

Integrated calcareous nannofossil and planktonic foraminiferal bioevents of the last 1.07 Ma: a case study from the East New Zealand Pacific Ocean

Claudia Lupi¹, Valeria Luciani², and Miriam Cobianchi¹

¹Dipartimento di Scienze della Terra, Università di Pavia, Via Ferrata 1, 27100 Pavia (Italy)

²Dipartimento di Scienze della Terra, Università degli Studi di Ferrara, Polo ScientificoTecnologico, Via Saragat 1, 44100 Ferrara (Italy)
email: clupi@dst.unipv.it

ABSTRACT: The core MD97-2114 (42°22.32'S; 171°20.42'W) on the northern slope of the submarine Chatham Rise (east of New Zealand, 1935m water depth), is a significant case-study for the improvement of the resolution of the mid-late Pleistocene integrated calcareous nannofossil and planktonic foraminiferal biostratigraphy.

Quantitative data of calcareous nannofossils and planktonic foraminifera, well preserved and abundant throughout the core, are correlated with magnetostratigraphy and oxygen isotope stratigraphy and indicate that the studied core contains a sedimentary record of the past ca. 1.07 Ma.

Several standard nannofossil events were documented and their correlation with Marine Isotope Stages (MIS) is consistent with previous calibrations. Moreover, some subsidiary events are here recorded thus improving the biostratigraphic resolution.

The identification of one standard and a number of additional foraminiferal bioevents have been achieved by using climatically/ecologically controlled entries/exits or variations in abundance. The integrated scheme obtained includes 17 bioevents, calibrated with magneto-isotope stratigraphy, and provides a biostratigraphic resolution of ca 63kyr.

The bioevents of the two investigated groups of calcareous plankton appear closely spaced in two selected intervals in the lower part of the core, placed at the middle-lower part of the Brunhes Chron and at the top of the Jaramillo Subchron. The implications for the recognition of the chronostratigraphic lower-middle and middle-upper Pleistocene boundaries are discussed.

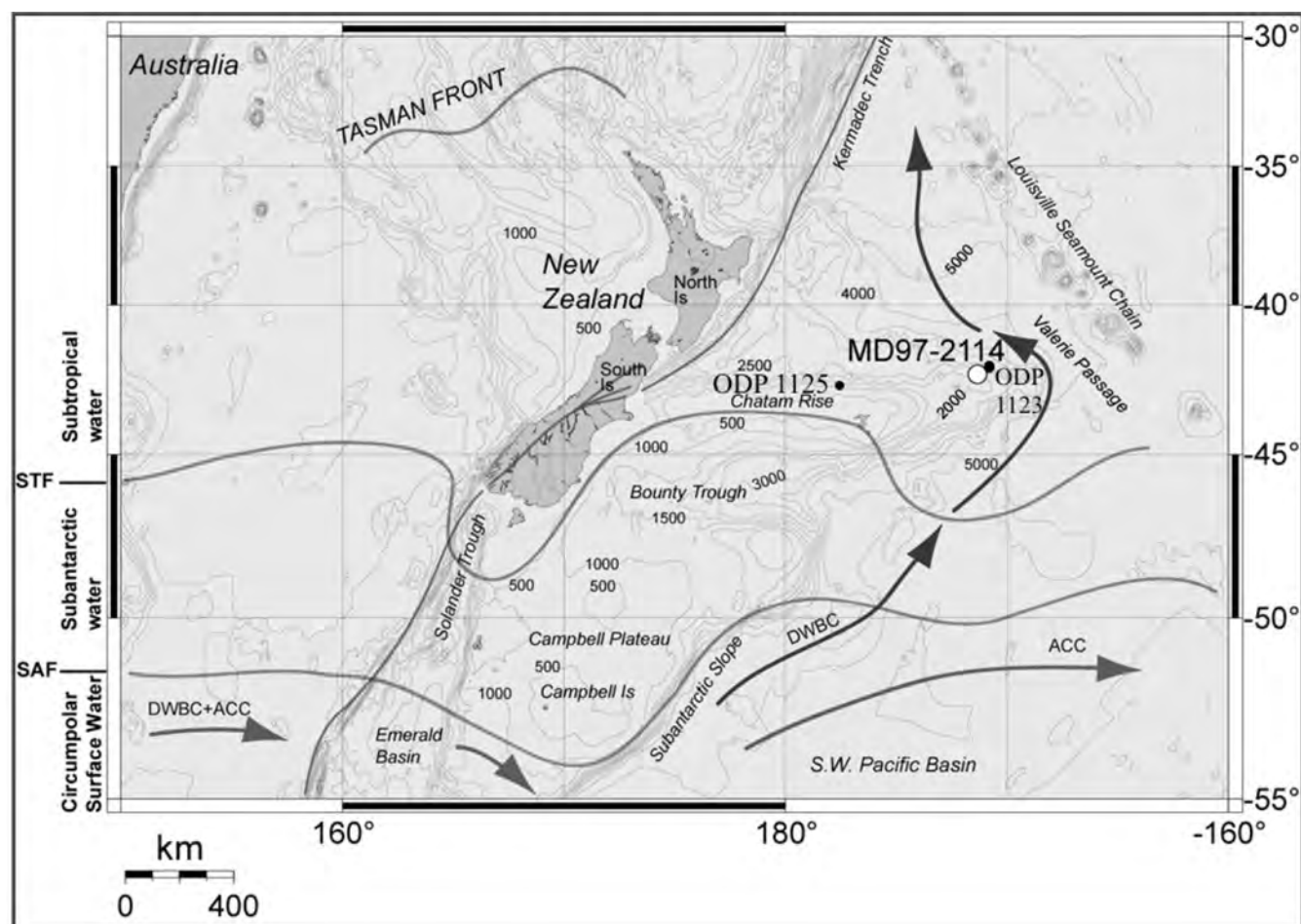
INTRODUCTION

This work is part of a research project aimed to highlight the interactions between marine organisms and the climate fluctuations in the Quaternary Oceans, the BIOCLIP Project (*Biological Productivity and Climate Interaction Project*). To better understand the complex relationships between marine biotic productivity and climate, the first step is to have a precise and correlatable stratigraphic frame. Moreover, the modern paleoclimate, paleoceanographic researches need a high-resolution stratigraphy (at the orbital and sub-orbital scale) and the recognition of new bioevents, also eco-stratigraphic events, is required. Albeit several biostratigraphic schemes are available for the Pleistocene (for the calcareous nannofossils see for example: Martini 1971; Gartner 1977; Okada and Bukry 1980, Rio et al. 1990; Young 1991; Raffi et al. 2006; for the planktonic foraminifera: Berggren et al. 1995), papers based on integrated calcareous nannofossil and planktonic foraminiferal biostratigraphy are uncommon.

Core MD97-2114 (42°22.32'S; 171°20.42'W; text-fig. 1), deriving from the IMAGES (*International Marine Past Global Change Study*), has recovered an expanded and continuous sedimentary record from mid-late Pleistocene containing well-preserved calcareous nannofossils and foraminifera, thus providing the opportunity to investigate the two fossil groups. Moreover, the magneto- and isotope stratigraphic calibration (Venuti et al. 2007) allows us to correlate the bioevents with other geochronological methods.

About magnetostratigraphy, in the MD97-2114 succession Venuti et al. (2007) documented the Brunhes Chron, from 0 to 19.70m and the Matuyama chron, from 19.70m to the bottom. Moreover, the interval from 25.22m to the bottom of the core was assigned to the Jaramillo Subchron. The $\delta^{18}\text{O}$ isotope measurements provided a curve with 29 glacial and interglacial periods, that have been correlated with the magnetic polarity zonation (Venuti et al. 2007). Particularly, two tie points, i.e. the Brunhes/Matuyama and the upper Jaramillo reversal boundaries clearly identify respectively the MIS 19 and the MIS 27. The correlation between the $\delta^{18}\text{O}$ and the global benthic stack curve of Lisiecki and Raymo (2005) was further supported by micropaleontological analyses of calcareous nannofossil and planktonic foraminiferal assemblages.

The core has been collected at 1935m water depth on the north-eastern slope of the Chatham Rise (East New Zealand Pacific Ocean), which is a major E-W trending submarine high extended for 1000km eastward from the New Zealand (text-fig. 1). The crest of the Chatham Rise coincides with the subtropical front (STF) separating the subantarctic and subtropical surface water masses (Carter et al. 1998). The importance of the area located east of New Zealand is the occurrence of the Deep Western Boundary Current (DWBC), which exports bottom waters from the Antarctic sinking regions to the Pacific Ocean (Warren 1981). The DWBC is a key component of the Global Thermohaline Circulation, which plays an important role in the regulation of the Earth's climate (Orsi et al. 1999). For these



TEXT-FIGURE 1

Bathymetric map of the East New Zealand Pacific Ocean with the location of the studied IMAGES Core MD97-2114. The location of the adjacent ODP sites 188-1123 and 188-1125 is also reported. The map shows the major surface water masses, oceanic fronts and currents: STF, Subtropical Front; SAF, SubAntarctic Front; DWBC, Deep Western Boundary Current; ACC, Antarctic Circumpolar Current (modified from Carter et al. 1998).

reasons, in the last decade the region has been object of many micropaleontological, paleoclimate and paleoceanographic studies (e. g., Fenner et al. 1992; Nelson et al. 1993; Wells and Okada 1997; Weaver et al. 1998; Nelson et al. 2000; Shipboard Party 2000; Sikes et al. 2002, Fenner and Di Stefano 2004; Scott and Hall 2004; Wilson et al. 2005; Schaefer et al. 2005; Venuti et al. 2007; Crundwell et al. 2008). Because of the great interest of the scientific community for the Pleistocene-Holocene interval, the aim of this paper is to present a sedimentary record from SW mid-latitude Pacific, potentially improving the resolution of mid-late Pleistocene being characterized by an exceptionally high-quality time control and by an excellent calcareous plankton preservation. In addition, the analysis will provide a helpful assessment of stratigraphic continuity introducing to further measurements (e. g., stable isotopes, radio-isotopes) for the needed high-resolution stratigraphy at orbital and sub-orbital scale essential for modern paleoceanography.

CORE MD97-2114: DESCRIPTION AND SAMPLING

The core MD97-2114, 28m thick, exhibits pelagic and hemipelagic sediments, characterised mainly by grey limy ooze, locally interbedded with several micro- and macroscopic

amorphous silty silica layers. The carbonate fraction, reaching 90% in volume, is mainly given by abundant and well preserved calcareous plankton (calcareous nannofossils, foraminifera and *Thoracosphaera* spp.), whereas siliceous plankton is rare. Several silica layers occur and have been documented also through the analyses of the paleomagnetic properties of the core. They have been recognised as tephra, probably related to the activity of the Taupo Volcanic Zone, located on the North Island of the New Zealand (Carter et al. 2004; Venuti et al. 2007).

Oxygen isotope stratigraphy and magnetostratigraphy were given by Venuti et al. (2007). This integrated data set indicates that the studied core contains a continuous sedimentary record of the past c.1.07 Ma.

METHODOLOGIES

Calcareous nannofossil analysis

The calcareous nannofossil content was analysed on 235 samples, taken at 10cm intervals, and prepared as smear slides following the standard techniques (Bown and Young 1998) and examined using a polarising light microscope at 1250x magnifications. Counting of the species abundance was performed quantitatively in three steps, producing three sets of data for

each sample. This method is proposed for the first time in this work.

Owing to the strong difference in size among the several species and the dominance of small taxa over the large taxa, we decided to count in each smear slide 650 specimens in three steps. In the first one we counted 350 nannofossil specimens per sample among the abundant and rare species. In the second step, we counted 150 specimens with size larger than 4µm and, finally, the third step concerns counts of 150 specimens smaller than 4µm.

Actually, this counting approach is similar to the method used for the nannofossil analyses of the ODP site 1123 (Fenner and Di Stefano 2004). This ODP site is located near the IMAGES core MD97-2114 but is 1000 m deeper, and shows the same characters. For the site 1123, the authors counted the calcareous nannofossil content following the method used by Okada (1992) and Okada and Wells (1997). They firstly counted 350 specimens of the most abundant species and secondly 150 specimens of the subordinate species.

In this work for biostratigraphic purpose, we mainly use the results coming from the two counts of 150 specimens (> and < of 4µm) joined together to perform for each sample assemblages of 300 specimens to represent better the taxonomic composition and particularly the relative abundance of the smaller taxa.

Finally, we have introduced the size value of 4µm, because it represents the boundary between the small- and medium-size *Gephyrocapsa* spp. (Raffi et al. 1993).

The genus *Gephyrocapsa* dominates most of the Pleistocene nannofossil assemblages and experiences many shifts in dominance among its species and morphotypes. Our quantitative counting method could be useful to check these shifts, some of which are isochronous and could increase the Pleistocene biostratigraphic resolution. From a taxonomic point of view, the core studied contains abundant specimens of the genus *Gephyrocapsa*. This genus, known for its taxonomic complexity, records during the Early and Middle Pleistocene interval changes in abundance and size. In fact, its Pleistocene evolution is characterised by several exits or entries and acme intervals of different morphotypes useful for a biostratigraphic purpose. However, as shown in Table 1, there are some discrepancies about the morphometric definition of the species, therefore in this work, the biometric subdivision proposed by Raffi et al. (1993) is used. Moreover, for the *Gephyrocapsa* subdivision into species we used the taxonomic concepts proposed by Young et al. (2003), except for *G. aperta* for which we used the definition of Kamptner (1963) because this species is not included in Young et al. (2003).

The quantitative analyses performed allowed us to detect: the lowest (LO) or highest (HO) occurrence of index species (entry and exit); the abundance changes of some taxa (rise or decline) interpreted as lowest consistent occurrence (LCO), highest consistent occurrence (HCO) events and acme intervals (AB = acme beginning; AE = acme end); a shift in dominance between two taxa producing a cross-over in abundance (X) (see Raffi et al. 2006).

The acme definition for the nannofossils is not formalized in any works, neither in Raffi et al. (2006) that represents the most recent paper dealing with the standard quantitative biostratigraphy of the past 25 million years. We have placed, therefore,

qualitatively our AB and AE where the relative abundance sharply increases and the species occurs continuously. It must be noted that in our study this falls where the relative species abundance reaches values more than 20%. With this strategy we have obtained results which correlate the acme events of previous authors.

A taxonomical reference list of the cited species is given in Appendix A. Selected species are figured in Plate 1; row count data are in Appendix C, online at www.micropress.org.

Planktonic foraminiferal analysis

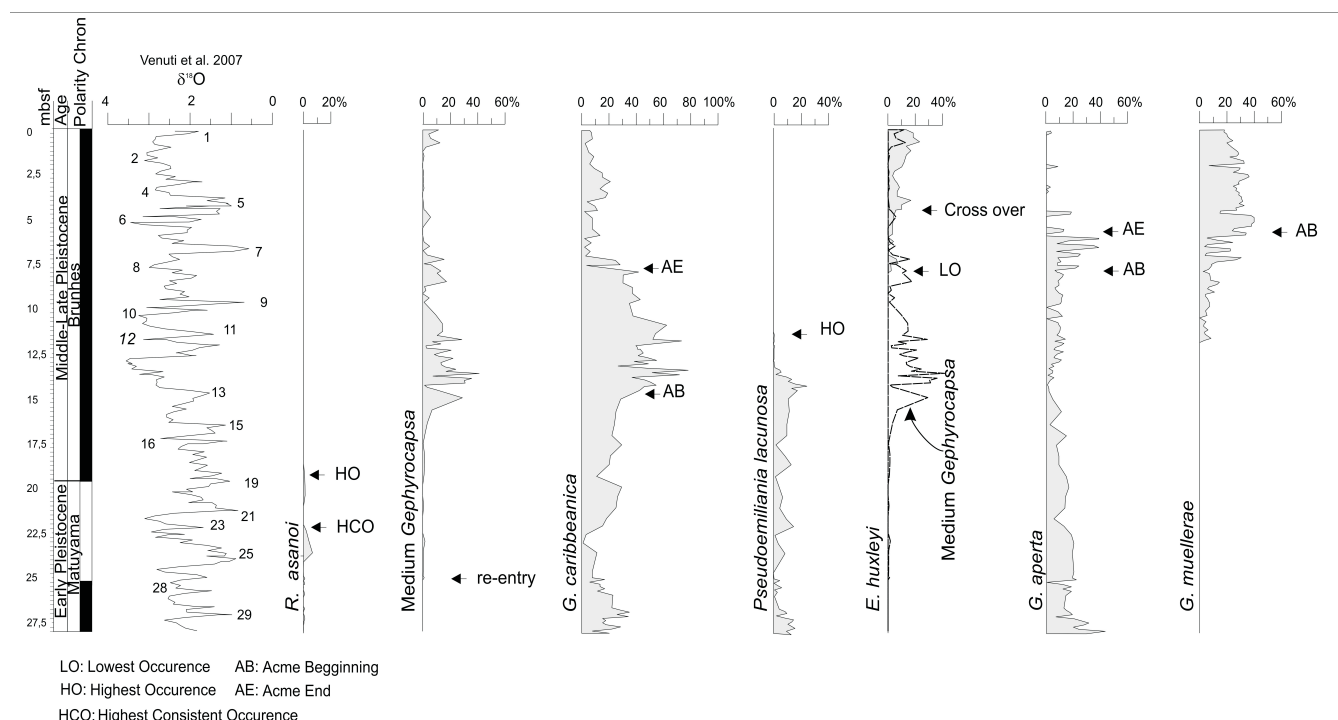
Sediment samples examined for planktonic foraminifera were disaggregated using distilled water and then washed using 63µm and 150µm sieves; washed residues were dried in the oven at 50°C. The analysis comprised 114 samples at 20cm interval. Planktonic foraminiferal assemblages were carefully searched to accurately define highest and lowest occurrences (or entry and exit) of species. The planktonic foraminiferal analysis was performed on two fractions. Splits of the >150µm and >60µm fractions were used for the census of planktonic foraminifera. Finest fraction, partially constituted by juveniles, was investigated to identify the smaller species. The quantitative analysis was carried out by counting planktonic foraminiferal species from the >150µm on a statistical population of about 300 specimens.

The size of the fraction to be analyzed for planktonic foraminiferal studies is object of continuous discussion for every stratigraphic interval because the data obtained can vary consistently depending on the fraction preferred with the possibility of introducing artefacts in the distribution of planktonic foraminifera. Pleistocene and Holocene assemblages have generally been analysed using the standard >150µm sieve size, nevertheless recent results testing the reliability of the different size fraction over all the Atlantic Ocean bio-provinces demonstrate that counts from the >125µm better approximate maximum diversity whereas the fraction >63µm should be used for the polar oceans (Al-Sabouni et al. 2007). Our analysis actually confirms that some small species are represented mainly in the >63µm fraction, such as *Tenuitella iota*, *T. parkerae* and *Globigerinita uvula*, that represent, however, a minor component of the assemblages. On the other hand, quantitative analysis on the populations >150µm allows us a direct comparison with the majority of planktonic foraminiferal studies that are performed on the same fraction. A taxonomical reference list of cited species is given in Appendix B and selected species are figured in Plate 2; row count data are available in Appendix C.

The qualitative and quantitative analyses and the excellent state of preservation of assemblages allow us to identify diverse types of events: highest occurrence (HO), first entry (FE), highest and lowest common occurrences (HCO, LCO). HCO and LCO were selected where the mean relative abundance of the species moves respectively to values below and above 8% at least.

The taxonomy here adopted essentially follows Saito et al. (1981) and Kennett and Srinivasan (1983). The species *Globorotalia tosaensis* is distinguished from the close *G. truncatulinoides* by its lack of peripheral keel, curve spiral suture and rounded equatorial periphery.

Transitional forms between the two species show a peripheral keel only in the last chamber/s of the final whorls.



TEXT-FIGURE 2

Species abundance curves of the main nannofossil stratigraphic markers plotted against magnetostratigraphy and oxygen isotope stratigraphy planktonic record (*Globigerina bulloides*, Venuti et al. 2007) and expressed in percentage. For the MIS 12 attribution see Discussion paragraph.

The morphological variability of *Globorotalia truncatulinoides* in its coiling direction, size and shape of the test is well known (see Renaud and Schmidt 2003 for a review) and includes genetic differences in living population that implies a complex of four species (De Vargas et al. 2001). The different morphotypes have not been distinguished in this paper and the *Globorotalia truncatulinoides* comprises here all the different morphotypes; distribution and abundance of them will be object of a separate study.

According to Giraudeau (1993) *Neogloboquadrina dutertrei* was identified as specimens having at least five chambers in the last whorl, a wide umbilicus and relatively high spire whereas forms with four, or four and a half, chambers in the final whorl, a closed umbilicus and the aperture bordered by a lip have been assigned to *N. pachyderma*. Precisely, in our core occurs almost exclusively the right coiling morphotype. Following the Darling et al. (2006)'s studies on the genetic differences in the living *N. pachyderma*, the right morphotype should be assigned to the species *N. incompta*.

Our taxonomical concept of *Globorotalia crassaformis*, following Saito et al. (1981), includes forms with laterally compressed chambers on the spiral side. It is however possible that our *Globorotalia crassaformis* might include *Globorotalia crassula* of some other workers (e. g., Schaefer et al. 2005; Crundwell et al. 2008).

RESULTS

Calcareous nannofossil biostratigraphy

Calcareous nannofossils are abundant and well diversified throughout the core. The assemblages show a good degree of

preservation and record the occurrence of susceptible dissolution taxa as the *Emiliania huxleyi* and/or the small-sized *Gephyrocapsa* spp.

Several calcareous nannofossil biohorizons are detected in the MD97-2114 succession (text-fig. 2), some of these have been previously included in the standard biostratigraphic schemes of Martini (1971), Gartner (1977), Okada and Bukry (1980), Rio et al. (1990), Young (1991) and de Kaelen (2000) or discussed as biohorizons (i.e. Gartner 1977; Thierstein et al. 1977; Matsuoka and Okada 1990; Weaver and Thomson 1993; Wei 1993; Raffi et al. 1993; de Kaelen et al. 1999; Raffi 2002; Maiorano and Marino 2004; Maiorano et al. 2004; Raffi et al. 2006).

The nannofossil biohorizons recognised in the succession studied and considered by Raffi et al. (2006) as standard bioevents, i.e. events well-defined and demonstrably isochronous over wide geographic distance, are from the top to the bottom:

- *Emiliania huxleyi* LO (7.86mbsf);
- *Pseudoemiliania lacunosa* HO (11.50mbsf);
- *Reticulofenestra asanoi* HCO (22.25mbsf);
- Medium-sized *Gephyrocapsa* spp. re-entry (25.08mbsf).

Moreover, other subsidiary biohorizons were detected in the core. These events are not included in the biostratigraphic scheme of Raffi et al. (2006) because considered diachronous worldwide or regional events. These bioevents, however, are documented by several authors (e.g. Weaver and Thomson 1993; de Kaenel et al. 1999; Flores et al. 1999, 2000; Baumann and Freitag 2004) in different paleogeographic settings (Atlantic Ocean, Mediterranean Sea, and Indian Ocean). They are:

- Medium-Large *Gephyrocapsa-Emiliania huxleyi* cross-over (4.28mbsf);

- *Gephyrocapsa muelleriae* AB (4.50mbsf);
- *Gephyrocapsa aperta* AE (4.50mbsf);
- *Gephyrocapsa aperta* AB (7.75mbsf);
- *Gephyrocapsa caribbeanica* AE (7.75mbsf);
- *Gephyrocapsa caribbeanica* AB (14.75mbsf);
- *Reticulofenestra asanoi* HO (19.21mbsf)

The recorded calcareous nannofossil bioevents were correlated with the magnetic reversal intervals and the Marine Isotope Stages (MIS) detected from the *Globigerina bulloides* $\delta^{18}\text{O}$ measurements from the MD97-2114 Core (Venuti et al. 2007).

One of the most conspicuous findings of this study is the record of the acme events of the genus *Gephyrocapsa*. These acme events, occurred in the middle-late Pleistocene and particularly during the Mid-Brunhes, have been documented worldwide and in different paleoceanographic settings.

In particular, we discuss in this work the acme intervals represented in text-figure 2.

In the core studied, the *Gephyrocapsa muelleriae* AB is marked by a strong shift from relative abundance always less than 20% to abundance consistently more than this value. The acme interval of the *G. aperta* shows relative abundance values more than 12%. The *G. caribbeanica* acme interval is characterised by relative abundance values ranging from 30 to 80%. Chronologically from the top to the bottom, the acme intervals of *G. muelleriae* (Pujos 1988; Weaver and Thomson 1993; Flores et al. 1997; Bollmann et al. 1998; Baumann and Freitag 2004), *G. aperta* (Winter and Martin 1990; Weaver and Thomson 1993; Flores et al. 1999; de Kaenel 2000; Baumann and Freitag 2004), and *G. caribbeanica* (Pujos 1988; Pujos and Giraudeau 1993; Weaver and Thomson 1993; Bollmann et al. 1998; Flores et al. 1999; de Kaenel 2000; Baumann and Freitag 2004) are documented.

The correlation among our acme events and the same events documented by the previous authors proves that they are homotaxic over the world, and have a good fit proving their reliability and reproducibility for biostratigraphic studies. Actually, a biohorizon is considered isochronous when its age estimate is constrained within a single orbital cycle, spanning a time interval approximately from 20 to 100 ka (Raffi et al. 2006). Therefore, we can consider these acme events isochronous and useful biostratigraphically because paleoecological response related to global paleoenvironmental changes.

Planktonic foraminiferal biostratigraphy

Planktonic foraminiferal preservation is generally good to excellent throughout the core. Counting was performed on entire specimens since dissolution only weakly affects foraminiferal assemblages. The *Globorotalia inflata*, typical species of southern margin of subtropical gyres (e. g., Scott and Hall 2004), is the most abundant form at Chatham Rise throughout the studied core. This species is strongly resistant to corrosion (Parker and Berger 1971; Malmgren 1983), however, its relative abundance > 50%, considered as indicative of possible selective dissolution (Niebler and Gersonde 1998), was reached only in one sample at 10.71mbsf (62.6%). *G. inflata* is followed in abundance by *Globigerina bulloides* and *Neoglobobulimina incompta*.

Despite the interest for this key area, recent studies dedicated to planktonic foraminiferal biostratigraphy are absent. On the

TABLE 1

Summary of the different morphometric constraints used by different authors to define the *Gephyrocapsa* morphotypes.

AUTHOR	SIZE RANGE	DENOMINATION OF THE GROUP
Matsuoka & Okada (1989)	> 5 μm	Large
	2.5-5 μm	Medium
	< 2.5 μm	Small
Rio et al. (1990)	> 5.5 μm	Large
	4-5.5 μm	Medium
	< 4 μm	Small
Raffi et al. (1993)	> 5.5 μm	Large
	4-5.5 μm	Medium
	< 4 μm	Small
Okada (2000)	> 5 μm	Large
	3-5 μm	Medium
	2-3 μm	Small
	< 2 μm	Very Small

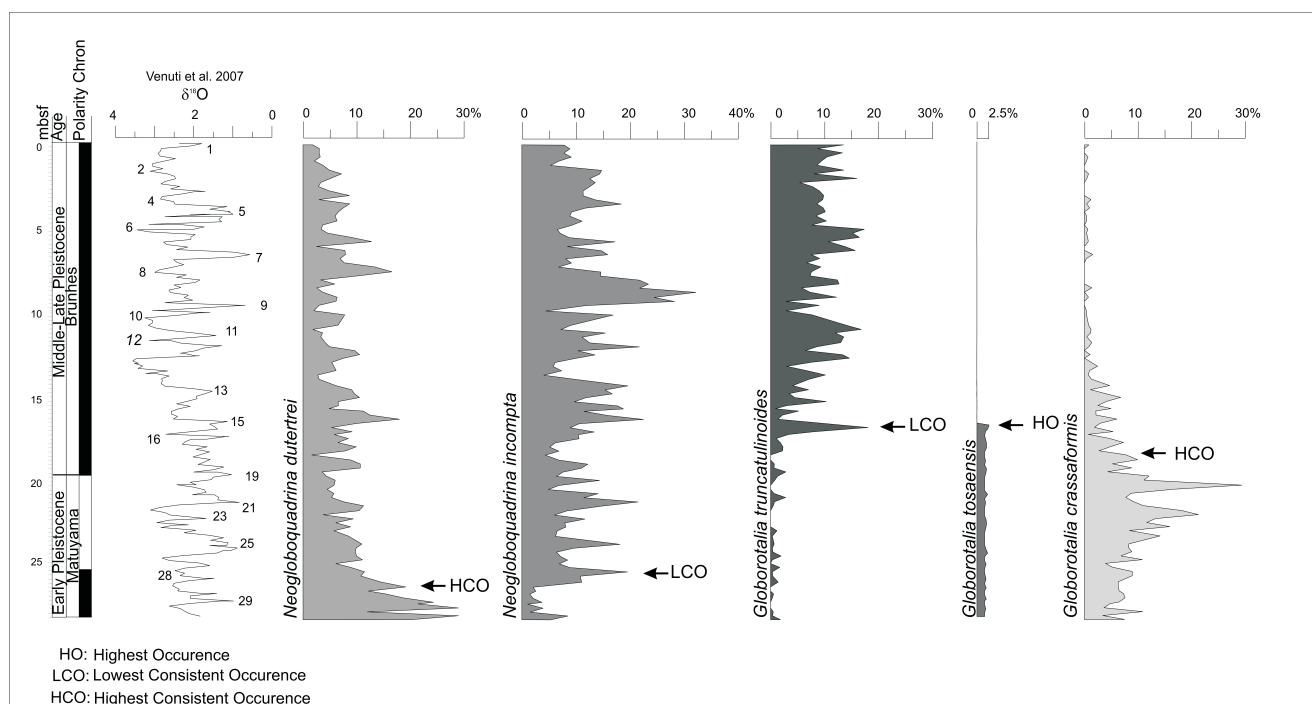
other hand, this group has been the object of analyses aimed to reconstruct past sea-surface temperatures and establish the position of the STF (SubTropical Front), resulting locked to the Chatham Rise during the Pleistocene (e.g., Scott and Hall 2004; Schaefer et al. 2005; Wilson et al. 2005; Crundwell et al. 2008). Our study confirms that planktonic foraminiferal subtropical assemblages dominate the Core MD97-2114 during the last 1.07Myr.

Results of our analysis reveal that several planktonic foraminiferal biohorizons are detectable in the MD97-2114 core (text-fig. 3).

The last appearance of *Globorotalia tosaensis* is the event proposed by Berggren et al. (1995) to subdivide the Pt1 planktonic foraminiferal zone in Pt1a (*Globigerinoides fistulosus*-*Globorotalia tosaensis*) and Pt1b (*Globorotalia truncatulinoides*) for the subtropical open oceans and eastern equatorial Pacific (see also Lourens et al. 2004). The HO of *G. tosaensis* was recognized in the core MD97-2114 at 16.50mbsf. The transitional specimens *G. tosaensis*/*G. truncatulinoides*, exhibiting an incompletely developed peripheral keel, occur up to 14.20mbsf.

On the basis of the HO of typical *G. tosaensis* the core is referable to the upper part of the Pt1a and to the Pt1b subzones. The last appearance datum of *G. tosaensis* is calibrated at 610 ka according to Lourens et al. (2004). This age falls in the MIS 15 of Lisiecki and Raymo (2005). The HO of *G. tosaensis* occurs at the MD97-2114 core in the lower part of the Brunhes Chron and correlates the MIS 15, adopting the correlation of the $\delta^{18}\text{O}$ curve of Venuti et al. (2007). Unexpectedly, this species has not been reported from the nearby ODP Sites 1123, 1125 and 594 (Scott and Hall 2004; Schaefer et al. 2005; Crundwell et al. 2008).

The identification of additional bioevents has been achieved by using entries/exits or variations in relative abundance. The following events were selected among others to tentatively improve the planktonic biostratigraphic resolution of the area according to their easy identification. They are from the highest to the lowest (text-fig. 3):



TEXT-FIGURE 3

Species abundance curves of the main planktonic foraminiferal stratigraphic markers plotted against magnetostratigraphy and oxygen isotope stratigraphy planktonic record (*Globigerina bulloides*, Venuti et al. 2007) and expressed in percentage. For the MIS 12 attribution see Discussion paragraph.

- *Globigerinoides tenellus* LO (0.24mbsf),
- *Globorotalia truncatulinoides* LCO (16.70mbsf),
- *Globorotalia crassaformis* HCO (18.32mbsf),
- *Neogloboquadrina incompta* LCO (25.21mbsf),
- *Neogloboquadrina dutertrei* HCO (25.82mbsf),

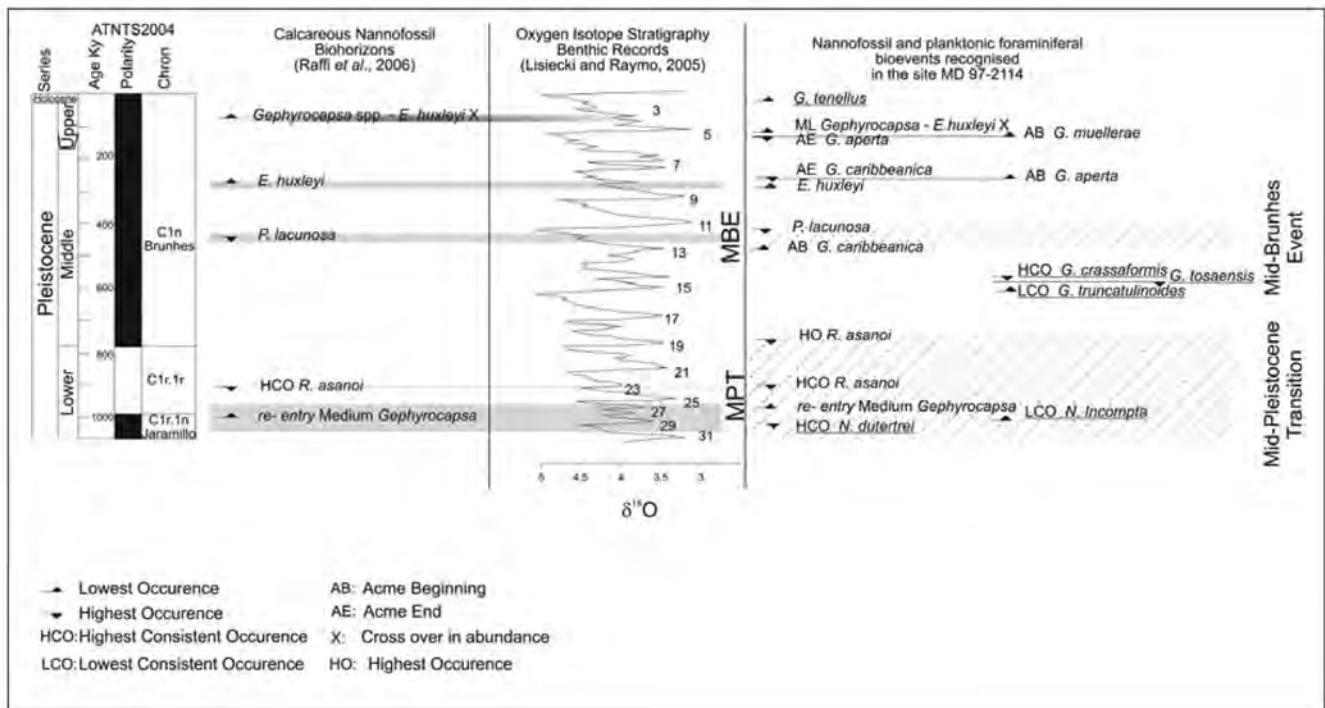
The first entry of the warm index *Globigerinoides tenellus*, evolutionary appeared in the Late Pliocene evolving from *Globigerina rubescens* according to Kennett and Srinivasan (1983), correlates at the core MD97-2114 with the MIS 1/MIS 2 transition.

The quantitative distribution of *Globorotalia crassaformis* shows a progressive increase from the base of the core up to a prominent peak (about 30%) that correlates with MIS 20 at the top of the C1r.1r Subchron. Above this acme the relative abundance of the species returns to values slightly lower with respect to those recorded at the base. The HCO of *Globorotalia crassaformis* was placed where its mean relative abundance reaches values less than 8%. It is problematic to accurately compare this event with data from the near ODP Sites because of the possible different taxonomical concept of *G. crassula*/*G. crassaformis* (see paragraph 3.2.). In both 1125 and 1123 Sites the HCO of *G. crassula*/*G. crassaformis* is ca. 630-660 ka (MIS 16; Schaefer et al 2005; Crundwell et al. 2008). The HCO recorded in our site correlates an interval poorly defined of the $\delta^{18}\text{O}$ curve proposed by Venuti et al. (2007), spanning from MIS 19 to MIS 16.

The LCO of the species *Globorotalia truncatulinoides* consists of a marked increase of its mean relative abundance (from 0.8% to 9.5%) just below the disappearance of *G. tosaensis*, in correspondence with MIS 15/16, very close to MIS 15, using the MIS identification of Venuti et al. (2007) (text-fig. 3). In the lower part of the core, *G. truncatulinoides* is rare and unevenly

distributed; the horizon that marks the rise in relative abundance corresponds to the highest values recorded in the core (18.34%). An increase in relative abundance of this species has been observed at the nearby ODP Sites 1125 and 1123 in a comparable horizon with an estimated age at 597 kyr (Schaefer et al. 2005; Crundwell et al. 2008; Hayward, pers. com.). Moreover, the transition MIS 15/16, following the MIS identification of Venuti et al. (2007), is also characterized at our site by the onset of stronger fluctuation in abundance, climatically controlled, of *N. incompta*, a feature recorded in the ODP Site 1125 at the same level (Schaefer et al. 2005).

Two events were observed near the basal part of the core and correlate the minimum values of $\delta^{18}\text{O}$ within MIS 28: LCO of *N. incompta* at 25.21mbsf very close to the top of the Jaramillo Subchron and the HCO of *Neogloboquadrina dutertrei* (25.82mbsf). The former species is evenly present and displays cyclical fluctuations in abundance throughout the core. However, its mean relative abundance moves from 3.2% to 12.6% above the selected horizon where it shows prominent peaks in abundance (up to 32.2%, text-fig. 3). Increase in abundance of *N. incompta* has been detected by Scott and Hall (2004) in a comparable interval. However, data from the Site 1123 (Crundwell et al. 2008) show that this species increases again in relative abundance back in the 1–1.2 Ma interval. This time interval is not recorded in our core making uncertain the reliability of this event. On the other hand, we cannot completely exclude that at our site this event is actually a genuine LCO because of the possible variation in planktonic foraminiferal assemblages (both abundances and composition) within this peculiar area at the boundary of different water masses.



TEXT-FIGURE 4

Integrated calcareous nannofossil and planktonic foraminiferal (underlined) bioevents recorded in the core studied in the time interval 0 - 1.07 Ma compared with the standard events defined by Raffi et al. (2006). The $\delta^{18}\text{O}$ curve is from Lisiecki and Raymo (2005); magnetic reversal and stage boundary ages are from ATNTS2004 (Lourens et al. 2004). Grey boxes straddle age ranges of bioevents, striped boxes represent the Mid-Pleistocene Transition and the Mid-Brunhes Event intervals.

The species *Neoglobobulimina dutertrei* was continuously present in the entire core and decreases from a mean abundance of 20% to mean values below the 7% above the horizon selected as its HCO.

Other potential events consist of the first entry and last exit of *Sphaeroidinella dehiscens* at 24.5 and 9.6 mbsf respectively, even if this morphologically distinctive species is very rare and intermittently present within this interval.

Except for the HO of *G. tosaensis*, the LCO of *N. incompta* and the LCO of the species *Globorotalia truncatulinoides*, the other events are for the first time recognized in Pleistocene-Holocene at the Core MD97-2114. Further analyses are necessary to verify the reliability and width of correlation of the events here selected in other sub-tropical areas. Unlike calcareous nannofossils, Pleistocene-Holocene planktonic foraminifera appear to demonstrate high specialization/provincialism resulting in a low degree of correlation. Differently from calcareous nannofossils, correspondence of bioevents is particularly difficult to establish between southern latitude oceans and the Mediterranean area (Rio et al. 1990).

DISCUSSION

Integrated nannofossil and foraminiferal biochronology and chronostratigraphy

The data presented in the previous paragraphs represent a good opportunity to provide an integrated calcareous nannofossil planktonic foraminiferal biostratigraphy (text-fig. 4). Table 2 reports calcareous nannofossil and planktonic foraminiferal

bioevents documented in this work and their age and/or isotopic calibrations provided by previous authors.

Our biostratigraphic data are moreover correlated with the oxygen isotope curve of Venuti et al. (2007), confirming almost entirely their MIS identification. However, the position of one event in the core MD 97-2114, could imply a different calibration of the $\delta^{18}\text{O}$ signal for the interval MIS 11 – MIS 12. In particular, the HO of *P. lacunosa* has been worldwide documented in the MIS 12 whereas, according to the correlation of Venuti et al. (2007), in our core this event would be recorded in the MIS 11, younger than previous calibrations. Generally, the glacial stage 12 is marked by the widest shift of the $\delta^{18}\text{O}$ curve of the last 6 Ma (e.g. Becquey and Gersonde 2002; Wang et al. 2003) and most likely Venuti et al. (2007), lacking of detailed biostratigraphic data, identified as MIS 12 the maximum $\delta^{18}\text{O}$ value recorded at about 12.7 mbsf in the MD 97-2114. There is consequently the possibility that the glacial interval across 11.7–11.5 mbsf could be the MIS 12 because in the studied core *P. lacunosa* disappears in that interval (text-figures 2-4).

The HO of *G. tosaensis*, considered to be a standard planktonic foraminiferal event for the eastern equatorial Pacific, precedes the HO of the calcareous nannofossil *P. lacunosa*, as reported in Lourens et al. (2004) even if our estimated age is slightly younger and precisely at 584,6 kyr instead of 610 kyr. Nevertheless, the HO of *G. tosaensis* has been approximated to 590 kyr by Thompson and Sciarrillo (1978) and to 650 kyr by Berggren et al. (1995). Further data are necessary to clarify if these differences are related to a minor diachronism or to some imprecision in the calculation. The finding of this event at the Core

TABLE 2

Oxygen isotope calibrations of the microfossil bioevents recorded in the studied core compared with the literature data.

The numbers reported indicate: 1 Baumann and Freitag 2004; 2 Bickert et al. 1997; 3 Castradori 1993; 4 Curry et al. 1995; 5 de Kaenel et al. 1999; 6 de Kaenel 2000; 7 Flores et al. 1999; 8 Lourens et al. 2004; 9 Maiorano and Marino 2004; 10 Mix et al. 1995a, b; 11 Raffi 2002; 12 Raffi and Flores 1995; 13 Raffi et al. 1993; 14 Raffi et al. 2006; 15 Shackleton et al. 1990; 16 Shipboard Scientific Party ODP Leg 111, 1988; 17 Sprovieri et al. 1998; 18 Thierstein et al. 1977; 19 Thompson and Sciarrillo 1978; 20 Weaver and Thomson 1993; 21 Wells and Okada 1997.

Nannofossil & planktonic foraminiferal bioevents	Age and References	MIS and References	MIS (this work)
LO <i>Globigerinoides tenellus</i>			MIS 2/1
Medium-Large <i>Gephyrocapsa</i> - <i>Emiliana huxleyi</i> cross-over	128 ky (21)	MIS 5 (7)	MIS 5
AB <i>Gephyrocapsa muelleriae</i>	161 ky (5)	MIS 6 (1; 20)	MIS 5/6
AE <i>Gephyrocapsa aperta</i>	161 ky (5)	MIS 6 (20)	MIS 5/6
AB <i>Gephyrocapsa aperta</i>	262 ky (5)	MIS 8 (20)	MIS 8
AE <i>Gephyrocapsa caribbeanica</i>	262 ky (5)	MIS 8 (1; 20)	MIS 8
LO <i>Emiliana huxleyi</i>	291 ky (15; 16; 18); 289 ky (2; 4); 265 ky (3; 8)	MIS 8 (6; 7; 14; 2)	MIS 8
HO <i>Pseudoemiliana lacunosa</i>	436 ky (10; 12; 13; 15; 16; 18); 440 ky (2; 4); 467 ky (3; 8; 11; 17); 406 ky (6)	MIS 12 (14; 20)	MIS 12
AB <i>Gephyrocapsa caribbeanica</i>	527 ky (5)	MIS 14/15 (1)	MIS 13
HCO <i>Globorotalia crassaformis</i>			MIS 15
LO <i>Globorotalia tosaensis</i>	650 ky (8); 590 kyr (19)		MIS 15
LCO <i>Globorotalia truncatulinoides</i>			MIS 15/16
HO <i>Reticulofenestra asanoi</i>	781 ky (5)		MIS 19
HCO <i>Reticulofenestra asanoi</i>	905 ky (2; 4; 11); 901 ky (8; 9; 11)	MIS 23 (14)	MIS 23
re-entry Medium-sized <i>Gephyrocapsa</i> spp.	1040 ky (10; 12; 13; 15; 16); 1007 ky (2; 4; 11); 956-985 ky (3; 8; 9; 11)	MIS 30 - MIS 26 (14)	MIS 27/26
LCO <i>Neogloboquadrina incompta</i>			MIS 28
HCO <i>Neogloboquadrina dutertrei</i>			MIS 28

MD97-2114 represents a significant result since indicates that the standard eastern equatorial Pacific scheme reported in Lourens et al. (2004) could be applicable at the relatively south-western latitude of the Chatham Rise.

Examining the bioevents of the two groups of calcareous plankton here investigated as displayed in figure 4, clearly emerges that they are closely spaced in two intervals, positioned at the middle-lower part of the Brunhes Chron and at the top of the Jaramillo Subchron.

It must be noted that the younger interval recording closely-spaced events of calcareous plankton (text-fig. 4, from MIS 15 to MIS 12) correlates with the mid-Brunhes event which records the largest amplitude change in $\delta^{18}\text{O}$ since 6 Ma ago, probably related to a major ice-sheet expansion (e.g. Becquey and Gersonde 2002; Wang et al. 2003). Furthermore, the older interval recording several calcareous planktonic events and spanning the MIS 29 to MIS 25, falls within the so-called Middle Pleistocene Transition (MPT), an interval characterised by a variation from lower amplitude 41-kyr to dominant high-amplitude 100-kyr climate cycles (e.g. Clark et al. 2006).

This evidence opens new perspectives on the relationship between biological evolution and climate changes and stimulate further investigation.

In addition, results derived from our integrated analyses, provide significant implications concerning the chronostratigraphy of the interval, not yet definitely established. The Pleistocene/Holocene boundary is difficult to place at the latitude of the Core MD97-2114. It is possible that the first entry of the warm index *Globigerinoides tenellus* at the MIS 2/MIS 1 boundary might correspond to the Pleistocene/Holocene limit, even though the evolutionary appearance of this species occurs back in the Late Pliocene (Kennett and Srinivasan 1983).

The middle-upper Pleistocene boundary is generally placed at the base of the MIS5 (substage e), precisely at the midpoint of Termination II or the MIS 6-5 transition. This convention follows the general agreement that the basal boundary of the upper Pleistocene corresponds with that of the last interglacial stage, as proposed by the International Quaternary Association (INQUA) Commission on Stratigraphy (Berlin 1995, unpublished; Lourens et al. 2004). This proposal, however, implies the acceptance that MIS5e in the ocean equals the terrestrial northwest European Eemian Stage (Shackleton 1977). We document across the MIS 6/MIS 5 a flurry of calcareous nannofossil events that appear widely correlatable (text-fig. 4).

The micropaleontological data thus would allow an easy identification of the middle-upper Pleistocene boundary through bioevents, even in the absence of isotope data. These events consist of: a) the AE of *Gephyrocapsa aperta*, b) the AB of *G. muelleri*, documented for the Mediterranean area as well, according to de Kaenel (2000) and for the Atlantic Ocean by Weaver and Thomson (1993) and for the Southeast Atlantic by Baumann and Freitag (2004); c) the ML *Gephyrocapsa* – *Emiliania huxleyi* cross-over recorded in the Southern Atlantic Ocean in agreement with Flores et al. (1999).

The lower-middle Pleistocene boundary is generally placed at the Matuyama/Brunhes boundary, according to Richmond (1996). Calcareous plankton events, however, are absent within this interval. Conversely, Cita and Castradori (1995) proposed to locate the boundary in coincidence with the base of the calcareous nannofossil *P. lacunosa* Zone that corresponds to the re-entry of the medium size *Gephyrocapsa* which occurs at the top of the Jaramillo Subchron. In addition, this event is slightly preceded at our site by the LCO of *N. incompta* and HCO of *N. dutertrei*. This lower position of the lower-middle Pleistocene boundary would be advantageous therefore for the co-occurrence of time-diagnostic bioevents beside the magnetostratigraphy.

SUMMARY AND CONCLUSIONS

Sediments from the IMAGES Core MD97-2114 (42°22.32'S; 171°20.42'W) located on the north-eastern slope of the Chatam Rise (East New Zealand Pacific Ocean) were analysed for both calcareous nannofossil and planktonic foraminiferal content. The calcareous microfossil assemblages are extremely abundant and diversified throughout the core. Quantitative data of calcareous nannofossils and planktonic foraminifera (this work), magnetostratigraphy and oxygen isotope stratigraphy (Venuti et al. 2007), indicate that the succession studied exhibits a continuous sedimentary record of the past 1.07 Ma (from MIS 1 to MIS 29). The biostratigraphic analyses allowed us to provide an integrated scheme for the mid-late Pleistocene interval comprising 17 events with a biostratigraphic resolution of ca. 63kyr.

Our data demonstrate that numerous events among calcareous plankton are clustered in two particular intervals during the last 1.07 Ma. The younger one (from MIS 15 to MIS 12) correlates with the mid-Brunhes event, interpreted as related to a major ice-sheet expansion (e.g. Becquey and Gersonde 2002; Wang et al. 2003); the older interval (from MIS 29 to MIS 25) falls within the Middle Pleistocene Transition (MPT), characterised by a variation from lower amplitude 41-kyr to dominant high-amplitude 100-kyr climate cycles (e.g. Clark et al. 2006). These results draw attention to how inadequate our knowledge still is about evolutionary mechanisms and their relationships with climate and major global changes.

From a chronostratigraphic point of view, our results provide significant matter for debate, about the middle/upper Pleistocene and the lower-middle Pleistocene boundaries, not yet definitely stabilized. In particular, according to our data, a possible location of the lower-middle Pleistocene boundary at the top of the Jaramillo Subchron (Cita and Castradori 1995) would correlate with a number of both calcareous nannofossil and planktonic foraminiferal bioevents, instead of the current Matuyama/Brunhes boundary (Richmond 1996) that falls within an interval lacking of calcareous plankton events. Furthermore, close to the middle/upper Pleistocene boundary, con-

ventionally placed in the MIS 5e (Lourens et al. 2004), we document the *Gephyrocapsa aperta* AE and the *Gephyrocapsa muelleri* AB (MIS 5/MIS 6 transition). These bioevents, reported in the same position for the Mediterranean area (Kaenel 2000) and for the Atlantic Ocean (Weaver and Thomson 1993; Baumann and Freitag 2004), would supply easy recognition of the middle-upper Pleistocene boundary even in absence of isotope data.

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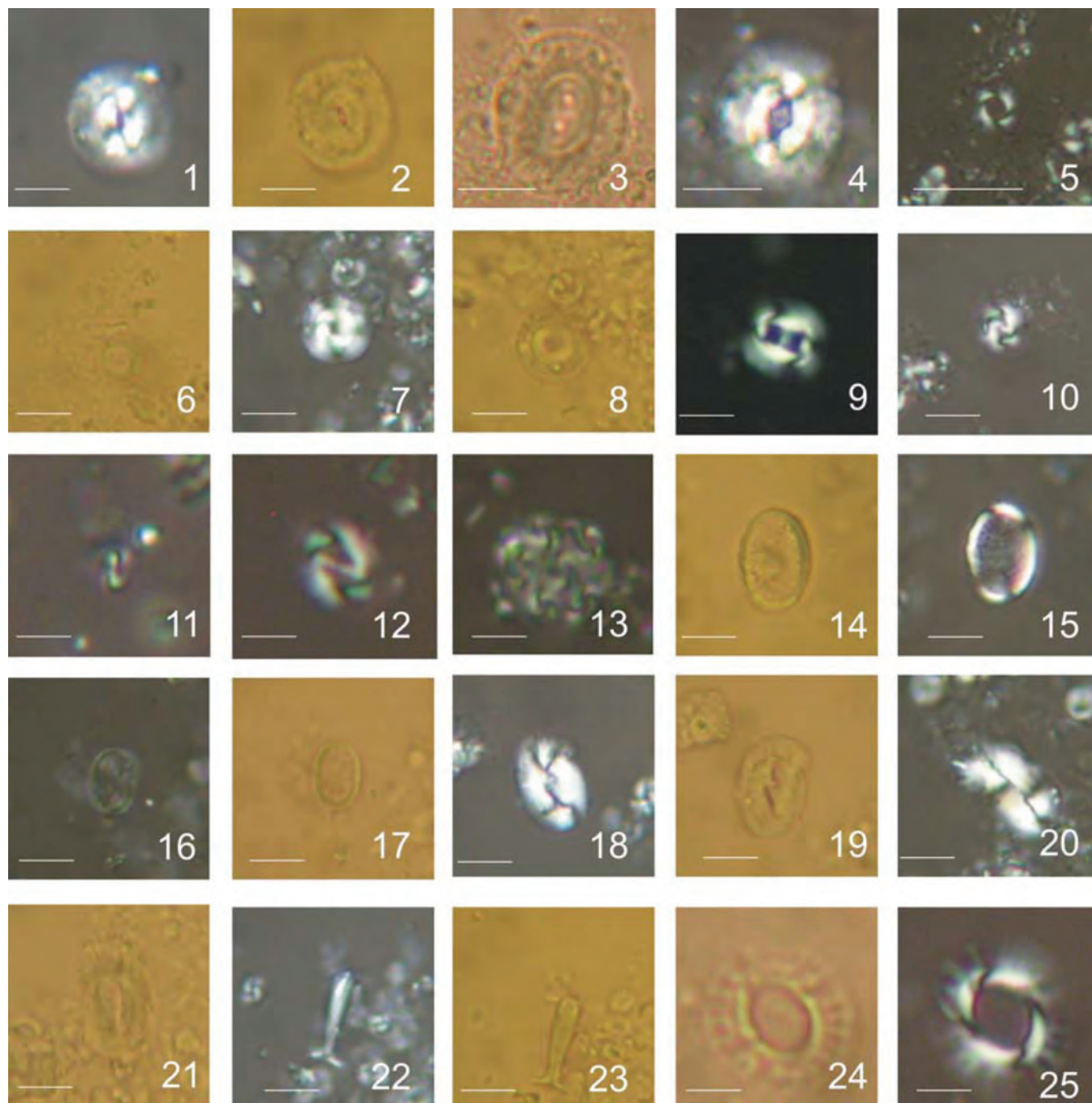
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PLATE 1

The most abundant calcareous nannofossil species from the MD97-2114 Core, Chatham Rise. Scale bar = 5µm.
Polarized and differential-interference contrast light view.

- | | |
|---|---|
| 1-2 <i>Coccolithus pelagicus</i> (sample MD97-2114, 21, 72-21,74mbsf); | 13 <i>Coccosphere</i> sp. (sample MD97-2114, 28, 47-28, 49mbsf); |
| 3-4 <i>Coccolithus pelagicus</i> var. <i>braarudii</i> (sample MD97-2114, 21,72-21,74mbsf); | 14-15 <i>Pontosphaera discopora</i> (sample MD97-2114, 28,47-28,49mbsf); |
| 5-6 <i>Pseudoemiliania lacunosa</i> (small specimen) (sample MD97-2114, 21,72-21,74mbsf); | 16-17 <i>Syracosphaera pulchra</i> (sample MD97-2114, 28,47-28,49mbsf); |
| 7-8 <i>Reticulofenestra asanoi</i> (sample MD97-2114, 21, 72-21,74mbsf); | 18-19 <i>Helicosphaera carteri</i> var. <i>wallichii</i> (sample MD97-2114, 28,47-28,49mbsf); |
| 9 <i>Gephyrocapsa omega</i> (sample MD97-2114, 18, 24-18,22mbsf); | 20-21 <i>Helicosphaera paleocarteri</i> (sample MD97-2114, 28, 47-28,49mbsf); |
| 10 <i>Gephyrocapsa caribbeanica</i> (small specimen) (sample MD97-2114, 18,24-18,22mbsf); | 22-23 <i>Rhabdosphaera clavigeri</i> (sample MD97-2114, 18, 24-18,22mbsf); |
| 11 <i>Gephyrocapsa ericsonii</i> (sample MD97-2114, 18, 24-18,22 mbsf); | 24-25 <i>Pseudoemiliania lacunosa</i> specimens larger than 5µm) (sample MD97-2114, 21,72-21,74mbsf). |
| 12 <i>Gephyrocapsa oceanica</i> ; | |



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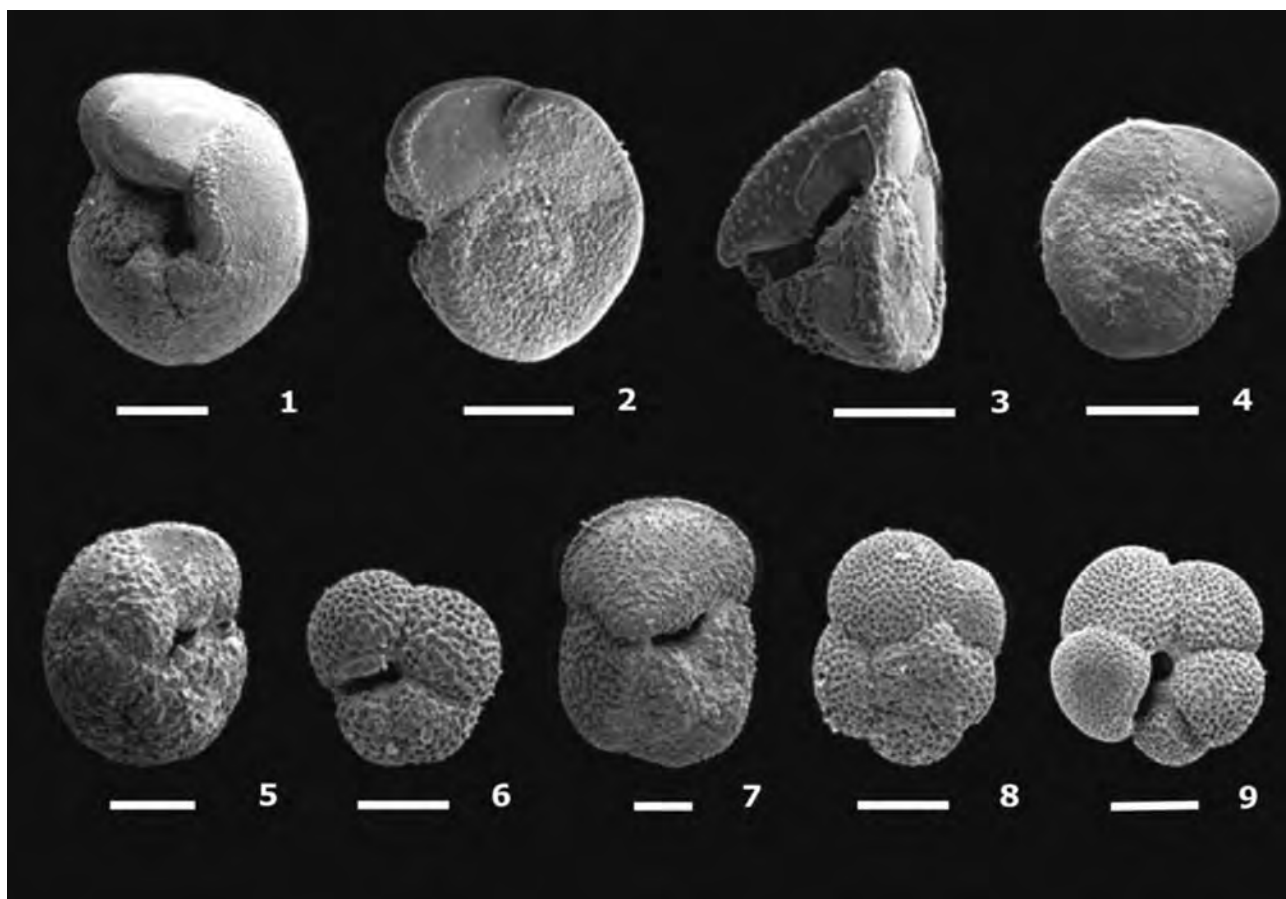


PLATE 2

SEM photographs of selected planktonic foraminifera from the MD97-2114 Core, Chatham Rise. Scale bar for 1-4 = 200µm, for 5-9 = 100µm.

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| <p>1-3 <i>Globorotalia truncatulinoides</i> (d'Orbigny), 1: ventral view, 2: spiral view, 3: profile (sample MD97-2114, 12.24-26mbsf).</p> <p>4 <i>Globorotalia tosaensis</i> (Takayanagi and Saito) - <i>Globorotalia truncatulinoides</i> (d'Orbigny), transitional form, spiral view, (sample MD97-2114, 16.06-08mbsf).</p> <p>5 <i>Globorotalia tosaensis</i> Takayanagi and Saito, ventral view (sample MD97-2114, 21.24-26mbsf).</p> | <p>6 <i>Neogloboquadrina incompta</i> ventral view (sample MD97-2114, 6.48-50mbsf).</p> <p>7 <i>Globorotalia crassaformis</i> (Galloway and Wissler), ventral view (sample MD97-2114, 23.44-46mbsf).</p> <p>8-9 <i>Neogloboquadrina dutertrei</i> (D'Orbigny), 8: dorsal view, 9: ventral view (sample MD97-2114, 13.02-04mbsf).</p> |
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Manuscript accepted
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- APPENDIX A
Calcareous nannofossils considered in this report (in alphabetical order of generic epithets).
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- Calcidiscus leptoporus* (Murray and Blackman 1898) Loeblich and Tappan 1978 *Coccolithus pelagicus* (Wallich 1877) Schiller 1930 (Plate 1, images 1-2)
Coccolithus pelagicus var. *braarudii* (Gaarder 1962) Geisen 2002 (Plate 1, images 3-4)
Emiliania huxleyi (Lohmann 1902) Hay and Mohler, in Hay et al. 1967
Gephyrocapsa aperta Kamptner 1963
Gephyrocapsa caribbeanica Boudreaux and Hay 1967 (Plate 1, image 10)
Gephyrocapsa ericsonii McIntyre and Bé 1967 (Plate 1, image 11)
Gephyrocapsa muelleriae Bréhéret 1978
Gephyrocapsa oceanica Bréhéret 1978 (Plate 1, image 12)
Gephyrocapsa omega Bukry 1973 (Plate 1, image 9)
Helicosphaera carteri (Wallich 1877) Kamptner 1954
Helicosphaera carteri var. *wallichii* (Lohmann 1902) Theodoridis 1984 (Plate 1, images 18-19)
Helicosphaera paleocarteri Theodoridis 1984 (Plate 1, images 20-21)
Pontosphaera Lohmann 1902
Pontosphaera discopora Schiller 1925 (Plate 1, images 14-15)
Pontosphaera japonica (Takayama 1967) Nishida 1971
Pseudoemiliania lacunosa (Kamptner 1963) Gartner 1969 (Plate 1, images 5-6; 24-25)
Rhabdosphaera clavigeri Murray and Blackmann 1898 (Plate 1, images 21-22)
Reticulofenestra asanoi Sato & Takayama 1992 (text-fig. 2; images 9-10)
Syracosphaera pulchra Lohmann 1902 (text-fig. 2, images 19-20)
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- APPENDIX B
Planktonic foraminifera cited in this report (in alphabetical order of generic epithets).
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- Globigerina bulloides* D'Orbigny 1826
Globigerina rubescens Hofker 1956
Globigerinita uvula (Erhrensberg) 1861
Globigerinoides fistulosus (Schubert) 1910
Globigerinoides tenellus (Parker) 1856
Globorotalia crassaformis (Galloway and Wissler) 1927 (text-fig. 4, image 7)
Globorotalia truncatulinoides (D'Orbigny) 1839 (text-fig. 4, images 1-3)
Globorotalia tosaensis Takayanagi and Saito 1962 (text-fig. 4, image 5)
Neoglobobadrina dutertrei (D'Orbigny) 1839 (text-fig. 4, images 8-9)
Neoglobobadrina incompta (Cifelli 1961), (text-fig. 4, image 6)
Sphaeroidinella dehiscens (Parker and Jones) 1865
Tenuitella iota (Parker) 1962
Tenuitella parkerae (Broennimann and Resig 1972)