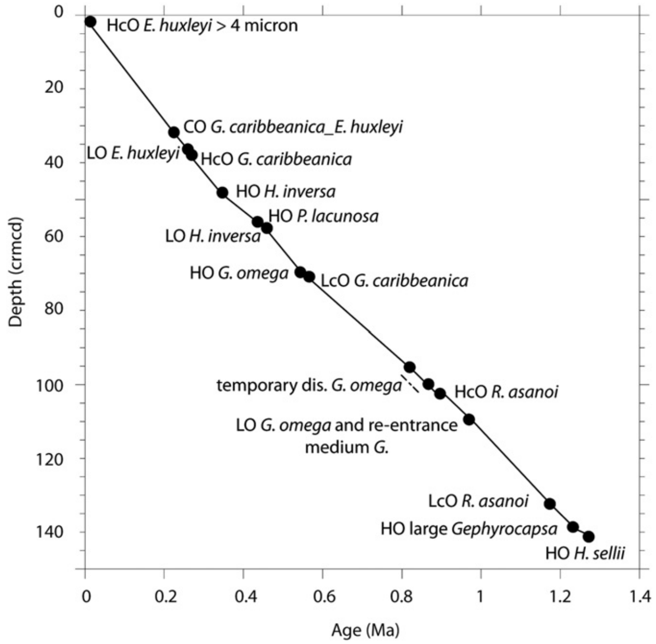

Fig. 3. Biostratigraphic events plotted versus the depth and the age tuned of U1385 (Hodell et al., 2015).

the *R. asanoi* morphology but with dimension < 6 μm, have been distinguished and called circular - subcircular *Reticulofenestra*.

Some morphotypes of elliptical placoliths with a low-birefringence shield and open central area have been observed and counted. In this study, we refer to them as *Pseudoemiliania* cf. *ovata*.

Otherwise, taxonomic concepts for Neogene taxa were adopted from Perch-Nielsen (1985).

4. Chronology of Site U1385

A benthic oxygen isotope record reveals that Site U1385 contains a complete record from the Holocene to 1.45 Ma (MIS 1 to 47) (Hodell et al., 2013; 2015). It is noteworthy that in a specific interval corresponding to the base of MIS 11 a small condensed section or a brief hiatus has been recognized (Hodell et al., 2015). However, the entire record can be correlated unambiguously to the LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005) to provide a refined age model (Hodell et al., 2015). The variations in sediment color contain a very strong precession signals that has been used for orbital tuning (Hodell et al., 2013; 2015). We thus use this record to astrochronologically tune and calibrate evolutionary calcareous nannofossil appearances, extinctions and other useful biohorizons such as CO episodes.

Table 1
List of calcareous nannofossil events, bottom depth of the recognized event (crmcd), correlation to Marine Oxygen Isotope (MIS) and age evaluation; the events of LO and LcO, have been signed at the sample where the taxon first occurs or becomes common, respectively, while the HO and HcO at the sample where the final occurrence and final common occurrence of the taxon are recorded.

Calcareous nannofossil events	U1385 depth (crmcd)	Age (ka) U1385 tuned	MIS
HcO *E. huxleyi* > 4	1.93	14.2	1 (T1)
CO *G. caribbeanica_E. huxleyi*	32.69	233.0	7
LO *E. huxleyi*	36.51	261.0	8
HcO *G. caribbeanica*	38.08	270.8	8
HO *H. inversa*	48.29	348.1	9
HO *P. lacunosa*	56.14	437.2	12
LO *H. inversa*	57.84	459.6	12
HO *G. omega*	70.65	560.0	14
LcO *G. caribbeanica*	71.08	567.0	14
Temporary disappearance *G. omega*	96.64	832.0	20
	101.71	880.0	22
HcO *R. asanoi*	103.51	908.7	23
LO *G. omega* and re-entrance medium *G.*	110.53	974.0	26
LcO *R. asanoi*	132.98	1175.0	35
HO large *G.*	139.60	1233.0	37
HO *H. sellii*	141.42	1273.0	37

5. Results and discussion

5.1. Calcareous nannofossil biochronology

Below, we discuss the identified biohorizons listed in stratigraphic order from the youngest to the bottom of the record. Figs. 4 and 5 represent the distribution patterns of the species considered and their correlation with the oxygen isotope stratigraphy (Hodell et al., 2015). Preservation of coccoliths was estimated following Marino and Flores (2002). In general, preservation is good to very good, allowing the identification of all the species observed. Because the presence of reworked specimens is not relevant, to this study, they have not been included in the quantitative abundances.

5.1.1. The HcO of *Emiliania huxleyi* > 4 μm

The first to recognize the potential use of *Emiliania huxleyi* <and >4 μm was Flores et al. (1997), followed by Colmenero-Hidalgo et al. (2002; 2004). However, only Flores et al. (2010) compiled a set of data of the temporal and spatial distributions of the large *E. huxleyi* form in the North Atlantic from the Last Glacial Maximum (LGM) to the late Holocene. These data were used to determine any synchronicity during this time interval, to reconstruct and monitor the displacement of surface water masses, and to investigate the relationship between fossil abundance patterns and oceanographic features such as the Arctic Front (AF). In Site U1385, the change in abundances of the two *E. huxleyi* morphotypes < and >4 μm, has been placed between the two samples U1385A, 2H, 1, 148–149 (1.88 crmcd) and U1385A 2H, 2, 4–5 cm (1.93 crmcd) that corresponds to the period between 11.9 and 14.2 ka. The comparison of this event to the isotope stratigraphy, confirms the values to approximate the end of Termination 1 (T1) at this latitude (Lisiecki and Raymo, 2005).

5.1.2. The CO *Gephyrocapsa caribbeanica*/*Emiliania huxleyi* event

The CO has been detected between U1385A, 4H, 7, 76–77 cm (31.61 crmcd, 222 ka) and U1385B, 4H, 3, 76–77 cm (32.69 crmcd, 233 ka) (MIS 7). Thierstein et al. (1977) revealed the reversal in dominance between *Gephyrocapsa caribbeanica* and *E. huxleyi*, as time-transgressive. The authors correlated it with MIS 5b and 5a, approximately at 85 ka in tropical and subtropical waters, while in transitional waters it was found at MIS 4 at ~73 ka. More recently in Baumann and Freitag (2004) the CO was reported around MIS 8 in ODP Site 1082 in the Benguela Current System. In the region of Site U1385, this event is useful as an alternative to the standard LO *E. huxleyi* event, because the taxon sometimes is affected by dissolution or present in low abundance (see next section).

5.1.3. The LO of *Emiliania huxleyi*

The LO of *E. huxleyi* has been placed between Hole U1385A, 5H, 3, 4–5 cm (36.51 crmcd) and Hole U1385A, 5H, 3, 76-77 cm (37.26 crmcd), between 261 ka and 266 ka) and corresponds to MIS 8. Our datum correlates well with Thierstein et al. (1977) who recognized and correlate this event with MIS 8 providing an estimated age for this synchronous datum at 268 ka. In 2006, Raffi et al. summarized the astronomical age of this taxon according to the Astronomical Tuned Neogene Time Scale 2004 (ATNTS, Lourens et al., 2004) between 291 and 265 ka.

5.1.4. The HcO and LcO of *G. caribbeanica*

The HcO and LcO of *G. caribbeanica* have been placed respectively between U1385A, 5H, 3, 76–77 cm at 37.26 crmcd and U1385A, 5H, 4, 4–

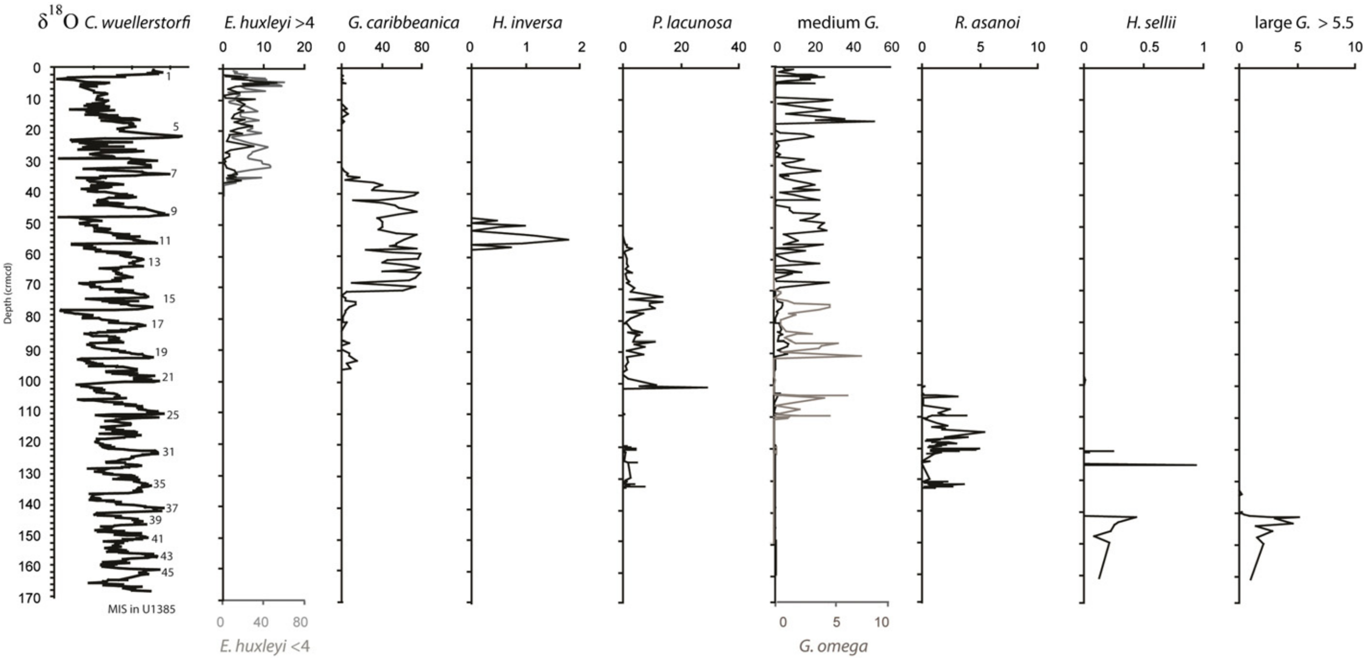

Fig. 4. Distribution patterns (%) of the species considered and their correlation with the oxygen isotope stratigraphy (Hodell et al., 2015).

5 cm at 38.08 crmcd (266 and 270.8 ka, MIS 8) and between U1385A, 8H, 4, 76–77 cm at 71.08 crmcd and U1385A, 8H, 5, 76–77 cm, at 72.59 crmcd (between 567 and 574 ka, MIS 14). The change in abundance of this taxon (in our data it reaches 80% in abundance) is not considered as a useful biostratigraphic event in the literature (e.g. Raffi et al., 2006). However, it has been discussed and recorded in several sites in the Atlantic Ocean and in the Mediterranean Sea (Hine and Weaver, 1998; Bollmann et al., 1998; Flores et al., 1999; Baumann and Freitag, 2004; Baumann et al., 2004; López-Otálvaro et al., 2008; Marino et al., 2014; Maiorano et al., 2015). Because *G. caribbeanica* is usually well preserved, highly calcified and not easily affected by taphonomic processes such as dissolution, the abundance pattern of this taxon provides relevant stratigraphic information for an interval without standard markers.

5.1.5. The HO and LO of Helicosphaera inversa

The HO of this species falls between U1385A, 6H, 3, 4–5 cm at 47.57 crmcd and U1385A, 6H, 3, 76–77 cm at 48.29 crmcd (between 341.4 and 348.1 ka, lowermost MIS 9). The LO instead, occurs between U1385A, 7H, 2, 36–37 cm at 57.84 crmcd and U1385A, 7H, 2, 108-109 at 58.57 (between 459.6 and 464.8 ka, MIS 12). Hine (1990) suggested that the Last Occurrence of *H. inversa* is slightly time transgressive (over 47 kyr) with an average age of 140 ka, within MIS 5 and 6. Subsequently, Hine and Weaver (1998) reported the Last Occurrence of this taxon around 150 ka (~MIS 6) in agreement with Takayama and Sato (1987). Recently, Maiorano et al. (2013a) evaluated the paleoecological and paleobiogeographic meaning of this taxon, comparing different records in the Mediterranean Sea, Atlantic Ocean and Pacific Ocean. They discussed the First Occurrence, finding a high degree of diachrony,

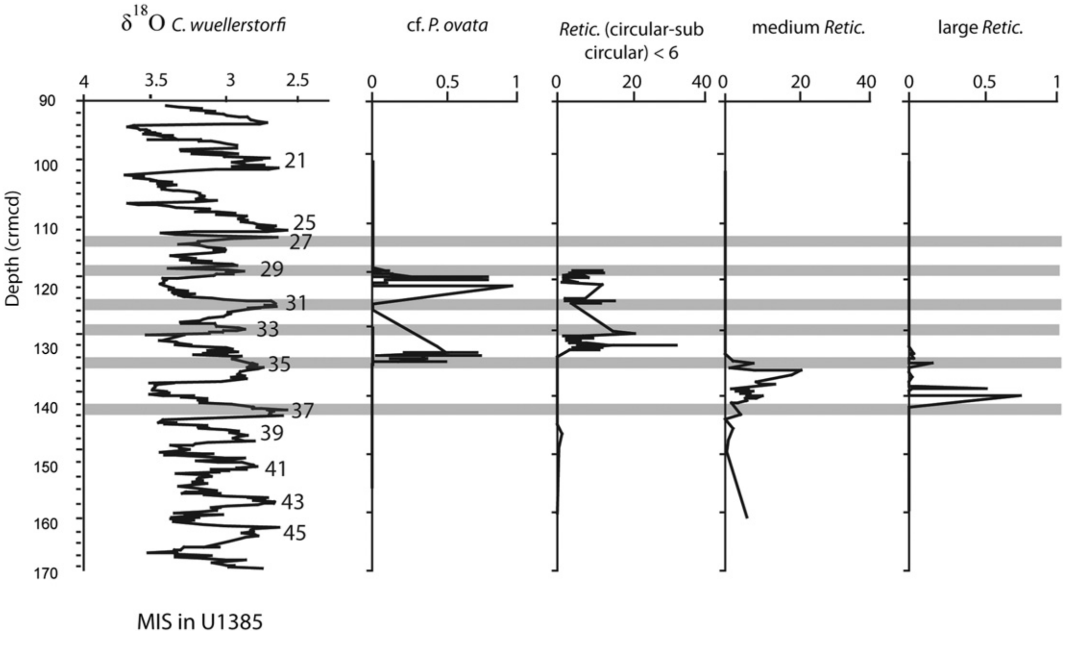

Fig. 5. Distribution patterns (%) of *Pseudoemiliania* cf. *ovata* and selected reticulofenestrids. The gray bars represent the MIS following Hodell et al. 2015.

between lower and higher latitudes. For instance, from the Pacific Ocean (at lower latitudes) it appears at about 800 ka while in the mid-latitude North Atlantic records it appears between 510 ka (within MIS 13, Amore et al., 2012) and 460 ka (uppermost MIS 12, Maiorano et al., 2013).

5.1.6. The HO of Pseudoemiliania lacunosa

The HO of *Pseudoemiliania lacunosa* has been detected between U1385B, 6H, 5, 124–125 at 55.88 crmcd and U1385B 6H, 6, 4–5 at 56.14 crmcd, (between 424.9 and 437.2 ka, MIS 12). Thierstein et al. (1977) established that *P. lacunosa* became extinct in MIS 12 with an estimated age and synchronicity of this datum at ~458 ka. Raffi et al. (2006) summarized the astronomical age of this taxon according to the ATNTS2004 (Lourens et al., 2004) between 436 and 467 ka, in the Pacific Ocean and Mediterranean Sea respectively (MIS 12).

5.1.7. The HO and the LO of Gephyrocapsa omega and re-entrance of medium Gephyrocapsa

The HO falls between U1385A, 8H, 3, 76–77 cm at 69.50 crmcd (553 ka), and U1385A, 8H, 4, 36–37 cm at 70.65 crmcd, (at 560 ka, MIS 14). The LO occurs between U1385B, 11H, 6, 12-13 cm at 110.53 crmcd, and U1385B, 11H, 6, 20-21 cm, at 110.6 crmcd, (between 974 and 978 ka, MIS 26). Raffi et al. (2006) suggested the regional value of the HO of this species because it is documented only in some deep-sea cores and on-land sections from the Mediterranean region. Most recently, this event has been correlated to MIS 15 (Sprovieri et al., 1998) while it has been dated at 580 ka (Castradori, 1993). Concerning the LO according to Wei (1993), Raffi et al. (1993) and Raffi (2002), this event is diachronous between low and mid-to-high latitudes. This event has been recorded in the interval between MIS 25 and 26, showing a certain degree of diachrony also in the Mediterranean Sea (Rio, 1982 = *Gephyrocapsa* sp.3) (Sprovieri, 1993; Sprovieri et al. 1998; de Kaenel et al. 1999; Maiorano and Marino, 2004; Reale and Monechi, 2005). Our interpretation of the oxygen isotope stratigraphy at Site U1385 supports the correlation of the LO of *G. omega* to MIS 26.

This event is coincident with the so-called re-entrance of medium *Gephyrocapsa* (Raffi, 2002; Raffi et al., 2006). This group presents low abundances in the lower part of the section (Fig. 4).

5.1.8. Temporary disappearance of Gephyrocapsa omega

Between the HO and LO of *G. omega*, an interval occurs in which this species is absent which define a useful biostratigraphic event. The top of this interval is between U1385A, 10H, 4, 100–101 and U1385B, 10H, 4, 4–5 cm (91.38 crmcd and 96.64 crmcd, 785.3 and 832 ka) corresponding to MIS 20, whereas the bottom of this temporary disappearance has been detected between U1385A, 11H, 4, 4–5 and U1385A, 11H, 5, 4–5 cm (100.38 and 101.71 crmcd, 859 and 880 ka) correspondent to the upper part of MIS 22. In this interval, the presence of medium sized *Gephyrocapsa* is persistent, although in very low proportions. This temporary disappearance interval was recorded in the Atlantic Ocean and in the Mediterranean Sea (Castradori, 1993; Maiorano and Marino, 2004 and references therein). Maiorano and Marino (2004) found the presence of *G. omega* in low proportions around MIS 21, and thus they considered it as two temporary disappearances.

5.1.9. The HcO and LcO of Reticulofenestra asanoi and other reticulofenestrids

The HcO of *R. asanoi* has been placed between U1385A 11H, 6, 36–37 cm at 103.22 crmcd, and U1385A, 11H, 6, 76–77 cm at 103.51 crmcd, (902.6 and 908.7 ka, MIS 23). The LcO has been placed between U1385A 14H, 6, 108-109 cm at 132.98 crmcd and U1385B, 14H, 1, 92-93 cm at 134.13 crmcd, (1175 and 1179 ka, MIS 35). The HcO of *R. asanoi* has been classified as a recognizable bioevents that correlates with MIS 23 (Maiorano and Marino, 2004; Raffi et al., 2006). The LcO of this species has been suggested to be diachronous between the Atlantic Ocean (MIS 35) (Reale and Monechi, 2005) and the Mediterranean Sea (MIS 31–32) (Maiorano and Marino, 2004). The event was also found to be slightly diachronous within the Mediterranean Sea, having an age slightly older in the eastern Mediterranean (Maiorano and Marino, 2004). In the Alboran Sea (Western Mediterranean Sea) this event has been calibrated to MIS 33–34 (Reale and Monechi, 2005). Taking in account our data, we further consider this event as diachronous having its LcO first in the Atlantic Ocean and western part of the Mediterranean Sea (Reale and Monechi, 2005) and later in the eastern part of the Mediterranean Sea (Maiorano and Marino, 2004; Reale and Monechi, 2005).

Interestingly**,** between samples U1385A, 14H, 6, 108–109 cm at 132.98 crmcd, (1175 ka, MIS 35) and U1385B, 14H, 1, 92–93 cm at 134.13 crmcd, (1179 ka, MIS 35) elliptical morphotype of medium *Reticulofenestra* (from the bottom of the analyzed section), similar in morphology to *Reticulofenestra minutula* have their HO (see Fig. 5). Coincident with the abundance interval of these medium sized specimens, a peak of elliptical forms with diameter larger than 6 μm (called "large *Reticulofenestra*" in Fig. 5) is also recorded, but with values always below 1%. Both, medium and large-sized *Reticulofenestra*, are particularly significant prior to the LcO of *R. asanoi*. In the interval from U1385B, 12H, 5, 4–5 cm at 119.62 crmcd, (1046 ka, MIS 29) to 14H, 6, 108–109 cm at 132.98 crmcd, (1175 ka, MIS 35), circular–subcircular *Reticulofenestra* < 6 μm, are present (see description in Taxonomic remarks). These morphotypes are not present in other intervals of the studied section (Fig. 5). We also noted the intermittent presence of elliptical morphotype of specimens close to medium-sized reticulofenestrids but with a shield close to the *P. lacunosa* light extinction type (crossed Nichols). These forms that have been called *Pseudoemiliania* cf. *ovata* (Fig. 5) are only present between U1385B, 12H, 5, 4–5 cm at 119.62 crmcd (1046 ka, MIS 29) and U1385A, 14H, 5, 124–125 cm at 131.92 crmcd (1163 ka, MIS 35). This potential event needs to be studied in other sections to determine its feasibility as a biostratigraphic datum.

5.1.10. The HO of large Gephyrocapsa (>5.5 μm)

The HO of large *Gephyrocapsa* has been recovered between U1385A, 15H, 4, 52–53 cm (139.54 crmcd) and U1385A 15H, 4, 60–61 cm at 139.60 crmcd, (between 1232 and 1233 ka, MIS 37). This event has been considered a reliable and isochronous event in mid and low latitudes, occurring at MIS 37 (Raffi et al., 1993; Wei et al., 1993; Reale and Monechi, 2005) as confirmed by our results.

5.1.11. The HO of Helicosphaera sellii

The HO of *H. sellii* has been placed between U1385A, 15H, 5, 132–133 cm at 141.26 crmcd, and U1385A, 15H, 6, 4–5 cm at 141.42 crmcd, (between 1264 and 1273 ka, lower MIS 37). A marked diachroneity has been suggested for this taxon concerning its HO between the Pacific Ocean, in which corresponds to MIS 49 (Raffi et al., 1993; Raffi et al., 2006) and the Atlantic Ocean in which corresponds to the MIS 37 (Raffi et al., 1993; Raffi et al., 2006), as recognized also in this study. Some specimens of this taxon have been also found in MIS 31 and MIS 32, and they can be considered as reworked species (Fig. 4).

5.2. Hypothesis on environmental control on specific stratigraphic patterns

Over the last decade the use of quantitative analysis as a key method to investigate abundance patterns of taxa in high resolution sample sets and their correlation to oxygen isotope stratigraphy and orbitally tuned cyclostratigraphic records, have provided significant improvements in the precision and accuracy of biohorizons (Raffi et al., 1993; Sprovieri, 1993; Lourens et al., 1996; Di Stefano, 1998; Lourens et al., 1998; Sprovieri et al., 1998; Flores et al., 2000; Raffi, 2002; Maiorano and Marino, 2004; Maiorano and Marino, 2004; Raffi et al., 2006; Maiorano et al., 2010; Maiorano et al., 2013a). Here we further discuss our data, comparing the quantitative distribution of specific different groups and taxa that suggest possible environmental controls based on their abundance patterns, to the oxygen isotope stratigraphy obtained on the same samples. Using the same samples to correlate biostratigraphy and isotope stratigraphy data is essential for a sound comparison especially in orbital and millennial scale studies, assuming climate/environmental variability, influences/controls ocean features and gradients. Other aspects concerning evolutionary strategies that could have affected also time-distribution of some taxa are taken in account and discussed, but not analyzed in detail.

5.2.1. *Emiliania huxleyi* > 4 μm

The available data on the geographical distribution of the morphotype *Emiliania huxleyi* > 4 μm and its relative abundance in the North Atlantic have been shown recently by Flores et al. (2010). *Emiliania huxleyi* > 4 μm seems to be influenced by a close relationship with cold surface waters (Flores et al., 1993, 1997; Weaver et al., 1999; Esposito, 1999; Colmenero-Hidalgo et al., 2002; 2004). In the latest Holocene, it occurs mostly in low proportions (below 10%) in subarctic regions, where the annual mean temperature is always below 5 °C (Locarnini et al., 2006), while in other regions it is almost absent. In our record we can expand this hypothesis to the other glacial/interglacial periods, down to the LO of the taxon (Fig. 6). The trend of the morphotype >4 μm suggests a preference for low temperature possibly related to displacement of southward oceanic fronts in time. This is especially clear from MIS 5/6 upwards. More data need to be collected on this topic to confirm this environmental control for the last climatic cycles, but the significance of the HcO as a useful biohorizon is demonstrated, even if diachronous.

5.2.2. *Gephyrocapsa caribbeanica*

This taxon has been recently targeted in several paleoceanographic studies and discussed for paleoecological and phylogenetic reasons (Bollmann et al., 1998; Flores et al., 1999; Baumann and Freitag, 2004; Baumann et al., 2004; López-Otálvaro et al., 2008; Marino et al., 2014; Maiorano et al., 2015). The heavily calcified *G. caribbeanica* has been considered as the most important producer of carbonate content through MIS 14 and 8 (Bollmann et al., 1998; Flores et al., 1999, 2012; Baumann and Freitag, 2004; Baumann et al., 2004; López-Otálvaro et al., 2008; Marino et al., 2014; Maiorano et al., 2015) and several evidences have been recorded of the wide-scale mid-Brunhes blooming of this species. Flores et al. (2012, and references therein) pointed out to a potential relationship between this episode of high calcification in the ocean with a general process of enhanced productivity, perhaps controlled by modifications in chemical parameters of the ocean itself not well understood yet. In U1385 the interglacials between MIS 14 and 8 are characterized by high values in the Ca/Ti ratio (Hodell et al., 2015). Possible reasons for the rise to global dominance of this species are still relatively speculative although potential causes have been discussed in previous literature (Bollmann et al., 1998; Baumann and Freitag, 2004; Flores et al., 2012). Our data can confirm once again the consistent distribution of this taxon between MIS 14 and MIS 8, in comparison to other locations in the Atlantic Ocean and Mediterranean Sea enhancing its importance as stratigraphic reference interval.

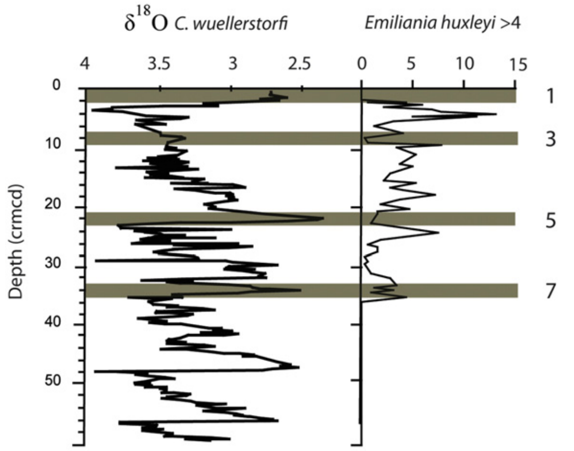

Fig. 6. *Emiliania huxleyi* > 4μm (%) and oxygen isotope stratigraphy (Hodell et al. 2015). The gray bars represent interglacial stages following Hodell et al. 2015.

5.2.3. *Helicosphaera inversa*

Recently, Maiorano et al. (2013a) examined the distribution pattern of *H. inversa*, in the North Atlantic Ocean and in the Mediterranean Sea. These authors found this taxon occurs mainly within 20° and 45°N and referring to previous data indicate that *H. inversa*, rarely occurs outside this latitudinal range that characterizes the modern subtropical and temperate coccolithophore biogeographic zones (Maiorano et al., 2013a). A distinct degree of diachrony between lower and higher latitudes has also been detected. At lower latitudes, based on data from the Pacific Ocean, the LO is at about 800 ka (MIS 19) (Maiorano et al., 2013a and references therein), while in the mid-latitude North Atlantic records it appears between 510 ka (within MIS 13, Amore et al., 2012) and 439 ka (uppermost MIS 12, Marino et al., 2014). In our data *H. inversa* presents higher abundance during MIS 11, confirming the ecological preference of this taxon for warmer surface water. In fact the MIS 11 is well known for being a long interglacial characterized by warm sea surface water temperature (McManus et al., 1999; Hodell et al., 2000; Maiorano et al., 2013b). Thus, our data support the environmental value of this taxon in its biogeographic zone.

5.2.4. *Gephyrocapsa omega*

The distribution of *G. omega* differs between the Mediterranean Sea and the Atlantic Ocean. In the Atlantic, this taxon is still considered extant (Maiorano and Marino, 2004). In this study, *G. omega* has not been identified in the upper part of the core and its HO is in MIS 14. Concerning the LO and the temporal disappearance, these events seem to be reliable just in the Mediterranean Sea. Two temporal disappearances have been recorded and interpreted as environmental signal in the Mediterranean Sea, because the taxon shows higher abundances in warm low salinity and high nutrient waters (Maiorano and Marino, 2004) in several sections. In our record the *G. omega* re-entrance has been detected during MIS 20 but is characterized by low abundances. Moreover, the general pattern is not clearly related to oxygen isotope fluctuations since it shows an increase in both glacial and interglacial stages. Thus, with the available data it is not possible to link the signal of this taxon to environmental conditions. Nevertheless, the LO and the temporary disappearance of *G. omega* can be considered as a valuable biostratigraphic tool in the Atlantic Ocean.

5.2.5. *Reticulofenestra asanoi*

The difficulties in placing the HcO and LcO of the species *Reticulofenestra asanoi*, in the past literature has been linked to the ambiguous taxonomy that defines this species. The LcO has also been suggested to be diachronous (Maiorano and Marino, 2004; Reale and Monechi, 2005) for environmental reason, appearing earlier in the Atlantic Ocean and western Mediterranean Sea and then in the eastern Mediterranean. In fact the abundance of this taxon, although highly variable through various sections (Maiorano and Marino, 2004; Baumann and Freitag, 2004; Reale and Monechi, 2005), is not clearly related to oxygen isotope fluctuations and it shows increases during both in glacial and interglacial stages also in our study (Fig. 4). Maiorano and Marino (2004) recorded higher abundances of *R. asanoi* in the Atlantic Ocean than in the Mediterranean Sea where a decreasing trend occurred toward the eastern basin. Although no ecological preferences are known for *R. asanoi*, it has been argued that this trend may be a response to increased in salinity, suggesting a preference for normal salinity waters (Maiorano and Marino, 2004). The diachrony observed both in the HcO that in LcO, seems to fit well with the idea of an environmental/biogeographic diachronous event, even considering the discrepancies between the age models used and different taxonomic concepts adopted by different authors.

6. Summary

High-resolution biostratigraphic analyses have permitted a revision of the principal nannofossil events in the last 1.4 Ma. The quantitative abundance patterns of calcareous nannofossil index taxa collected from Site U1385, the correlation with the oxygen isotope stratigraphy and the comparison with several mid-latitude sections studied previously in the Mediterranean Sea and Atlantic Ocean have resulted in an improved understanding of the diachronous character of selected bioevents. Finally an accurate revision of the events enabled us to test the stratigraphical value of the bioevents, thereby providing higher resolution biochronologic information.

In particular:

- *Emiliania huxleyi* > 4 μm is considered to be a cold water taxa showing low abundances patterns especially during the interglacials, and confirming a prominent decrease in mid-latitudes at Termination I.
- *Gephyrocapsa caribbeanica* is a common taxon between MIS 14 to 8. Its cosmopolitan distribution makes its LcO and HcO useful as biostratigraphic events.
- *Helicosphaera inversa* abundances confirm the bio-ecostratigraphic value of this taxon in mid-latitudes.
- *the Gephyrocapsa omega* distribution pattern is not linked to any particular environmental conditions. However, we support its biostratigraphic value, including an interval of absence/decrease in abundance between MIS 20 and 22.
- *Reticulofenestra asanoi* data suggest a certain degree of diachrony, linked to environmental/biogeographic influence, but they confirm its potential as a reference biohorizon.

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Appendix A. Complete list of the species mentioned in the text

Emiliania Hay and Mohler in Hay et al., 1967.
Emiliania huxleyi > 4 Flores et al., 2010.
Emiliania huxleyi (Lohman) Hay and Mohler, 1967.
Gephyrocapsa Kamptner, 1943.
Gephyrocapsa caribbeanica Boudreaux and Hay, 1967.
large *Gephyrocapsa* > 5.5 μm Rio (1982).
Gephyrocapsa omega Bukry (1973) *Gephyrocapsa parallela* = *Gephyrocapsa* sp. 3, sensu Rio, 1982.
Helicosphaera Kamptner, 1954.
Helicosphaera sellii (Bukry and Bramlette) Jafar and Martini, 1975.
Helicosphaera inversa (Gartner) Theodoridis 1984.
Pseudoemiliania Gartner, 1969c.
Pseudoemiliania lacunosa (Kamptner) Gartner.
Reticulofenestra Hay et al., 1966.
Reticulofenestra asanoi Sato & Takayama, 1992.

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