SEPM Society for Sedimentary Geology

4111 S Darlington
Suite 100
Tulsa, Oklahoma 74135
USA

Phone: 918-610-3361
Fax: 918-621-1685
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HIGH PRODUCTION AND HIGHSTAND SHEDDING FROM DEEPLY SUBMERGED CARBONATE BANKS, NORTHERN NICARAGUA RISE[1]

KAREN S. GLASER AND ANDRE W. DROXLER
Department of Geology and Geophysics
Rice University
Houston, Texas 77251

ABSTRACT: Because the shallow isolated carbonate banks on the northern Nicaragua Rise, the Nicaragua/Honduras and southern Jamaica carbonate shelves, and many other modern carbonate banks worldwide, are covered by an average of 20 to 30 m of water and by a thin blanket of coarse carbonate sediments, other carbonate sedimentologists have considered these banks good examples of "incipiently drowned", or even "drowned" carbonate banks. However, based on recent research on the northern Nicaragua Rise, we can demonstrate that these banks currently are healthy producers of large volumes of periplatform sediments (fine aragonite and magnesian calcite), which are exported almost entirely to the deep surrounding slopes. These sediments, which were deposited during the past 9000–10,000 years, form periplatform wedges on the middle and upper slopes, which are seen clearly on 3.5 kHz seismic profiles. Radiocarbon ages of the wedge surface sediment range between 230 and 610 YBP and provide clear evidence for the contemporaneous production of sediments on the shallow bank and shelf and their instantaneous export to the upper slopes. For the last 5000 years, sedimentation rates ranged from 2000 mm/ky off Pedro Bank to 1300 mm/ky off Jamaica. These rates are somewhat lower than, but of the same order of, magnitude as sedimentation rates on the western (leeward) slopes of Great Bahama Bank. Deposition of the metastable carbonate sediments discussed in this paper occurred as soon as sea level rose to flood the bank and shelf which flank Walton Basin, following the last glacial lowstand. They comprise a wedge-shaped package of transgressive and highstand sediments on the upper and middle slopes of Pedro Bank and the southern Jamaica shelf.

INTRODUCTION

Water depth and bank top sediment composition comprise the most acceptable criteria used to determine whether a modern carbonate bank is "drowned" or "incipiently drowned". Bank drowning occurs when relative sea-level rise (tectonics, eustacy and sediment supply) outpaces the rate of bank top accumulation of shallow carbonate sediments. This results in the submersion of the platform/reef system below the portion of the euphotic zone where carbonate production is prolific (Schlager 1981). The narrow depth limit of neritic carbonate production is considered the main constraint on drowning of modern carbonate platforms. Because neritic carbonate production drops by a factor of two between 10 and 20 m (Schlager 1981, his fig. 2), carbonate banks covered by more than 10 to 15 m of water usually are considered poor producers of metastable carbonate sediment and therefore "drowned" or "incipiently drowned" (Hine and Steinmetz 1984; Dominguez et al. 1988) and essentially non-productive. A second characteristic of "incipiently drowned" or "drowned" banks is the omnipresent veneer of thin (< 4 m) coarse-grained relict sand (Dominguez et al. 1988; Triffleman 1989) and the limited reef material and muddy deposits.

Many modern carbonate banks have been classified "drowned" or "incipiently drowned" based on the above criteria without examination of the nature of sediments deposited on the upper slope. An alternate method of testing the drowning concept on modern banks, is to examine their sediment production rate, since production should be virtually non-existent on a truly drowned platform. One approach to determining sediment productivity of deeply submerged banks is to determine whether the upper slope sediments are totally devoid of shallow bank-derived material.

Because 20 or 30 m of water and a coarse veneer of carbonate sediment cover the shallow isolated carbonate banks on the northern Nicaragua Rise and the Nicaragua/Honduras and southern Jamaica shelves (Zans 1958; Dolan 1972; Roberts and Murray 1983; Greenidge and Hendry 1989; Triffleman 1989), many carbonate sedimentologists consider them good examples of "incipiently drowned," or even "drowned" carbonate banks. This premature deduction has contributed to the virtually unstudied nature of the isolated platforms of the northern Nicaragua Rise, despite their proximity to the well-studied carbonate province of the Bahamas.

During part of a month-long cruise on the R/V Cape Hatteras funded by the National Science Foundation, we conducted a detailed study of the upper slopes of Walton Basin, the seaway separating Pedro Bank (PB) from the southern Jamaican shelf (SJS). The objective of our study was to test the hypothesis that shallow carbonate banks submerged to depths of 15 m or more and covered by a thin veneer of coarse sandy sediment are not necessarily nonproductive, and that application of the term "drowned" or "incipiently drowned" to these banks and shelves is misleading. The data reveal the existence of well defined Holocene sediment wedges of bank-derived metastable carbonate on the upper and middle slopes of Walton Basin. Our results demonstrate that despite having physical characteristics associated with incipiently drowned or drowned banks, the deeply submerged banks of the northern Nicaragua Rise are healthy producers of large volumes of carbonate sediment, the vast majority of which is exported to the deep surrounding slopes.

STUDY AREA

Location

The northern Nicaragua Rise, a NE-SW oriented submarine swell, manifests itself as a broad carbonate province topped by a series of isolated shallow carbonate banks,

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which are separated by NW-SE trending basins and sea ways (Fig. 1). The Nicaragua Rise begins off the east coasts of Nicaragua and Honduras and runs eastward to Jamaica. Pedro, Rosalind and Serranilla, the three major flat-topped, northward deepening, isolated carbonate banks, are covered by an average of 25 to 30 m of water with only a few small areas reaching sea level. The rare shallow or emergent areas constitute sand shoals and cays and lie along the southern edges of the banks. The carbonate shelves of Nicaragua, Honduras, and southern Jamaica are covered by an average of 30 to 40 m of water but are not pure carbonate systems, unlike the isolated banks. On the shelves of Nicaragua and Honduras, the siliciclastic sediments occur only in the near shore area, within (an 8-km-wide zone) (Roberts and Murray 1983). These authors attribute this restriction to the southward flow of a coastal boundary current, generated by the sustained northeast trade winds. Offshore of this band of terrigenous material, 80% of the sediments on the Nicaragua and Honduras shelves consist of carbonate. The SJS also is covered by essentially pure carbonate sediment, with the exception of a narrow band of terrigenous material found along the coast (Greenidge and Hendry 1989).

Sediments on the Banks and Shelves

The sediments found on the tops of the banks and shelves of the northern Nicaragua Rise are similar in composition. Algal, mollusc, sponge and foraminiferal debris with some coral fragments form the primary components of the sediment on PB (Zans 1958; Dolan 1972). The sediments on Serranilla Bank, located to the west of PB, are also dominated by algal and molluscan material and have no coral-derived component (Triffleman 1989). Mud contributes only a minor component and typically occurs on the northwest or leeward bank margins (Dolan 1972; Triffleman 1989). The sediments on the SJS consist of *Halimeda* plates, cryptocrystalline grains, mollusc and coralline algal fragments, with other minor biological components (Greenidge and Hendry 1989). Assuming that sediment production presently occurs on the shallow banks and shelves, the observed thin sediment cover and its coarse nature attest to the fact that sediments presently are not accumulating in significant quantities on top of PB and the SJS (Triffleman 1989; Hine et al. 1988) and that the majority of the sediments produced here are exported toward the deeper periplatform environments.

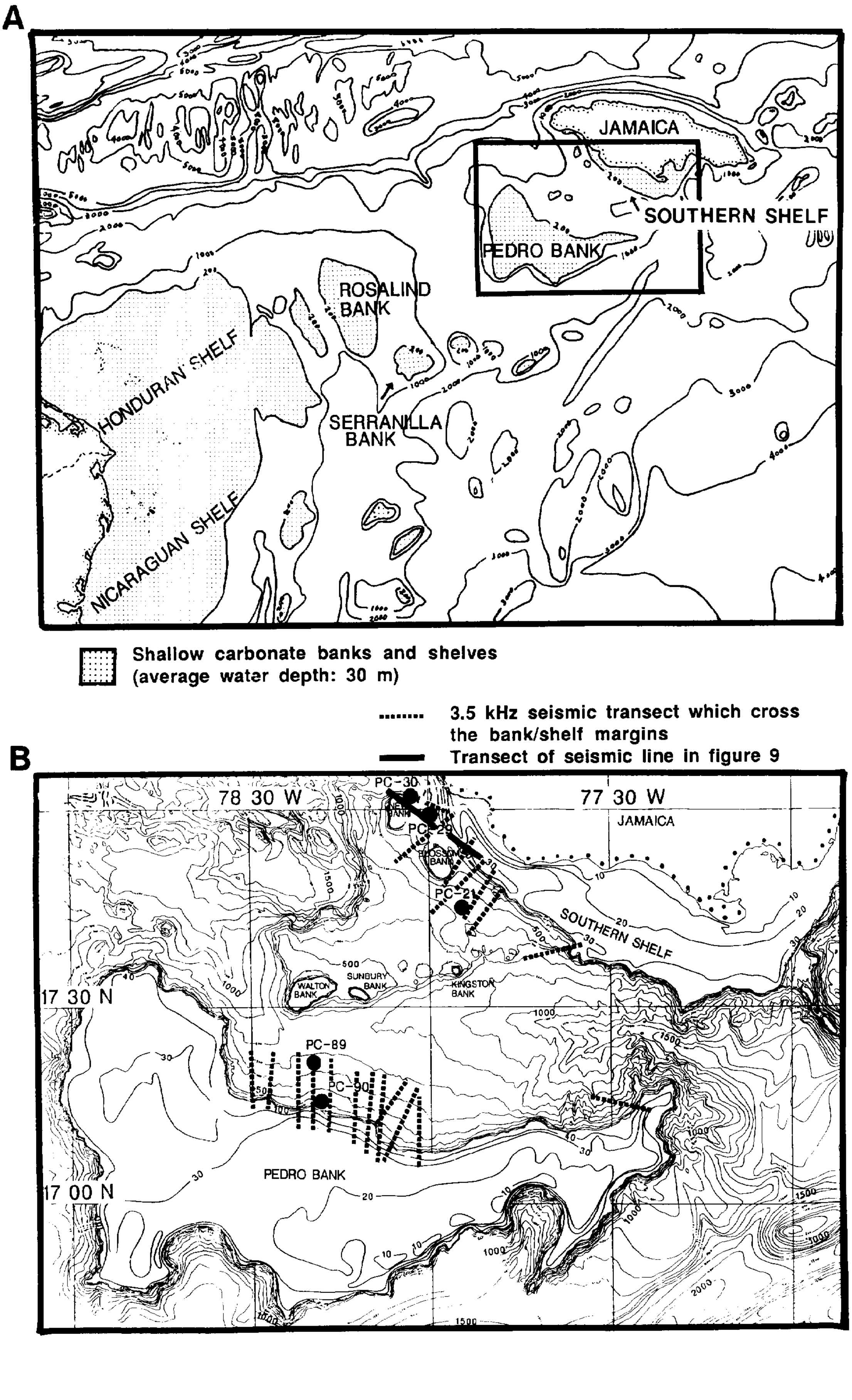
Ocean Currents

Most of the Caribbean Current flows over the Nicaragua Rise between Miskito Bank and the southern coast of Jamaica (Wust 1964; Kinder et al. 1985; Hine et al. 1988). The relatively strong flow results in current velocities over the banks of the Nicaragua Rise exceeding 20 cm/s (Hallock et al. 1988). This vigor explains the occurrence of coarse sediments on the bank and shelf tops as the effect of winnowing. Thus, the thin Holocene sediment cover found on the bank tops results from the export of the fine (silt and mud) bank-derived sediment which is deposited from suspension on the basin slopes. In addition to these effects, the Caribbean Current also controls the nutrient concentration of the waters flowing over the Nicaragua Rise. Sea surface chlorophyll concentrations, measured from Coastal Zone Color Scanner data, show an east-west gradient in nutrient concentrations (Hallock et al. 1988). These authors show that oceanic waters flowing north of Jamaica carry 40% less biotic pigments than those flowing through the western Nicaragua Rise (0.020 mg Ch/m^3), and the oceanic waters flowing through the eastern Nicaragua Rise carry 20% less. Upwelling of deep nutrient-rich waters from the Columbia and Venezuela Basins, both poorly ventilated below their sill depths of 1500 m, occurs at the southern edge of the Nicaragua Rise (Worthington 1971; Rooth, pers. comm.). These nutrient-rich waters then are carried over the Nicaragua Rise by the Caribbean Current. Furthermore, strong northerly winds, associated with winter cold fronts, generate upwelling of nutrient-rich water, from the Cayman trough along the northern edge of the Nicaragua Rise. This reverse flow periodically flushes the bank and shelf tops along the Nicaragua Rise (Hallock et al. 1988). Finally, waters of the Caribbean Current also are enriched in nutrients by runoff from the Magdalena and Orinoco rivers and by general upwelling off the northern coasts of Venezuela and Columbia.

Hallock et al. (1988) suggest that the high concentration of nutrients in the waters passing over the Nicaragua Rise is detrimental to the growth of hermatypic corals. This explains the prominence of *Halimeda* on the bank and shelf tops and their upper margins. Bands of *Halimeda* bioherms, growing on the rims of isolated banks and shelves of the Nicaragua Rise, have been observed by Hine et al. (1988), Triffleman (1989), and Roberts and Murray (1983). Dolan (1972) described *Halimeda* "meadows" on PB, and Liddell et al. (1988) reported similar "meadows" along the northern shelf of Jamaica. The *Halimeda* bioherms on the northern Nicaragua Rise generally exist in 40 to 50 m of water and display relatively low relief (Hine et al. 1988). Similar *Halimeda* bioherms occur in other modern environments, for example, behind the Great Barrier Reef (Northeast Australia) (Davies and Marshall 1985) and in the Java Sea (Roberts et al. 1988). The volume of fine aragonite sediment produced by the algal mounds behind the Great Barrier Reef appears equivalent to the volume of fine carbonate sediment produced by modern coral reef systems (Davies and Marshall 1985).

METHODS

Five piston cores and nineteen 3.5 kHz seismic transects from bank (shelf) to basin were selected from the 50 piston cores and 3700 km of 3.5 kHz seismic profiles, collected as part of a National Science Foundation-funded R/V Cape Hatteras cruise in April 1988. the 3.5 kHz transects (twelve transects cross the PB northern margin


A
JAMAICA
SOUTHERN SHELF
PEDRO BANK
ROSALIND BANK
HONDURAN SHELF
SERRANILLA BANK
NICARAGUAN SHELF
Shallow carbonate banks and shelves
(average water depth: 30 m)
3.5 kHz seismic transect which cross
the bank/shelf margins
Transect of seismic line in figure 9
B
78 30 W
77 30 W
JAMAICA
PC-30
PC-29
PC-21
SOUTHERN SHELF
WALTON BANK
SUNBURY BANK
KINGSTON BANK
17 30 N
PC-89
PC-90
PEDRO BANK
17 00 N

and eight cross the western and northern margins of the SJS, Figs. 1B and 3A and B) and the five piston cores (Figs. 1, 2, 3, 4 and 5) form the data base used to establish the occurrence, areal extent, timing, and composition of the sedimentary wedges deposited on the upper and middle slopes of PB and the SJS.

Five cores composing two slope transects were selected to give a representative example of the periplatform sediments shed off the pure carbonate system of PB (cores CH0288-89 and 90) and the mixed siliciclastic/carbonate system of the SJS (cores CH0288-29, 30, and 21). Each core transect consists of one shallower core collected in 275–310 m of water at distances of 1.25 and 2.5 km from the bank (shelf) edge (cores 90 and 29, respectively) and one (or two) deeper cores in 470-570 m of water, at distances from the bank (shelf) edge of 3.5, 7.5, and 12.6 km (cores 30, 89, and 21, respectively). The five cores average 6 m in length and consist of periplatform oozes and muds.

The five cores were sampled and analyzed at 10 cm intervals. Samples were wet sieved at 63 μm to separate fine and coarse fractions. The fine fraction (< 63 μm) was analyzed for carbonate content by Carbonate Bomb and for carbonate mineralogy by X-ray diffraction (detailed methods can be found in Droxler et al. 1988). Carbonate mineralogic data are plotted two ways, first as "raw data," where the proportion of the three carbonate phases, aragonite, calcite (< 4 mole percent $MgCO_3$) and magnesian calcite (> 4 mole percent $MgCO_3$) within the fine carbonate fraction are plotted (Fig. 4). In the second presentation these data are plotted as "fine aragonite (magnesian calcite) to total sediment," calculated as "aragonite (magnesian calcite) raw data percent × carbonate content percent in fine fraction × fine fraction percent" (Fig. 5).

Beta Analytic Laboratory, Miami, Florida, provided seven radiocarbon dates of bulk sediments. Analyses of the coarse fraction established the foraminifer biostratigraphy based on the *Globorotalia menardii* complex (Ericson and Wollin 1956; Prell and Hays 1976; Prell 1978) to differentiate interglacial from glacial sediments. Oxygen isotope stratigraphy was applied to PC-21 by analyzing mono-species samples of *Globogerinoides sacculifer* (25–30 specimens from the 300–350 μm fraction). This work was done on the VG602E mass spectrometer in Dr. Robert Dunbar's oxygen isotope laboratory at Rice University. The *G. menardii* complex stratigraphy in Walton Basin was calibrated using the oxygen isotope record for core 21. Figure 2 is a composite of the data used to establish the stratigraphy in Walton Basin.

RESULTS

Our results clearly establish the existence of a significant Holocene sediment wedge consisting of periplatform sediments, on both the northeastern and southern margins of Walton Basin.

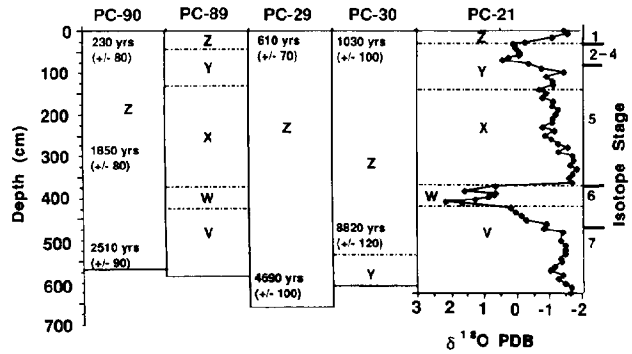


FIG. 2.—Information used to establish the stratigraphy in Walton Basin. Oxygen isotope stratigraphy is shown for PC-21. The letters V–Z indicate forminifer biostratigraphic zones based on the *Globorotalia menardii* complex. The biostratigraphic zone boundaries are indicated by dashed lines. Dates in years are radiocarbon dates of bulk sediments. Note that the oxygen isotope stage boundaries do not always coincide with the *Globorotalia menardii* complex zone boundaries.

3.5 kHz Seismic Data

In Walton Basin, nineteen bank (shelf) to upper slope 3.5 kHz seismic profiles show a well-defined wedge of transparent sediment. This wedge is up to 20 m thick in a water depth of 300 m and less than 2.5 km from the bank (shelf) edge. The wedge thins exponentially to less than 0.5 m at a distance of 7.5 km from the bank (shelf) edge. The base of the sediment wedge usually is defined by an erosional unconformity on the upper part of the slope, which becomes conformable farther down the slope (Fig. 3A and B).

The sedimentary wedge off PB, associated with cores 90 and 89 (projected), displays a number of internal hummocky reflectors, implying possible mass wasting or slumping within the wedge (Fig. 3A). The sediment wedge above the most continuous reflector averages 20 m in thickness 1.25 km off the bank edge, where core 90 only penetrated the upper third of the wedge. Off the SJS, core 29 (located 2.5 km from the shelf edge) penetrated only the upper third of the 20-m-thick transparent sediment wedge. Core 30, located 3.5 km from the edge, penetrated the 5 to 6-m-thick transparent sedimentary wedge (Fig. 3B). Cores 21 and 89 located on the distal part of the wedges off SJS and PB, respectively, contain less than 50 cm of Holocene sediments, and document the rapid thinning of the wedges in a down slope direction.

Stratigraphy

The results of the foraminifer and $\delta^{18}O$ stratigraphies as well as the radiocarbon dates for the five piston cores are plotted in Figure 2. The planktonic oxygen isotope record for core 21 enabled us to calibrate the *Globorotalia menardii* complex in Walton Basin (Ericson and Wollin 1956, 1968; Prell and Hays 1976). The $\delta^{18}O$ curve for core 21 documents glacial/interglacial stages 1 to 7.

←

FIG. 1.—(**A**) Map of the Nicaragua Rise. The dotted pattern corresponds to shallow carbonate banks and shelves. The study area is also shown. (**B**) Bathymetric map of study area (contours in meters). Core locations, 3.5 kHz seismic data, and the location of a high resolution seismic line are indicated.

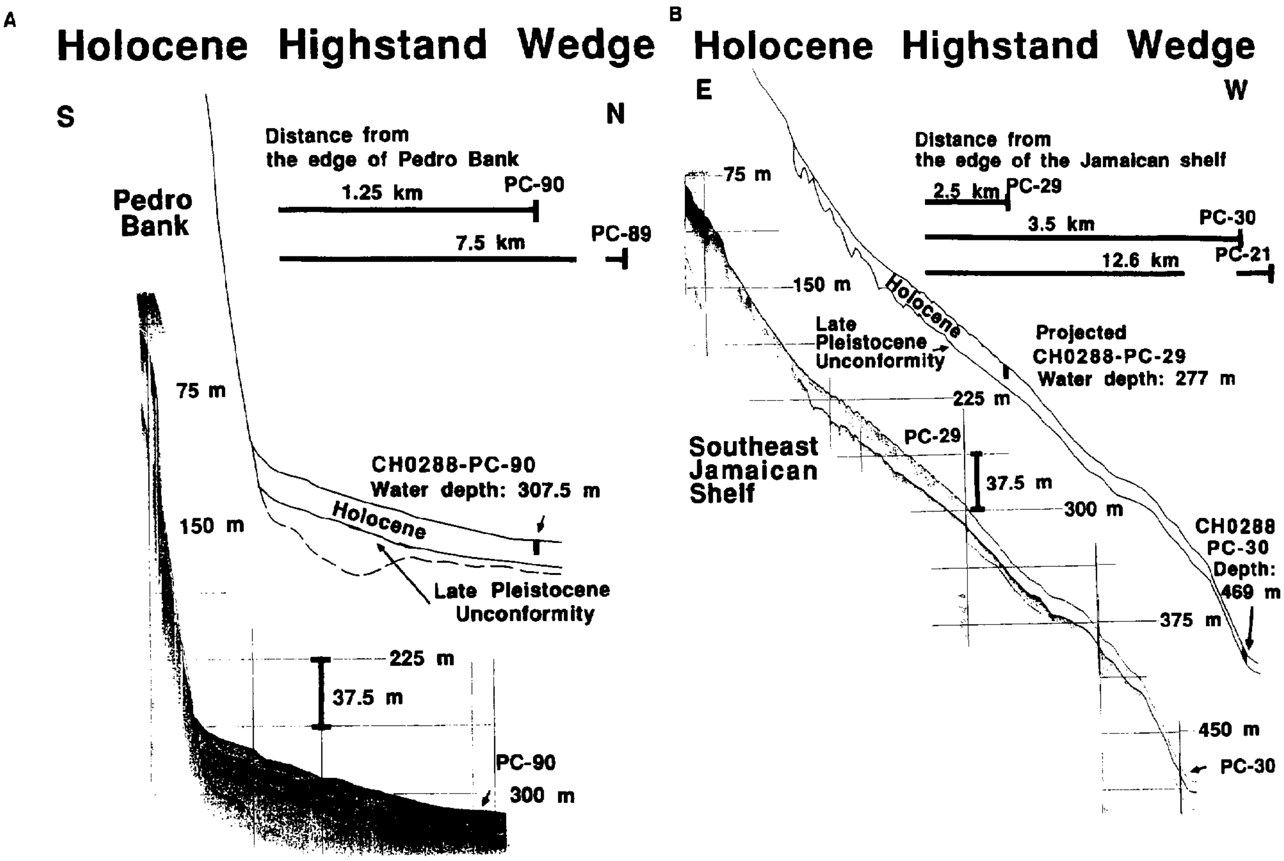


FIG. 3.—(A) 3.5 kHz profile off Pedro Bank at the location of PC-90. Line drawing above the profile shows interpretation of Holocene section and depth of penetration of the piston core. The distance to core 89 also is indicated. (B) 3.5 kHz profile off the southern Jamaican Shelf at the location of PC-30, with PC-29 projected onto the section. Note that PC-30 penetrates the entire section interpreted as Holocene. Locations of seismic lines are shown in Figure 1.

Heavier-than-normal $\delta^{18}O$ values of 1 to 1.5 per mil during stage 6 are due to the presence of cement. The *G. menardii* complex boundaries Y/Z and W/X correspond to the transitions from glacial stage 2 to interglacial stage 1 and from glacial stage 6 to interglacial stage 5. Interglacial to glacial stage boundaries 5/4 and 7/6 do not correspond exactly to the *G. menardii* complex boundaries X/Y and V/W. The X/Y boundaries occurs within interglacial $\delta^{18}O$ isotope stage 5a, and the V/W boundary falls in the first part of glacial stage 6.

The *G. menardii* complex, in association with radiocarbon dating, clearly establishes that cores 29, 30 and 90 are mostly Holocene in age. The Z zone of the *G. menardii* complex occurs throughout cores 29 and 90, while its Z/Y boundary occurs at 5.25 m below sea floor (mbsf) in core 30, at 0.4 m in core 89, and at 0.25 m in core 21, as indicated in Figure 2. The bases of cores 90 (at 5.30 mbsf) and 29 (at 6.10 mbsf) yield ages of 2500 YBP and 4690 YBP respectively. The radiocarbon date for the interval just below 5 m in core 30 yields an age of 8820 YBP, implying that the underlying unconformity formed prior to 9000–10,000 yr ago, sometime during stage 2, and that the transparent sedimentary wedge is Holocene in age. The following discussion shows that the major sedimentary change in core 30 at 5 mbsf corresponds with the strong reflector (unconformity) at the base of the wedge (Figs. 3B and 5).

The two ages obtained for the surface sediments of cores 90 and 29 (230 and 610 YBP respectively) are unusually young (Fig. 2). These ages imply that 1) sediment production on the bank and shelf top and instantaneous export toward the upper slopes occur today; and 2) the sedimentation rates in these two cores must have been very high, therefore minimizing the effects of bioturbation. The radiocarbon date of 1030 YBP for the surface sediment in core 30 is approximately the same as similar sediments found off the Bahama Platform (Droxler 1985). The three radiocarbon dates for core 90 (Fig. 2) show a linear age increase downcore, indicating a steady sedimentation rate (2000 mm/ky) for the past 2500 yr. This linear trend also indicates that the hummocky seismic signal on the 3.5 kHz line is unlikely the result of mass wasting processes (Fig. 3A).

Fine Fraction

The percent fine material (< 63 μm) contained in the five cores is displayed in Figure 4A. The cores in the PB transect show no change in the amount of fine material as a function of distance from the bank. In contrast, the

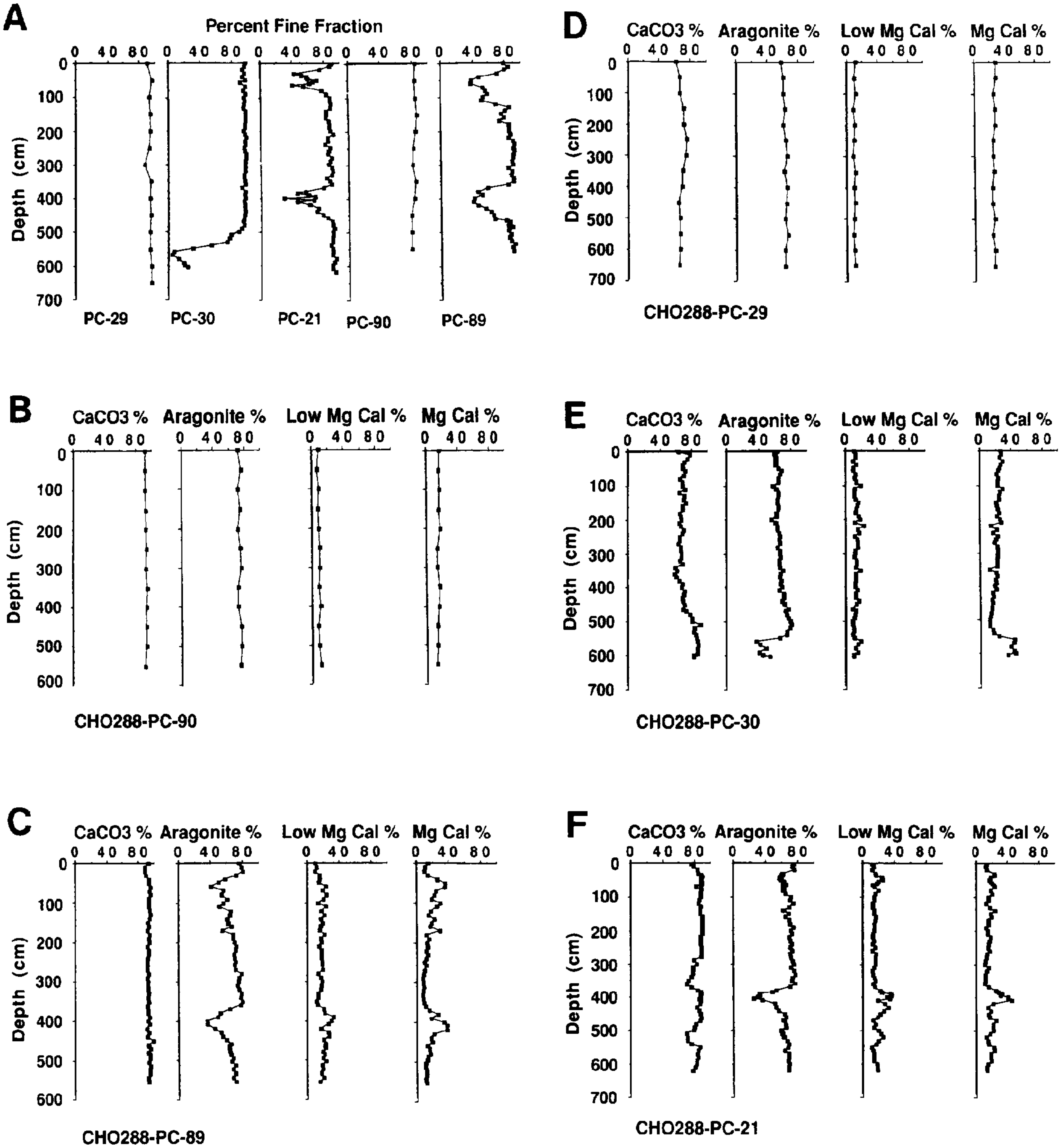


FIG. 4.—(A) Percent fine fraction plots for the five cores used in this study. The percent carbonate and the carbonate mineralogy for the fine fraction of these cores is also shown (< 63μm) (B–F). Locations of the cores are shown in Figure 1.

cores in the SJS transect exhibit a slight increase in percent fine material as distance from the bank increases.

The percent of the Holocene sediments made up of fine material averages between 80 and 95% in these five cores. The three cores which penetrate older sediments (30, 21 and 89) show a striking cyclic pattern in the percent fine material between glacial and interglacial stages. Cores 21 and 89 display values between 80 and 90% for all three interglacial intervals penetrated ($\delta^{18}O$ stages 1, 5 and 7), while the last two glacial intervals average less than 40% fine material (cores 30, 21 and 89).

Carbonate Content

As expected, carbonate content values of the fine fraction in the Holocene sedimentary wedge are higher on the upper slope off PB (a pure carbonate system) than off the SJS (Fig. 4), where erosional products of metamorphic

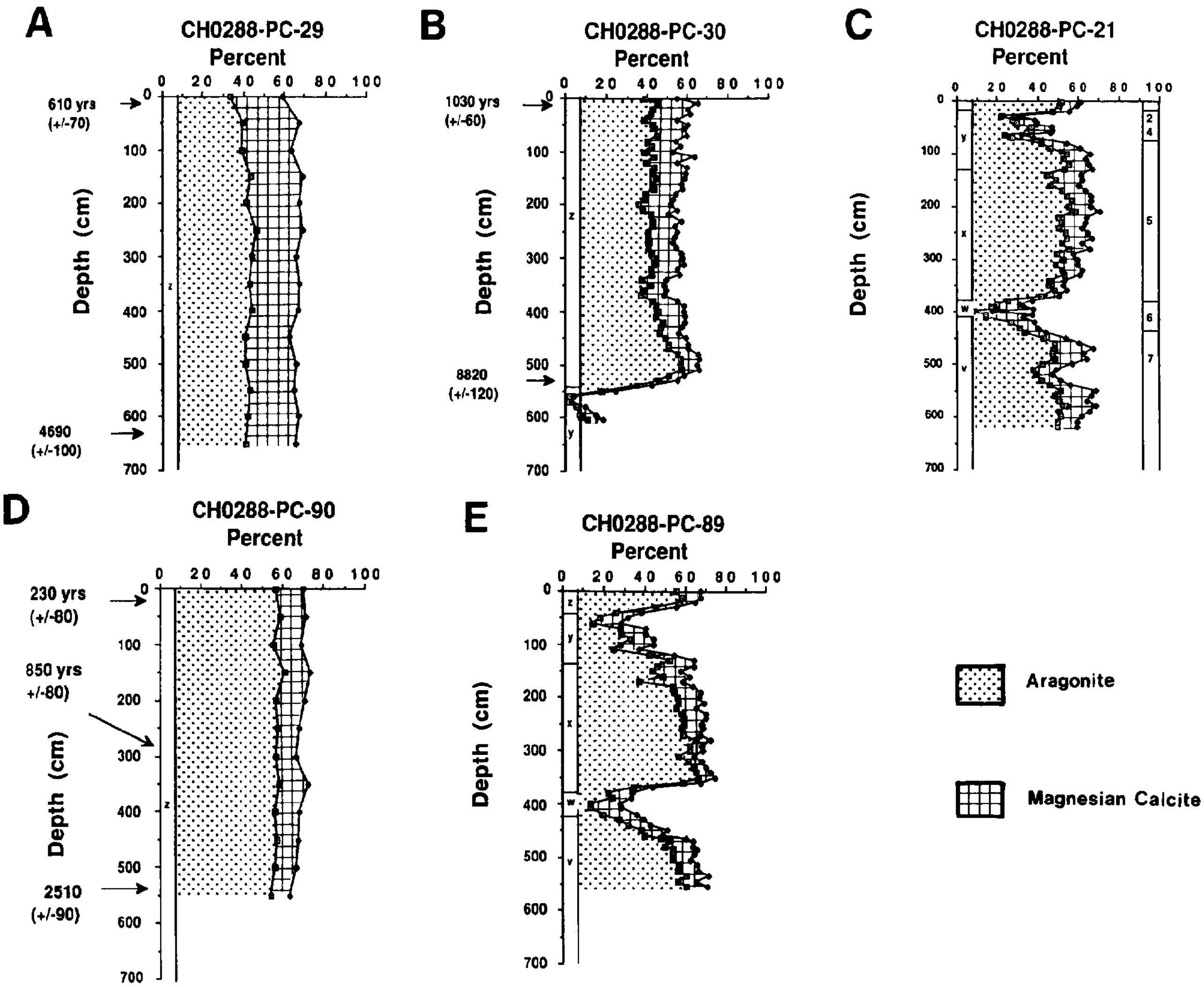


FIG. 5.—(A-E) Plots of the proportion of bank-derived carbonate (aragonite and magnesian calcite) in the total sediments for PCs 90, 89, 29, 30, and 21. Radiocarbon dates, $\delta^{18}O$ stratigraphy, and biostratigraphic zones based on the *Globorotalia menardii* complex also are indicated.

and volcanic rocks from the southern and central portions of Jamaica contribute to the shelf sediments. In the PB transect, core 90 and the top 0.4 m (Holocene, Z zone) of core 89 off PB, carbonate values range between 87.5 and 95%. In contrast, the three cores from the SJS transect (29, 30 and 21) carbonate values vary within a 30% range, between 60 and 90%. In core 30, sediments just below the unconformity (the Z/Y boundary), and thus older than 10,000 to 13,500 yr, display high carbonate values, peaking at 85%. The highest values (90%) on this transect are seen in core 21, which is located farthest from the edge of the SJS. The relatively lower carbonate values for the sediments from the Holocene sedimentary wedge off the SJS (cores 29, 30 and 21) compared to the PB transect indicate the mixed carbonate/siliciclastic nature of the sediment sources in that area, with the highest input of siliciclastics to the upper slope occurring during the first part of the Holocene (cores 30 and 21) and the beginning of the last interglacial interval (core 21).

Carbonate Phases

The carbonate mineralogy of the cores from both areas also varies over time. The mineralogy of the fine carbonate fraction in core 90 and the top 0.4 m of core 89, in the PB transect, remains constant, with the carbonate sediment consisting roughly of 80% aragonite, 10% magnesian calcite and 10% calcite (Fig. 4B and C). These proportions are typical for periplatform muds (Schlager and James 1978). The fine aragonite and magnesian calcite are produced on the tops and edges of shallow carbonate banks by green algae (mostly *Halimeda*) and by coralline algae. In contrast, fine calcite has a planktonic origin, consisting mostly of coccolith plates and very small and juvenile planktonic foraminifers.

In the transect off the SJS, calcite values in the fine carbonate fraction range between 10 and 20% and show only small variation between glacial and interglacial intervals in core 21; however, the percents of aragonite and magnesian calcite do show some glacial/interglacial cyclicity. The fine carbonate fraction in core 29, corresponding to the past 5000 yr, and the top 3 m of core 30 consist of 10% calcite, 58–66% aragonite and 22–28% magnesian calcite. Fine aragonite shows a maximum value of 80% for 9000-year-old sediment (core 30) at the base of the sedimentary wedge and a minimum value of 60% in the surface sediments. The fine magnesian calcite distribution mirrors the aragonite with a 10% minimum value at the base of the sedimentary wedge 9000 yr ago (in core 30) and a 30% maximum value in the surface sediments. The distribution of the carbonate phases in core 21 is similar to that for cores 29 and 30 (Fig. 4D and E); however, core 21 penetrated much older sediment (Fig. 4F) and represents the last two glacial/interglacial cycles ($\delta^{18}O$ stages 1–7). In core 21, fine aragonite is highest during the interglacial intervals (average 70%) and lowest during glacial times. The low aragonite and high magnesian calcite values for stage 6 are believed to be the result of the formation of magnesian calcite cements. The proportions of these three carbonate phases in the fine carbonate fraction of these cores are typical of periplatform sediments.

One of the main producers of carbonate sediment on PB and the SJS today is believed to be green algae such as the ubiquitous *Halimeda* described by Hine et al. (1988), Triffleman (1989), Dolan (1972) and Liddell et al. (1988). *Halimeda* produces plates composed of aragonite needles. Various researchers (e.g., Neumann and Land 1975) have described the tendency for these aragonite plates to be broken down by bioerosion and turbulence into their smaller needle-like components. The main producers of magnesian calcite are red algae, sponges, benthic foraminifers and echinoderms.

The downcore variations of the fine aragonite and magnesian calcite, relative to the total sediment, is presented in Figure 5 for cores 29, 30, 21, 89 and 90. The fine aragonite component comprises 60% of the total sediment off PB and 40 to 50% off the SJS. The rather small fluctuations in the amount of fine aragonite and magnesian calcite deposited during the last 6000 yr in the Holocene periplatform wedge reflects essentially constant production and export of sediment to the upper slope during that period. This interval corresponds to a period during which a minimum of 75% of PB and the SJS were covered by more than 15 m of water. Cores 21 and 89 penetrated older sediments than the other three cores analyzed. Foraminifer and $\delta^{18}O$ stratigraphy indicates that the sediments represent deposits of at least two consecutive glacial/interglacial cycles. As in the Bahamas (Droxler et al. 1983; Boardman et al. 1986), the content of bank-derived material varies between glacial and interglacial stages. Interglacial stages (1, 5 and 7) correspond to high bank-derived sediment values (aragonite and magnesian calcite), whereas glacial stages (2–4 and 6) have low values. Sediment accumulation rates are high during interglacial stages (60–85 mm/ky), while the rates for glacial stages are about a tenth as large.

DISCUSSION

The data from the margins of Walton Basin document the presence of a sedimentary wedge on the upper and middle slopes off PB and the SJS. The wedge is up to 20 m in thickness and 8 km in width. It consists primarily of bank-derived fine aragonite and magnesian calcite, deposited over the past 9000 to 10,000 yr. The wedge is the locus of modern deposition of sediment from PB and SJS. Because an average of 20 to 30 m of water covers PB and the SJS, they would be considered "drowned" or "incipiently drowned" platforms. The occurrence of this Holocene sediment wedge, however, contradicts the well accepted concept that deeply submerged banks are nonproductive. Three questions must be answered to test the significance of the presence of this wedge: 1) how closely is the development of the Holocene periplatform wedge tied to the last flooding of PB and the SJS; 2) how significant is the volume of bank- and shelf-derived sediment within the sedimentary wedge; and 3) how does this sediment volume compare with estimates from the Bahamas, the epitome of a healthy, productive, modern carbonate platform (Wilber et al. 1990)?

Flooding History

The majority of the top of PB and the SJS presently lies in 20 to 40 m of water (Fig. 6C). Pedro Bank is shallowest on its southeastern (windward) margin, where some small shoals and cays occur. The bank top deepens to the north where the bank edge is defined by the 40 m contour. The edge of the SJS similarly is defined by the 40 m contour. Ten to twenty meters of water cover its southeastern portion (windward side), while its western portion lies in water depths ranging between 20 and 40 m (Fig. 1B).

Figure 6A compares the sea-level curve for the past 11,000 yr from Barbados (Fairbanks 1989), the curve from western Jamaica developed by Digerfeldt and Hendry (1987) and curves from Florida Bay (Scholl et al. 1969), and Bermuda (Neumann 1971). Combining the general sea-level curve for the early Holocene with the present bathymetric maps of PB and SJS tops (Fig. 1), a series of hypsographic curves were constructed for four time periods, 10,000, 8000, 6000 YBP and present time (Fig. 6B and C). The similarity between the Jamaican sea-level curve and the other regional sea-level curves brings confidence to our exercise. We cannot rule out however, that some tectonic effects might also have influenced the flooding history of this area of the Caribbean Sea. Since the Holocene sediment cover on the carbonate banks of the Nicaragua Rise is rather thin (< 4 m on Serranilla Bank, Triffleman 1989), the present bathymetry of the

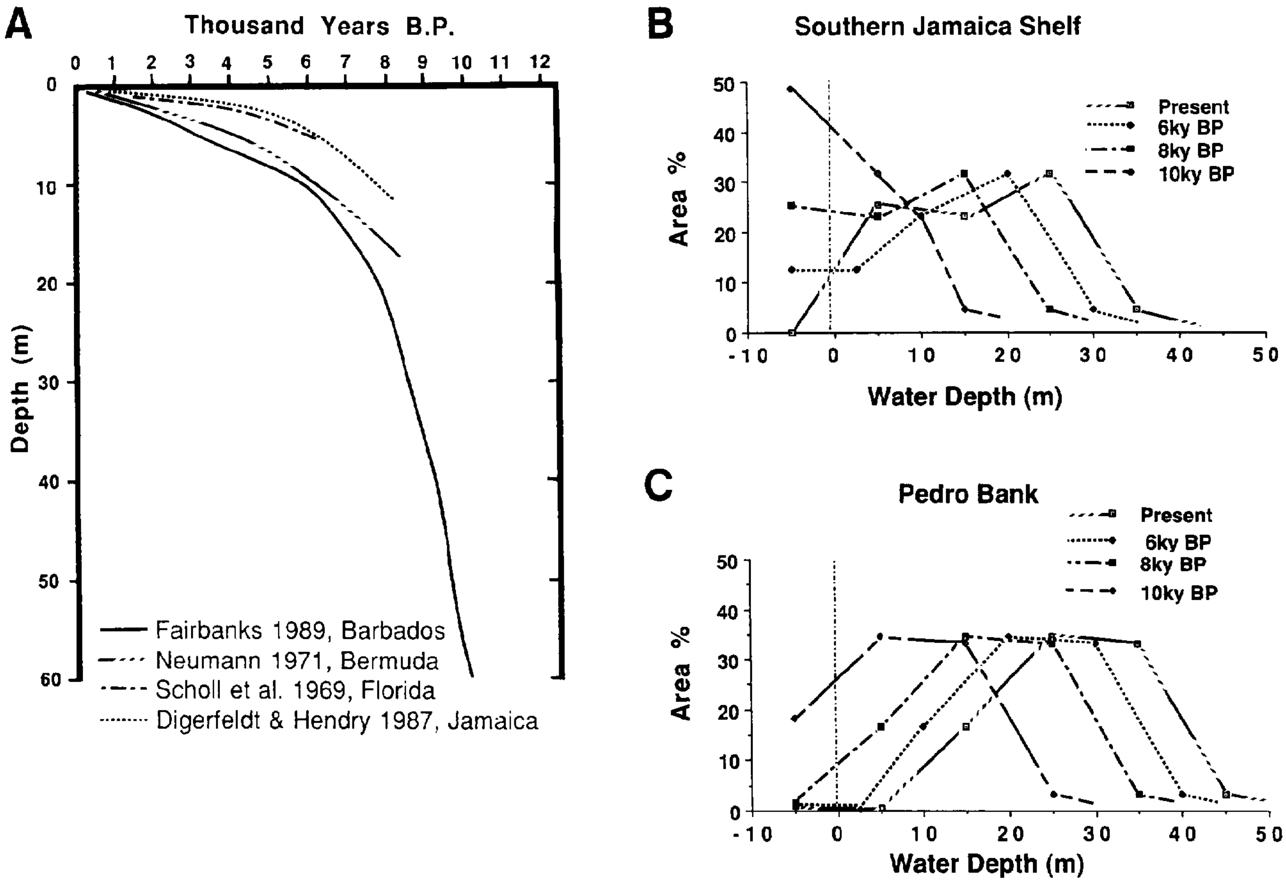


FIG. 6.—(A) Sea-level curves for the last 11,000 years from Jamaica, Florida, Bermuda and Barbados. (B and C) Hypsographic curves for the southern shelf of Jamaica and Pedro Bank. Curves are for present day, and 6000, 8000, and 10,000 years B. P.

top of PB is believed to resemble closely its pre-flooding late Pleistocene bathymetry. Contrary to our visual estimate that the tops of both PB and SJS were covered by the same average water depth, the measured flooding curves show that the water depths on top of PB were usually twice those covering the top of the SJS. This may be due to the presence of a thicker Holocene sediment cover on the SJS, a possible result of its sheltered nature and its proximity to additional sediment sources from Jamaica. The water depths on the SJS, mentioned above, therefore represent minimum values.

The hypsographic curves show that the tops of PB and the SJS already were flooded 10,000 YBP by an average of 10 and 5 m of water, respectively (Fig. 6B and C). Our estimation of the timing of initial flooding corresponds quite well with the age of the oldest sediment (9000 YBP in core 30) found overlying the basal unconformity of the Holocene periplatform wedge seen in the 3.5 kHz data. The initiation of deposition of this periplatform wedge, therefore, is related closely to the initial flooding of the bank and shelf tops. This means that this wedge is not a lowstand deposit but rather incorporates sediments that would be considered transgressive and highstand in terms of their sequence stratigraphy (Posamentier et al. 1988; Sarg 1988). The distal part of the sediment wedge in cores 21 and 89 clearly shows that most of the sediment was deposited while the banks were flooded. We will therefore refer to it as a highstand periplatform wedge to emphasize that these are not lowstand sediments.

The top of PB was covered by an average of 20 m of water and the top of the SJS by roughly 10 m, 8000 YBP. The top of PB was covered by roughly 28 m of water, while the SJS was covered by 15 m, 6000 yr ago. It was only at that time that the initial flooding of Great and Little Bahama Banks occurred (Droxler 1985; Neumann and Land 1975; Boardman 1976). The most striking finding, however, is that PB was covered by an average of 30 m of water during the time interval represented by core 90 (the last 2500 yr). Core 90 displays sedimentation rates of 2000 mm/ky. Core 29, which represents the last 4700 years, has calculated sedimentation rates of 1200 mm/ky. During this time SJS lay below an average of 15 m of water. Although these water depths are indicative of "drowned" platforms, the depositional rates of the sediments found on the slopes of these deeply submerged platforms appears equivalent to those of "healthy" producing platforms. This finding substantiates our claim that these two bank/shelf areas have produced significant

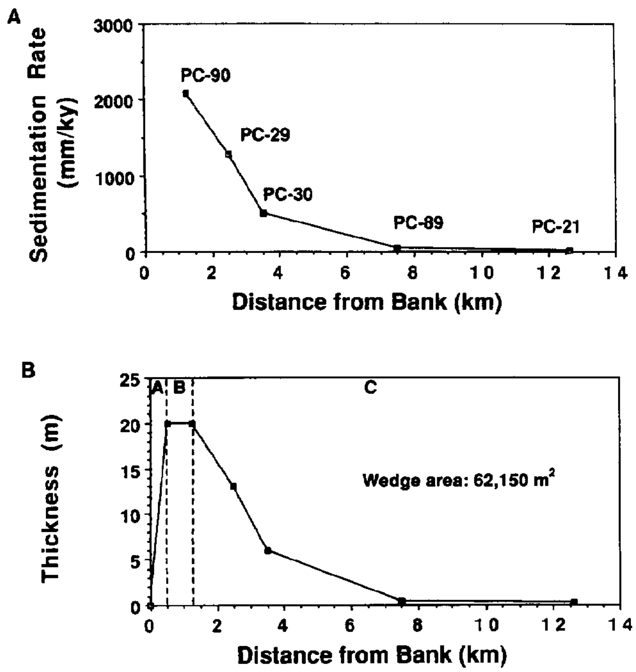


FIG. 7.—(A) Plot of Holocene sedimentation rate versus distance from bank/shelf margin for the five piston cores. (B) Schematic areal cross section of the periplatform wedge, showing thickness versus distance from the bank/shelf margin. The cross section is based on observations from the 3.5 kHz transects indicated in Figures 1B and 2A and B. Also indicated are the wedge subdivisions: escarpment edge segment A, proximal slope segment B, and distal slope segment C.

amounts of metastable carbonate sediment in the past and are still highly productive today.

Estimated Volume of Sedimentary Wedge

On the basis of the nineteen available bank (shelf) to slope 3.5 kHz profiles and the data from the five cores, a schematic 2-D cross section of the periplatform wedge, subdivided into three segments was drawn (Fig. 7B). The escarpment edge segment A includes the bank and shelf drop off, ranges in water depth from 40 to 225 m, and has a Holocene sediment cover which increases from 0 to 20 m. The proximal slope, segment B, consists of a 0.75-km-wide belt of the periplatform wedge, ranges in water depth from 225 to 300 m, and represents the locus of deposition during the past 10,000 yr. Sediment thicknesses in B average 20 m. Finally, the distal slope, segment C, consists of a 6.5-km-wide zone which ranges in water depth between 300 and 500 m. The sediment thickness in C decreases approximately exponentially with distance from the bank (shelf). The total area of the wedge cross section, an estimated 62,150 m^2, gives a wedge volume of 62 10^6 m^3 for each km of bank length. This value, in combination with the calculated values for carbonate content and mineralogy, and a calculated porosity of 56% (from water loss), enables us to estimate the volume of fine aragonite and magnesian calcite (bank-derived material). The volume of bank-derived sediment in the wedge off PB is 18.6 10^6 m^3/km. A slightly smaller volume (16.1 10^6 m^3/km) is calculated for the wedge off the SJS. Finally, by using an average sediment density of 2.75 g/cm^3, the calculated mass of bank-derived sediment within the wedges off PB and the SJS is estimated at 56.15 10^6 t/km and 48.76 10^6 t/km, respectively. These values prove that PB and the SJS are producing a significant amount of metastable sediment. The comparison of these values with the ones estimated for a similar Holocene highstand periplatform wedge from the western margin of Great Bahama Bank (GBB) will place these figures into proper perspective.

Comparison with the Bahamas

Downcore variations of bulk carbonate mineralogy from core 15 off GBB is shown in Figure 8A. The bottom of core 15 has been dated by ^{14}C at 2700 YBP. Because more than 80% of the sediment in core 15 consists of fine (< 63 μm) material (Wilber et al. 1990; Droxler, unpubl. data), carbonate mineralogy of the bulk sample is equivalent to the carbonate mineralogy of the fine fraction. This allows us to compare this data directly with the carbonate mineralogy in cores from Walton Basin. Core 15, on the leeward side of GBB, presents a perfect analogue of core 90 off PB. Both lie less than 2 km from their respective bank edge and in similar water depths (245 and 300 m, respectively). Sedimentation rates, 2700 and 2000 mm/ky for the past 2500 yr in cores 15 and 90 respectively, are almost identical. Figure 8B compares the sedimentation rates for the Bahamas core and the five cores from the Nicaragua Rise. The sedimentation rates for the Holocene periplatform wedge of Walton Basin are smaller by roughly a factor of 2 than those for the leeward side of the Bahama Platform, but they are still of the same order of magnitude.

Wilber et al. (1990) describe a Holocene periplatform wedge averaging 50 m thick (maximum 90 m) off the leeward edge of GBB. There the initiation of sedimentation is estimated to range between 6000 and 10,000 YBP. However, the hypsography of the late Pleistocene surface shows that flooding of most of the platform interior of GBB could not have begun before 6000 YBP (Droxler 1985). The areas of the oldest Holocene sediments usually range between 6000 and 5000 yr on GBB (Hardie 1977) and 6600 and 5500 yr on Little Bahama Bank (Neumann and Land 1975). Flooding of the deeper bank margins where the Pleistocene surface is 20–33 m below sea level may offer a solution to the apparent conflict between the ages of the oldest Holocene bank top and upper slope sediments. The establishment of a shallow carbonate producing environment on the shoulders of the Bahama banks would have occurred at approximately the same time as the initiation of flooding and carbonate production on Pedro Bank and the southern Jamaica shelf, 9000 to 10,000 yr ago (Hine and Neumann 1977; Hine et al. 1981).

The volume per kilometer of the Holocene periplatform wedge along the western upper slope of Great Bahama Bank, 200 10^6 m^3, represents a value three times

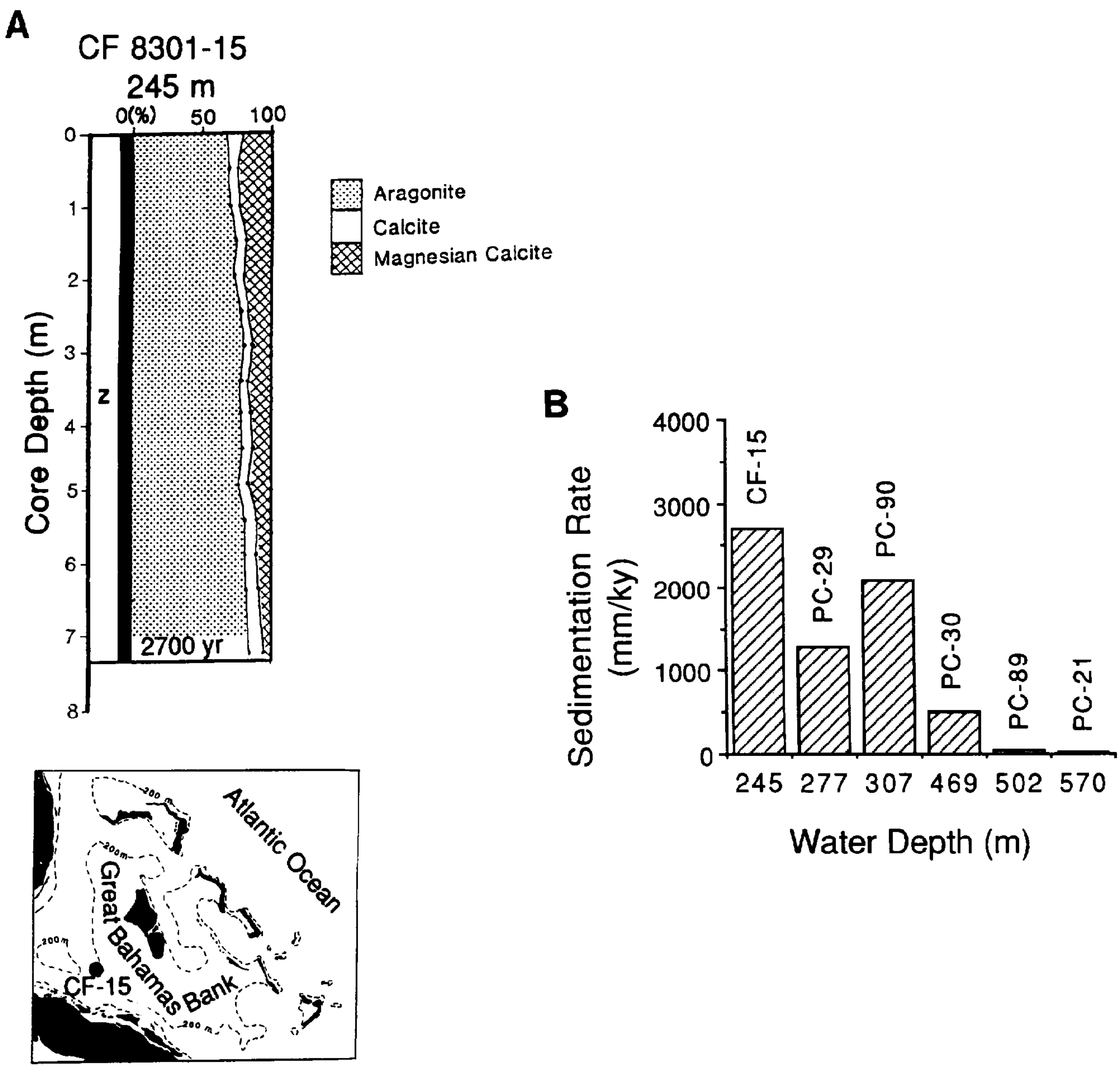


FIG. 8.—(A) Bulk mineralogy of core CF 8301-15 from the lee side of the Bahama platform. Radiocarbon and biostratigraphic data are included, and the location is indicated. (B) Comparison of the sedimentation rates for CF-15 and the four pistion cores from the Nicaragua Rise. Note the similarity in rates for CF-15 and PC-90, both located in similar water depths and at similar distances from the lee side of their respective banks.

larger than our estimate of 62 10^6 m^3 per km for the periplatform wedge on the slopes of Walton Basin. If it is taken into account that 1) the periplatform ooze within the Holocene wedge off GBB consists of 80% fine fraction (< 63 μm); 2) has a porosity of 56%; and 3) the fine sediment consists of 90% bank-derived aragonite and magnesian calcite with an average density of 2.75 g/cm^3, the mass of bank-derived sediment per kilometer equals 174 10^6 t, a value three times larger than the one calculated for the bank-derived aragonite and magnesian calcite within the Holocene wedge off PB (56 10^6 t) and three and one half times larger than the value for the shelf-derived metastable carbonate sediments within the Holocene wedge off the SJS (49 10^6 t).

Great and Little Bahama Banks typically are quoted as the standard examples of productive carbonate platforms because of their water depth and sediment cover. On the basis of the Bahamian model, platform productivity is defined in terms of the platform's ability 1) to keep up with sea-level rise, and 2) to accumulate a thick sediment cover on its bank top. This model assumes that the rim of these banks continually builds as sea level rises, thereby trapping most of the sediment on the bank and allowing the bank as a whole to keep pace with sea-level rise (bucket effect, Schlager 1981). This also means that the banks must have been flooded when sea level was rising at a rate at or below that of carbonate productivity. The Late Pleistocene surface of the Bahamas Platform is 20–30 m higher than that of the banks on the Nicaragua Rise, so the carbonate system only had to keep up with the low rates of sea-level rise that have occurred during the last 6000 years. The banks of the Nicaragua Rise were flooded when the rate of sea-level rise reached 20 mm/ky (Fairbanks 1989). At these rates, coralgal accretion could not keep up with sea-level rise. Grigg and Epp (1989) and Agegian et al. (1988) have described banks in the Hawaiian Archipelago whose Pleistocene surfaces were also flooded during the rapid rise and failed to keep up. Productivity of metastable carbonates on these banks is nonetheless high. Like the banks of the Nicaragua Rise the faunal assemblage found on these banks is composed of primarily opportunistic species and is different from the faunal communities associated with nearby shallow carbonate systems (Agegian and Mackenzie 1989).

IMPLICATIONS

Influence on Carbon/Carbonate Budget

The export of fine aragonite and high magnesian calcite from banks and shelves such as those of the Nicaragua Rise normally is not considered in terms of its CO_2 buffering potential. Most assessments of the CO_2 buffering capabilities of metastable carbonates include carbonates produced and deposited in the shallow waters of banks and shelves and exclude the slopes of carbonate margins at greater depths which receive most of the bank derived material (e.g., Garrels and Mackenzie 1981). If our estimate of metastable carbonate accumulation in the deep surroundings of PB and the SJS represents the norm rather than a special case, our findings become significant, particularly with respect to the global carbon/carbonate budget. As most of the sediment produced on these shallow carbonate banks is metastable, the introduction of large amounts of this material into deep waters could influence the carbonate chemistry of the water column at intermediate depths. The dominant effect would be the buffering of any excess dissolved CO_2 within the oxygen minimum zone, which usually ranges between 300 and 1200 m. Recent work in the Hawaiian Archipelago (Agegian et al. 1988) suggests that up to 25% of the alkalinity excess found in the Pacific Ocean may be due to the dissolution of magnesian calcite and aragonite produced on shallow and mid-depth (50–100 m) banks. Many banks and shelves, covered by 15 to 50 m of water and located in the same latitudes as those of the Nicaragua Rise, exist around the world, for example, Nazareth and Saha de Malha banks on the Mascerene Plateau, Chagos Bank and the Maldives/Laccadives Archipelago in the equatorial Indian Ocean, banks in the Java Sea, the northwestern shelf of Australia, several banks on the Queensland Plateau, Nova and Kelso banks in the Coral Sea, carbonate shelves around the Fiji Islands, banks around New Caledonia and the shelves and banks of the Hawaiian Archipelago. The potential for carbonate production on the tops of these banks and shelves should be taken into account in any calculations of global carbonate production and in estimating the amount of metastable carbonate introduced into intermediate water depths, particularly where the saturation levels of aragonite and magnesian calcite in the water column are very shallow as in the Pacific Ocean (500 m) and Indian Ocean (1000 m), or intermediate as in the Caribbean Sea (1750 m).

Aggradation of the Upper Slope During High Sea Level Stand

A characteristic Holocene pattern clearly emerges from this study of PB, SJS and from the Wilber et al. (1990) study on the sediment packaging along the upper slope of GBB. Most of the upper slope sediment deposition occurs during the late part of sea-level transgression and the highstand period following the flooding of bank and shelf tops. These sediments form a well-defined characteristic wedge 8 to 10 km in width and 20 to 50 m in thickness. The concept of carbonate highstand shedding, already established in several studies in the periplatform environments of the Bahamas, relies heavily on core data in the lower slopes and basins (Kier and Pilkey 1971; Lynts et al. 1973; Droxler et al. 1983; Mullins 1983; Boardman and Neumann 1984; Droxler and Schlager 1985; Boardman et al. 1986; Austin et al. 1988). By using high frequency (high resolution) seismic sources such as a boomer (Wilber et al. 1990) or an 80 cubic inch water gun (Fig. 9), it becomes obvious that Pleistocene carbonate slopes consist of a series of stacked highstand periplatform wedges. Off GBB, Wilber et al. (1990) were able to count at least five stacked periplatform wedges, representing the highstands of the last half-million years.

The stacking of several small highstand periplatform wedges is well illustrated in a single-channel digitized seismic profile off the edge of SJS (Fig. 9 and Fig. 1 for location). The series of stacked highstand periplatform wedges, contained in a larger sediment wedge, overlie a major unconformity (late Miocene?) interpreted as the top of a large drowned shallow mid-Miocene carbonate bank. The geometry of these stacked wedges resembles the Holocene highstand periplatform wedges identified off the margins of PB and the SJS. They are usually constrained by a well defined lower unconformity, which is overlain by a thick homogeneous sedimentary wedge, and are interpreted to be highstand deposits. Thicknesses of the successive wedges seem to decrease upward and the thickness of the individual wedges decreases rapidly away from the shelf escarpment. In spite of the downfaulting of the shelf edge, the margin is still aggrading and shows slight progradation to the northwest (roughly 2 km) during the Plio-Pleistocene.

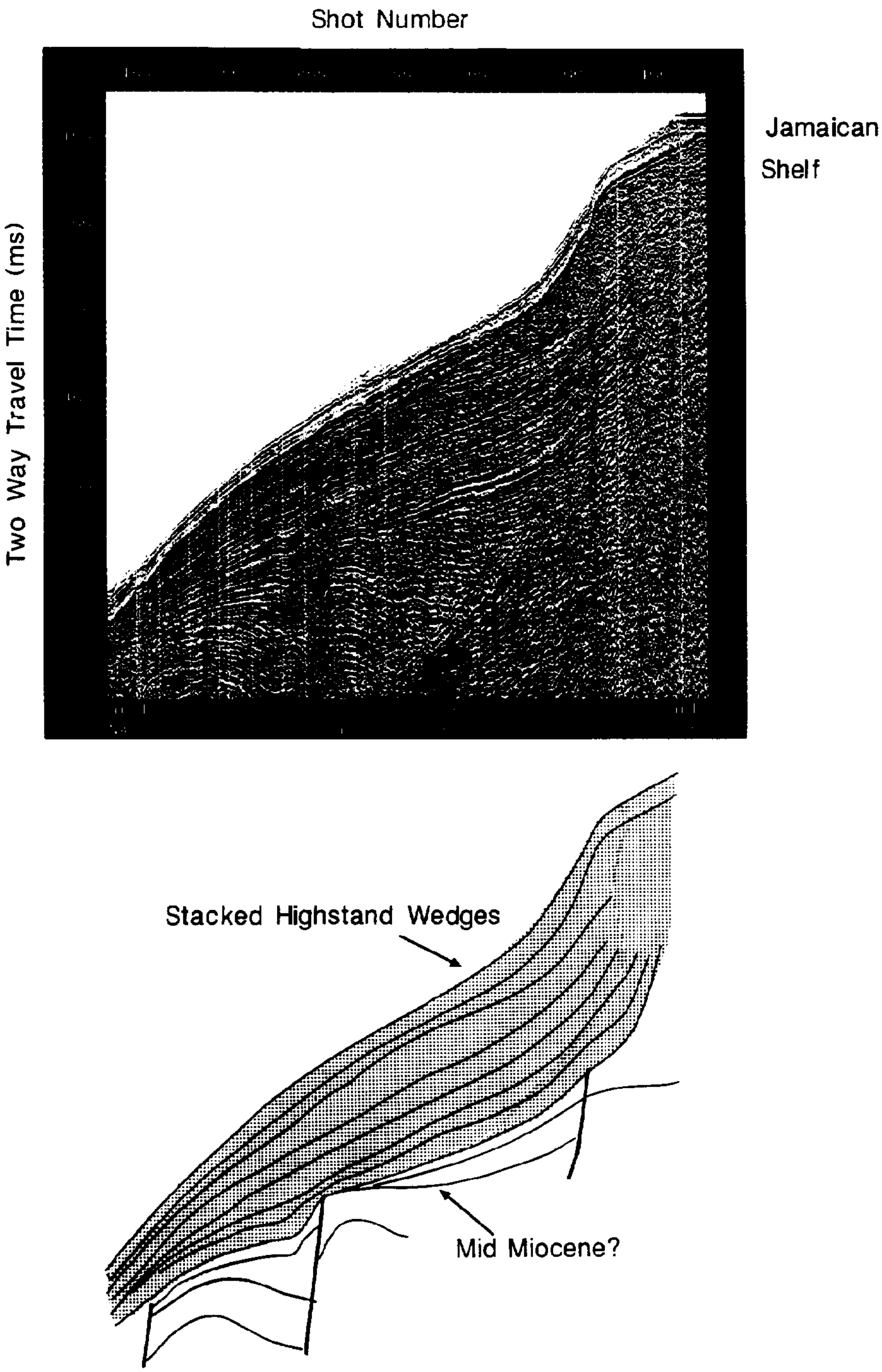


FIG. 9.—Seismic profiles of a high resolution seismic line off the southern Jamaican Shelf showing the wedge shaped sedimentary deposit, consisting of a series of stacked highstand sediment wedges. Location of seismic line shown in Figure 1.

CONCLUSIONS

1) Holocene highstand periplatform wedges occur along the upper slopes off Pedro Bank and the southern Jamaica shelf on the northern Nicaragua Rise. Initiation of deposition corresponded to the flooding of bank and shelf tops approximately 9000 to 10,000 yr ago. The fine sediments within the wedge consist predominantly of bank (shelf)-derived metastable aragonite and magnesian calcite.
2) Deposition along the periplatform wedge occurs at the present time, based on the very young ^{14}C dates (none exceeding 1100 yr) for the bulk surface sediment. Sedimentation rates for the past 2500 yr range between 2000 mm/ky off Pedro Bank to 1200 mm/ky off the southern Jamaica shelf. These rates imply that Pedro

Bank and the southern Jamaica Shelf have remained healthy producers of large volumes of sediment now found as a periplatform wedge on the upper slope. They cannot be considered "semi-drowned" or "drowned" banks/shelves, as most carbonate sedimentologists would have concluded on the basis of their water depths (25 to 35 m) and their thin winnowed, coarse, Holocene sediment cover.

3) Estimated masses of bank-derived metastable fine aragonite and magnesian calcite, included within the Holocene periplatform highstand wedge on the upper slope of Pedro Bank (56 10^6 t/km) and the southern Jamaica Shelf (49 10^6 t/km), are comparable in order of magnitude, with the estimated volume of bank-derived fine sediment along the upper slope of Great Bahama Bank (174 10^6 t/km).
4) The unaccounted for, rather large volume of metastable fine aragonite and magnesian calcite produced on these "semi-drowned" or "drowned" carbonate systems and exported toward the deep environments, might play a significant role in buffering CO_2 excesses at intermediate water depths. This is particularly true in the Pacific and Indian Oceans, where ocean waters are undersaturated with respect to both aragonite and magnesian calcite at depths shallower than 1000 m.
5) High-resolution seismic profiles across the slopes off Pedro Bank and the southern Jamaica Shelf show evidence of slope sediment deposition consisting of a series of stacked highstand periplatform wedges deposited on the upper slope during times of bank and shelf top flooding.
6) Finally, because carbonate banks and shelves can produce significant volumes of material while they are submerged by more than 15 m of water (25–30 m), they might not always be the accurate "dip-stick" that they supposedly are in recording highstands of sea level. A determination of whether the bank-top sediments are of the type associated with deep banks (coarse) or the mud characteristic of shallow platforms will have to be made before a paleo-water-depth can be assigned.

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