Biostratigraphy and Paleoceanographic Evolution of Calcareous Nannofossils Assemblages through the Neogene at the equatorial region of the Eastern Pacific and Western Atlantic (Caribbean)

Abstract

Earth's climate owes its configuration, to the interaction between tectonics, defining surface morphology and orbital parameters, controlling solar insolation. The Pliocene is the most recent period in the Earth's history when the climatic conditions, particularly the CO_2 levels, were similar to today's concentrations, sea surface temperatures were ~3°-4°C higher and a warmer climate characterized the planet.

Global climatic changes are a natural cyclic phenomenon that occurs as a response to orbital forcing and geological processes over longer and shorter time intervals. Several major geological events have occurred throughout the Neogene time. The continuous uplift of the Himalayas and the closure of the Indonesian and the Central American Seaway (CAS), are outstanding examples of processes that changed the Earth's morphology, wind and oceans circulation patterns, and consequently, the global climate. The uplift of the Central American land barrier correspond to a tectonic stepwise process that occurred about 16.1 to 1.8 Ma (Duque-Caro, 1990; Keigwin, 1982; Keller et al*.,* 1989; Coates et al*.,* 1992; Haug et al., 2001), reaching a critical threshold at about 4.7-4.2 Ma, when the sill shoaled at a depth of <100 m (Haug & Tiedemann, 1998; Haug *et al.*, 2001), and its final phase lasting from 4.7 to 1.9 Ma (e.g. Keigwin, 1978, 1982a; Lundelius, 1987; Keller, 1989; Coates *et al.*, 1992; Webb, 1997; Haug & Tiedemann, 1998; Haug *et al.*, 2001).

The emergence of the Isthmus is explained mainly by tectonic activity, which has led to the displacement of the South American plate moving eastwards colliding with the Central American volcanic arc (Caribbean plate), the Cocos and Nazca plates (Coates *et al.*, 1992; Pindell & Kennan, 2001) establishing a land barrier. The final closure has been dated at ~2.7 Ma, based on foraminiferal assemblages (e.g. Keigwin, 1982a; Kameo & Sato, 2000), oxygen and carbon isotope records of planktic foraminifers (Haug *et al.*, 2001) and a higher interchange of North and South America land

mammals (Webb, 1985; Lundelius, 1987). Additionally, the southward shift of the Intertropical Convergence Zone (ITCZ)in the Pacific and Atlantic oceans until its modern configuration occurred between 4.4 to 4.3 Ma, with the consequent change of the wind circulation patterns and increasing advection of warmer and brackish surface waters into the subtropical and North Atlantic, contributing to the thermohaline overturn circulation (Billups *et al.*, 1999).

Previous to this event, the Caribbean Sea received influxes from the Atlantic waters, but mainly from the Pacific Ocean (Keigwin, 1982; Maier-Reimer et al., 1990; Haug et al., 2001). The closure of the CAS determined the arrangement of the semi-enclosed Caribbean basin, and the modifications of the physical and geochemical properties causing an increase of the salinity gradient between Caribbean and Pacific waters. The Caribbean Sea became saltier as a result of higher evaporation, transported by the trade winds to the eastern Pacific Ocean in the form of water vapor and rainfall, causing a decrease of the salinity at the Pacific (Keigwin, 1982; Haug & Tiedemann, 1998; Haug *et al.*, 2001; Haug *et al.*, 2004). This salinity gradient is the motor of the modern ocean conveyor belt strengthening of the production of North Atlantic Deep Water (NADW) (Berger *et al.*, 1993; Raymo *et al.*, 1996; Haug & Tiedemann, 1998; Ravelo & Andreasen, 2000). Different studies concluded that this was the main cause of the strengthening the North Atlantic Deep Water production and therefore of meridional overturning circulation [e.g., Berger et al., 1993; Berggren and Hollister, 1974; Haug and Tiedemann, 1998; Steph, 2005; Schneider & Schmittner, 2006;) leading to increased moisture to the Arctic (Haug *et al.*, 2004) provoking the intensification of the Northern Hemisphere glaciations (NHG) at about 2.75 M. This induced the reconfiguration of the circulation patterns of the oceanic deep and shallow currents and the modern conveyor belt and, therefore, of the modern climate (Berger et al., 1993; Raymo et al., 1996; Haug & Tiedemann, 1998; Ravelo & Andreasen, 2000; Haug et al., 2004). The intensification of the NHG and the interchange of vertebrate faunas between North and South America have occurred about 2.75 Ma (Lundelius, 1987; Webb, 1997; Haug & Tiedemann, 1998; Bartoli et al*.,* 2005), what is the assumed age for the final closure of the Central American Seaway (CAS).

Studies based on micropaleontological and isotopic data have been carried out through the equatorial region to investigate the past conditions and climate variability in the ocean as a consequence of the establishment of the Central American land-bridge. Once Central America shoaled, planktonic foraminifera from the Caribbean and Pacific displayed isotopic differences related to an increase in the salinity of the Caribbean Sea (Keigwin, 1982) and to an intensification of the thermohaline circulation in the North Atlantic (e.g. Bickert et al., 1997; Haug & Tiedemann, 1998; Haug et al., 2001).

Eastern Equatorial Pacific Ocean (EEP) and Caribbean sediments store information about the response of the oceans to the emersion of Central America. We have selected material from two core Sites located at both regions to evaluate how they were affected by the disconnection of the two oceans. The geomorphology and location of the Caribbean basin is responsible for the distribution of the water layers and the ecosystems of this basin. Its modern shape results of tectonic evolutionary processes that have been active since the Jurassic. The modern semi-enclosed character of the Caribbean basin is a consequence of the emersion of Central America.

In many studies, oceanographic research is based on microfossils. Coccolithophores are useful as proxies for productivity, light availability, temperatures, and salinities, among others (Winter & Siesser, 1994; Roth, 1994; Thierstein & Young, 2004; Flores & Sierro, 2007). Such studies are based on the behavior of living specimens and the correlation with its ancestors, together with the geographic setting where the fossils have been founded. Horizontal and vertical distributions of assemblages in the ocean are controlled by water properties and some others like latitude, currents, interaction wind-water, etc (Okada & Honjo, 1973; McIntyre & Bé, 1967). Here, we are using calcareous nannofossils to record the climatic changes in the Upper Photic Zone (UPZ), and the ecological preferences defined for species, such as nutrient availability, temperature, salinity, transparence/turbidity and position at different depths of the water column. High resolution sampling allows the identification of El Niño Southern Oscillation (ENSO). Even more, assemblages are used as biostratigraphic markers.

Objectives

Several paleoceanographic previous studies of the EEP do not include the same interval, drill sites or microfossil groups. This study contributes to better knowledge of the processes and changes that affected oceanic configurations during the studied interval (~4.0–~1.9 Ma) and supply additional information that contributes to multidisciplinary research.

The main aims of this study are:

- ✓ Reconstruct the paleoproductivity at the EEP and the Caribbean for the interval comprised between ~4.0 and ~1.9 Ma (early Pliocene to early Pleistocene), based on the calcareous nannofossil quantitative assemblages
- ✓ Evaluate the occurrence of long-lasting ENSO events ("permanent El Niño-like events") based on the fluctuations of the thermo/nutricline at the EEP and to verify if these events are caused through teleconnection mechanisms between WHAT AND WHAT?.
- ✓ Analyze the effects of the closure of the Central American Isthmus on the calcareous nannofossils assemblages linking variability in paleotemperatures, paleosalinities and paleoproductivities.
- ✓ Determine the response of the assemblages to orbital parameters and its correlation to the equatorial (precession, eccentricity) or high latitudes (obliquity) ocean dynamics.
- ✓ Present a high resolution biostratigraphic frame for both sequences.

Materials and Oceanographic Setting

Selected sediments were obtained during two drillings by the shipboard teams and expedition scientists of the former Ocean Drilling Program (ODP) (after *Integrated Ocean Drilling Program*–IODP, and currently *International Ocean Discovery Program*–IODP), one at the EEP (ODP Site 846) and the other in the Caribbean (ODP Site 999).

The intertropical region is highly influenced by the trade winds that push the air and surface water currents from east to west, under the influence of the Coriolis forces converging in the Equator. The winds and water masses control the heat distribution and determine worldwide climate. Atmospheric and oceanic phenomena, as El Niño Southern Oscillation (ENSO) occurs at tropical Pacific Ocean as a result of the weakening/strengthening of the westward transport of air and water currents. The ENSO comprises a warm phase known as El Niño, characterized by a drop in eastward air pressure (weakening of the trade winds), which provokes a decrease in the westward pressure gradient and displaces warmer water and air masses through the central and eastern Pacific Ocean (Bonham *et al.*, 2008). This results in the deepening of the thermo/nutricline in the eastern equatorial Pacific, blocking the Peruvian upwelling. The opposite cold phase, known as La Niña, is characterized by the strengthening of the trade winds and the consequent increase of the westward pressure gradient that causes the movement of the warm water and air masses to the west, allowing the shoaling of the thermo/nutricline and the Peruvian upwelling.

The area where the southern and northern winds meet is known as the Intertropical Convergence Zone (ITCZ). Its position changes depending on stronger winds come from the north or the south (Figure 1).

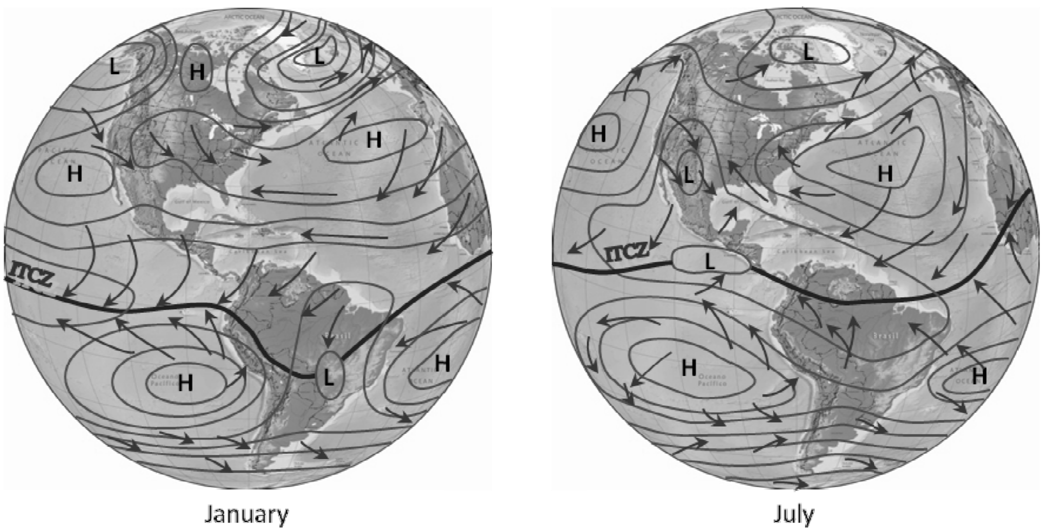

Figura 1. Sketch of the trade winds and modern position of the Intertropical Convergence Zone (ITCZ) during January and July, and high (H) and low (L) pressure cells. Modified from Lutgens & Tarbuck (2001)

The movement of the ITCZ is strongly seasonal, being in a northern position (up to ~10ºN) during August to December when the southeast trades are stronger and the northeast trades are weaker, and moves to a southward position during February to

April. The trade winds or easterlies push the surface waters of the ocean westward favoring the displacement of the shallow warmer waters toward the western equatorial Pacific (WEP), allowing the shallowing of the thermocline at EEP and the upwelling of cold and rich-nutrient waters which spread via the PC.

ODP Site 846

During ODP Leg 138, eleven holes were drilled to explore the paleoceanographic evolution of the EEP through Neogene to present time. Due to the proximity to Central America, and the influence of several equatorial surface water currents, we select the ODP Site 846 as the target of this work. This drilling is located at 3°5.802'S, 90°49.074'W, on the Nazca Plate, southward of the western part of Carnegie Ridge approximately 300 km south of the Galapagos Islands, at a water depth of 3295.8 meters below sea level (Figure 2). Currently, this Site is tectonically active due to the collision between Nazca and Cocos plates' subducting the Caribbean and South American plates. Additionally, volcanic activity occurred associated to the Galapagos hot spot.

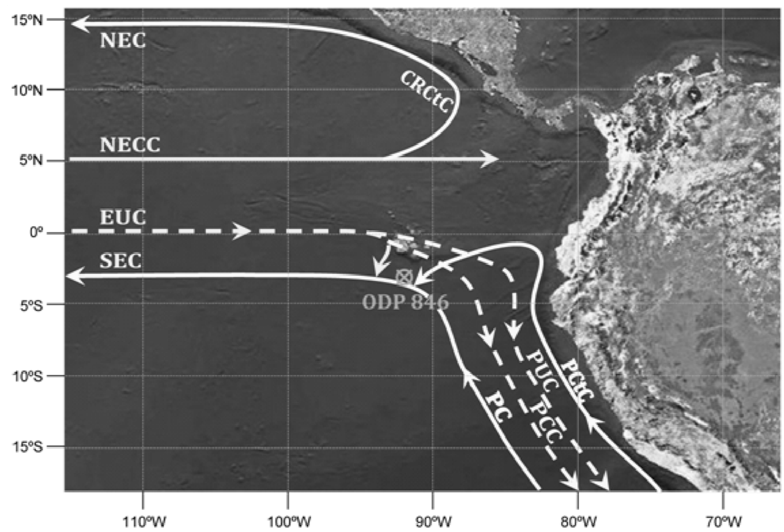

Figura 2. Location map of the ODP Site 846 (EEP) and main surface currents.

We selected the sediments from cores 7H until 14H (~55 to ~132 meters below sea floor). The shipboard team (Mayer *et al.*, 1992) studied the material and reported that the sediment from cores 6H to 9H (52.5-80.0 mbsf) contain bands dominantly with diatom oozes, some interstratified layers with nannofossil ooze (10%-40%) and high amount of clays. Cores 9H to 22X (80.0-200.0 mbsf) were described as "highly variable" between nannofossil ooze to diatom ooze, but dominantly nannofossil ooze (50%-80%) with foraminifers and diatoms. The nonbiogenic fraction is dominated by smectite, plagioclase, quartz and barite.

The main surface currents at the Eastern Equatorial Pacific Ocean are the North Equatorial Current (NEC), the Equatorial Countercurrent (ECC), the Equatorial Undercurrent (EUC), the South Equatorial Current (SEC); the California Current (CAC); the Peru Current (PC) also known as Humboldt Current; and the Chile Current (CHC). Site 846 is located South of the equator and is directly influenced by the PC, a cold, nutrient-rich northwestwards flow; the EUC flowing eastwards is nutrient-rich and salty, colder than the shallower layer and warmer than the layer below thermocline; the SEC is the resulting flow of a mixture of the PC shallow waters and upwelling EUC, characterized by a cold westward flow (Figure 2). Strength variability of the SEC reflects changes in the strength of the southern trade winds (Pisias *et al.*, 1995). Deep water masses that influence Site ODP 846 directly are the Antarctic Bottom Water (AABW), the Antarctic Intermediate Water (AAIW) and the Subantarctic Mode Water (SAMW).

ODP Site 999

The ODP Site 999 was drilled in the Colombian Caribbean basin during Leg 165, on a submarine promontory called informally Kogi Rise by the shipboard team of the Ocean Drilling Program–ODP. Its location is 12°44.639'N – 78°44.360'W (Figure 3) and rises 1000 m above the basin floor of the Colombian Caribbean basin, at a water depth of 2827.9 meters below sea level (Sigurdsson et al*.,* 1997). The targeted interval for this study is comprised between ~4.0 Ma and ~1.95 Ma.

In this study, 362 samples are analyzed from the cores 7H to 14H (~65 to ~126 meters below sea floor) with ages ranging between ~1.95 to 4.0 Ma. This sediment was described as nannofossil mixed sediment with foraminifers, nannofossil clayey mixed sediment, clayey nannofossil chalk with foraminifers, and volcanic ash layers (Sigurdsson et al*.,* 1997).

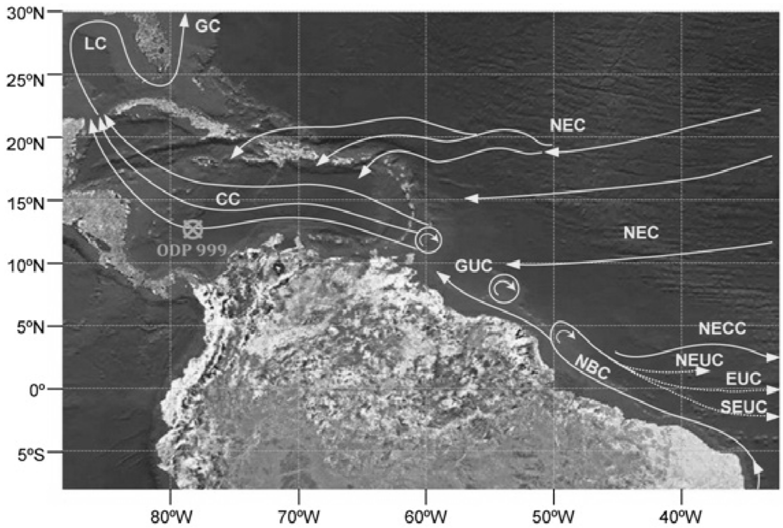

Figura 3. Location map of the ODP Site 999 (Caribbean) and main surface currents.

The Caribbean is fed from Atlantic waters through the North and South Equatorial currents. The Atlantic South Equatorial Current (SEC) and North Equatorial Current (NEC) enter the Caribbean through the sills between the islands of the Antillean Arc. The SEC is the northwestward flow that runs along the northern coast of South America, and corresponds to an extension of the cold Benguela Current. The SEC is named in different ways throughout its course due to seasonal changes in flow of the closest water currents (Flagg et al*.,* 1986). At the northeastern Brazilian coast it is defined as the North Brazil Current (NBC), which shows several retroflections in its path (Figure 3), dividing the flow in two main streams that feeds the North Equatorial Countercurrent (NECC) and the Guiana Current (GC). The GC is the portion of the SEC closest to the outer eastern boundary of the Caribbean basin that is fed by the NBC and the NEC waters, and enters to the Caribbean Sea across the Windward Islands Passages (Grenada, St. Vincent and St. Lucia) (Wüst, 1964; Gordon, 1967; Johns et al*.,* 2002) becoming the main surface flow in this basin: the Caribbean Current (CC) (Wüst, 1964; Gordon, 1967; Roemmich, 1981; Hernández-Guerra & Joyce 2000). A minor part of the CC is the result of the southwestward inflow of the NEC that enters to the basin through the Greater Antilles Passages (Windward and Mona) and the Leeward Islands passages (Dominica, Guadeloupe, Antigua and Anegada-Jungfern). Several studies involve surface drifters and complex nature of the Caribbean Current (e.g., Molinari et al., 1981; Carton & Chao, 1999; Pratt & Maul, 2000; Centurioni & Niiler, 2003; Richardson, 2005; Alvera-Azcárate et al., 2009).

The Caribbean upper water column has been subdivided in different layers characterized by different salinities (densities) and isotopic compositions. The surface layer with about 80 m; the high-salinity Subtropical Underwater (SUW) comprised between 80 and 180 m; the mixing layer of the SUW and the Antarctic Intermediate Water (AAIW) that reaches 550 m depth, considered as the thermocline; the AAIW that reaches depths between 550 and ~880m; the Atlantic Intermediate Water (AIW) is comprised between ~880 and ~1920 m depth, and corresponds to the mixture of the AAIW and the Upper North Atlantic Deep Water (UNADW); and below ~1920 m the UNADW (Kameo et al., 2004). The continuously depleted waters of the Caribbean Sea could be explained by the SUW permanent thermocline (Kameo et al., 2004) that impedes the shoaling of the nutricline. Cooler temperatures of the waters at ~100 km of the Caribbean shore, indicate upwelling along the coast (Muller-Karger & Aparicio, 1994).

Methods

The slides studied in this work (ODP 846: 374 samples; ODP 999: 362 samples) were prepared by using the settling technique proposed by Flores & Sierro (1997). This is an efficient method that allows preparing large amounts of slides in an efficient way and estimating absolute abundances of calcareous nannofossils due to a uniform distribution of the sediment on the slides. Each slide was analyzed under a polarized microscope at X1000 magnification, and two countings were performed. At least 400 calcareous nannofossils were counted during the first counting and more than 300 specimens during the second one. Thus, over 700 specimens were counted per slide. Finally, for biostratigraphic and paleoceanographic purposes, we analyzed the sketches of percentages and index of nannofossils per gram of dry sediment (Flores & Sierro, 1997).

Age models were achieved for both drillings based on the astronomically tuned time scales obtained by Shackleton et al. (1995a, b) for the ODP Site 846 and for the ODP Site 999 by Steph et al., 2010, using benthic $\delta^{18}O$, magnetostratigraphy and density records (GRA). The astrobiochronological calibration of Raffi et al. (2006) is used as a reference for the biochronologic study, and for determining the synchronism/diachronism of the calcareous nannofossils events in this work. Nine events were registered in the sequences, corresponding to the standard events in the calcareous nannofossils biozonations (Martini, 1971: NN; Okada & Bukry, 1980: CN emended by Raffi & Flores, 1995). For the definition of the events we have used the nomenclature of Raffi et al. (2006), where LO= *Lowest Occurrence* and HO= *Highest Occurrence*.

In order to evaluate the influence of the orbital forcing on calcareous nannofossils assemblages in this geographic setting, we performed spectral analyses in the frequency domain by using the software *Analyseries 2.0* (Paillard *et al.*, 1996) with the astronomical solution LA2004 (Laskar et al., 2004) using the Blackman-Tukey method (Blackman & Tukey, 1958), what calculates the covariance of the dataset and applied a standard Fourier analysis. Spectral analyses are useful to find harmonic signal components in a time series, or phase relations between harmonic signal components in two different time series (cross-spectral analysis) (Schulz & Stattegger, 1997).

Calcareous Nannofossils Ecological Remarks

In the geographic setting, the influence and the strengthening of the trade winds and the consequent position of the ITCZ, the westward and eastward oceanic currents influence the vertical and horizontal distribution of the coccolithophores assemblages. The strategies adopted by the coccolithophores, related to the water properties as nutrient/productivity variables (*k* or *r*-selection), the adaptation to colder or warmer waters, the preference for upper or lower photic zone, the ability to resist higher or lower salinities, among others, configure diverse scenarios for the evolutionary success or extinction or disappearance of species.

It has taken into account that the assemblages are mostly related to warm waters, linked to the latitudinal location, but its relationship with the specimens associated to colder waters and, nutrient and light availability, allowed us to infer the paleoceanographic shifts during the studied interval.

The reticulofenestrids <5µm represent eutrophy; *Florisphaera profunda* is related to oligotrophy at the UPZ and stratification of the upper water layer; *P. lacunosa* is linked to eutrophy (placolith bearing taxa); *C. leptoporus* and *Helicosphaera* spp. (*Helicosphaera carteri*, *Helicosphaera sellii*), that are warm, cosmopolitan taxa, highly adaptable to changes in nutrients and salinities; *Umbilicosphaera* spp. (*Umbilicosphaera sibogae*, *Umbilicosphaera jafari*), *Rhabdosphaera clavigera*, *Calciosolenia murrayi*, *Pontosphaera multipora* and *Syracosphaera pulchra*, are taxa linked to warm waters, therefore they were grouped within the informal denomination "warm taxa"; *Discoaster* spp. is also related to warm waters but was studied separately because a stepwise extinction process affecting the species belonging to this genus extinction in this order: *Discoaster variabilis*, *Discoaster tamalis*, *Discoaster surculus*, *Discoaster pentaradiatus*, *Discoaster asymmetricus*, and finally the last representatives of the *Discoaster brouweri* and *Discoaster triradiatus* that disappeared at ~1.95 Ma. The ecological preferences of the most abundant species in our assemblages are listed in the Table 1.

Results

To achieve the aims, several tools were used, such as the *N ratio* (Flores et al., 2000) that is a reference parameter in this work because it is based on quantitative analysis to calculate the relative position of the thermo/nutricline and allows to interpret numerically that values closer to zero (0) represent deepening and closer or equal to 1 indicate a near or superficial position or the thermo/nutricline. Additionally, proxies as benthic $\delta^{18}O$ and $\delta^{13}C$; previously published for the ODP Site 846 by Shackleton *et al.* (1995a, b) and for the ODP Site 999 by Steph *et al.* (2010); were useful for comparison of the age models obtained with the calcareous nannofossils, and provide information about the nutrients supply of the deep water masses to the oceanic surface, respectively. $\delta^{15}N$ data (Liu *et al.*, 2008) was used for comparison with results obtained in this work respect to lowest productivity intervals that could be related to denitrification processes. Sea Surface Temperatures (SSTs) record obtained by Steph et al. (2010) based on Mg/Ca (*Globigerinoides sacculifer*) was useful for comparing our results respect to the position of the thermo/nutricline in this region and thus to test the utility of the *N ratio*.

Table 1. Ecological preferences of the calcareous nannofossils species

Especie/Grupo	Preferencias ecológicas	Referencias bibliográficas
Reticulofenestrids <5μm (Noëlaerhabdaceae)	Eutrophic (shallow nutricline/ upwelling), high light availability, upper photic zone, r-selected: opportunistic taxa, subpolar waters and marginal seas	Okada & Honjo, 1973; Okada & McIntyre, 1977; Okada & McIntyre, 1979; Perch-Nielsen, 1985; Molfino & McIntyre, 1990; Okada & Wells, 1997; Takahashi et al., 2001; Flores et al., 2005; Marino et al., 2008
Florisphaera profunda	Oligotrophy at the upper photic zone and eutrophy in its dwelling depth: the lower photic zone (deep nutricline), stratified water column, warm waters	Molfino & McIntyre, 1990, 1991; Wells & Okada, 1996; Okada & Wells, 1997; Beaufort et al., 1997; Flores et al., 2000; Marino et al., 2008
Pseudoemiliania lacunosa	Not well known. By association with placolith-bearing taxa: Coastal and upwelling areas, cold and eutrophic waters.	De Kaenel et al., 1999; Young, 1994; Negri et al., 2003; Maiorano et al., 2008; Lancis, 1998; Gibbs et al. (2005); Marino et al., 2008
Calcidiscus spp.	Large (8-11μm): oportunistic, warm waters and high nutrients availability. Intermediate (5-8μm): wide temperatures range, oligotrophic waters. Small (<5μm): depend on the intermediate and larger sizes response, possibly prefer colder and eutrophic waters.	McIntyre & Bé, 1967; McIntyre et al., 1970; McIntyre et al., 1972; Gard & Backman, 1990; Gard & Crux, 1991; Haidar & Thierstein, 1997; Flores et al., 1999; Renaud & Klaas (2001); ; Beaufort & Heussner (2001) Renaud et al. (2002); Ziveri et al., 2004; Quinn et al., (2004)
Umbilicosphaera spp.	Warm waters, open ocean, subtrópical to tropical regions, oligotrophic to eutrophic environment.	Roth & Berger, 1975; Okada & McIntyre, 1979; Giraudeau, 1992; Young, 1994; Flores et al., 2003; Boeckel & Baumann, 2004
	Umbilicosphaera sibogae var. *foliosa*: High nutrients availability (upwelling).	Broerse et al., 2000a; Ziveri & Thunell, 2000
	Umbilicosphaera sibogae var. *sibogae*: Warm and oligotrophic waters	Okada & McIntyre, 1979; Ziveri et al., 1995
	Umbilicosphaera jafari: Warm surface and hypersaline waters, mesotrophic to oligotrophic.	Lancis, 1998; Flores et al., 2005

Especie/Grupo	Preferencias ecológicas	Referencias bibliográficas
Coccolithus pelagicus	Aguas frías con altas concentraciones de nutrientes	McIntyre & Bé, 1967; Okada & McIntyre, 1979; Winter et al., 1994; Roth, 1994; Baumann, 1995; Samtleben et al., 1995; Andruleit, 1997
	C. pelagicus var. *pelagicus* Cold waters -Subpolar and polar water masses	Samtleben et al., 1995; Geisen et al., 2002; Parente et al., 2004; Jordan et al., 2004; Narciso et al., 2006
	C. pelagicus var. *braarudii* Upwelling regions - temperate waters, low salinity	Cachão & Moita, 2000; Baumann et al., 2000; Geisen et al., 2002; Parente et al., 2004; Jordan et al., 2004; Narciso et al., 2006; Amore et al., 2012
	C. pelagicus var. *azorinus* Influence of the Azores Current at the Eastern side of the North Atlantic.	Parente et al., 2004; Jordan et al., 2004; Narciso et al., 2006; Palumbo et al., 2013
Discoaster spp.	Warm waters, low latitudes, oligotrophic, low adaptability to salinity changes, deep photic zone, open seas	Hekel, 1973; Haq, 1980; Lohmann & Carlson, 1981; Flores, 1985; Perch-Nielsen, 1985; Flores & Sierro, 1987; Chepstow-Lusty et al., 1989, Chepstow-Lusty et al., 1992; Aubry, 1992; Chapman & Chepstow-Lusty, 1997; Young, 1998; Flores et al., 2005
Helicosphaera carteri	Cosmopolitan: neritic and open ocean, eutrophic - upwelling regions, high adaptability to salinity changes (hyposaline to brackish waters), warm waters, upper photic zone.	Schmidt, 1978; Perch-Nielsen, 1985; Giraudeau, 1992; Cros, 2002; Colmenero-Hidalgo et al., 2004; Wade & Bown, 2006
Syracosphaera spp. *Rhabdosphaera clavigera* *Calciosolenia murrayi*	Warm and oligotrophic waters. Changing salinity levels.	McIntyre et al., 1972; Roth & Coulbourn, 1982; Brand (1994); Young (1994); Flores et al., 1997; Ziveri et al., 2004; Maiorano et al., 2008; Dimiza et al., 2008; Malinverno et al., 2009
R. pseudoumbilicus	Open ocean, low to subtropical latitudes, temperate to cold waters, eutrophic conditions, high turbulence areas.	Driever, 1988; Haq, 1980; Takayama, 1980; Lohmann & Carlson, 1981; Flores, 1985; Flores et al., 2005
Sphenolithus spp.	Low latitudes, warm waters, oligotrophy. Coastal areas or nearest to submarine rises.	Millow, 1971; Bukry, 1972; Haq & Lohmann, 1976; Haq, 1980; Lohmann & Carlson, 1981; Perch-Nielsen, 1985

The abundances of accessory components such as *Ceratolithus cristatus*, *Umbilicosphaera sibogae*, *Umbilicosphaera jafari*, among others, were analyzed quantitatively but not showed in the results, because it were not considered as relevant paleoceanographic proxies. The abundance of *Reticulofenestra pseudoumbilicus* (>7µm) and *Sphenolithus* spp. was not deeply analyzed because we only registered its presence in our samples during a short period before its extinction.

ODP Site 846

We analyzed the absolute abundances of the calcareous nannofossils represented by the Nannofossil Accumulation Rates (NAR), and the relative abundances that correspond to the percentages (%), calculated with the method of Flores & Sierro (1997). In general, we observed more gradual changes during the interval previous to the Central American Seaway closure, between ~3.9 and ~2.78 Ma, but stronger fluctuations are evident after ~2.78 until ~1.86 Ma. Each one of these intervals were analyzed (Figure 4).

Throughout the interval before the final closure of the Central American Isthmus, the reticulofenestrids <5µm dominated the assemblage, with relative abundances ranging between 64% and 94%, and NAR oscillating from $1.34x10^{12}$–$4.15x10^{10}$ n/cm^2*ka. *Pseudoemiliania lacunosa* varied slightly, within values from 1% to 16%, and NAR $6.98x10^{10}$–$1.56x10^{9}$ n/cm^2*ka. In this interval its abundances were very low, with slight fluctuations in the curve, especially for the period before 3.40 Ma. *Florisphaera profunda* varied in a short range from 0% to 16% and the NAR fluctuated with values lower than $7x10^{10}$ n/cm^2*ka. A period of sustained very low relative abundances (%) took place since 3.75 to 3.35 Ma. *Calcidiscus* spp, mainly represented by *Calcidiscus leptoporus*, oscillated between 1 and 25%, and NAR ranging between $6.49x10^{10}$ and $4.28x10^{9}$ n/cm^2*ka. *Discoaster* spp. reached percentages up to 7.2% and NAR up to $2.79x10^{10}$ n/cm^2*ka. *Helicosphaera* spp. peaked at percentages of 3.57% and NAR with values lowest than $1.88x10^{10}$ n/cm^2*ka; and the *C. pelagicus* higher percentage was 3.1% and NAR lower than $1.57x10^{10}$ n/cm^2*ka.

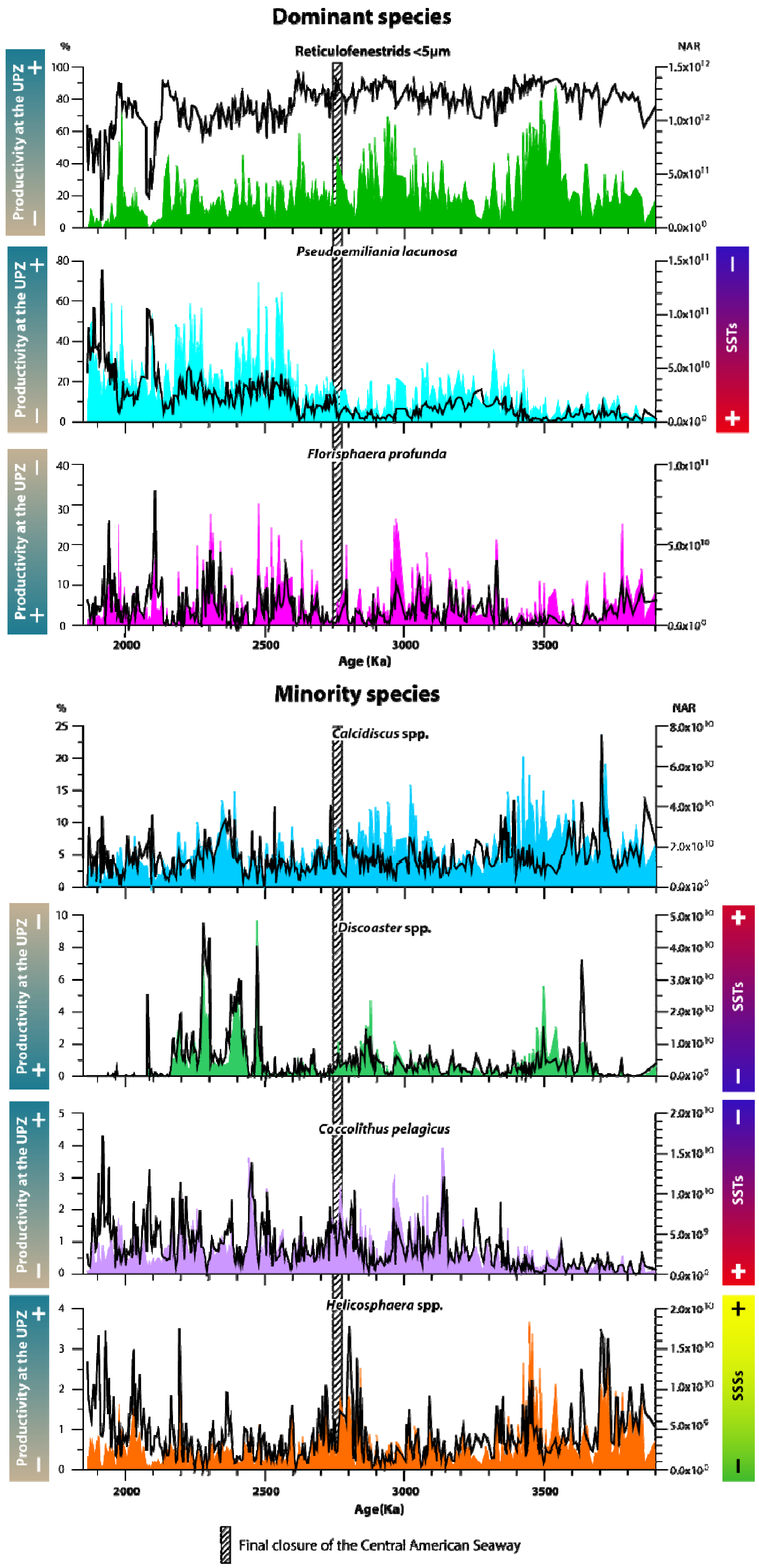

Figura 4. **Relative abundances (solid black line) and absolute abundances (NAR= solid colors areas) of the dominant and minority species at the ODP Site 846 for the studied interval. Ecologic preferences of the taxa based on the concepts described in chapter 2 of this work**

Once the isthmus completely emerged, since ~2.78 Ma until the top of the sequence the abundances of the assemblage fluctuated with higher amplitudes, and most drastic changes occurred. The reticulofenestrids <5µm were still abundant but only dominated the assemblage during some intervals, with relative abundances of 5%–95%, and NAR oscillating from 1.58×10^{12}–2.38×10^{10} n/cm^2*ka. *F. profunda* peaked up to 33.61% and its highest NAR value reached 8.34×10^{10} n/cm^2*ka. *P. lacunosa* showed its highest values during this interval, with percentages up to 75.63%, and NAR between 1.43×10^{11} and 5.30×10^{9} n/cm^2*ka; *Calcidiscus* spp. reached percentages were up to 12.68% and NAR up to 4.77×10^{10} n/cm^2*ka; *Discoaster* spp. relative abundances reached up to 9.54% and NAR lower than 4.83×10^{10} n/cm^2*ka; *Helicosphaera* spp. abundances were up to 3.50% and NAR up to 1.62×10^{10} n/cm^2*ka; and *C. pelagicus* peaked up to 4.31% and NAR up to 1.45×10^{10} n/cm^2*ka.

The N ratio at the ODP 846 drilling showed the higher values during the interval previous to the emersion of the Central American Isthmus, high abundances of reticulofenestrids <5µm and *P. lacunosa*, and low abundances of *F. profunda*. Additionally, N ratio values ranged between 0.82 and 1.0, which is interpreted as conditions mainly eutrophic at the UPZ through that period. Thus, indicating that the thermo/nutricline was at or near to the surface (Figure 5). Three intervals with different trends were defined, the first one between 3.90 and 3.37 Ma when the N ratio values showed an increasing tendency of thermocline shoaling, the second one since 3.37 to 2.96 Ma when the thermocline deepens, and the third interval between 2.96 and 2.78 Ma when the values display an increment again.

Stronger fluctuations of the position of the thermo/nutricline have occurred after the establishment of the land bridge, and it is evident in the values of the N ratio which fluctuated between 0.65 and 1.0. This proxy have allowed to define the periods that potentially could be interpreted as events El Niño-like (Figure 5), particularly one identified at ~2.1 Ma when the N index descend until its lower value (0.65), that also present higher values of the benthic $\delta^{13}C$ (Shackleton *et al.*, 1995a, b) and of the $\delta^{15}N$ (Liu *et al.*, 2008).

El Niño-like condition represents a deepening of the thermo/nutricline, which alter the life conditions of the surface waters dwellers. The effect of an El Niño-like state on the calcareous nannofossils species is the decreasing in the abundance of the eutrophic species that inhabits the UPZ (reticulofenestrids) and the increasing of *F. profunda* that represents oligotrophic conditions at the UPZ.

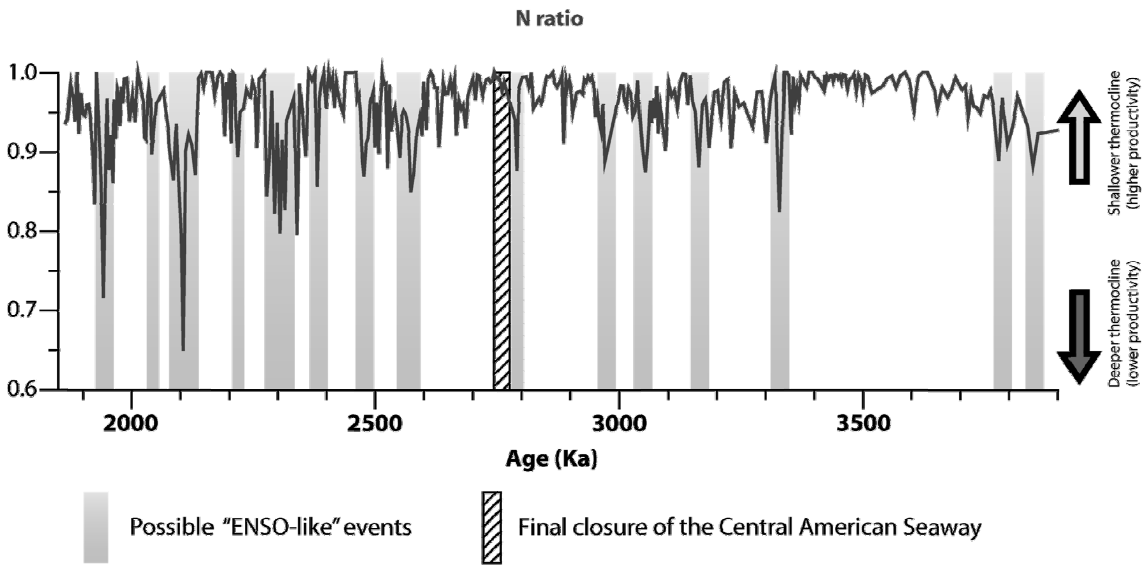

Figura 5. N ratio at the ODP Site 846 and possible El Niño-like events

Power spectra performed to the NAR of the species related to productivity (reticulofenestrids <5µm; *F. profunda* and *P. lacunosa*) showed response at the obliquity band (41 ka), which represents the high latitudes control of the productivity at the EEP (Figure 6).

The Peru upwelling waters directly influence ODP Site 846. Several authors have also established a relationship between the upwelled waters and the deep water mass Subantarctic Mode Water (SAMW) (Toggweiler *et al.*, 1991; Dugdale *et al.*, 2002; Sarmiento *et al.*, 2004), which feeds the EUC and subsequently the SEC. Thus, the response of the assemblage at the obliquity band correlates the productivity of the EEP with the Southern Ocean dynamics and the SAMW.

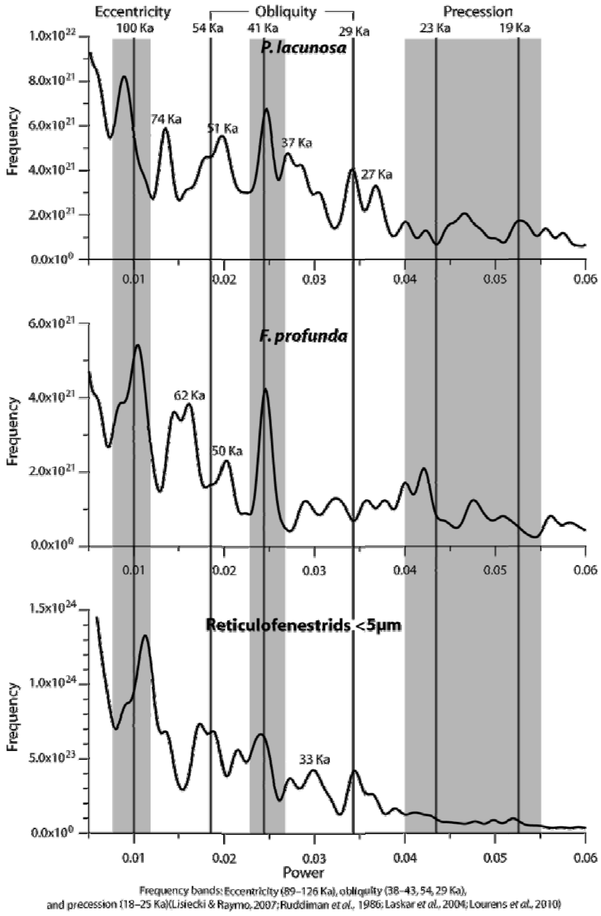

Figura 6. Power spectra of the NAR of the species used in this work as productivity proxies.

ODP Site 999

The calcareous nannofossils assemblages that dwelled the Caribbean Sea during the period ranging from 4.0 to 1.95 Ma, exhibited high amplitude fluctuations in the abundances, mainly related to the nutrients availability, SSTs and Sea Surface Salinities (SSSs). In this drilling the assemblages were dominated by the reticulofenestrids <5µm, *F. profunda* and *P. lacunosa*. High rates of *F. profunda* and scarce presence of terrigenous in this sequence suggest strong stratification of the surface water column. Within the "warm taxa" group (*U. sibogae*, *U. jafari*, *R. clavigera*, *C. murrayi*, *P. multipora* and *S. pulchra*) are clustered species related to changes in salinities, such as *Umbilicosphaera* spp., *R. clavigera*, and *S. pulchra* (Flores *et al.*, 1997; Wade & Bown, 2006; Di Stephano *et al.*, 2010). Minority species like *Calcidiscus* spp. (*C. leptoporus* and *C. macintyrei*), *Discoaster* spp. (*D. asymmetricus*, *D. brouweri*, *D. pentaradiatus*, *D.*

surculus, *D. tamalis*, *D. triradiatus*, *D. variabilis*), and *Helicosphaera* spp. (*H. carteri* and *H. sellii*) were also analyzed. Additionally, the scarcity of *C. pelagicus* (cold species) allowed us to infer that the SSTs through the studied interval were high enough to impede the increasing of this species. *C. cristatus*, *G. rotula* and *Scyphosphaera* spp. were rare or absent.

The relative and absolute abundances of the calcareous nannofossils at the ODP Site 999 showed nine biozones with noticeable differences in the response of the species to the changes of the oceanic conditions at the Caribbean basin, two (2) intervals at the previous period to the final emersion of the Central American Isthmus, and seven (7) intervals after (Figure 7). It represents stronger variability not only of the abundances but also of the position of the thermo/nutricline.

The first interval spans between ~4.01 Ma and ~3.32 Ma and is noticeable because of the high abundances of the reticulofenestrids <5µm, which varied between 34.15% and 85.60%, and NAR ranging between $9.64x10^{10}$ and $8.58x10^{11}$ n/cm^2*ka; and *P. lacunosa* with relative abundances between 0.94% and 15%, and NAR with values between $2.46x10^9$ and $9.98x10^{10}$ n/cm^2*ka; *F. profunda* showed relative abundances between 5.50% and 53.25%, and NAR ranging between $4.07x10^{10}$ and $3.40x10^{11}$ n/cm^2*ka; the "warm taxa" showed the lowest abundances during this interval, reaching values up to 1.89%, and NAR between $2.05x10^8$ and $1.52x10^{10}$ n/cm^2*ka; *Calcidiscus* spp. fluctuates between 0.26% and 3.94%, and NAR between $1.20x10^8$ and $2.93x10^{10}$ n/cm^2*ka; *Discoaster* spp. showed abundances between 0.21% and 5.73%, and NAR ranging between $7.75x10^8$ and $2.49x10^{10}$ n/cm^2*ka; and the relative abundances of *Helicosphaera* spp. ranged between 0.43% and 6.1%, and NAR between $2.59x10^9$ and $1.56x10^{10}$ n/cm^2*ka.

The second interval spans from 3.32 until 2.78 Ma, when the relative and absolute abundances of *P. lacunosa* sharply dropped and the reticulofenestrids <5µm decreased gradually, and *F. profunda*, "warm taxa", *Discoaster* spp. and *Helicosphaera* spp. increased, but *Calcidiscus* spp. did not changed notoriously. In this interval, the reticulofenestrids <5µm fluctuated between 32.55% and 71.02%, and NAR between $6.74x10^{10}$ and $7.59x10^{11}$ n/cm^2*ka; *F. profunda* ranged between 10.95% and 52.22%, and NAR between $4.02x10^{10}$ and $4.03x10^{11}$ n/cm^2*ka; P. lacunosa decreased drastically since 3.32 until 3.22 Ma when the relative abundances dropped from 14% to values between 0 and ~4.0%, and remained in low values until the end of this interval, and the absolute abundances decreased from ~$7.94x10^{10}$ to values between 0 and $2.77x10^{10}$ n/cm^2*ka; the warm taxa oscillated between 0.53% and 8.44%, and NAR values between $2.47x10^9$ and $2.71x10^{10}$ n/cm^2*ka; *Calcidiscus* spp. percentages fluctuated between 0 and 5.05%, and NAR up to $1.66x10^{10}$ n/cm^2*ka; *Discoaster* spp. ranged between 0.35% and 6.85%, and NAR between $1.76x10^9$ and $3.68x10^{10}$ n/cm^2*ka; and *Helicosphaera* spp. ranged between 0.71% and 5.91%, and NAR values between $4.38x10^9$ and $3.17x10^{10}$ n/cm^2*ka.

After the final closure of the Central American Seaway, during the interval between 2.78 and 1.94 Ma, the abundances of the assemblage showed stronger fluctuations and seven (7) different intervals were defined based on the changes of the general trends. During this period, the minority taxa abundances increased markedly and compete for the ecological niche with the dominant species. The highest abundances of the taxa that represents oligotrophy at the UPZ were observed during the intervals: 2.78–2.66 Ma, 2.61–2.39 Ma, 2.14–2.08 Ma y 1.98–1.94 Ma, with the most outstanding increase of the relative abundances of *F. profunda* (~80%.) between 2.14–2.08 Ma. The fluctuations of the relative and absolute abundances of the assemblage during the seven intervals previously mentioned were compiled at the Table 7.1 of the thesis volume.

Broadly, during this interval (2.78–1.94 Ma) the reticulofenestrids <5µm fluctuated between 4.98% and 74.36%, and NAR between $1.21x10^{10}$ and $4.79x10^{11}$ n/cm^2*ka; *F. profunda* ranged between 13.73% and 79.70%, and NAR between $3.0x10^{10}$ and $4.06x10^{11}$ n/cm^2*ka. The abundances of *P. lacunosa*, *Calcidiscus* spp. and the "warm taxa" increased in relationship with the previous interval. *P. lacunosa* fluctuated between 0.33% and 17.96%, and NAR between $1.12x10^9$ and $9.33x10^{10}$ n/cm^2*ka; *Calcidiscus* spp. fluctuated between 0.22% and 6.67%, and NAR between $1.14x10^9$ and $2.49x10^{10}$ n/cm^2*ka; the warm taxa oscillated between 1.05% and 18.34%, and NAR

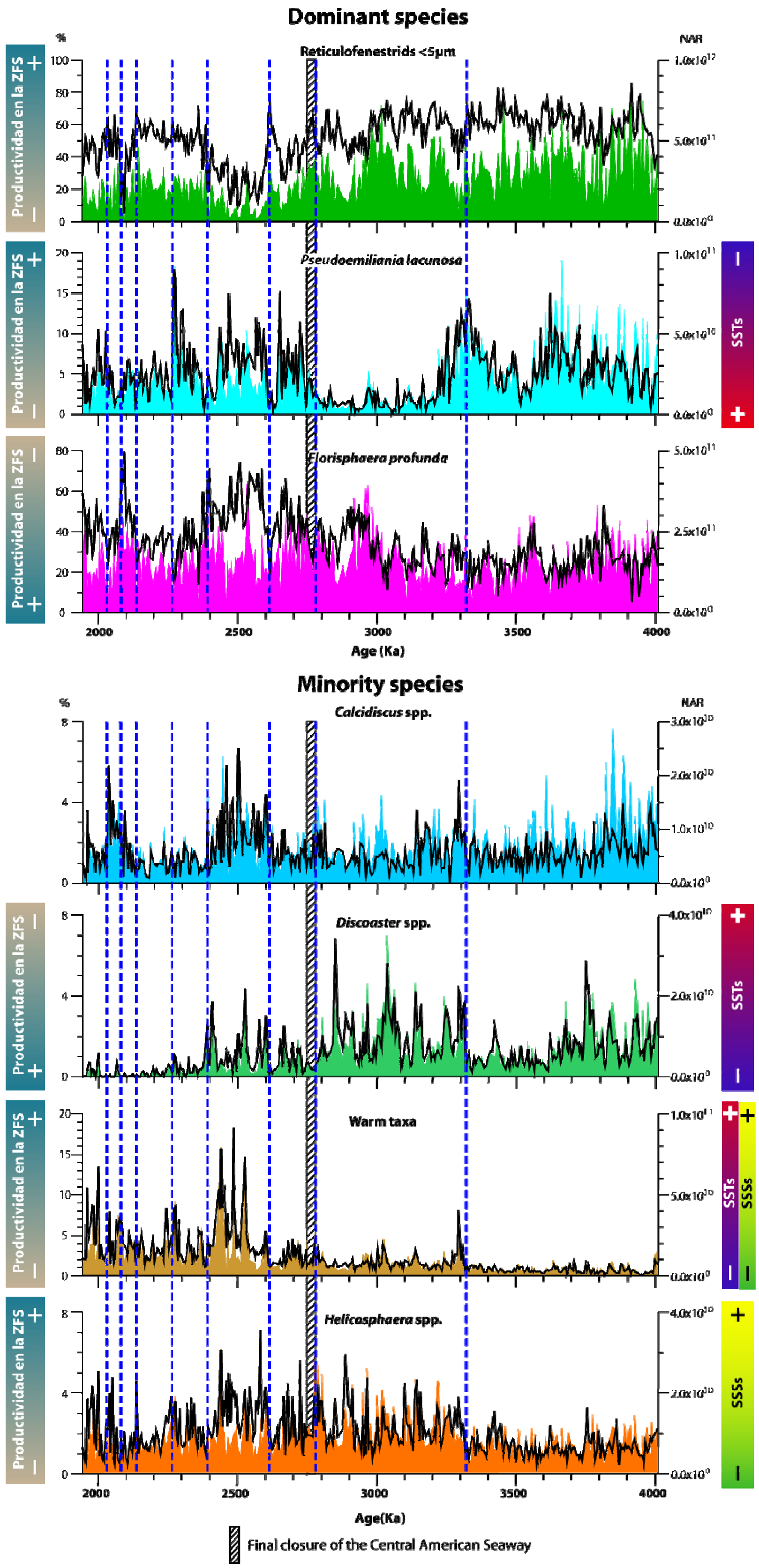

Figura 7. **Relative abundances (solid black line) and absolute abundances (NAR= solid colors areas) of the dominant and minority species at the ODP Site 846 for the studied interval. Ecologic preferences of the taxa based on the concepts described in chapter 2 of this work**

values between 3.09×10^9 and 8.33×10^{10} n/cm^2*ka; *Discoaster* spp. decreased until its highest occurrence, with relative abundances between 0 and 4.36%, and NAR up to 1.87×10^{10} n/cm^2*ka; and *Helicosphaera* spp. ranged between 0.47% and 7.10%, and NAR values between 2.44×10^9 and 3.26×10^{10} n/cm^2*ka.

Even though the N index represents the relative position of the thermo/nutricline, only based on calcareous nannofossils without including other components of the phytoplankton, in different areas its reliability as a thermo/nutricline proxy has been demonstrated. The N ratio has been used at the EEP, the Eastern and Western Equatorial Atlantic, the Antarctic Front and the Mediterranean Sea (Flores et al., 2000; Colmenero-Hidalgo et al., 2004; López-Otálvaro et al., 2008, 2009; Marino et al., 2009; Bolton et al., 2010a, b, 2011; Maiorano et al., 2013; Cabarcos et al., 2014). Nonetheless this tool should be used only at (sub)tropical latitudes, because is the habitat where *F. profunda* flourishes (Bolton et al., 2011).

The N index presents some drastic changes through the sequence, reaching its highest average values during the interval previous to the final closure of the Central American Seaway, and lower after the closure (Figure 8). Since ~4.01 Ma to ~3.32 Ma the N ratio values fluctuated between 0.44–0.94, which suggests wide fluctuations in the position of the thermo/nutricline, and conditions mainly eutrophic to mesotrophic at the

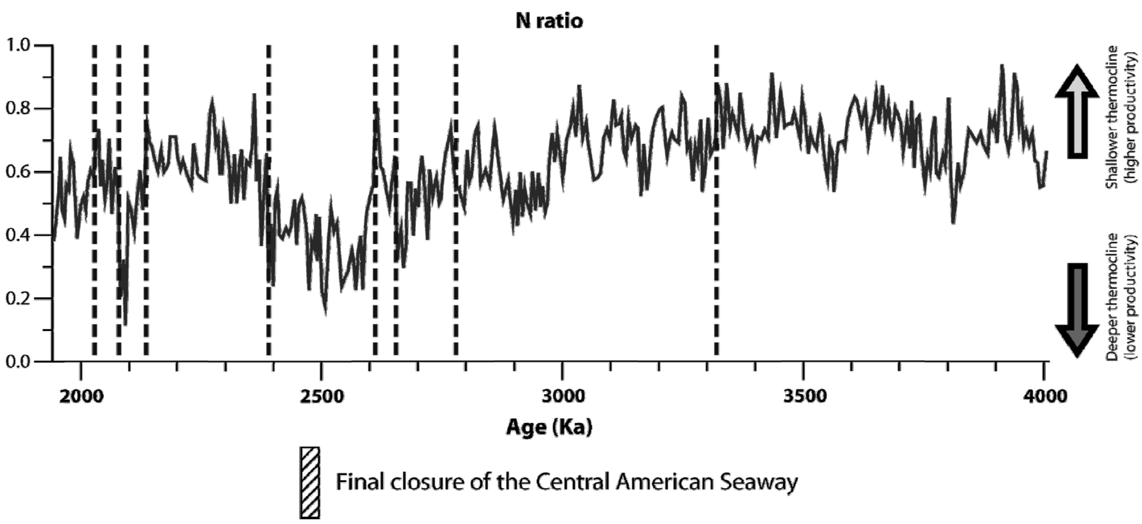

Figura 8. **N ratio at the ODP Site 999**

Caribbean basin. During the interval from ~3.32 Ma until 2.78 Ma the thermo/nutricline exhibits a general trend to get deeper indicating a decrease of the primary productivity compared with the previous interval, and N ratio values oscillating between 0.43 and 0.87.

After the emersion of the Central American Isthmus, we observed two short periods with a stronger deepening of the thermo/nutricline. The first, between ~2.61–2.39 Ma when the N ratio decreased until 0.18. The second one, between ~2.14 and 2.08 Ma when the N ratio dropped until 0.11, which corresponds to the lowest value for the whole studied interval. This interval was interpreted as a teleconnection effect of an El Niño-like event at the EEP that caused this sharp deepening of the thermo/nutricline at the western Caribbean. Additionally, species related to salinity fluctuations increased its abundances after the closure. Throughout the sequences no effects of dissolution or fragmentation of the calcareous nannofossils were observed. On the contrary, the preservation of the assemblages was very good and the morphologies are clearly defined.

Spectral analyses performed to the NAR of the productivity related species helped us to determine the influence of the orbital parameters through the studied interval (Figure 9). Power spectra showed responses of the assemblage at the main obliquity and precession bands (41 ka; 23–19 ka) and at secondary frequencies (obliquity: 57–54 ka, 34 ka; precession: 26 ka). Likewise we detected several peaks at frequencies that correspond to non-linear responses to the main orbital cycles.

Synthesis

Progressive decreasing is observed for the SSTs due to the intensification of the Northern Hemisphere glaciations and/or to orbital forcing, marked by the extinction of *Discoaster* genera. "Productivity pressure", what is an expression used by Chepstow–Lusty *et al.* (1989, 1991) for defining the trend of this genera, is observe, where this genera decreases under high productivity conditions and viceversa, as a primary control factor of its population.

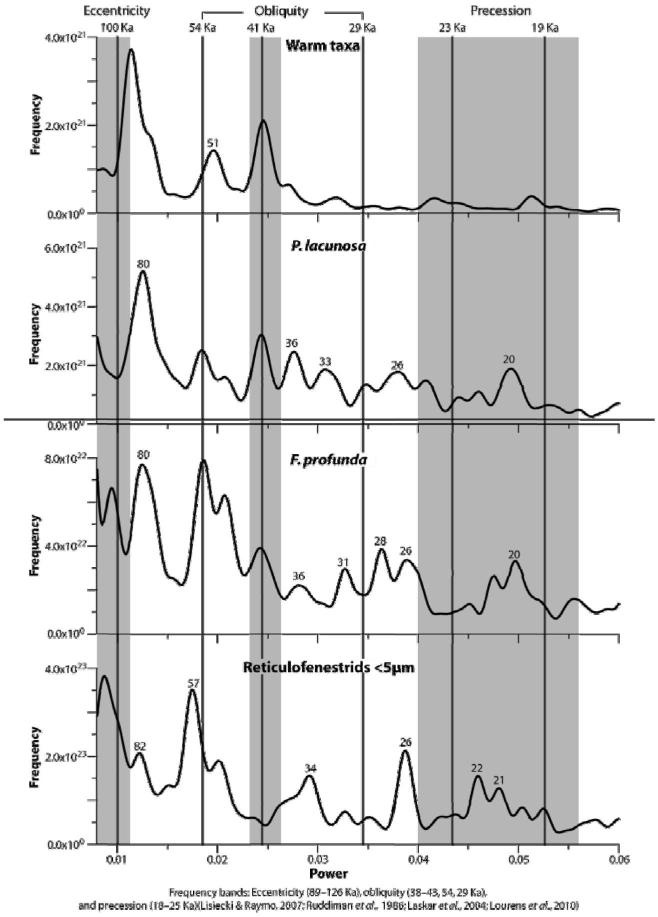

Figura 9. Power spectra of the NAR of the species used in this work as productivity proxies.

Three periods of major variability of the productivity were detected at both drill Sites, approximately at ~4.0–3.32 Ma, 3.32–2.78 Ma and stronger fluctuations begin at ~2.78 Ma until the top of the sequences when the thermo/nutricline deepenings reached lower levels.

A common deepening of the thermo/nutricline was observed at both drillings between ~2.14 and 2.08 Ma when the N ratio dropped, with a more drastic decrease at the Caribbean basin. This period corresponds to the one with the lowest N value for the whole studied interval and it was interpreted an El Niño-like event at the EEP that has teleconnection effect causing the deepening of the thermo/nutricline at the western Caribbean. It is remarkable the presence of species related to salinity fluctuations in the Caribbean that increased its abundances after the closure, but in the Pacific only *Syracosphaera pulchra* and *Umbilicosphaera* spp. were present in very low proportions. Throughout both sequences no effects of dissolution or fragmentation of the calcareous nannofossils were observed. On the contrary, the preservation of the assemblages was very good and the morphologies are clearly defined.

Trying to establish a correlation of the lowest productivities at both drillings, by comparison of the N ratio, it was clear that there are more coincidence during the interval after the closure of the seaway, which could be linked to the strengthening of the glacial-interglacial variability and to the intensification of the northern hemisphere glaciations and the establishment of the permanent ice sheets at this region since ~2.75 Ma.

Spectral analysis revealed a common response of productivity related species at the obliquity main band (41 ka), however in the Caribbean a higher variability was also evident, and responses at the main frequency bands (obliquity and precession) but also at frequencies that do not correspond to the main orbital cycles.

Biostratigraphy

Biostratigraphic events obtained at both drillings showed synchrony or a slight diachronism in some cases such as the HO of *R. pseudoumbilicus*, HO of *D. tamalis*, HO of *Sphenolithus* spp. and HO of *D. brouweri*, marked diachronism in the case of the HO of *D. surculus*, however all of them are included between the age ranges calculated in different biochronological tunings around the globe.

The HO of *D. brouweri* occurs synchronically at both basins, which is coincident with the standard calibrations (e.g. Backman & Shackleton, 1983; Raffi & Flores, 1995; Raffi *et al.*, 2006). The HO of *D. asymmetricus* is diachronic, and was firstly observed at the EEP and ~220 ka after in the Caribbean. It is a diachronic event globally and for this reason is not useful as a biostratigraphic marker. The HO of *D. pentaradiatus* is diachronic, and there is a difference about 170 ka between these basins, however this event is considered a biostratigraphic marker notwithstanding the temporal gap at different regions. The HO of *D. surculus* is moderately diachronic with a difference about ~95 ka between the EEP and the Caribbean, and at global calibrations the time gap for this event is ~200 ka. The HO of *D. tamalis* is synchronic at the two studied basins, and is a biostratigraphic marker that has been calibrated with differences about

220 ka between different regions. The HO of *D. variabilis* is globally diachronic and for this reason is not useful as a biostratigraphic marker, and it was also evident at the EEP and the Caribbean.

The HO of *Sphenolithus* spp. present a slight age difference between these basins (<55 ka) and was observed at first at the EEP and after at the Caribbean, but in global calibrations have been observed as diachronic because its abundance decline begins at ~3.71–3.67 Ma but its HO was determined at ~3.56–3.52 Ma. The LO of D. tamalis is not useful as a biostratigraphic marker because of its diachronism, and in this work we observed this event at first in the Caribbean basin and after in the Pacific basin with an age difference ~240 ka. Finally the HO de *R. pseudoumbilicus* is highly synchronic between the EEP and the Caribbean, and it has been described as an synchronism example (Gibbs *et al.*, 2005).

Conclusions

- ✓ The calcareous nannofossils assemblages at both sites were characterized by high abundances of the reticulofenestrids <5μm, *F. profunda*, and *P. lacunosa*. In lower proportions were *C. leptoporus*, *Helicosphaera* spp., *Discoaster* spp. At the EEP, *C. pelagicus* is a minority taxon whereas it was a rare species in the Caribbean basin. In addition, at the Caribbean basin *Umbilicosphaera* spp. and *R. clavigera,* which have been linked to higher salinities, showed high abundances, contrasting with the EEP record where they are rare taxa.
- ✓ Nine (9) calcareous nannofossils events were identified within the studied interval. The synchronism or diachronism of the events was established by comparison with previously published data of astrobiochronological calibrated datums (by using magnetostratigraphy and isotope stratigraphy) at the western equatorial Atlantic, Mediterranean and eastern equatorial Pacific. Synchronic or slightly diachronic events include the HO of *D. brouweri*, the HO of *D. tamalis*, the HO of *R. pseudoumbilicus*, while diachronic events are the HO of *D. asymmetricus*, the HO of *D. pentaradiatus*, the HO of *D. surculus*, the LO of *D. tamalis*, the HO of *Sphenolithus* spp. and the HO of *D. variabilis*. The sequential occurrence of these events following

the standard biozonations order, indicates that the sedimentation was more or less continuous at both basins and no hiatuses were detected.

- ✓ Major shifts in the behavior of the assemblages and the reconstruction of the position of the thermo/nutricline by using the N ratio, allowed us to determine the stronger changes of the primary productivity. The N ratio was also used to interpret possible El Niño-like events at the EEP throughout the target interval. In addition, it enables establishing whether teleconnection processes that caused changes at the Sea Level Pressures (SLPs) affected the Caribbean basin. At the EEP and the Caribbean basin, three (3) intervals were differentiated:

  - The first one, from ~4.0 to ~3.32 Ma was defined as the highest productivity period with the uppermost values of N ratio for the studied interval. At this time, the reticulofenestrids <5µm and *P. lacunosa* dominated the assemblage; at the EEP the *F. profunda* abundances were very low, but at the Caribbean were approximately two times higher. Warm taxa were present in very low proportions at the Caribbean, and at the EEP only *R. clavigera* and *Umbilicosphaera* spp. were present as rare species. *Calcidiscus* spp. presented higher relative and absolute abundances at the EEP than in the Caribbean basin; *Discoaster* spp. was generally more abundant at the Caribbean but during the interval between 3.45 and 3.65 Ma showed highest values in the EPP. *Helicosphaera* spp. had low abundances at these two basins, but showed a decreasing trend in the EEP, while in the Caribbean slightly fluctuated. During this interval three (3) periods with lower productivities at the EEP (N ratio < 0.9) were interpreted as possible El Niño-like events, but only one (~3.33 Ma) probably have some effect at the Caribbean basin through atmospheric teleconnection by altering the SLPs, which could cause the deepening of the thermocline.
  - A second period was comprised between ~3.32 and 2.78 Ma. It could be defined as mainly eutrophic to mesotrophic at the EEP, and mostly mesotrophic for the Caribbean. It was characterized by a decrease in the abundances of the reticulofenestrids <5µm. *F. profunda* increased slightly at the EEP and notoriously at the Caribbean. *P. lacunosa* dropped to very low values at both sites. *Calcidiscus* spp. abundances remained low at the Caribbean but at the EEP

were low until 3.05 Ma, but afterwards its abundance increase. At the Caribbean the *Discoaster* spp. abundances reached the highest values for the entire studied interval, and at the EEP they remain low until 3.1 Ma since when they increased until ~2.83 Ma, but dropped again to very low values showing high variability. *Helicosphaera* spp. showed low to very low values at the EEP but at the Caribbean basin were notoriously higher; however, from 2.89 Ma onwards, the abundances of *Helicosphaera* spp. dropped at the Caribbean and increased at the EEP reaching similar values up to ~2.78 Ma, then the tendencies changed and raised in the Caribbean and dropped at the EEP. Finally the "warm taxa", only defined for the Caribbean, showed a marked increase. Four (4) possible El Niño-like events were identified at the EEP during this interval, and probably one could have (~3.18 Ma) affected the Caribbean basin.

* The third period begins after the closure of the Central American Seaway (CAS) (~2.78 Ma) until the top of the sequences. This lapse was characterized by the lower productivities. The EEP was mainly mesotrophic to eutrophic but the Caribbean was mesotrophic to oligotrophic. Also high productivities were reached at both sites, which represent a highly unstable period. At the EEP the reticulofenestrids <5µm present high abundances up to 2.61 Ma, since when they begin to decrease until 2.28 Ma, after they showed a slight increase until ~2.14 Ma; from this time onwards, their abundances drastically dropped until 2.08 Ma when they increased again. Subsequently, the abundances sharply increased until reaching a high abundances peak at ~1.98 Ma and then it dropped again. At the Caribbean basin, the reticulofenestrids <5µm present the lowest absolute abundances for the studied interval, and the highest fluctuations are observed in the relative abundances. This taxa showed a decreasing trend between ~2.78 and 2.65 Ma, afterwards its abundances increased until 2.61 Ma, then dropped to very low values which remained until 2.39 Ma, when sharply increased until 2.36 Ma, but decreased again until 2.31 Ma, when the abundances tended to increase until 2.14 Ma when a drastic decrease was observed until 2.08 Ma, and afterwards the abundances reached intermediate values. *F. profunda* showed its highest values throughout the entire interval with the major fluctuations marked for the same intervals than the reticulofenestrids <5µm. *P. lacunosa* increased at both basins but particularly at the EEP.

Calcidiscus spp. increased at the Caribbean basin but at EEP showed wider fluctuations. *Discoaster* spp. showed higher abundances at the Caribbean and very low values at the Pacific until ~2.5 Ma, afterwards it became more abundant at the EEP and decreased at the Caribbean. *Helicosphaera* spp. showed an increase of its abundances, which were generally higher at the Caribbean than at the EEP. At the Caribbean, the warm taxa reached its highest values in the whole studied period. Through this period, seven (7) possible El Niño-like events were observed at the EEP, and three (3) of them could be linked through atmospheric teleconnections with the Caribbean, (~2.1 Ma, ~2.47 Ma, ~2.57 Ma)

- ✓ A striking result after this study was the finding of the drop of the productivity (deepening of the thermo/nutricline) at both basins between 2.08 and 2.14 Ma with the minimum value of the N ratio at ~2.1 Ma (MIS 79). This interval was interpreted as a long lasting El Niño-like event that occurred at the EEP and by effect of atmospheric teleconnections that affected the SLPs, caused the deepening of the thermo/nutricline in the Caribbean. Anomalies of the benthic $\delta^{13}C$ (ODP Site 846-EEP) and the $\delta^{15}N$ (ODP Site 1012-Eastern Tropical North Pacific) have also been observed in this period.
- ✓ The higher values of the N ratio at both basins were reached during glacial stages; while lower values during the interglacials. The stronger fluctuations of the thermo/nutricline and the lowest values of the N ratio were observed after the closure of the Central American Seaway, once the North Hemisphere glaciations were strengthened and the glacial-interglacial variability was established. It allowed us to suggest that the periods with higher productivities at glacial stages are linked to stronger trade winds and therefore to enhanced coastal upwelling in the Caribbean and at the EEP, and conversely, lowest productivities could be related to weaker trade winds facilitate the occurrence of large scale ENSO-like events.
- ✓ Power spectra performed to the absolute abundances represented by the Nannofossils Accumulation Rates (NAR) of the species used as productivity proxies. At the EEP the response was primarily in the obliquity band (41 ka), which implies the control of high latitudes on the productivity of this region. Productivity patterns have been linked to the SAMW that supplies nutrients to the EUC, which in turn feeds the SEC and the Peru upwelling. At the Caribbean, a stronger variability was

evident. Responses at the main and secondary obliquity bands (41 and 54 ka) were observed, and at the precession band (23-19 ka). In addition, signals at different bands that correspond to non-linear responses of the main orbital cycles. This result in the Caribbean was correlated with the influx of different water masses, from the Northern Hemisphere (NEC) and from the Southern Hemisphere (SEC) which mix into the Caribbean basin.

- ✓ Cross power spectra showed that the N ratios of both drillings present coherence >95% at the main obliquity band (41 ka) and at the precession band (23 ka, 21 ka). The influence of the obliquity indicates the control exerted by high latitudes on the productivity at the intertropical region of the Atlantic and the Pacific oceans during the target interval. The response of the taxa to the precession band was expected, given that this orbital parameter controls the strength of the trade winds, and thus the intensity of the upwellings of Peru and of the northern coast of South America.