

A HIGH-RESOLUTION LATE QUATERNARY
UPWELLING RECORD FROM THE ANOXIC
CARIACO BASIN, VENEZUELA

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Abstract. Results are presented of a high-resolution study of the planktonic foraminiferal faunas from two piston cores recovered from the Cariaco Basin in the southern Caribbean Sea. The Cariaco Basin is a small anoxic marine basin on the northern continental margin of Venezuela in an area today characterized by both seasonal trade wind-induced upwelling and pronounced dry and wet seasons. Our data indicate that large changes in the intensity of upwelling, and hence trade wind strength, occurred in this region during the last glacial-interglacial transition and throughout the Holocene. During the last glacial lowstand of sea level, the Cariaco Basin was effectively isolated from the open Caribbean along its northern margin by the then largely emergent Tortuga Bank. Oxic conditions existed in the deep Cariaco Basin at this time, and surface productivity was low. About 12,600 years ago, the abrupt initiation of strong upwelling over the basin and the onset of permanent anoxia in the deep waters are coincident with the rapid rise of sea level that accompanied the peak

interval of meltwater discharge from the Laurentide Ice Sheet into the Gulf of Mexico. Strong upwelling between 12,600 and about 10,000 years ago may be related to intensified trade winds resulting, in part, from cooler sea surface temperatures in the Caribbean and Gulf of Mexico. After about 10,000 years ago, upwelling intensity was reduced, though highly variable. A preliminary frequency domain analysis of the Holocene portion of the Cariaco Basin time series suggests that solar forcing may explain a significant component of the century-scale variability observed in the record of upwelling and trade wind strength.

INTRODUCTION

Circulation in the tropical oceans is strongly coupled to the dynamics of circulation in the overlying atmosphere. Whereas the Indian and Pacific oceans are heavily influenced by monsoonal and El Niño-Southern Oscillation (ENSO) variability, respectively, circulation in the tropical North Atlantic is largely forced by seasonal and interannual variations in the trade winds and in the position of the Intertropical Convergence Zone (ITCZ [Hastenrath and Lamb, 1977; Katz, 1987]). Along the northern coast of South America, upwelling of cool, nutrient-rich water occurs in response to the prevailing trade wind field and varies in frequency and intensity in response to movement of the ITCZ [Redfield, 1955; Wust, 1964; Richards, 1960, 1975; Aparicio, 1986].

¹Deceased December 29, 1989.

Sediments of the Cariaco Basin, a small anoxic marine basin situated along the southern Caribbean margin, preserve a detailed late Quaternary record of this upwelling and hence a history of past trade wind variations in the region.

The Cariaco Basin is a small (160 km long, 60 km wide), deep (up to 1400 m), east-west trending depression located on the northern continental shelf of eastern Venezuela (Figure 1). Largely isolated from the open Caribbean Sea by a series of shallow sills, the Cariaco Basin is presently anoxic below a depth of about 300 m. Since the early work of Heezen et al. [1958, 1959], it has been known that sediments that accumulate here are nearly undisturbed by bioturbation, exhibit high deposition rates (20-100 cm/kyr), and contain an extremely well-preserved assemblage of both calcareous and siliceous microfossils. In this paper, we present selected results of a high-resolution study of the planktonic foraminiferal faunas from two piston cores recovered from within the anoxic portion of the Cariaco Basin. As part of the Climate: Long-Range Investigation, Mapping, and Prediction

(CLIMAP) Project, Kipp and Towner [1975] published preliminary findings from one of these cores, data which suggested that upwelling over the basin had varied in strength over the last few hundreds of years. The data set that we describe here builds upon this earlier work but is much more comprehensive in scope: a 17,000-year foraminiferal-based record with an average sample spacing of about 30 years. These new data indicate that trade wind-induced upwelling over the Cariaco Basin has undergone considerable variability in the past over time scales ranging from 10^2 to 10^4 years.

REGIONAL AND OCEANOGRAPHIC SETTING

Structurally similar to fault-bounded basins known from the California Borderland [Lidz et al., 1969], the Cariaco Basin is the largest pull-apart basin found along the Caribbean-South American plate boundary [Schubert, 1982] and has the distinction of being, after the Black Sea, the second largest anoxic marine basin in the world [Richards, 1975]. What is called the Cariaco Basin actually consists of two small

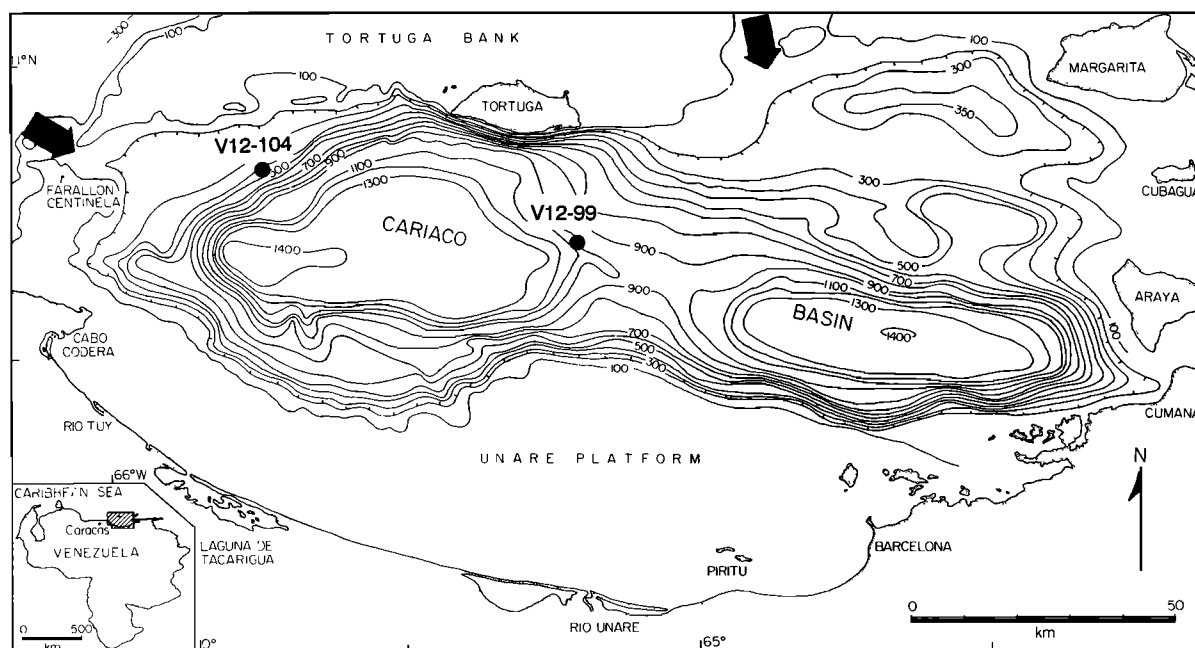


Fig. 1. Bathymetric map of Cariaco Basin showing location of piston cores examined in this study. Arrows indicate principal inlet sills that control horizontal exchange with the open Caribbean Sea. Regional bathymetry comes from a detailed recent survey (June 1990) of the basin led by the two senior coauthors (R/V *Thomas Washington*, cruise PLUME leg 7).

subbasins that both reach depths of about 1400 m, separated from each other by a central saddle that shoals to about 900 m (Figure 1). Along its northern margin, the basin is bounded by a submarine ridge that extends from Margarita Island west to Cabo Codera on the Venezuelan mainland. The deepest connections through this ridge between the Cariaco Basin and the open Caribbean are at depths close to 146 m near Farallon Centinela at the western end of the basin and near 120 m across the wider sill to the north between Tortuga and Margarita Island [Richards and Vaccaro, 1956; Maloney, 1966].

The most significant aspect of water circulation in the Cariaco Basin is the restriction of horizontal exchange with the rest of the Caribbean imposed by the shallow inlet sills. This effect is clearly seen in depth profiles of conservative hydrographic properties, with uniform temperatures (16–17°C) and salinities ($\sim 36.20/00$) observed in the Cariaco Basin below sill depth [Richards, 1975]. Vertical exchange within the basin is also inhibited by the presence of a strong pycnocline below the 100-m-thick mixed layer. Because of the limited deepwater renewal, dissolved oxygen in the basin is not replenished rapidly enough to offset the demand created by high upwelling-induced surface productivity, and the Cariaco Basin deep waters are anoxic below about 300 m [Richards and Vaccaro, 1956; Scranton et al., 1987].

The general pattern of surface circulation in the Caribbean and the causal relationships between that circulation and the annual march of the trade wind fields are reasonably well known [e.g., Wust, 1964; Hastenrath, 1978]. Surface circulation in the Caribbean Sea as a whole is dominated by the general east-to-west flow of the Caribbean Current which carries equatorial Atlantic water into the Gulf of Mexico and ultimately to the North Atlantic. Due to the seasonal migration of the ITCZ, however, the patterns of upwelling along the southern margin of the Caribbean, as well as precipitation patterns and circulation patterns in the western tropical Atlantic and eastern Caribbean, are markedly skewed. Between January and March, when the ITCZ is south of the equator, strong easterly trade winds predominate along the coast of Venezuela and result in Ekman drift-induced upwelling of cool, nutrient-rich waters (Figure 2). In the Cariaco Basin itself, vertical advection is generally most active during January and February, with isotherms raised by as much as 90–175 m and

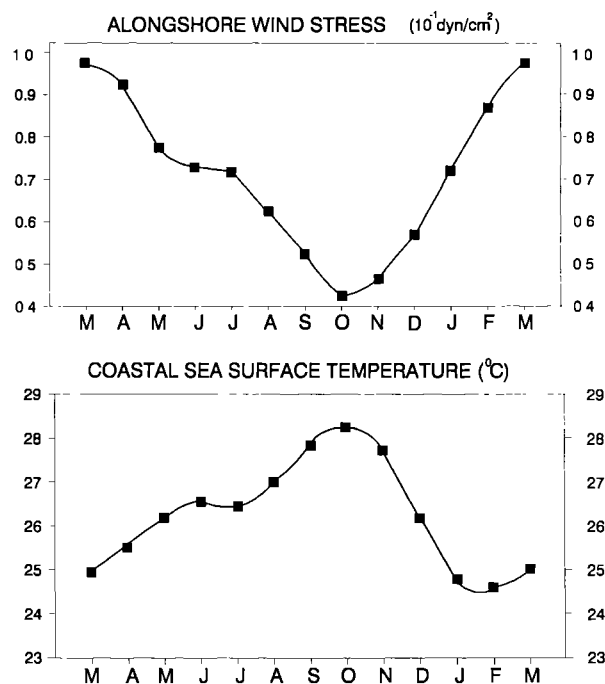


Fig. 2. The mean seasonal cycle of (top) alongshore wind stress and (bottom) coastal sea surface temperature as recorded between 1965 and 1970 at La Guaira, just west of the Cariaco Basin on the Venezuelan coast. Coolest SSTs are associated with high wind stress that occurs in the winter-spring season of coastal upwelling. (Data courtesy of R. Aparicio, Universidad de Oriente, Cumana, Venezuela.)

sea surface temperatures recorded as cool as 22°C [Herrera and Febres-Ortega, 1975; Kinder et al., 1985]. At such times, the highest gross production rates over the Basin ($2.3 \text{ g C m}^{-2} \text{ day}^{-1}$) are some 20 times greater than those found in the open Caribbean [Curl, 1960], with upwelling somewhat stronger over the eastern subbasin than over the western subbasin [Okuda et al., 1969]. Beginning in June or July, when the ITCZ has reached its northernmost position over the Venezuelan coast, the upwelling is weakened or largely shut off and sea surface temperatures warm to 27–28°C [Herrera and Febres-Ortega, 1975; Aparicio, 1986].

The seasonal march of the ITCZ also imposes a dry and a wet season on the region [Etter et al., 1987], with rainfall variations having a strong influence on the discharge of rivers that affect the southern Caribbean. At present, the dry season over the southern Caribbean begins in January when the ITCZ is farthest south.

When combined with the strong trade winds along the coast at this time, the result is intense evaporation. The dry season ends in June or July as the northward motion of the ITCZ triggers the rainy season north of about 5°N [Richards, 1975]. Fluvial discharge from the Orinoco River, which exerts the dominant influence on salinity depressions over the eastern Caribbean [Gade, 1961; Muller-Karger, 1988], reaches a maximum between about August and September of each year. Over the Cariaco Basin, surface salinities typically exceed 36.50/00 for much of the year, dipping below that level only during these peak months of freshwater discharge [Ljoen and Herrera, 1965]. Fluvial input from the Manzanares River, which empties into the eastern end of the Cariaco Basin near Cumana (Figure 1), also peaks at about this time, although the flow of this and other smaller rivers along the coast (the Neveri, Unare, and Tuy) is volumetrically much smaller and is thought to have little effect on the present-day salinity of the basin [Richards, 1975].

SEASONAL PLANKTON BIOLOGY

The pronounced seasonal changes in the surface hydrography along the north coast of Venezuela give rise to a systematic seasonal turnover in the local biota [Ferraz-Reyes, 1983]. During the summer-fall rainy season when coastal upwelling is reduced or absent, stability in the water column is high, and the level of primary productivity is comparatively low. Blue-green algae and dinoflagellates tend to dominate the phytoplankton, with diatoms only of minor importance. During the dry season, the strong upwelling of cool, nutrient-rich water along the coast causes high productivity, with diatoms the dominant primary producers. Satellite observations of pigment distributions using Coastal Zone Color Scanner imagery [Muller-Karger, 1988; Muller-Karger et al., 1989] confirm this basic seasonal contrast in phytoplankton abundance.

The presence of colder waters, at least through part of the year, along the north coast of Venezuela gives rise to a planktonic foraminiferal population that is distinctly different from that of the open Caribbean Sea. Perhaps the most notable difference is the high abundance of *Globigerina bulloides* found in both the coastal waters and in sediments underlying the upwelling zone [Miro, 1971; Rogl and Bolli, 1973]. *G. bulloides*, typically a subpolar species [Bé and Tolderlund, 1971;

Kipp, 1976], adheres to this association with tropical upwelling environments elsewhere in the world as well and has been used by numerous investigators as a proxy index for upwelling conditions [Duplessy et al., 1981; Ganssen and Sarnthein, 1983; Prell, 1984a, b; Prell and Van Campo, 1986]. Noting the occurrence of *G. bulloides* in both subpolar and tropical regions, Reynolds and Thunell [1985] have suggested that the distribution and abundance of this species are directly related to food availability and not to a specific temperature range.

The study by Miro [1971] of plankton tow samples from the surface waters of the Cariaco Basin provides important data on seasonal turnover in the local foraminiferal population, and supports the use of *G. bulloides* as an upwelling indicator. Figure 3, adapted from Miro [1971], summarizes the generalized annual cycle. During January and February, the portion of the upwelling season when vertical advection is strongest, the initial bloom of phytoplankton (mainly diatoms) over the Cariaco Basin is closely followed by a nearly monospecific

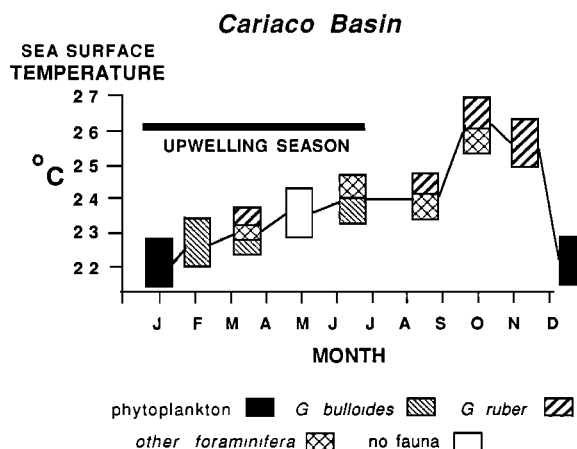


Fig. 3. Modern seasonal changes in the planktonic foraminiferal population of the Cariaco Basin that occur in response to the seasonal cycle of upwelling (adapted from Miro [1971]). During January and February, when vertical advection is most intense, a local phytoplankton bloom is closely followed by a bloom of *Globigerina bulloides*. This represents the time of maximum standing stock and minimum faunal diversity in coastal surface waters. During the nonupwelling season, minimum standing stock coincides with a more diverse living assemblage usually dominated by *Globigerinoides ruber*.

bloom of *G. bulloides*. Foraminiferal standing stock is at a maximum and faunal diversity at a minimum in surface waters along the Venezuelan coast at this time. Although faunal diversity increases later in the upwelling season, *G. bulloides* remains a dominant component of the fauna. During the nonupwelling season, conditions of minimum standing stock over the basin are found to coincide with a more diverse living assemblage of foraminifers usually dominated by the warm water taxon *Globigerinoides ruber*. Conspicuously absent from the assemblage data reported for this part of the year is *G. bulloides*. Based on his distribution of samples, Miro [1971] also noted a strong positive correlation between the distribution of *G. bulloides* and measured chlorophyll concentration.

MATERIALS AND CHRONOLOGY

We focus here on data from two piston cores recovered from the anoxic portion of the Cariaco Basin by the R/V *Vema* in the late 1950's (Figure 1). Core V12-104 (10°52.1'N, 65°44.8'W) was recovered at a water depth of 466 m from the northwestern flank of the western deep. Core V12-99 (10°42.2'N, 65°12.4'W) was collected on the western edge of the central saddle at a water depth of 1005 m. Both cores exhibit limited flow in at their base; the length of good core in each is about 5.5 m.

Two major sediment units are apparent in both cores (Figure 4), units that are consistent with those described by Heezen et al. [1958, 1959], Athearn [1965], Lidz et al. [1969], and Needham [1972] from piston cores, and by Edgars et al. [1973] from Deep Sea Drilling Project (DSDP) Site 147. The upper sediment unit consists of dark green to grayish-green silty clays that are faintly laminated over the top 2 m of core and much more distinctly laminated below. Where visible, the laminae are millimeter- to submillimeter-scale in thickness and are recorded as light-dark sediment couplets. Sediments of the lower unit in both cores consist of homogeneous yellowish-brown silty clays that are weakly bioturbated, suggesting deposition under oxic conditions. In both cores, the contact between upper and lower sediment zones is fairly sharp. This contact occurs at 375 cm in V12-104 and at 455 cm in V12-99. The more gradational contact within the upper anoxic unit between weakly and strongly laminated intervals is centered on a depth of about 200 cm in both cases.

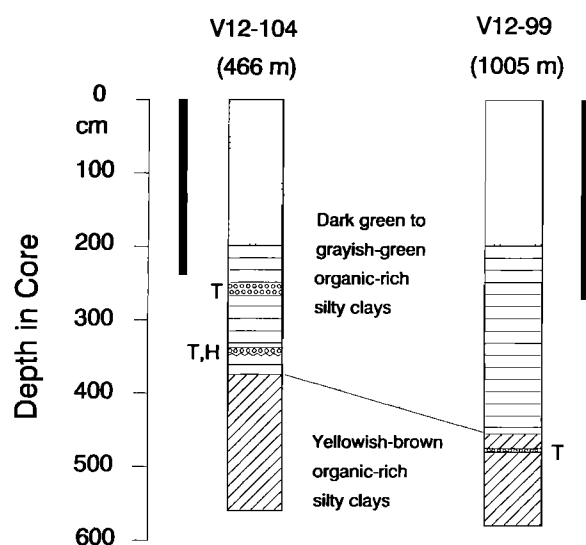


Fig. 4. Lithologic description of piston cores V12-104 and V12-99 from the Cariaco Basin. Symbol types indicate the distribution of (from top to bottom) weakly laminated, strongly laminated, and weakly bioturbated intervals. The location of several thin turbidites in both cores are shown, as well as the position of an inferred hiatus in V12-104. Vertical black bars identify the Z zone of Ericson and Wollin [1968] in these cores as defined by the stratigraphic presence of *Globorotalia menardii*.

Core V12-104 was sampled for this study at approximately 1-cm intervals, with each sample integrating 1 cm of deposition. All samples from this core were gently disaggregated and washed through a 63- μ m sieve under a weak spray of water. The remaining coarse fraction was then oven dried at 50°C and dry sieved. For core V12-99, washed coarse fractions from samples taken at an average interval of 3 cm were made available by D.B. Ericson of the Lamont-Doherty Geological Observatory. For all of the foraminiferal census data presented here, species counts were made by N.G. Kipp on splits of the >150- μ m size fraction containing approximately 300 or more specimens.

Because of the extremely close sampling and the lack of bioturbation throughout most of the sequence, the planktonic foraminiferal records from the two cores could be used both to make highly detailed intercorrelations and to identify several short intervals where stratigraphic problems affect the records. Based upon careful faunal comparisons, we have concluded that deposition was continuous and that an

essentially linear correspondence with depth exists between the two cores down to a subbottom depth of about 240 cm (Figure 5). Below that level, sedimentation rates in core V12-99 increase relative to those in V12-104 despite the presence of two thin turbidites (Figure 4) observed in the archive section and in original core photos of V12-104 that artificially expand its section. To remove these turbidites, we subtracted out sediment between 258-267 cm and 338-349 cm from the V12-104 record. Further comparison suggested an additional complication in V12-104 in the form of a hiatus at the base of the lower turbidite. We suspect that erosion associated with deposition of that turbidite has removed faunal events in V12-104 for which there are obvious counterparts in V12-99. Our best estimate at this time, based on the position of recognizable events in both cores and relative accumulation rate differences, is that approximately 30 cm of section is missing from V12-104. In V12-99, samples were eliminated between 475-480 cm to correct for the presence of a single thin turbidite observed in that core.

Our age control for this study is provided by a series of 12 radiocarbon dates made on samples of bulk carbonate from core V12-104. To

correct for the difference in radiocarbon content between surface waters and atmosphere, 400 years were first subtracted from the measured radiocarbon age of each dated level [Bard, 1988]. The resulting series of dates show no downcore age reversals. An age model for V12-104 was then constructed using the corrected radiocarbon dates and a depth scale corrected for the exclusion of turbidites and the inclusion of 30 cm of missing section. After numerous experiments, we settled on a chronology based on a fourth-order polynomial fit to the data ($R^2=0.996$; Figure 6). This age model provides a good fit to all of the radiocarbon dates except one at 11,750 years B.P., a date which we feel is likely to be contaminated by older material. For core V12-99, a chronology for events was developed by applying the radiocarbon-based age model of V12-104 via the correlation shown in Figure 5.

The age model assigned to V12-104 indicates an age of about 1000 years at the top of the piston core. Our attempts to patch together a more complete faunal record by using the short trigger-weight core were unsuccessful because of the poor match between faunal events in it and the piston core; we therefore suspect overpenetration of the piston core in the fine-grained soupy sediments and the resultant loss of the topmost sediment. Although core V12-99

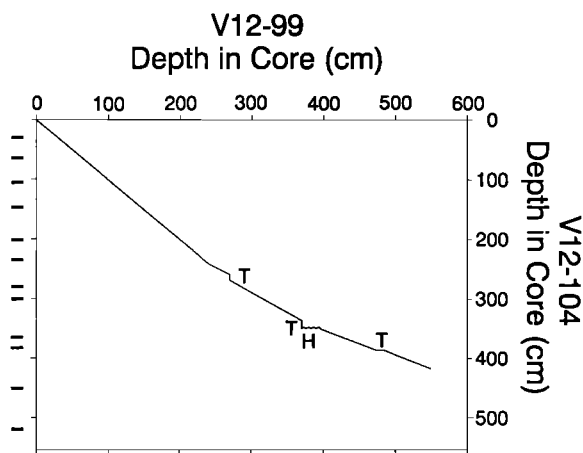


Fig. 5. Line of correlation between piston cores V12-104 and V12-99 based on a comparison of faunal events in the two cores. The stratigraphic position of turbidites (T) and the V12-104 hiatus (H) are shown. Although only the depths at which relative changes in sedimentation rate occur are indicated, individual line segments are in each case well constrained by multiple events. Symbols along the left vertical axis indicate the distribution of radiocarbon dated intervals in V12-104.

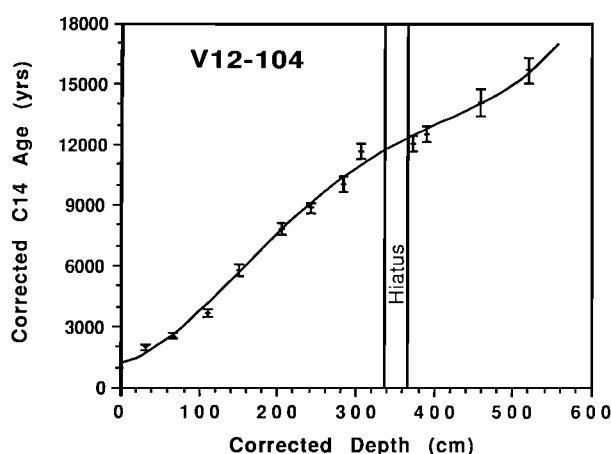


Fig. 6. Age model for core V12-104 based on 12 radiocarbon dates of bulk carbonate. All dates have been adjusted by 400 years to correct for the difference between surface water and atmospheric radiocarbon content. Error bars on the radiocarbon dates indicate $\pm 1 \sigma$ of the analytical data. Subbottom depths in V12-104 are corrected as described in text.

records events at its top not recorded in V12-104, the similar lack of a match with its trigger-weight core argues for missing section as well. At the base of V12-104, extrapolation of our age model yields an estimated age of about 17,000 years for the oldest sediment recovered. Our more indirect age model for V12-99 yields an estimated age of about 13,300 years for the base of that record.

Over the last 9000 years or so, where a linear correspondence with depth exists between the two cores (~0-240 cm), sedimentation rates in both averaged about 30 cm/1000 years. In core V12-104, this average rate of sedimentation gives us a temporal resolution of approximately 33 years given our 1-cm sampling interval. As our age model (Figure 6) suggests, sedimentation rates in V12-104 increase downcore, reaching a maximum of ~60 cm/1000 years at or about 12,000 years ago, before they drop again toward the base of the core. At peak sedimentation rates in V12-104, our 1-cm sampling translates to an estimated temporal resolution of about 17 years.

Based on our between-core correlations (Figure 5), we have already inferred that sedimentation rates in V12-99 are proportionately higher than those in V12-104 at subbottom depths greater than 240 cm (i.e., before ~9000 years ago). As in V12-104, sedimentation rates in V12-99 appear to have reached maximum values about 12,000-13,000 years ago, near the very base of the core. The highest sedimentation rates recorded at that time in V12-99 approach 110-115 cm/1000 years. With the wider average sample spacing of that core (~3 cm), our closest temporal sampling (25-30 years) is achieved in V12-99 during this period of peak accumulation.

RESULTS AND DISCUSSION

Planktonic Foraminiferal Time Series

The two piston cores examined in this study were collected some 50 km apart, yet their remarkably similar time series of foraminiferal abundance indicate that the faunal records shown here are representative of at least the western and central portions of the Cariaco Basin. Although Rogl and Bolli [1973] commented on the very diverse nature of the endemic fauna, our quantitative investigation has found that only a small number of the planktonic foraminiferal taxa routinely exceed 5% of the total assemblage. Large downcore variations in the relative abundances of the

dominant taxa, however, indicate considerable past change in the surface waters of this region. These variations are illustrated in Figure 7 for core V12-104 and in Figure 8 for core V12-99.

The record of *G. bulloides* in both cores is of primary interest because of the strong seasonal association of this species with upwelling conditions in the modern region. In sediments deposited prior to about 12,600 years ago, *G. bulloides* is generally found in low relative abundances (<10%), although this pattern is interrupted in the longer record of V12-104 by several short intervals where it makes up to 30-50% of the population. At 12,600 years ago, both cores recorded a dramatic increase in the average abundance of *G. bulloides* in the Cariaco Basin. Shortly thereafter, core V12-99 records a relatively brief (~500 years) drop in *G. bulloides* abundance, an event which is

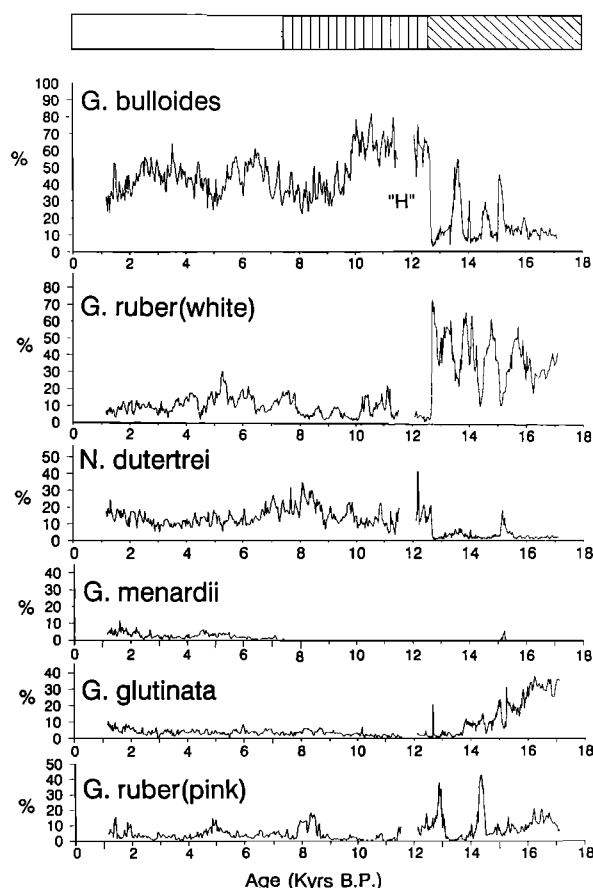


Fig. 7. Time series of relative abundance changes in selected planktonic foraminifer species from core V12-104. Lithologic intervals are indicated across the top using the symbols defined in Figure 4. H is position of hiatus.

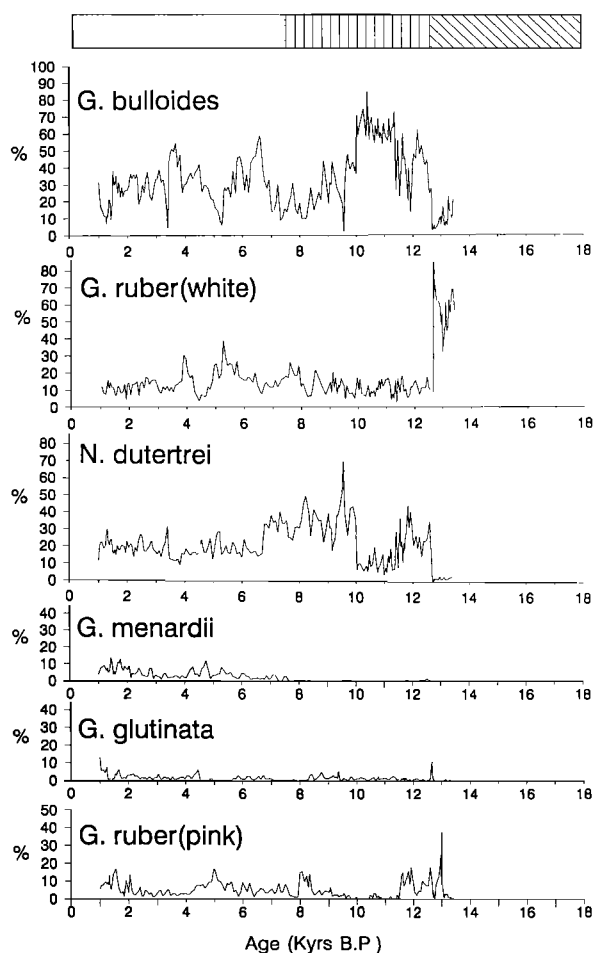


Fig. 8. Time series of relative abundance changes in selected planktonic foraminifer species from core V12-99. Lithologic intervals are indicated across the top using the symbols defined in Figure 4.

missing in V12-104 and whose absence largely forms the basis for our presumption of a hiatus in that core. With the exception of this short interval, however, *G. bulloides* was clearly the dominant local taxon between about 12,600 and 10,000 years ago, comprising between 60 and 80% of the foraminiferal fauna. After about 10,000 years ago, the relative abundance of *G. bulloides* dropped abruptly in both cores but remained well above average levels found in the lower glacial section. Throughout the record of the last 10,000 years, *G. bulloides* abundance fluctuations show very similar patterns of broad low-frequency maxima and minima, with a large amount of high-frequency variability clearly superimposed on these longer-period late Holocene variations.

Prior to 12,600 years ago, when *G. bulloides* abundance was low, the white morphotype of *G. ruber* dominated the foraminiferal assemblage in the Cariaco Basin (Figures 7 and 8). The high relative abundances of *G. ruber*, today the major component of the warm, nonupwelling season fauna (Figure 3 [Miro, 1971]), suggests that upwelling was shut off or at least greatly reduced during last glacial time. Sediments deposited during this interval are those of the lower yellowish-brown silty clay facies. The color of the sediment plus the presence of benthic foraminifers (Figure 9) indicates oxic conditions in the deep basin, although the observation that this is an impoverished, bolivinid-dominated fauna would suggest low oxygen levels and a restricted circulation [e.g., Ingle et al., 1980; Resig, 1981].

We interpret the abrupt rise in *G. bulloides* abundance about 12,600 years ago to indicate the initiation of strong Ekman drift-induced upwelling over the Cariaco Basin. The onset of strong upwelling at the surface was accompanied by the development of anoxic conditions in the deep Cariaco Basin, as indicated by the disappearance of benthic foraminifers (Figure 9) and the change in lithology from bioturbated to well-laminated sequences clearly deposited under reducing conditions (Figure 4). Qualitatively, the distribution of biogenic silica would appear to support an upwelling interpretation, with diatoms found to be particularly abundant in the distinctly laminated interval where *G. bulloides* dominates the foraminiferal assemblage. Within this interval, diatom frustules tend to be concentrated in the lighter colored sediment laminae and presumably record seasonal bloom conditions. Although the age control at the one available DSDP site in the Cariaco Basin is very poor, the general association at various subsurface levels of *G. bulloides* and diatom-rich layers can also be found in the data and discussion of DSDP Site 147 by Rogl and Bolli [1973].

Neogloboquadrina dutertrei, a taxon also commonly recorded in abundance in upwelling regions or in areas marginal to high productivity [e.g., Bradshaw, 1959; Bé and Tolderlund, 1971; Thiede, 1975; Bé, 1977], reached its maximum abundance in the Cariaco Basin between about 10,000 and 7000 years ago (Figures 7 and 8), with a secondary peak between about 12,600 and 11,500 years ago. These intervals of greater *N. dutertrei* abundance tend to bracket the interval of highest *G. bulloides* abundance; this is more

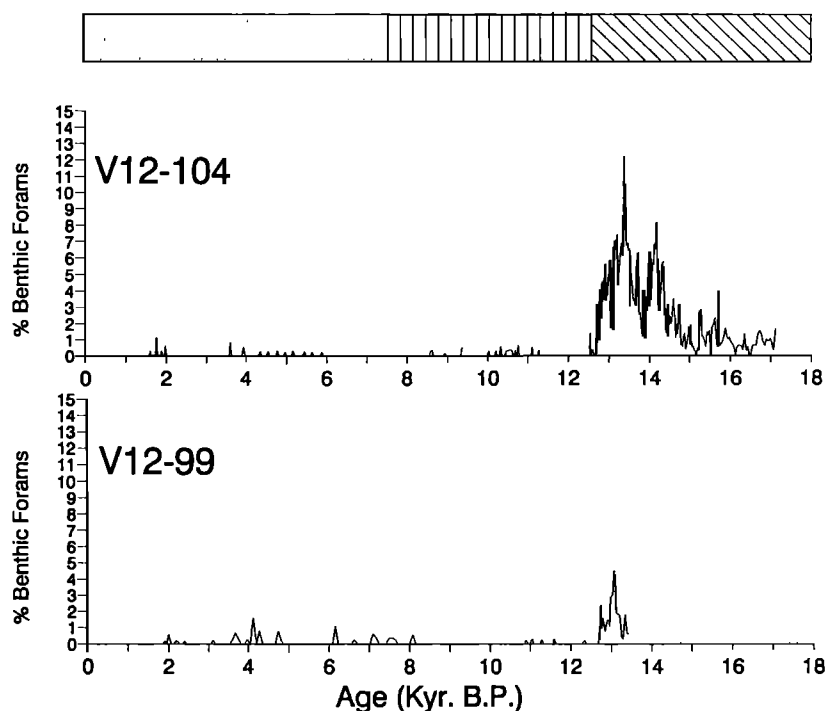


Fig. 9. Percent abundance of benthic foraminifera in cores V12-104 and V12-99 as a function of estimated age and lithology. Percent abundance is calculated as (number benthic / number benthic + planktonic foraminifera) \times 100.

easily seen in the record of core V12-99 (Figure 8), where *N. dutertrei* is also, on average, more commonly found. Foraminiferal preservation is excellent at both sites during these times so that the elevated abundances of *N. dutertrei* in V12-99 appear to record a real ecological response and not one biased by increased dissolution at this deeper site. In both cores, the stratigraphic level at which *N. dutertrei* begins to decrease in abundance (\sim 7000 years ago) occurs shortly upcore of the point at which the character of the sediment changes gradually from the more distinctly laminated facies below to the more faintly laminated facies above. Although sediment laminations become less pronounced through this interval, the continuity of anoxic conditions throughout the remainder of the Holocene is implied by the near total absence of a preserved benthic fauna (Figure 9). This indicates that upwelling-related productivity, though apparently less intense after about 7000 years ago, was still sufficient to create an oxygen demand in the deep waters of the Cariaco Basin greater than that which could be supplied by normal inflow processes.

The abundance patterns of a number of lesser species are also illustrated in Figures 7 and 8.

Percent census data on *Globorotalia menardii*, for example, were used to identify the Y/Z biostratigraphic boundary of Ericson and Wollin [1968] shown in Figure 4. Based on our age model, the first consistent appearance in the Cariaco Basin of *G. menardii*, which marks the beginning of the Z zone, occurs somewhere between 7500 and 7000 years ago. This is significantly later than the 11,000 year B.P. date for the Y/Z boundary reported by Broecker et al. [1960] and Ericson and Wollin [1968], but is close to the accelerator mass spectrometry (AMS) ^{14}C dated first appearance age of 6600 years reported by Jones [1988]. In sediments of our cores older than what we consider to be about 7000-7500 years, the presence of occasional specimens of *G. menardii* can probably be attributed to minor reworking and downslope transport.

Globigerinita glutinata (Figures 7 and 8) typically makes up less than 5% of the total assemblage in sediments deposited during the anoxic phase of the Cariaco Basin. The longer record of V12-104, however, indicates that *G. glutinata* was considerably more abundant during glacial times, making up to 35% of the assemblage near the base of the record. Unlike

the abrupt shift 12,600 years ago from a white *G. ruber*-dominated fauna to one dominated by *G. bulloides*, the decrease in *G. glutinata* was more gradual, spread over some 3000 years. In the modern ocean, *G. glutinata* is a fairly ubiquitous species, occurring from tropical to polar regions [Bé and Tolderlund, 1971]. In tropical and subtropical waters, sediment trap studies have reported that *G. glutinata* is often one of the more dominant taxa collected [Thunell and Honjo, 1981; Thunell and Reynolds, 1984]. The rather cosmopolitan distribution of this species in the water column of the Atlantic is accurately reflected in its distribution in the underlying surface sediments [Kipp, 1976]. In the open Caribbean, the map of Kipp [1976] indicates relative sea bed abundances of 2-10% for *G. glutinata*, numbers that are similar to what we observe for the most recent part of the Cariaco Basin record. Our finding that *G. glutinata* is more abundant in glacial age sediments is consistent with what has been reported for the open Caribbean by Prell and Hays [1976] and Prell et al. [1976].

Finally, data on the downcore distribution of the pink-pigmented morphotype of *G. ruber* are shown in Figures 7 and 8 as well. For this study, we chose to examine the variability of white *G. ruber* and pink *G. ruber* separately because they display modern abundance maxima that are geographically distinct in the tropical Atlantic. Although both morphotypes have a wide geographical range, the white variety of *G. ruber* has been found to dominate in sediments that underlie the central Sargasso Sea, while pink *G. ruber* are more typically found in the Caribbean Sea and Gulf of Mexico [Kipp, 1976]. Plankton tow studies, on the other hand, have suggested that pink *G. ruber* lives only during the warmer summer months, while the white variety lives year round [Tolderlund and Bé, 1971; Deuser and Ross, 1989]. In the sediment records of the Cariaco Basin, the abundance patterns of the two varieties seem to be somewhat uncoupled in time as well. Probably the most noticeable difference is simply the observation that pink *G. ruber* does not show the same dramatic change in average relative abundance as does white *G. ruber* between the anoxic and oxic units. Instead of the abrupt change in the latter from high mean abundance to low about 12,600 years ago, the record of pink *G. ruber* tends to be punctuated by periodic intervals where its abundance reaches 15% or greater, superimposed on generally low (<5%) background values. Only over two very short intervals does the

abundance of the pink-pigmented form exceed 35%. These both occur in the lower oxic unit, with the later one having occurred just before the oxic/anoxic transition and the increase in *G. bulloides* abundance at 12,600 years ago. Though we presume that fluctuations in pink *G. ruber* abundance may be telling us something about past summer conditions in the Cariaco Basin, we are still working to understand the significance of these data.

The Last Glacial and Glacial-Interglacial Transition

The most obvious single event in the Cariaco Basin's record is the abrupt change from oxic to anoxic conditions that was recorded at about 12,600 years ago. Heezen et al. [1958] previously interpreted this sharp boundary to represent the Pleistocene/Holocene boundary based on a radiocarbon date of organic matter that yielded an age of about 11,000 years. On the basis of a general survey of the foraminifera present, they further suggested that sea surface temperatures in the region warmed rapidly at this time, from glacial values of 12-15°C to about 20°C, and then warmed more gradually to present surface values of about 25°C.

During the last glacial, lowered sea level would have largely isolated the Cariaco Basin from the open Caribbean. Recent work by Fairbanks [1989] has placed the maximum sea level lowstand at 121±5 m below present, a level just at or below the average depth of the submarine ridge that connects Tortuga and Margarita Island (Figure 10). Though certainly marine at this time, and better ventilated, the Cariaco Basin's principal connection with the open ocean would have been near its western end at a depth of about 25 m. The major locus of coastal upwelling, assuming it was still active during the glacial, would presumably have been shifted seaward of the then largely emergent Tortuga Bank (Figure 10).

According to the reconstruction of Fairbanks [1989], sea level rose only about 20 m between 17,100 and 12,500 years ago. This early phase of deglaciation was subsequently terminated by an exceedingly rapid sea level rise of 24 m that took place in less than 1000 years. This event, referred to by Fairbanks [1989] as meltwater pulse 1A (mwp-1A), correlates in time with the peak of Laurentide Ice Sheet meltwater discharge into the Gulf of Mexico, as recorded in oxygen isotope records [e.g., Emiliani et al., 1975; Kennett and Shackleton, 1975; Leventer et al., 1982; Broecker et al., 1988, 1989]. We

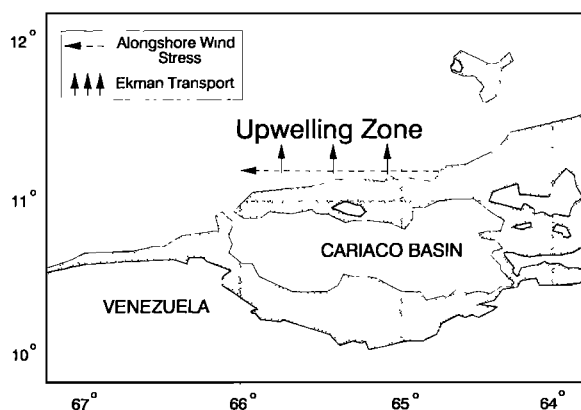


Fig. 10. Map view of the Cariaco Basin showing the inferred consequences of a 120 m lowering of sea level during the last glacial maximum. The stippled area indicates seafloor shallower than the 120-m isobath that would have been subaerially exposed at this time. At the full glacial lowstand, the Cariaco Basin was largely isolated from the open Caribbean except near its western end. We suggest that coastal upwelling was still active prior to 12,600 years ago but that the major zone of upwelling was displaced seaward of the exposed banks to the north of the basin by lowered sea level.

suggest here that the rapid sea level rise resulting from mwp-1A was sufficient to establish a direct surface connection between the open Caribbean and the Cariaco Basin along its northern margin, allowing Ekman pumping over the basin to begin as the upwelling cell migrated shoreward. The resulting increase in productivity and higher rain rates of organic detritus increased oxygen consumption in the deep Cariaco Basin to the point where anoxic conditions quickly developed.

As noted earlier, bulk sedimentation rates in both cores reached maxima at levels centered on about 12,000 years ago and then dropped gradually before leveling off to late Holocene levels. The high sedimentation rates of this interval appear to be, at least in part, the result of an increased biogenic flux from the surface. Figure 11 shows reconstructed shell accumulation rates of the total planktonic foraminifera ($>150\text{-}\mu\text{m}$) in core V12-104, as well as separate estimates for *G. bulloides*, *G. ruber* (white), and *N. dutertrei*. Accumulation estimates (in number of individuals $\text{cm}^{-2}\text{yr}^{-1}$) were calculated using sample weight and split information, sedimentation rates, and an assumed dry bulk density of 0.4 g/cm^3 . Both

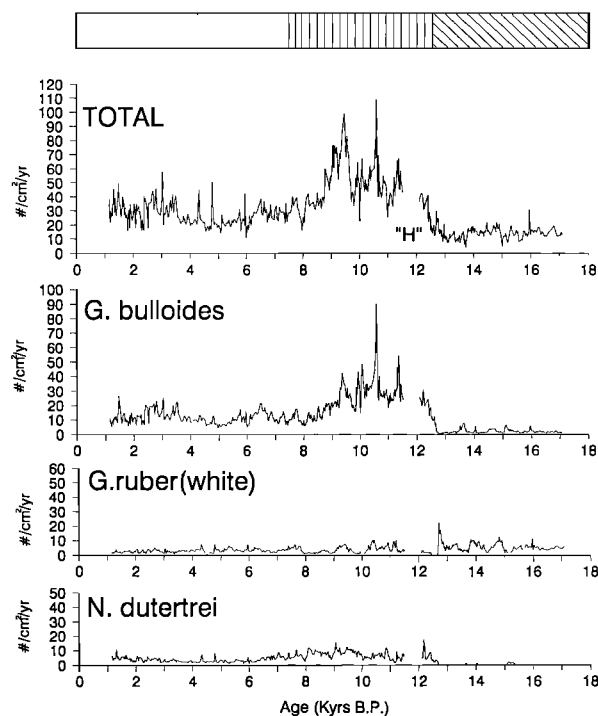


Fig. 11. Estimated accumulation rates (in number of individuals $>150\text{ }\mu\text{m cm}^{-2}\text{yr}^{-1}$) of total planktonic foraminifera, *G. bulloides*, *G. ruber* (white), and *N. dutertrei* in core V12-104 as a function of age and lithology.

total and *G. bulloides* accumulation rates show abrupt increases at 12,600 years ago, indicating the onset of the present upwelling regime. Though the fauna before that time was clearly dominated by *G. ruber* in a proportional sense (Figures 7 and 8), the input of *G. ruber* to the seafloor has been low and relatively constant with time.

In cores from the open Caribbean to the north, Prell and Hays [1976] and Prell et al. [1976] identified a similar glacial age assemblage characterized by *G. ruber* and, to a lesser extent, by *G. glutinata*. These authors suggested that the presence of a *G. ruber*-dominated assemblage in the glacial Caribbean indicated surface conditions reminiscent of the high-salinity, low-productivity surface waters of the southern Sargasso Sea, an area where *G. ruber* today flourishes. They further inferred that the extension of Sargasso Sea-like conditions into the Caribbean during the last glacial was due to a southerly shift of the ITCZ, with the ITCZ located, on average, over South America longer than it is today during the present-day Caribbean winter. As supporting

evidence, Prell and Hays [1976] cited studies of van der Hammen [1961] and Damuth and Fairbridge [1970], among others, that indicate more arid conditions in northern South America during glacial time, conditions consistent with a southerly shift of the ITCZ and of the accompanying rain belt. More recent data confirm the notion that aridity was pervasive along the Caribbean coast during the last glacial and up until about 10,000-11,000 years ago [Bradbury et al., 1981; Piperno et al., 1990].

Although productivity in the open Caribbean may well have dropped during the last glacial, as suggested by Prell and Hays [1976] and Prell et al. [1976], this does not necessarily mean that upwelling along the whole northern coast of Venezuela was shut down or weakened prior to 12,600 years ago, as the Cariaco Basin records might be interpreted to indicate. Instead, one can make the argument that a southward shift of the glacial ITCZ should, in fact, have resulted in more intense upwelling along the Venezuelan coast, and perhaps a longer upwelling season, based on the modern seasonal analogy where upwelling is strongest in winter when the ITCZ is at its southernmost position. More intense coastal upwelling during glacial times might also be expected given evidence for stronger, and probably more zonal, glacial trade winds resulting from heightened latitudinal temperature gradients [see Mix et al., 1986, and references therein].

In the absence of data to the contrary, we presume upwelling along the Venezuelan coast to have been active during the last glacial, but not to have been recorded in the Cariaco Basin because of the basin's relative isolation during the full glacial lowstand of sea level. As Figure 10 infers, we envision the most likely glacial scenario being one where the principal region of upwelling was displaced seaward of the basin by lowered sea level. Alternatively, upwelling may still have been active within the basin, but local hydrographic conditions may have limited the availability of nutrients or limited plankton growth. In support of the latter possibility, we note that *G. ruber*, in addition to its association with low-productivity conditions, is also a very salinity tolerant species [Bé, 1977]. Locke and Thunell [1988], for example, have found *G. ruber* to dominate in glacial age sediments of the Red Sea where high-salinity surface conditions were known to exist. In the Cariaco Basin, the blockage of surface flow from the east with lowered sea level, and the arid local conditions, may have resulted in a hypersaline

environment during the last glacial that only *G. ruber* could tolerate. Whatever the case may be, however, the renewal of surface water connections along the basin's northern margin seems to have been the trigger for the abrupt change recorded at 12,600 years ago.

Instead of the substantial warming of Cariaco Basin surface waters postulated by Heezen et al. [1958], we believe it more likely that SSTs either cooled at 12,600 years ago as upwelling established itself within the basin, or changed little. Much of the faunal evidence, taken at face value, would seem to support a cooling scenario. For example, both the dextral (subpolar) and sinistral (polar) coiling forms of *Neogloboquadrina pachyderma* make their first appearance in the sediments at the 12,600 year level, and are recorded in the sequence in small numbers (<1%) until they disappear again near the top of the well-laminated interval (~7500 years ago). Under normal circumstances, the presence of this taxon in either of its coiling forms would signal cooler waters. We note, however, that the unusual physical setting of the shallow-silled Cariaco Basin perhaps complicates the interpretation of these data. Rogl and Bolli [1973] were the first to point out that certain deep dwelling forms, such as *Sphaeroidinella dehiscens*, are extremely scarce in Cariaco Basin sediments but are more common outside the basin. Their observation suggests that the relatively shallow surrounding bathymetry precludes the advection of deep dwelling plankton into the Cariaco Basin by the prevailing surface currents. One may presume that such a depth-filtering process must have operated much more efficiently when sea level was at its full glacial low. Although a difficult bias to reconstruct and correct for, the dominance of the shallow dwelling *G. ruber* in the glacial Cariaco Basin is perhaps also partly the result of the basin having an effective sill depth of only about 25 m at that time. Similarly, the sudden appearance of *N. pachyderma* at 12,600 years ago may be related to the rapid sea level rise of mwp-1A, rather than to a distinct cooling, since *N. pachyderma* is generally considered to be a deeper dwelling species that lives at or below the thermocline [Fairbanks and Wiebe, 1980; Fairbanks et al., 1982]. Because of this potential for uncertainty, we consider more quantitative faunal-based temperature estimates in this interval to be somewhat equivocal for the moment, except to say that there is no evidence for the abrupt warming envisioned in the earlier work of Heezen et al. [1958].

Of the last 12,600 years of active upwelling over the Cariaco Basin, the abundance record of *G. bulloides* suggests that upwelling and trade winds were at their strongest between 12,600 and about 10,000 years ago. During this interval, *G. bulloides* dominates the foraminiferal assemblage in both a relative (Figures 7 and 8) and absolute (Figure 11) sense. Biogenic silica (mostly diatoms) is abundant, and the sediments are distinctly laminated. In core V12-99, sedimentation rates for this part of the sequence are considerably higher than in V12-104 (Figure 5). Since upwelling today tends to be stronger as one moves from west to east across the Cariaco Basin [Okuda et al., 1969], the proportionately higher sedimentation rates between 12,600 and 10,000 years ago in V12-99, the more eastern of the two cores, are perhaps the result of an enhanced productivity gradient across the basin as a result of the intensified upwelling of this time. Alternatively, the observed differences in sedimentation rates may in part be related to differences in site location (i.e., central saddle versus the slope) and accumulation processes thereon at this time. Unfortunately, we lack the original weight data for samples obtained from V12-99, which precludes our resolving this question by reconstructing biogenic and terrigenous accumulation rates for this core and comparing them to those in V12-104.

The Holocene

Between 10,000 and about 7000 years ago, we interpret increased abundances of *N. dutertrei* in both cores (Figures 7, 8, and 11) to indicate upwelling stronger than the post-7000 year period, but somewhat weaker than the earlier *G. bulloides*-rich interval. As noted earlier, *N. dutertrei* is a tropical-subtropical species which occurs abundantly in active current systems, along continental margins, and in upwelling regions [e.g., Kipp, 1976; Bé, 1977]. Plankton tow studies in the tropical Atlantic have shown *N. dutertrei* to be concentrated in greatest abundance at subsurface levels where chlorophyll concentration and primary production are at a maximum [Fairbanks and Wiebe, 1980; Ortner et al., 1980]. Along the Venezuelan coast, the observations of Miro [1971] suggest that *N. dutertrei* are presently most abundant during the upwelling time of year in surface waters off of Tortuga, seaward of the more productive region directly over the Cariaco Basin where *G. bulloides* dominates the fauna. Though the data base of Miro [1971] is

limited, we take the apparent preference of *N. dutertrei* for the fringe of the modern upwelling zone to imply that this taxon thrives under somewhat less productive conditions than *G. bulloides*, thus leading to our assertion of a weakening of upwelling at about 10,000 years ago. Sedimentation rates in both cores drop steadily and converge by about the 9000 year level, and the pronounced contrast between sediment laminae gradually disappears near the top of the section where *N. dutertrei* is more abundant.

Although we currently prefer upwelling as the mechanism for explaining the abundance pattern of *N. dutertrei* in the Cariaco Basin, an alternate scenario perhaps exists. Showers and Margolis [1985] and Showers and Bevis [1988] have argued for a substantial discharge of freshwater into the western tropical Atlantic from the Amazon River during the deglaciation based on oxygen isotope data from planktonic foraminifers and coccoliths. In high sedimentation rate cores from the upper fan of the Amazon Cone, this tropical freshwater spike seems well documented in planktonic foraminifers [Showers and Bevis, 1988]. In low sedimentation rate box cores from the southern Caribbean, anomalously depleted isotopic values are recorded in coccoliths only [Showers and Margolis, 1985]. These latter values, together with an age model, have been interpreted to indicate that freshwater discharge into the southern Caribbean peaked about 9600 years ago and terminated somewhere between 6000 and 5000 years ago, an interval that roughly correlates in time with the period of increased *N. dutertrei* abundance in our cores. In addition to its common association with upwelling and higher productivity, *N. dutertrei* has been linked to low salinity conditions in a number of regions. In the eastern Mediterranean, for example, high abundances of *N. dutertrei* have been found to characterize unusual assemblages associated with a number of Quaternary sapropels [e.g., Cita et al., 1977; Thunell, 1979]. Bé and Tolderlund [1971] and Ruddiman [1971] have noted correlations between *N. dutertrei* and low salinity in the North Atlantic, while Cullen [1981] has reported similar associations in the Bay of Bengal. In the Gulf of Mexico, high abundances of *N. dutertrei* have also been associated with the deglacial meltwater spike recorded there [Kennett and Shackleton, 1975; Kennett et al., 1985]. Though we think it more likely that *N. dutertrei* in the Cariaco Basin records upwelling than salinity variations, abundance variations of

this taxon may also, at least in part reflect freshwater dilution. In this regard, we note that *N. dutertrei* tends to be generally more abundant at the eastern site, at a location (V12-99; Figure 8) closer to both present and potential freshwater sources in the past. Our hope is that currently ongoing stable isotope studies of the Cariaco Basin cores will shortly resolve this question. Until then, however, we point to the uninterrupted continuation of well-laminated sediments from the *G. bulloides*-rich zone well up into the interval of higher *N. dutertrei* abundance as evidence that the latter signal is probably also an upwelling one.

Evidence for a Sun-Climate Link?

Over the last 10,000 years or so, upwelling in the Cariaco Basin, and hence the strength of the North Atlantic trade winds, is inferred to have been highly variable around some average state. The general pattern observed in the abundance record of *G. bulloides* is one of considerable century-scale variability superimposed on a lower-frequency component of change. In contrast with lower (e.g., Milankovitch) and higher (e.g., annual) frequency bands, the century- and millennial-scale bands of climate variability do not have well-tested forcing mechanisms. Evidence such as that presented here, however, suggests that variability within these bandwidths is an important part of the natural climate spectrum.

Perhaps the leading candidate for generating climatic variability in the century-scale frequency band is solar forcing through variations in solar output [Stuiver and Braziunas, 1989; Overpeck, 1991]. Although the general lack of densely sampled, well-dated paleoclimatic time series has left us without clear proof of a Sun-climate link [Stuiver and Braziunas, 1989], modern satellite data have helped to confirm that variations in sunspots, and ^{14}C and ^{10}Be production all tend to vary systematically with changes in the solar constant [Eddy et al., 1982; Willson et al., 1986; Willson and Hudson, 1988; Beer et al., 1988, 1990]. Over Holocene time scales, much of the century-scale variation in the long-term natural radiocarbon record, well documented from tree ring studies, has been attributed to solar forcing [Sonett, 1984; Stuiver and Braziunas, 1989]. The real test of a Sun-climate link, however, will come with the accumulation of suitable paleoclimatic time series.

Our foraminiferal time series from the Cariaco Basin were sampled densely enough

and dated suitably well to warrant a preliminary frequency domain examination of paleoclimatic variance in the Holocene section. To permit comparison of our Cariaco Basin data with the long-term (9600 year) tree ring ^{14}C record of solar activity [Stuiver and Braziunas, 1989], we first used tree ring (for the first five dates) and coral data (for the oldest date) to correct the six Holocene-aged radiocarbon samples from core V12-104 for secular variations in ^{14}C production (Figure 12) [Stuiver and Reimer, 1986; Bard et al., 1990]. The revised age model (Figure 12) was then applied to the *G. bulloides* record in that core over the interval from 1000 to 10,000 years B.P., and the resulting time series (now calibrated as 1400 to 9640 calendar years B.P.) was interpolated to a uniform sample interval of 40 years. The variance spectrum for the calibrated *G. bulloides* time series was then generated by taking the Fourier transform of the smoothed autocorrelation function of the prewhitened series [Blackman and Tukey, 1958; Imbrie et al., 1989]. The resulting spectrum (Figure 13), when examined at low-resolution, was found to be near-white at periods longer than about 90 years. Concentrations of variance broadly centered on periods of 200 and 136 years in the high-

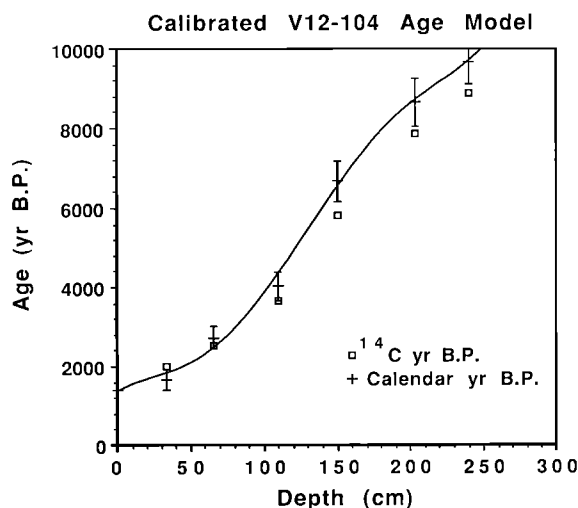


Fig. 12. Revised Holocene age model for core V12-104 based on original radiocarbon dates (Figure 6) that have been corrected for secular variations in ^{14}C production using both tree ring and coral data (see text). The error bars denote two standard deviations in the original measurements. The uncorrected radiocarbon dates are plotted as small boxes.

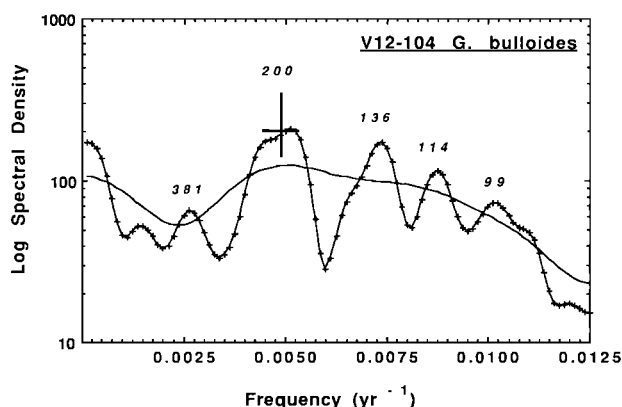


Fig. 13. Variance spectra obtained for the Holocene portion of the V12-104 *G. bulloides* time series after its correction to calendar years using the calibrated age model of Figure 12 (actual time series is 1400-9640 calendar years B.P.). Spectra were calculated for both 40 lags (high-resolution spectrum) and 20 lags (low-resolution spectrum) of the autocorrelation function. The 80% confidence interval (constant for all frequencies) and bandwidth for the high-resolution spectrum are plotted at 1 cycle/200 years. Spectral peaks centered on periods of 200 and 136 years in the high-resolution spectrum rise significantly above the low-resolution spectrum, whereas the other peaks do not rise as far above the smoothed background spectrum. The broad peaks centered on periods of 381, 200, and 136 years in the *G. bulloides* spectrum all overlap with spectral peaks identified in the long-term ^{14}C production spectrum [Stuiver and Braziunas, 1989], suggesting a possible link between upwelling, trade wind intensity, and solar forcing.

resolution spectrum rise significantly above the background continuum. Smaller spectral peaks, centered on periods of 381, 114, and 99 years do not rise significantly above the background.

The most striking result of our preliminary frequency domain analysis is the observation that the variance spectrum of *G. bulloides* (Figure 13) contains concentrations of power in each of the three frequency bands that are characterized by peaks (~ 420 , ~ 218 , and ~ 143 years) in the long-term ^{14}C production spectrum of Stuiver and Braziunas [1989]. In both data sets, the peak near 200 years dominates that part of the spectrum; and in both spectra there is a significant fall off in power at periods shorter than about 90 years. Although these tentative findings clearly

warrant further analysis, they do suggest the possibility that a significant fraction of the large Holocene variability in *G. bulloides* in the Cariaco Basin, and hence in the regional variability of upwelling and trade wind intensity, may have been forced by solar changes. Support for a Sun-climate link elsewhere comes from time series of ^{10}Be concentration in an ice core from the south pole [Raisbeck et al., 1990], and by possible correlations between ^{14}C variations, tree ring, and glacial advance-retreat data [Sonett and Finney, 1990; Wigley and Kelly, 1990; Stuiver et al., 1991]. Further evaluation of a Sun-climate link in our own data must await our ongoing efforts to generate a more detailed varve and AMS ^{14}C -based age model for the Holocene section and to perform direct comparisons (i.e., cross-spectral analysis) of our paleoclimatic time series with the long-term ^{14}C record.

Our ability to develop the greatly refined chronostratigraphies needed to fully evaluate the solar forcing hypothesis and to begin to focus attention on upwelling variability over time scales as short as interannual to decadal is considerably enhanced by the strong likelihood that paired sediment laminae within the Cariaco Basin represent annual varves. Within the well-laminated portions of the anoxic unit, the faunal and lithologic character of the sediments appears to clearly reflect the strong seasonality in the Ekman drift-induced upwelling and fluvial runoff that affect the Cariaco Basin, with the light-dark sediment couplets recording diatom-rich sediment accumulation in the dry upwelling season, and clay-rich accumulation in the wet nonupwelling season. Rough counts of sediment couplets in the original photographs of the two cores we have studied, as well as in fresh materials collected during a recent Cariaco Basin field program (June 1990), seem to confirm our belief that they represent annual varves that have been fortuitously preserved because of the basin's anoxic condition.

Ventilation of the Cariaco Basin

The virtual absence of benthic foraminifers after 12,600 years ago argues that the demand for oxygen in the deep Cariaco Basin has exceeded the supply since strong upwelling began. Hólmen and Rooth [1990] have recently presented tritium data for the deep waters of the Cariaco Basin and discussed transients in other chemical and physical properties that can only be explained by regular, if not fairly

frequent, convective ventilation events. Though these ventilation events clearly must occur, we see no evidence in the sediments of these two cores that they have at any time in the last 12,600 years provided sufficient oxygen to disrupt the anoxic state of the deep basin, at least over the time scales that we are capable of resolving. We think it unlikely at this time that the scattered occurrences of benthic foraminifers in the upper sediment unit record short periods of oxic. Instead, we suspect that the occasional benthic specimens found have been transported from the shallower surrounding shelf from water depths above the oxic/anoxic interface. In this regard, we note that H  lmen and Rooth [1990] have implicated the periodic input of warm, salty shelf water as an important ventilation source for the Cariaco Basin.

SUMMARY AND CONCLUSIONS

High deposition rate sediments of the anoxic Cariaco Basin preserve an extremely detailed late Quaternary record of Ekman drift-induced upwelling along the northern coast of Venezuela and hence a history of trade wind variations in the region as well. Information on past upwelling strength is contained primarily in the abundance record of *G. bulloides*, a planktonic foraminifer that has been shown to bloom locally during upwelling episodes. The changing proportions of this species, in addition to other lithologic and faunal data, suggest that both upwelling and trade wind strength have varied considerably on century and longer time scales.

Prior to 12,600 years ago, the Cariaco Basin was effectively isolated from the open Caribbean along its northern margin by lowered glacial sea level. Coastal upwelling was probably strong and active during the glacial, but the major upwelling center was shifted seaward of the then exposed Tortuga Bank. The presence of an impoverished benthic fauna suggests that oxic conditions existed in the deep Cariaco Basin at this time, though circulation was considerably restricted. Surface productivity was low, as indicated by the low total accumulation rates of foraminifers in the sediments, and the planktonic faunas were dominated by *G. ruber*, a taxon today characteristic of local surface waters during the nonupwelling season.

The abrupt initiation of upwelling over the Cariaco Basin at 12,600 years ago, as recorded by major increases in the abundance and accumulation of *G. bulloides*, is coincident with

the rapid rise of sea level that accompanied the peak interval of Laurentide meltwater discharge into the Gulf of Mexico. Although rising sea level actually enhanced connections between the Cariaco Basin and Caribbean Sea, the deep basin went anoxic at this time in response to higher surface productivity and increased rates of organic matter remineralization.

Upwelling was at its strongest level of the last 12,600 years between 12,600 and 10,000 years ago. Overpeck et al. [1989] have included this observation in their survey of paleoclimatic data from in and around the Caribbean and Gulf of Mexico region and suggested that both the evidence for stronger trade winds in this interval and the evidence from pollen and lake records for abrupt changes in regional moisture conditions can be explained by surface pressure anomalies generated by cooler SSTs in the Gulf of Mexico during the period of peak meltwater discharge. Cooler temperatures in the gulf were surmised to be the result of both cooler downstream SSTs in the Caribbean and the effects of the large influx of cold glacial meltwater. Data more recent than those summarized by Overpeck et al. [1989] tend to confirm that the southern Caribbean region probably remained cool and dry until after 11,000 years ago [Piperno et al., 1990], suggesting that northward advection of warm tropical water by the Caribbean Current may have been significantly lower than present until well after 11,000 years ago.

At about 10,000 years ago, upwelling over the Cariaco Basin weakened but was still probably stronger between then and about 7000-7500 years ago than has been observed since. This interpretation is largely based on the continued accumulation of well-laminated sediments after the *G. bulloides* drop at 10,000 years ago and on the somewhat elevated abundances of *N. dutertrei* in this interval. Throughout the whole of the Holocene, upwelling and trade wind strength are inferred to have been highly variable, with considerable century-scale variability superimposed on step changes and oscillations at lower frequencies. Though the patterns and sources of climatic variability on century to millennial time scales are poorly understood at this time, they are among the time scales of global environmental change most relevant to mankind's concerns for the future. Evidence such as that presented here from the anoxic Cariaco Basin indicates that variability within this band is clearly an important part of the natural climate spectrum.

Our preliminary examination of the Cariaco Basin record in the frequency domain suggests

that solar variability may explain a significant portion of the upwelling and trade wind variability observed during the Holocene. Both the Cariaco Basin upwelling record and the long-term record of ^{14}C production rate variability contain significant concentrations of variance in frequency bands centered near 1 cycle/200 years and 1 cycle/140 years. We are currently working to improve the chronostratigraphic framework for the Cariaco Basin record in an attempt to further evaluate this possible Sun-climate link. An improved temporal framework for most other paleoclimate records from the Caribbean region is also needed in order to better understand the larger picture of Holocene climate dynamics in the area.

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