

Paleoceanographic conditions in the western Caribbean Sea for the last 560 kyr as inferred from planktonic foraminifera

J. Ignacio Martinez ^{a,*}, Germán Mora ^b, Timothy T Barrows ^c

^a Departamento de Geología, Area de Ciencias del Mar, Universidad Eafit, A.A. 3300 Medellín, Colombia

^b Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA 50011, USA

^c Department of Nuclear Physics, Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia

Received 12 June 2006; received in revised form 2 April 2007; accepted 2 April 2007

Abstract

Faunal analyses of planktonic foraminifera and upper-water temperature reconstructions with the modern analog technique are studied and compared to the magnetic susceptibility and gamma ray logs of ODP Core 999A (western Caribbean) for the past 560 kyr in order to explore changes in paleoceanographic conditions in the western Caribbean Sea. Long-term trends in the percentage abundance of planktonic foraminifera in ODP Core 999A suggest two hydrographic scenarios: before and after 480 ka. High percentage abundances of *Neogloboquadrina pachyderma* and *Globorotalia inflata*, low abundances of *Globorotalia menardii* and *Globorotalia truncatulinoides*, low diversity, and sea-surface temperatures (SST) under 24 °C are typical characteristics occurring from 480 to 560 ka. These characteristics suggest a “shallow” well-oxygenated upper thermocline and the influx of nutrients by either seasonal upwelling plumes and/or eddy-mediated entrainment. The second scenario occurred after 480 ka, and it is characterized by high and fluctuating percentage abundances of *Neogloboquadrina dutertrei*, *G. truncatulinoides*, *G. menardii*, *Globigerinita glutinata*, *Globigerinella siphonifera*, and *Globigerinoides ruber*; a declining trend in diversity; and large SSTs. These characteristics suggest a steady change from conditions characterized by a “shallow” thermocline and chlorophyll maximum to conditions characterized by a “deep” thermocline (mainly during glacial stages) and by more oligotrophic conditions. The influence of the subtropical North Atlantic on the upper thermocline was apparently larger during glacial stages, thus favoring a deepening of the thermocline, an increase in sea-surface salinity, and a dramatic reduction of nutrients in the Guajira upwelling system. During interglacial stages, the influx of nutrients from the Magdalena River is stronger, thus resulting in a deep chlorophyll maximum and a fresher upper ocean. The eddy entrainment of nutrients is the probable mechanism responsible of transport from the Guajira upwelling and Magdalena River plumes into ODP 999A site.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Late Pleistocene; Planktonic foraminifera; Caribbean Sea; Paleoproductivity; Magdalena River; Guajira upwelling system; Colombia Basin

1. Introduction

The Caribbean Sea is an important source of heat and saline water to the North Atlantic and ultimately to global

thermohaline circulation. Numerous paleoceanographic studies have demonstrated its importance during the late Pleistocene through reconstruction of sea-surface temperatures and salinities, defining the past position of the Intertropical Convergence Zone (ITCZ), and millennial-scale correlations of climate records between the Caribbean Sea and the North Atlantic Ocean (e.g., [Prell](#)

* Corresponding author.

E-mail address: jimartin@cafite.edu.co (J.I. Martinez).

and Hays, 1976; Yarincik et al., 2000; Hüls and Zahn, 2000; Mora and Martinez, 2005; Peterson and Haug, 2006; Leduc et al., 2007).

An important source of paleoclimate information is the Cariaco Basin in the southern Caribbean Sea, which has provided valuable information of global significance (e.g., Peterson et al., 2000; Lea et al., 2003; Hughen et al., 2004). For example, Peterson et al. (2000) reconstructed freshwater discharge and upwelling conditions at millennial time scales based on geochemical data from laminated sediments accumulated in the Cariaco Basin. The data indicate that the ITCZ maintained a southern (northern) position during glacial (interglacial) periods and stadial (interstadial) stages, thus resulting in an increased (decreased) sediment yield from the rivers draining into the eastern Caribbean. These results corroborate early suggestions for a southern shift in the mean latitudinal position of the ITCZ during the last glacial interval (Prell and Hays, 1976). This change in regional atmospheric circulation coincided with an apparent increase of terrigenous sedimentation in the western Caribbean during glacial stages (Prell, 1978). A southward shift of the ITCZ would create saltier conditions in the Caribbean Sea, because of increased evaporation. Numerous proxy records have indeed suggested saltier conditions during the last glacial as indicated by the occurrence of a ‘Sargasso Sea’ planktonic foraminifera assemblage dominated by *Globigerinoides ruber* (Prell and Hays, 1976), salinity estimations from a Caribbean transfer function (Imbrie and Kipp, 1971), and elevated oxygen isotope ratios of planktonic foraminifera (Schmidt et al., 2004). The agreement between saltier conditions and a southerly location of the ITCZ then suggests a negative precipitation minus evaporation ($P-E$) balance in the Caribbean, which should reduce sediment yields to the Colombia Basin during glacial stages due to decreased terrestrial runoff, despite a lower base level for rivers draining into the Basin. This reduction of detrital materials would then decrease the supply of nutrients by northern South American rivers, which, in turn, would affect the plankton community.

At present the Magdalena river is the main source of detritus, and possibly nutrients, to the western Caribbean, yielding $\sim 144 \times 10^6$ t-yr⁻¹ of sediments eroded from a 257,438 km² drainage basin in the northern Andes (Restrepo and Kjerfve, 2000, 2004; Restrepo et al., 2006). A second and largely unexplored source of nutrients to the western Caribbean is the Guajira upwelling system (Corredor, 1979; Müller-Karger et al., 1989) and the Guajira Peninsula desert (Andrade and Barton, 2005). Although nutrients are supplied to the Guajira upwelling system by the Subtropical Underwater (SUW) that originates in the Sargasso Sea, cyclonic eddies also entrain

some sub-thermocline nutrients (Schmuker and Schiebel, 2002; Andrade and Barton, 2005). Additionally, the northeast trade winds could transport sediments composed of quartz, kaolinite, smectite, and micas present in the clay fraction of soils from the Guajira Peninsula (Fernandez, 1995) to the western Caribbean, thus providing an additional source of nutrients. However, this potential source of nutrients has not been studied. Similarly, no consensus exists on the contribution of the North or South Atlantic intermediate water masses to the western Caribbean during glacial stages or on the structure of the upper water column (e.g., Kameo et al., 2004).

Here we study the assemblage variations of planktonic foraminifera from ODP Core 999A, focusing on the last 560 kyr. We explore their response to possible changes in paleoceanographic conditions. Our goal is to evaluate if changes to the boundary conditions of global climate at this time had a significant effect on planktonic foraminifera in the Caribbean Sea. We also explore long-term trends in the abundance of planktonic foraminifera to evaluate changes in hydrographic conditions in the water column, demonstrating that, similar to the Amazon basin (Harris et al., 1997; Harris and Mix, 1999), rainfall in the Magdalena basin increased during oxygen isotope stages (MIS) 13–14, increasing marine productivity in the western Caribbean. This episode was followed by mesotrophic conditions during MIS 11 and by a steady change to more oligotrophic conditions towards the Holocene.

1.1. Climate and hydrography of the Caribbean Sea

Precipitation variations in the Caribbean and northern South America result from the seasonal migration of the ITCZ, creating drier conditions during boreal winter and rainy conditions during boreal summer (e.g., Poveda et al., 2006). Consequently, water discharge and sediment yield from the Magdalena (Restrepo and Kjerfve, 2000), the Orinoco (Morell and Corredor, 2003; Corredor et al., 2004), and the Amazon (Müller-Karger et al., 1989) rivers seasonally increase during boreal summer.

The upper water column of the Caribbean Sea consists of western Atlantic water masses that enter through the Antilles passages: ~ 10 Sv (1 Sverdrup = 10^6 m³ s⁻¹) through the Windward Island (Grenada, St. Vincent, St. Lucia), ~ 8 Sv through the Leeward Island (Dominica, Guadalupe, Antigua, Anegada), and ~ 10 Sv through the Greater Antilles (Johns et al., 2002). These water masses contribute to the west-flowing Caribbean Current (CC) which derives from the North and South Equatorial Currents (i.e., the Guyana Current) during boreal winter and summer, respectively. The southerly position of the

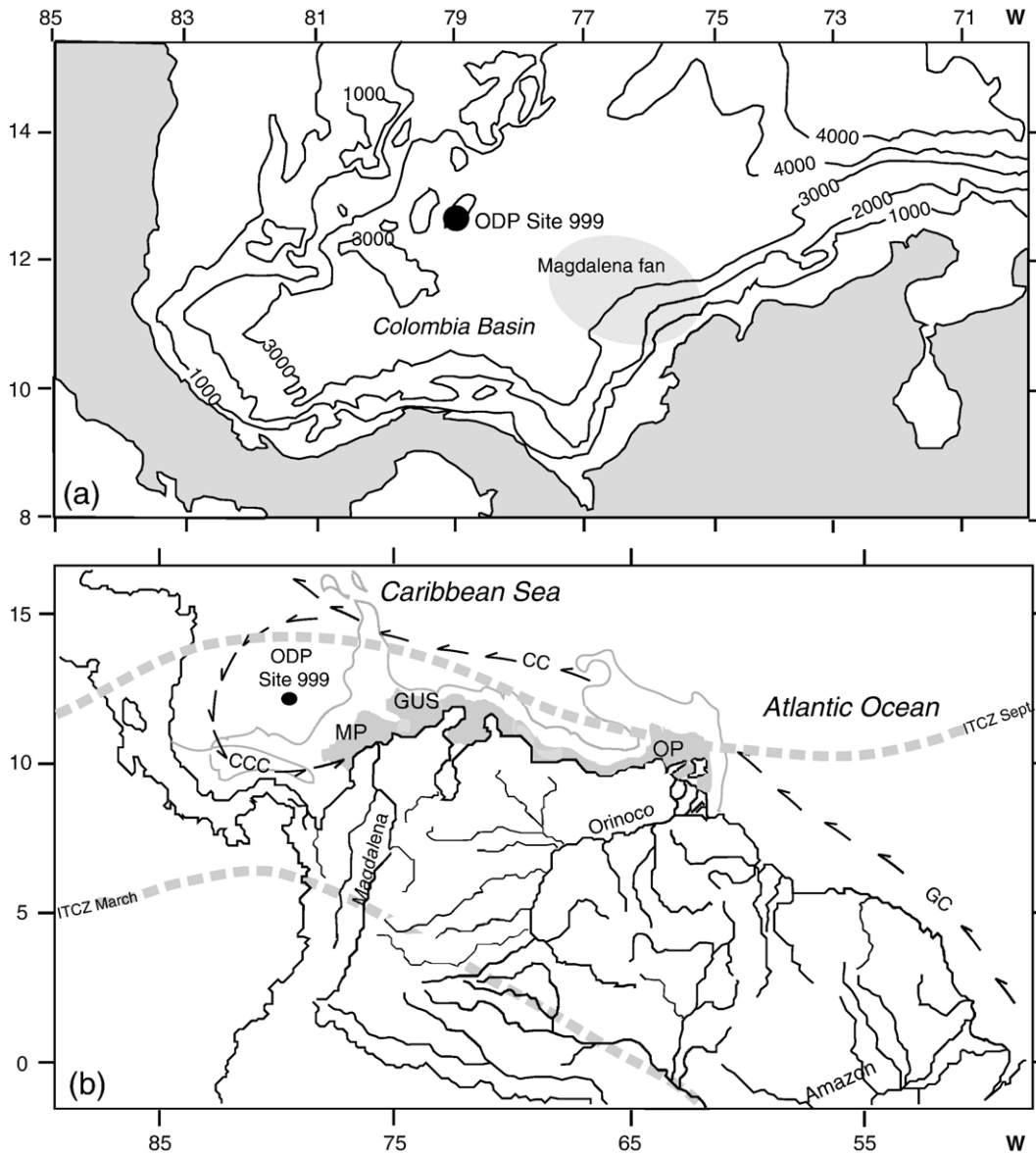


Fig. 1. ODP Site 999A in the western Caribbean: (a) Bathymetry of the Colombia Basin and location of the core site. Note that the Magdalena fan does not reach the site, (b) sea-surface circulation and sources of nutrients. CC=Caribbean Current, CCC=Caribbean Counter-Current, MP=Magdalena River plume, GUS=Guajira upwelling system, OP=Orinoco River plume. The extreme positions of the intertropical convergence zone (ITCZ) are also indicated. The Guajira upwelling filaments and the Magdalena and Orinoco plumes are based on satellite images of phytoplankton (Müller-Karger et al., 1989; Corredor et al., 2004; Andrade and Barton, 2005).

ITCZ during winter is associated with stronger northeast trade winds that favor a large influx of South Atlantic water and a stronger CC (Müller-Karger and Castro, 1994). Conversely, the influx of North Atlantic water (i.e., the Sargasso Sea) is large during boreal summer, thus increasing sea-surface salinity in the western Caribbean. When the CC passes north of the Guajira Peninsula, it continues into the northwestern Caribbean to eventually feed the Yucatan Current. Although the CC is composed

of a complex pattern of anticyclonic eddies all through its path (Andrade and Barton, 2005), the CC generates a cyclonic eddy in the southwest Caribbean, creating the Colombia or Darien Counter-Current, which is responsible of localized upwelling and the entrainment of nutrients (Andrade and Barton, 2000, 2005; Sheng and Tang, 2003). These eddies bring nutrients to the surface from thermocline waters, i.e., the SUW, which is a high saline, upper thermocline (100 to 150 m deep) water

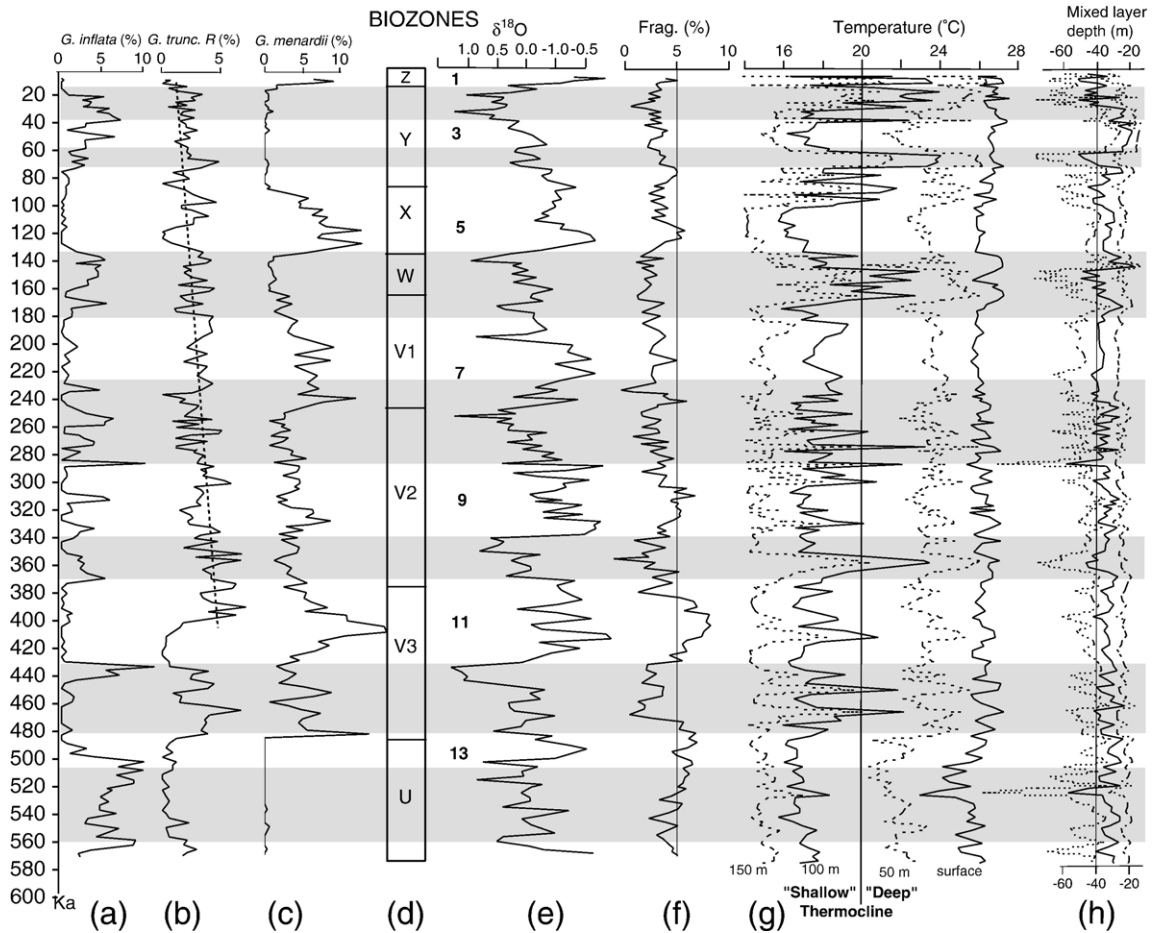


Fig. 2. Biostratigraphy and paleotemperatures of ODP Core 999A against time. Percentage abundance of (a) *G. inflata*, (b) *G. truncatulinoides* and (c) *G. menardii*, (d) Martin et al.'s (1990) biostratigraphic zones, (e) $\delta^{18}\text{O}$ record of *G. sacculifer*, (f) planktonic foraminiferal fragmentation (%), (g) modern analog technique (MAT) water temperature reconstruction for the surface, 50, 100 and 150 m water depth and thermocline depth, (h) mixed layer depth reconstruction. The tendency of *G. truncatulinoides* is indicated by a dashed line. Note also the log scale for fragmentation and maximum and minimum estimates of the mixed layer depth (dashed lines).

mass that originates in the Sargasso Sea. Therefore, secular variations in the dynamics of the North Atlantic should influence the SUW and productivity in the Caribbean Sea.

An upwelling system is present off the Guajira peninsula. This system is currently more dynamic during February–March when the northeast trade winds are stronger as the ITCZ is located further south. At the same time, cold-water filaments move northwestward, causing productivity blooms with chlorophyll values in excess of $0.5 \text{ mg}\cdot\text{m}^{-3}$ as far away as the northwestern Caribbean (e.g., Corredor, 1979; Müller-Karger et al., 1989, Andrade and Barton, 2003, 2005), thus influencing ODP 999A site.

1.1.1. Methods

A total of 195 samples, 5 cm^3 in volume, were collected every 10 cm from the uppermost 20 m representing the

late Pleistocene (Chaisson and D'Hont, 2000) of ODP Core 999A ($12^{\circ}44.64'\text{N}$, $78^{\circ}44.36'\text{W}$, 2827.9 m water depth; Fig. 1). Planktonic foraminifera were extracted from sediment samples following standard procedures. Briefly, samples were soaked in water and diluted hydrogen peroxide until any visible reaction stopped. Samples were then wet sieved at 63 and 150 μm and dried at $\sim 40^{\circ}\text{C}$. Counting of 300 specimens was performed on the $>150 \mu\text{m}$ size fraction with the aid of an Otto microsplitter. The specimens were identified to the species level, and planktonic foraminifera fragmentation (%) was determined.

We measured oxygen isotope ratios ($\delta^{18}\text{O}$) on *Globigerinoides sacculifer* picked from the 125–250 μm size fraction, thus minimizing size-dependent effects on isotopic composition (Oppo and Fairbanks, 1989; Bauch et al., 2000). Specimens were cleaned with alcohol

Table 1
Correlation points between *G. sacculifer* $\delta^{18}\text{O}$ values and the Specmap record

Section	Interval (cm)	Depth (mbsf)	Age (kyr)
165-999A-1H-1	7–10	0.085	4.0
165-999A-1H-1	17–19	0.180	4.9
165-999A-1H-1	53.5–56	0.548	12.5
165-999A-1H-2	7–9	1.580	31.6
165-999A-1H-2	55–60	2.075	43.4
165-999A-1H-2	107–109	2.580	56.1
165-999A-1H-3	7–9	3.080	68.4
165-999A-1H-4	17.5–20	4.688	111.1
165-999A-1H-5	7–9	6.080	149.6
165-999A-1H-5	17–19	6.180	152.5
165-999A-2H-1	7–9	7.680	197.9
165-999A-2H-1	77–79	8.380	230.6
165-999A-2H-1	117–119	8.780	237.7
165-999A-2H-2	107–109	10.180	266.6
165-999A-2H-3	147–149	12.080	313.0
165-999A-2H-4	27–29	12.380	319.0
165-999A-2H-5	17–19	13.780	354.7
165-999A-2H-6	87–89	15.980	431.9

and sonicated for few seconds and then roasted at 400 °C to remove hydrolysable organic matter. The oxygen isotopic composition of roasted foraminifera tests was determined via phosphorolysis using a Finnigan Gas Bench-II system fitted to a Delta-Plus XL mass-spectrometer. NSB-18 and NSB-19 were used as standards.

An age model for ODP Core 999A was established on the basis of the oxygen isotope stratigraphy (Fig. 2e). Age tie points (Table 1) were used from the SPECMAP chronology of Imbrie et al. (1984). The developed time-scale for the upper 5 m of the core is within the standard error (<1 kyr) to that developed by Schmidt et al. (2004), which is based on $\delta^{18}\text{O}$ values of *G. ruber*. Below the upper 5 m of the core, the two chronologies are within 2 kyr, although the maximum deviation is of 5 kyr in the interval covering MIS 12 (12 to 13 mbsf). The age model is consistent with the biostratigraphic scheme of Martin et al. (1990) which is based on the relative (%) abundances of *Globorotalia menardii* complex, *Globorotalia inflata*, and the right–left coiling varieties of *Globorotalia truncatulinoides*. Martin et al. (1990) revised the Ericson and Wollin (1954) zonation scheme for the Caribbean, dividing the Pleistocene interval into 17 zones with an average resolution of ~100 kyr. Our age model for ODP 999A indicates an average sedimentation rate of 3.75 cm/kyr, and an average sample resolution of 3 kyr (Table 2).

Mean sea-surface temperatures (SST) were estimated from the planktonic foraminifera assemblage data using the modern analog technique (MAT), in conjunction with the AUSMAT-F4A analog database. This subset of the F4 global database (Barrows and Juggins, 2005) consists of

only coretops from the subtropical (<25°S) and North Atlantic Ocean. Because of endemism, faunas in the high latitudes of the South Atlantic (or elsewhere in the Southern Hemisphere) are not representative of conditions in the North Atlantic (Kucera et al., 2005). We estimated mean annual SST, and the temperature of the warmest and coolest months. In a tropical setting, the months with the most extreme temperatures are usually not the calendar months in the middle of summer and winter. In addition to SST, we estimated temperature at water depth levels of 50, 100, 150 m and the depth of the mixed layer (MLD). All temperature values for the modern analogs were calculated from the World Ocean Atlas 2001 (Conkright et al., 2002). Modern mixed layer depths for the modern analogs were derived from Kara et al. (2003). These depth levels are important because the highest concentration of foraminifera live below the surface, in the mixed layer and at the top of the thermocline. Therefore these temperature variables should be more representative of the changes influencing the assemblage. Particularly, our study focuses on temperature variations in the 100–150 m depth interval, where the

Table 2
Taxonomic list

<i>Globigerina bulloides</i> d'Orbigny, 1826
<i>Globigerina calida</i> Parker, 1962
<i>Globigerina digitata</i> Brady, 1879
<i>Globigerina falconensis</i> Blow, 1959
<i>Globigerina quinqueloba</i> Natland, 1938
<i>Globigerinella siphonifera</i> (d'Orbigny), 1839
<i>Globigerinoides conglobatus</i> (Brady), 1879
<i>Globigerinoides elongatus</i> (d'Orbigny), 1839
<i>Globigerinoides ruber</i> (d'Orbigny), 1839
<i>Globigerinoides sacculifer</i> (Brady), 1877
<i>Globoturborotalia rubescens</i> (Hofker), 1956
<i>Globoturborotalia tenella</i> (Parker), 1958
<i>Hastigerina pelagica</i> (d'Orbigny), 1839
<i>Orbulina universa</i> d'Orbigny, 1839
<i>Sphaeroidinella dehiscens</i> (Parker and Jones), 1865
<i>Candeina nitida</i> d'Orbigny, 1839
<i>Globigerinita glutinata</i> (Egger), 1893
<i>Globorotalia anfracta</i> Parker, 1967
<i>Globorotalia crassaformis</i> (Galloway and Wissler), 1927
<i>Globorotalia crotonensis</i> Conato and Follador
<i>Globorotalia menardii</i> (d'Orbigny), 1826
<i>Globorotalia hirsuta</i> d'Orbigny, 1839
<i>Globorotalia inflata</i> (d'Orbigny), 1839
<i>Globorotalia scitula</i> (Brady), 1882
<i>Globorotalia truncatulinoides</i> (d'Orbigny), 1839
<i>Globorotalia tumida</i> (Brady), 1877
<i>Globorotalia unguolata</i> Bermudez, 1960
<i>Globorotaloides hexagonus</i> (Natland), 1939
<i>Neogloboquadrina dutertrei</i> (d'Orbigny), 1826
<i>Neogloboquadrina pachyderma</i> (Ehrenberg), 1861
<i>Pulleniatina obliquiloculata</i> (Parker and Jones), 1862

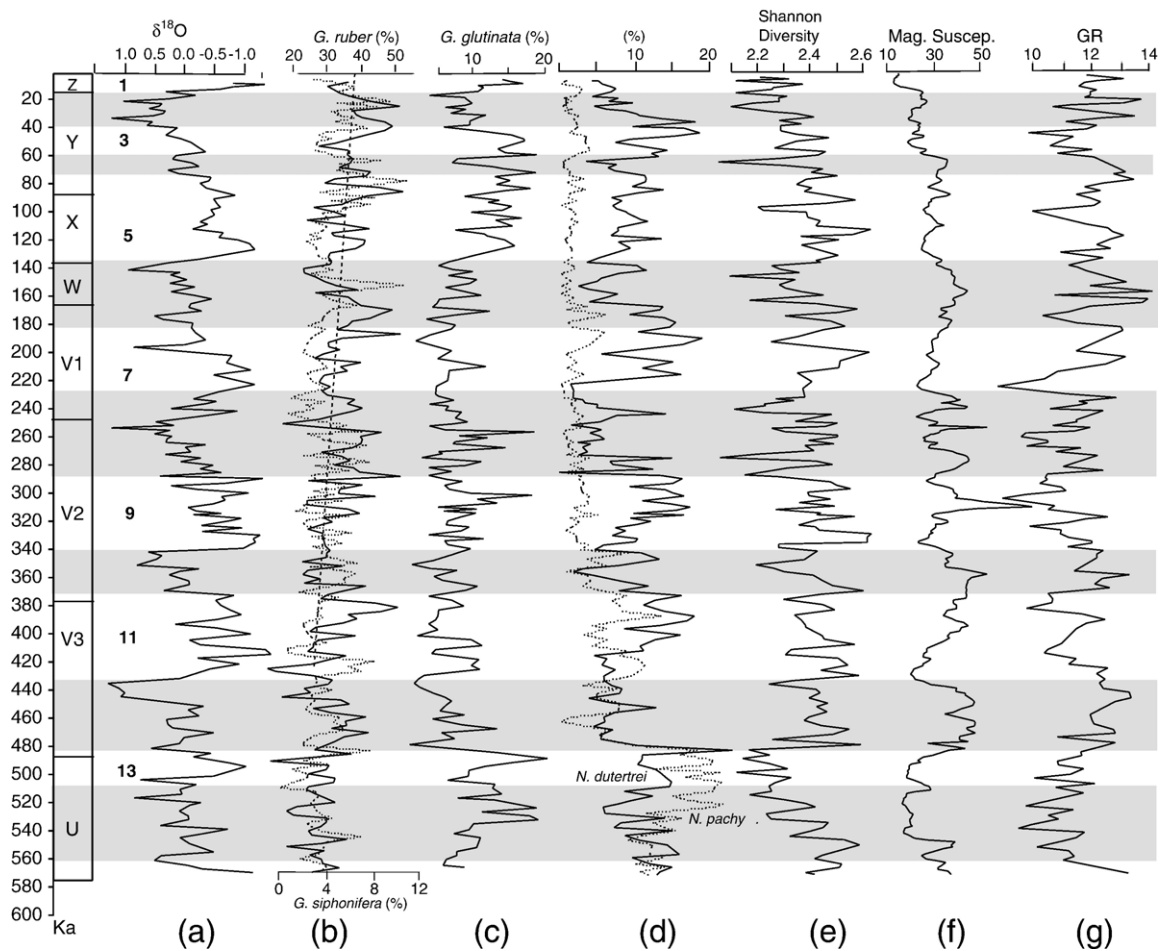


Fig. 3. Planktonic foraminifera trends and petrophysical properties of ODP Core 999A against time. (a) Martin et al.'s (1990) biostratigraphic zones and $\delta^{18}\text{O}$ record of *G. sacculifer*. Percentage abundance of: (b) *G. ruber* (continuous line) and *G. siphonifera* (dotted line), (c) *G. glutinata*, (d) *N. pachyderma* (dotted line) and *N. dutertrei* (continuous line). (e) Shannon diversity index of planktonic foraminifera. (f) Magnetic susceptibility and (g) gamma ray (GR) logs. Physical properties data from Sigurdsson et al. (1997).

SUW presently occurs. Each estimate was calculated as the mean of the best 10 analogs from the global database, using the square cord distance as the dissimilarity coefficient. The distance to the nearest analog (the mean distance) and the standard deviation were also calculated to assess the quality of the analogs.

2. Results

The $\delta^{18}\text{O}$ record of *G. sacculifer* and the percentage abundance of *G. inflata*, *G. truncatulinoides*, and *G. menardii* indicate that the top 20 m represents the last ~560 kyr (Fig. 2). This period encompasses biostratigraphic zones U to Z (Fig. 2d) previously identified in the nearby DSDP Core 502B (11°26.51'N, 79°22.69'W, 3051.5 m) and in other cores from the Gulf of Mexico and the equatorial Atlantic (Martin et al., 1990).

Planktonic foraminifera fragmentation exceeds 10% at discrete intervals during interglacial stages, more conspicuously during MIS 9, 11, 13, and 14 (Fig. 2f). This pattern was previously described by Schmidt et al. (2006), and it is comparable with the one found by Prell (1982) for DSDP 502B. Despite the potential effect of dissolution on some solution-susceptible species, e.g., *G. ruber*, dissolution on the entire assemblage does not seem to be significant as indicated by the high Shannon Diversity values prevailing during interglacial stages (Fig. 3e), when fragmentation is large (e.g., during MIS 11; Fig. 2f).

The abundance of selected species of planktonic foraminifera shows long-term trends at ODP Site 999A. For instance, *Globigerinella siphonifera* and *G. ruber* show high-amplitude, high-frequency fluctuations, relatively high abundances during glacial stages, and a steady increase towards the Holocene (Fig. 3b). *Globigerinita*

glutinata also increases towards the Holocene but tends to be more abundant during interglacial stages (Fig. 3c). In contrast, *G. truncatulinoides* (right coiling) is almost absent during MIS 13–14, peaks first in abundance during MIS 12, and exhibits a decreasing trend from late MIS 11 to the Holocene (Fig. 2b). We separated the right- and left-coiling forms of *G. truncatulinoides* and found that the left variety is seldom >1%. From molecular systematics of *G. truncatulinoides* in the tropical Atlantic (de Vargas et al., 2001), we suggest that the specimens on ODP core 999A belong to species 2, at least for the last 170 kyr when apparently genetic species 1 and 2 became differentiated. Because the only genetic species that poses a right-coiling variety is species 2 (de Vargas et al., 2001), it appears that this species (or its ancestor) was dominant at ODP Site 999A for the last 560 kyr. Unlike the downcore pattern of *G. truncatulinoides*, *Neogloboquadrina pachyderma* is only abundant at the end of MIS 14 and through MIS 13 and 11 (Fig. 3d).

Another conspicuous, long-term trend is depicted by the Shannon Diversity Index, which follow glacial/interglacial cycles but steadily decreases from MIS 12 to the Holocene (Fig. 3e), though this decrease is steeper since MIS 5. The gamma ray (GR) pattern also follows the glacial/interglacial cycles (Fig. 3g), and it is somewhat analogous to the percentage abundance patterns of *G. ruber* and *G. siphonifera*.

In general, the percentage abundance of some species (e.g., *G. inflata* and *G. menardii*) through time closely follows glacial/interglacial cycles. The exception occurs in MIS 13 and 14, when *G. menardii* is almost absent and the percentage abundance of *G. inflata* is high. Other species, like *Neogloboquadrina dutertrei* (Fig. 3d), begin to increase in abundance at the beginning of interglacial stages and drop in abundance during glacial stages. The exception to this is MIS 1.

The quality of the faunal SST estimates is fair. The squared chord ‘distance’ between fossil and modern samples provides a good measure of how well the training set provides analogs for the down-core assemblages (Barrows and Juggins, 2005). The average distance to the nearest analog is 0.174, indicating that there are sufficient analogs in the North Atlantic database to characterize the fossil assemblages. Distances tend to increase with time, and are greatest for MIS 13–14. The variability between the analogs, as measured by the standard deviation between the top ten analogs, provides a useful indicator for the internal consistency of the analogs. Typical standard deviation varies between ± 0.5 and 1.5 °C, with an average of ± 1 °C. The highest standard deviation is for MIS 14 (up to 2.2 °C). In summary, fossil assemblages from the last 500 kyr are well characterized by modern

faunas, and the fewest analogs are found for the oldest levels during MIS 13–14.

Our SST reconstructions for the western Caribbean indicate little change for the last 400 kyr, varying between 25.5 and 27.5 °C (Fig. 2g). In contrast, the reconstructed water temperatures at 50, 100 and 150 m show high-amplitude fluctuations. A comparison between our MAT SST reconstructions for ODP 999A and Schmidt et al.’s (2006) SIMMAX 28 SST reconstruction shows comparable results for August. For February, however, SIMMAX 28 results are cooler by 2 °C. Colder SSTs (~ 3 °C) were also inferred from Mg/Ca for the LGM (Schmidt et al., 2006). These cooler Mg/Ca SST reconstructions might reflect sub-surface shell growth.

In contrast to the SST estimates, the temperatures at 50, 100, and 150 m fluctuate by up to 8 °C on short time scales (Fig. 2g). At shallow depths (50 m), temperatures are ~ 4 °C cooler than SST, with the exception of most glacial stages when the difference tends to be < 2 °C. This pattern is broadly followed by temperatures at 100 and 150 m. The temperature difference between the surface and 100 m can be used as a broad proxy of the upper thermocline depth. In Fig. 2g, we distinguish a steep or “deep” from a smooth or “shallow” thermocline on the basis of the 20 °C isotherm, which is a widely accepted value for the depth of the thermocline (Conkright et al., 2002). Based on this distinction, our data suggest a deepening and warming of the upper thermocline during glacial stages, relative to its average depth and temperature during interglacial stages (Fig. 2g).

The mixed layer depth does not fluctuate systematically with glacial–interglacial cycles, though it fluctuates by as much as 30 m, e.g., between MIS 3 and 2 (Fig. 2h). Despite some noise in the signal, mixed layer depth fluctuations correspond to changes in the temperature difference between the surface and 150 m, which is small (3 – 7 °C) during glacial stages and large (8 – 12 °C) during interglacial stages. This correspondence is unsurprising because we used the same data set to derive both reconstructions. Our data then suggest that the surface ocean was stratified and that the thermocline was shallow during interglacial stages, when the temperature difference between the surface and 150 m was as much as 12 – 13 °C. Conversely, the surface ocean was apparently homogeneous and the thermocline was deep during glacial stages, when the temperature difference between the surface and 150 m was as low as 6 – 8 °C.

3. Discussion

Two paleoceanographic scenarios are evident from the microfaunal abundance patterns of ODP Core 999A:

one occurring before 480 ka (MIS 13–14), and one occurring after 480 ka (MIS 1–12). The former scenario is characterized by high abundances of *N. pachyderma* and *G. inflata*, low abundances of *G. menardii* and *G. truncatulinoides*, relatively low diversity, reduced SSTs, a shallow thermocline, and a mixed layer that was as deep as ~50 m at 520 ka. These characteristics suggest the presence of well-oxygenated thermocline waters and the influx of nutrients by either the influence of seasonal upwelling plumes and eddy-mediated entrainment, or a combination of these factors.

G. menardii is absent at ODP Site 999A during MIS 13–14, which might be related to reduced SSTs (cf. [Prell and Hays, 1976](#)). In contrast, *G. inflata* is abundant during the same time interval. *G. inflata* is an intermediate- to shallow-dwelling transitional (subtropical to polar) species that prefers SSTs between 15 and 20 °C, a reduced salinity seasonality, and the absence of the oxygen minimum zone that would interfere with its life cycle (e.g., [Luz, 1973](#); [Hemleben et al., 1989](#); [Hilbrecht, 1996](#)). The presence of *G. inflata* during glacial MIS 14 then suggests well-oxygenated and cooler conditions in thermocline waters of the western Caribbean. Conversely, the large abundance of *N. pachyderma* and *G. glutinata* at ODP Site 999A during MIS 13–14 ([Fig. 3c, d](#)), suggest a large nutrient supply brought to the surface by upwelling plumes (cf. [Hemleben et al., 1989](#)) from the Guajira system and/or by northwestward eddies that might have brought nutrients to the surface ([Schmuker and Schiebel, 2002](#)). However, the presence of *N. dutertrei* during MIS 13–14 might reflect the seasonal input of freshwater and nutrients from the Magdalena River, as it is the case in the eastern Caribbean where this species appears to be related to the deep chlorophyll maximum ([Fairbanks et al., 1982](#)) and apparently to freshwater and nutrients supply from the Amazon and Orinoco rivers ([Schmuker and Schiebel, 2002](#)). If the Magdalena River supplied the nutrients, then they were carried along the upper-water column given the distance to northern South America and the bathymetric location of ODP Site 999A. The reduced values in magnetic susceptibility (~15 SI), gamma ray (GR = ~10 counts), and SiO₂, and Al₂O₃ in ODP Core 999A sediments accumulated during MIS 13–14 ([Mora and Martinez, 2005](#)) indicate low terrigenous inputs from the Magdalena River during MIS 13–14. Furthermore, the magnetic susceptibility pattern is analogous to that found in the subtropical South Atlantic ([Schmieder et al., 2000](#)), suggesting that detrital riverine inputs were low in tropical South America. Partial support for a reduced supply of detrital sediments to ODP Site 999A is provided by the presumed southerly location of the Magdalena River's mouth during the early Pleistocene, relative to its present

location ([Bordyne, 1974](#)). An alternative hypothesis involves the input of nutrients and freshwater from other sources. For example, the Orinoco River plume presently penetrates the eastern Caribbean as far as south of Puerto Rico (67°W, 17°36'N), i.e., more than 1000 km northwest from its river mouth. The Orinoco cyclonic eddies affect the Caribbean Surface Water by reducing its salinity and by supplying nutrients (nitrate, silica, and ammonia), thus causing an increase in biomass (diatoms) and a shoaling of the chlorophyll-*a* maximum ([Corredor and Morell, 2001](#)). Besides affecting the eastern Caribbean, the Orinoco cyclonic eddies could also have reached the western Caribbean as a freshwater veneer that could have episodically disrupted the mixed layer of the ocean, thereby explaining the presence of *N. dutertrei* in ODP Site 999A sediments accumulated during MIS 13 and 14.

This paleoceanographic scenario in the western Caribbean, spanning MIS 13 and 14, corresponds to: (1) the accumulation of sapropel A (~525 ka) in the Ionian Sea, which is interpreted to be the product of a massive monsoon that yielded large volumes of freshwater from the Nile River to the eastern Mediterranean ([Rossignot-Strick et al., 1998](#)), and (2) changes in vegetation in Africa resulting from changes in moisture driven by Atlantic SSTs and the dynamics of the African monsoon ([Schefuß et al., 2003](#)). If a thermal anomaly over the tropical Atlantic existed as a result of the northward displacement of southern oceanic fronts during the mid Pleistocene ([Schefuß et al., 2004](#)), *G. inflata* would have easily invaded the Caribbean Sea. This is particularly evident in glacial MIS 14 ([Fig. 2a](#)).

The second paleoceanographic scenario, occurring from MIS 12 to MIS 1, is characterized by (1) high and fluctuating percentage abundances of *N. dutertrei*, *G. truncatulinoides*, *G. menardii*, *G. glutinata*, *G. siphonifera*, and *G. ruber*, (2) a declining trend in diversity, (3) large SSTs, and (4) a mixed layer that seldom exceeded the 40 m depth. This scenario, therefore, represents a steady change from conditions characterized by a shallow thermocline and chlorophyll maximum and the apparent presence of intermediate-water thermostads to conditions characterized by a deeper thermocline (mainly during glacial stages) and by more oligotrophic conditions. These characteristics are inferred from the declining abundance of *G. truncatulinoides*, which is an indicator of the presence of the high salinity SUW, and the increasing abundance of *G. ruber* and *G. siphonifera*, which are indicators of oligotrophic conditions in the Caribbean ([Schmuker and Schiebel, 2002](#)).

G. truncatulinoides is a subtropical species that has a long life cycle and apparently prefers a deep and permanent thermocline related to the presence of

Subantarctic Mode Water (SAMW) thermostads (Martinez, 1997) and free of any pycnocline barrier, i.e., a deep chlorophyll maximum (Lohmann and Schweitzer, 1990; de Vargas et al., 2001; Renaud and Schmidt, 2003). However, the right-coiling variety, which is also common in the South Atlantic, can be more abundant in equatorial regions where the thermocline is shallower and mostly affects the life cycle of the left-coiling form (Lohmann and Schweitzer, 1990; Mulitza et al., 1997; de Vargas et al., 2001). Furthermore, *G. truncatulinoides* also supports broad changes in salinity seasonality but not in temperature (e.g., Hemleben et al., 1989; Hilbrecht, 1996). Therefore, we interpret the decreasing abundance of *G. truncatulinoides* since late MIS 11 to MIS 1 as the result of: (1) the decreasing influence of intermediate water masses, i.e., SAMW from the South Atlantic and/or SUW from the Sargasso Sea, and (2) increasing oligotrophic conditions in the western Caribbean. This interpretation is supported by the increasing abundance of oligotrophic species, such as *G. ruber* and *G. siphonifera*. However, it is not the mere influence of water masses that controls planktonic foraminifera diversity but the structure of the upper-water column (e.g., Rutherford et al., 1999) and, similar to animal and plant species, productivity levels (Rosenzweig and Abramsky, 1993). Therefore, the geographic distribution of planktonic foraminifera, i.e., its diversity, decreases from the central gyres of the ocean towards continental margins and/or eutrophic regions. The observed correspondence between low-diversity values and a “deep” thermocline during glacial stages (Figs. 2g and 3e) then suggest the influence of subtropical gyres in the western Caribbean. This interpretation is in agreement with the hypothesis that stronger trades and westerlies in the subtropical Atlantic induced greater Ekman pumping and a deeper thermocline in the equatorial Atlantic during glacial stages, when thermohaline circulation was reduced (Luyten et al., 1983; Slowey and Curry, 1995; Curry et al., 1999). This North Atlantic Ekman pumping and the formation of SUW are apparently supported by the cyclic variability of the percentage abundance of the calcareous nannofossil *Florisphaera profunda* and of the magnetic susceptibility data, which both show periodicities of 100 and 40 kyr (Kameo et al., 2004).

Our results are in agreement with Kameo et al.’s (2004) interpretation, suggesting that the upper-water column was well-stratified and the SUW was nutrient-rich in the western Caribbean during interglacial stages, but disagree in regard to the thermocline depth which we interpret to be shallow during interglacial stages. A possible explanation for this disagreement is that our MAT reconstruction may be biased towards cooler

temperatures in the 100- to 150-m depth interval because of the presence of a nutrient-rich SUW that might have favored cool-water species during interglacial stages (e.g., *N. dutertrei*). Alternatively, the abundance of *F. profunda* could be controlled by terrigenous supply from northern South American rivers as indicated by Kameo et al. (2004). However, the low GR values observed during interglacial stages (Fig. 3g) do not support this idea. Similarly, the inverse relationship between *F. profunda* and water turbidity documented in the northwestern Pacific by Ahagon et al. (1993) also does not support the control of terrigenous supply and *F. profunda* abundance. Because both *N. dutertrei* and *F. profunda* require a deep nutricline, the presence of a nutrient-rich SUW and/or the eddy entrainment of nutrients derived from either the Magdalena River or the Guajira upwelling system could explain the observed microfossil patterns.

The absence of *G. menardii* during glacial stages, except MIS 12, could be explained by high sea-surface salinity (cf. Prell and Hays, 1976; Schmidt et al., 2004), whereas its presence during interglacial stages could be related to a shallow thermocline (cf. Thunell and Reynolds, 1984; Martinez and Bedoya, 2001, and Fig. 2g). This glacial/interglacial trend is also present in the Ceara Rise of the South Atlantic (Chaisson and Ravelo, 1997), thus suggesting a possible connection with this region. Conversely, the presence of a Sargasso assemblage, dominated by *G. ruber* in the Caribbean Sea during glacial stages, could indicate a North Atlantic influence (Prell and Hays, 1976).

If it is true that the Magdalena River supplies a larger amount of nutrients to the western Caribbean during interglacial stages, we should expect this increase to be associated with an increase in detrital particles and, thus, the GR signal at ODP 999A site. This is not the case, however. The larger values of GR occur during glacial stages, when sea-level was low and sea-surface salinity was apparently larger (Schmidt et al., 2004). The increase in GR values in glacial intervals could be explained in terms of lower sea-level that facilitated the transport of particles from the continent to the Caribbean in combination with a possible salt-mediated flocculation of clays (e.g. Gibbs, 1985).

4. Conclusions

The micropaleontological (planktonic foraminifera) study and temperature reconstruction of the uppermost 20 m of ODP Core 999A reveals that:

1. There were two hydrographic scenarios: before and after 480 ka.

2. The first paleoceanographic scenario is dominated by *N. pachyderma* and *G. inflata*, low abundances of *G. menardii* and *G. truncatulinoides*, low diversity, SSTs under 24 °C, a “shallow” thermocline, and a mixed layer that was as deep as ~50 m at 520 ka. These characteristics suggest a well-oxygenated upper thermocline and the influx of nutrients by either seasonal upwelling plumes and eddy-mediated entrainment, or a combination of these factors.
3. The second paleoceanographic scenario is dominated by high and fluctuating percentage abundances of *N. dutertrei*, *G. truncatulinoides*, *G. menardii*, *G. glutinata*, *G. siphonifera*, and *G. ruber*; a declining trend in diversity; large SSTs; and a mixed layer that seldom exceeded the 40 m depth. It represents a steady change from conditions characterized by a “shallow” thermocline and chlorophyll maximum to conditions characterized by a deeper thermocline (mainly during glacial stages) and by more oligotrophic conditions.
4. The influence of the subtropical North Atlantic on the upper thermocline was apparently larger during glacial stages when the trade winds were strong and forced the re-distribution of heat at low latitudes.
5. During interglacial stages, the influx of nutrients from the Magdalena River is stronger, and a deepening of the chlorophyll maximum occurs. The eddy entrainment of nutrients appears to be the mechanism responsible for transporting these nutrients from the Guajira upwelling and Magdalena River plumes.

Acknowledgements

This research used samples and/or data provided by the Ocean Drilling Program (ODP). ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. This material is based upon work supported by the U.S. NSF Grant ATM-0217331 and by Universidad EAFIT. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. The authors would like to thank Dr. Shikha Sharma and Daniel Rincón for their assistance in samples preparation and for interesting discussions. This manuscript greatly benefited from helpful comments by S. Harris and S. Mulitza.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.marmicro.2007.04.004](https://doi.org/10.1016/j.marmicro.2007.04.004).

References

- Ahagon, N., Tanaka, Y., Ujiie, H., 1993. *Florisphaera profunda*, a possible nannoplankton indicator of late Quaternary changes in sea-water turbidity at the northwestern margin of the Pacific. *Marine Micropaleontology* 22, 255–273.
- Andrade, C.A., Barton, E.D., 2000. Eddy development and motion in the Caribbean Sea. *Journal of Geophysical Research* 105, 26,191–26,201.
- Andrade, C.A., Barton, E.D., 2003. Evidence for an eastward flow along the Central and South American Caribbean Coast. *Journal of Geophysical Research* 108, 3185. [doi:10.1029/2002JC001549](https://doi.org/10.1029/2002JC001549).
- Andrade, C.A., Barton, E.D., 2005. The Guajira upwelling system. *Continental Shelf Research* 25, 1003–1022.
- Barrows, T.T., Juggins, S., 2005. Sea-surface temperatures around the Australian margin and Indian Ocean during the Last Glacial Maximum. *Quaternary Science Reviews* 24, 1017–1047.
- Bauch, D., Carstens, J., Wefer, G., Thiede, J., 2000. The imprint of anthropogenic CO₂ in the Arctic Ocean: evidence from planktic δ¹³C data from water column and sediment surfaces. *Deep Sea Research* 47, 1791–1808.
- Bordyne, B., 1974. Neogene biostratigraphy and paleoenvironments, lower Magdalena Basin. PhD Thesis, Louisiana State University, 265 pp.
- Chaisson, W.P., D’Hont, S.L.D., 2000. Neogene planktonic foraminifer biostratigraphy at Site 999, western Caribbean Sea. In: Leckie, R.M., et al. (Ed.), *Proceedings of the Ocean Drilling Program. Scientific Results*, vol. 165, pp. 19–56.
- Chaisson, W.P., Ravelo, A.C., 1997. Changes in upper-water structure at Site 925, late Miocene–Pleistocene: planktonic foraminifera assemblage and isotopic evidence. *Proceedings of the Ocean Drilling Program. Scientific Results* 154, 255–268.
- Conkright, M.E., Levitus, S., O’Brien, T., Boyer, T.P., Antonov, J., Stephens, C., 2002. *World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures*, CD-ROM Documentation. National Oceanographic Data Center, Silver Spring, MD. 17 pp.
- Corredor, J.E., 1979. Phytoplankton response to low level nutrient enrichment through upwelling in the Colombian Caribbean Basin. *Deep-Sea Research* 26A, 731–741.
- Corredor, J.E., Morell, J.M., 2001. Seasonal variation of physical and biogeochemical features in eastern Caribbean Surface Water. *Journal of Geophysical Research* 106, 4517–4525.
- Corredor, J.E., Morell, J.M., Lopez, J.M., Capella, J.E., Armstrong, R.A., 2004. Cyclonic eddy entrains Orinoco River plume in eastern Caribbean. *EOS* 20, 197–208.
- Curry, W.B., Marchitto, T.M., Oppo, D.W., Laarkamp, K.L., 1999. Millennial-scale changes in ventilation of the thermocline, intermediate and deep waters of the glacial North Atlantic. In: Clark, P.U., Webb, R.S., Keigwin, L.D. (Eds.), *Geophysical Monograph*, vol. 112, pp. 59–76.
- de Vargas, C., Renaud, S., Hilbrecht, H., Pawlowski, J., 2001. Pleistocene adaptive radiation in *Globorotalia truncatulinoides*: genetic, morphologic, and environmental evidence. *Paleobiology* 27, 104–125.
- Ericson, D.B., Wollin, G., 1954. Pleistocene climates and chronology of deep-sea sediments. *Science* 162, 1227–1234.
- Fairbanks, R.G., Sverdrup, M., Free, R., Wiebe, P.H., Be, A.W.H., 1982. Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin. *Nature* 298, 841–844.
- Fernandez, J., 1995. Caracterización de los productos de alteración: arenas y arcillas en suelos de Colombia. In: Malagon, D., Pulido, C., Llinas, R.D., Chamorro, C. (Eds.), *Suelos de Colombia*. Instituto Geográfico Agustín Codazzi, vol. 5, pp. 134–219.

- Gibbs, R.J., 1985. Estuarine flocs: their size, settling velocity and density. *Journal of Geophysical Research* 90, 3249–3251.
- Johns, W.E., Townsend, T.L., Fatantoni, D.M., Wilson, W.D., 2002. On the Atlantic inflow to the Caribbean Sea. *Deep Sea Research Part 1* 49, 211–243.
- Harris, S.E., Mix, A.C., 1999. Pleistocene precipitation balance in the Amazon Basin recorded in deep sea sediments. *Quaternary Research* 51, 14–26.
- Harris, S.E., Mix, A.C., King, T., 1997. Biogenic and terrigenous sedimentation at Ceara Rise, western tropical Atlantic, supports Pliocene–Pleistocene deep-water linkage between hemispheres. *Proceedings of the Ocean Drilling Program. Scientific Results* 154, 331–345.
- Hemleben, G., Spindler, M., Anderson, R.O., 1989. *Modern Planktonic Foraminifera*. Springer, New York. 363 pp.
- Hilbrecht, H., 1996. Extant planktonic foraminifera and the physical environment in the Atlantic and Indian Oceans – an Atlas based on CLIMAP and Levitus (1982) data. *Mitt. Geol. Inst. Eidgen. Tech. Hochschule und Univ. Zurich N. F.*, vol. 300. 93 pp.
- Hüls, M., Zahn, R., 2000. Millennial-scale sea surface temperature variability in the western tropical North Atlantic from planktonic foraminiferal census counts. *Paleoceanography* 13 (6), 659–678.
- Hughen, K., Lehman, S., Southon, J., Overpeck, J., Marchat, O., Herring, C., Turnbull, J., 2004. ^{14}C activity and global carbon cycle changes over the past 50,000 years. *Science* 303, 202–206.
- Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., Shackleton, N.J., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}\text{O}$ record. In: Berger, A., Imbrie, J., Hays, J., Kukla, G., Saltzman, B. (Eds.), *Milankovitch and Climate*. D. Reidel, Dordrecht, Netherlands, pp. 269–305.
- Kameo, K., Shearer, M.C., Droxler, A.W., Mita, I., Watanabe, R., Sato, T., 2004. Glacial–interglacial surface water variations in the Caribbean Sea during the last 300 ky based on calcareous nannofossil analysis. *Paleoceanography, Palaeoclimatology, Palaeoecology* 212, 65–76.
- Kara, A.B., Rochford, P.A., Hurlburt, H.E., 2003. Mixed layer depth variability over the global ocean. *Journal of Geophysical Research* 108 (C3), 3079. doi:10.1029/2000JC000736.
- Kucera, M., Weinelt, M., Kiefer, T., Pflaumann, U., Hayes, A., Weinelt, M., Chen, M.-T., Mix, A.C., Barrows, T.T., Cortijo, E., 2005. Reconstruction of sea-surface temperatures from assemblages of planktonic foraminifera: multi-technique approach based on geographically constrained calibration data sets and its application to glacial Atlantic and Pacific Oceans. *Quaternary Science Reviews* 24, 951–998.
- Lea, D.W., Pak, D.K., Peterson, L.C., Hughen, K.A., 2003. Synchronicity of tropical and high-latitude Atlantic temperatures over the last glacial termination. *Science* 301, 1361–1364.
- Leduc, G., Vidal, L., Tachikawa, K., Rostek, F., Sonzogni, C., Beaufort, L., Bard, E., 2007. Moisture transport across Central America as a positive feedback on abrupt climatic changes. *Nature* 445, 908–911.
- Luyten, J., Pedlosky, J., Stommel, H., 1983. Climatic inferences from the ventilated thermocline. *Climate Change* 5, 183–191.
- Lohmann, G.P., Schweitzer, P.N., 1990. *Globorotalia truncatulinoides* growth and chemistry as probes of the past thermocline: 1. Shell size. *Paleoceanography* 5, 55–75.
- Luz, B., 1973. Stratigraphic and paleoclimatic analysis of Late Pleistocene tropical Southeast Pacific cores. *Quaternary Research* 3, 56–72.
- Martin, R.E., Johnson, G.W., Neff, E.D., Krantz, D.W., 1990. Quaternary planktonic foraminiferal assemblages zones of the northern Gulf of Mexico, Colombia Basin (Caribbean Sea), and tropical Atlantic Ocean; graphic correlation of microfossil and oxygen isotope datums. *Paleoceanography* 5, 531–555.
- Martinez, J.I., 1997. Decreasing influence of Subantarctic Mode Water north of the Tasman Front over the past 150 kyr. *Palaeogeography, Palaeoclimatology, Palaeoecology* 131, 355–364.
- Martinez, J.I., Bedoya, G., 2001. Recent planktonic foraminifera from deep-sea sediments from the eastern Equatorial Pacific: proxies of the equatorial front in the Late Quaternary. *Journal of Marine Coastal Research* 30, 151–176.
- Mora, G., Martinez, J.I., 2005. Sedimentary metal ratios in the Colombia Basin as indicators for water balance change in northern South America during the past 400,000 years. *Paleoceanography* 20, PA4013. doi:10.1029/2005PA001132.
- Morell, J., Corredor, J., 2003. Interannual variability of subsurface high salinity water in the northern tropical Atlantic and Caribbean: a climate–biogeochemistry teleconnection. *Geophysical Research Abstracts* 5, 07566.
- Mulitza, S., Durkoop, A., Walter, H., Wefer, G., Niebler, H.S., 1997. Planktonic foraminifera as recorders of past surface-water stratification. *Geology* 25, 335–338.
- Müller-Karger, F.E., McClain, C.R., Fisher, T.R., Esaiyas, W.E., Valera, R., 1989. Pigment distribution in the Caribbean Sea: observations from space. *Progress in Oceanography* 23, 23–64.
- Müller-Karger, F.E., Castro, R.A., 1994. Mesoscale processes affecting phytoplankton abundance in the southern Caribbean. *Continental Shelf Research* 14 (2–3), 199–221.
- Oppo, D.W., Fairbanks, R.G., 1989. Carbon isotope composition of tropical surface water during the past 22,000 years. *Paleoceanography* 4, 333–351.
- Peterson, L.C., Haug, G.H., 2006. Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). *Paleoceanography, Palaeoclimatology, Palaeoecology* 234, 97–113.
- Peterson, L.C., Haug, G.H., Murray, R.W., Yarincik, K.M., King, J.W., Bralower, T.J., Kameo, K., Rutherford, S.D., Pearce, R.B., 2000. Late Quaternary stratigraphy and sedimentation at ODP Site 1002, Cariaco Basin (Venezuela). In: *Leckie, R.M., Sigurdsson, H., Acton, G.D., Draper, G. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results*, vol. 165. Ocean Drilling Program, College Station, Texas, pp. 85–99.
- Poveda, G., Waylen, P.R., Pulwarty, R.S., 2006. Annual and inter-annual variability of the present climate in northern South America and southern Mesoamerica. *Paleoceanography, Palaeoclimatology, Palaeoecology* 234, 3–27.
- Prell, W.L., 1978. Upper Quaternary sediments from the Colombia: spatial and stratigraphic variations. *Geological Society of America Bulletin* 89, 1241–1255.
- Prell, W.L., 1982. Oxygen and carbon isotope stratigraphy for the Quaternary of Hole 502B: evidence for two modes of isotopic variability. In: *Prell, W.L., Gardner, J.V., et al. (Eds.), Initial Reports of the Deep Sea Drilling Program*, vol. 68, pp. 455–464.
- Prell, W.L., Hays, J.D., 1976. Late Pleistocene faunal and temperature patterns of the Colombian, Caribbean Sea. *Geological Society of America Memoir* 145, 201–220.
- Renaud, S., Schmidt, D.N., 2003. Habitat tracking as a response of the planktic foraminifer *Globorotalia truncatulinoides* to environmental fluctuations during the last 140 kyr. *Marine Micropaleontology* 49, 97–122.
- Restrepo, J.D., Kjerfve, B., 2000. Magdalena River: interannual variability (1975–1995) and revised water discharge and sediment load estimates. *Journal of Hydrology* 235 (1–2), 137–139.

- Restrepo, J.D., Kjerfve, B., 2004. Hydrochemical aspects of major Pacific and Caribbean rivers of Colombia. In: Lacerda, L.D., Santelli, R.E., Duursma, E., Abrao, J.J. (Eds.), *Facets of Environmental Geochemistry in Tropical and Subtropical Environments*. Springer Verlag, Berlin, pp. 169–187.
- Restrepo, J.D., Zapata, P., Diaz, J.M., Garzon-Ferreira, J., Garcia, C.B., 2006. Fluvial fluxes into the Caribbean Sea and their impact on coastal ecosystems: the Magdalena River, Colombia. *Global and Planetary Change* 50, 33–49.
- Rossignot-Strick, M., Paterne, M., Bassinot, F.C., Emeis, K.C., De Lange, G.J., 1998. An unusual mid-Pleistocene monsoon period over Africa and Asia. *Nature* 392, 269–272.
- Rosenzweig, M.L., Abramsky, Z., 1993. How are diversity and productivity related? In: Ricklefs, R.E., Schluter, D. (Eds.), *Species Diversity in Ecological Communities: Historical and Geographical Perspectives*. University of Chicago Press, pp. 52–65.
- Rutherford, S., D'Hont, S., Prell, W., 1999. Environmental controls on the geographic distribution of zooplankton diversity. *Nature* 400, 749–752.
- Schefuß, E., Schouten, S.S., Jansen, J.H.F., Sinninghe Damste, J.S., 2003. African vegetation controlled by tropical sea surface temperatures in the mid-Pleistocene period. *Nature* 422, 418–421.
- Schefuß, E., Sinninghe Damste, J.S., Jansen, J.H.F., 2004. Forcing of tropical Atlantic sea surface temperatures during the mid-Pleistocene transition. *Paleoceanography* 19, PA4029. doi:10.1029/2003PA000892.
- Schmidt, M.W., Spero, H.J., Lea, D.W., 2004. Links between salinity variation in the Caribbean and North Atlantic thermohaline circulation. *Nature* 428, 160–163.
- Schmidt, M.W., Vautravers, M.J., Spero, H.J., 2006. Western Caribbean Sea surface temperatures during the late Quaternary. *Geochemistry, Geophysics, Geosystems* 7 (2), Q0210. doi:10.1029/2005GC000957.
- Schmieder, F., von Dovenek, T., Bleil, U., 2000. The mid-Pleistocene climate transition as documented in the deep South Atlantic Ocean: initiation, interim state and terminal event. *Earth and Planetary Science Letters* 179, 539–549.
- Schmuker, B., Schiebel, R., 2002. Planktonic foraminifers and hydrography of the eastern and northern Caribbean Sea. *Marine Micropaleontology* 46, 387–403.
- Sheng, J., Tang, L., 2003. A numerical study of circulation in the western Caribbean Sea. *Journal of Physical Oceanography* 33, 2049–2069.
- Sigurdsson, H., Leckie, R.M., Acton, G.D., et al., 1997. *Proceedings of the Ocean Drilling Program. Initial Reports (CD-ROM)*, vol. 165. Texas A & M University, College Station, TX.
- Slowey, N.C., Curry, W.B., 1995. Glacial–interglacial differences in circulation and carbon cycling within the upper western North Atlantic. *Paleoceanography* 10, 715–732.
- Thunell, R., Reynolds, L.A., 1984. Sedimentation of planktonic foraminifera: seasonal changes in species flux in the Panama Basin. *Micropaleontology* 30, 243–262.
- Yarincik, K.M., Murray, R.W., Lyons, T.W., Peterson, L.C., Haug, G.H., 2000. Oxygenation history of bottom waters in the Cariaco Basin, Venezuela, over the past 578,000 years: results from redox-sensitive metals (Mo, V, Mn, and Fe). *Paleoceanography* 15, 593–604.