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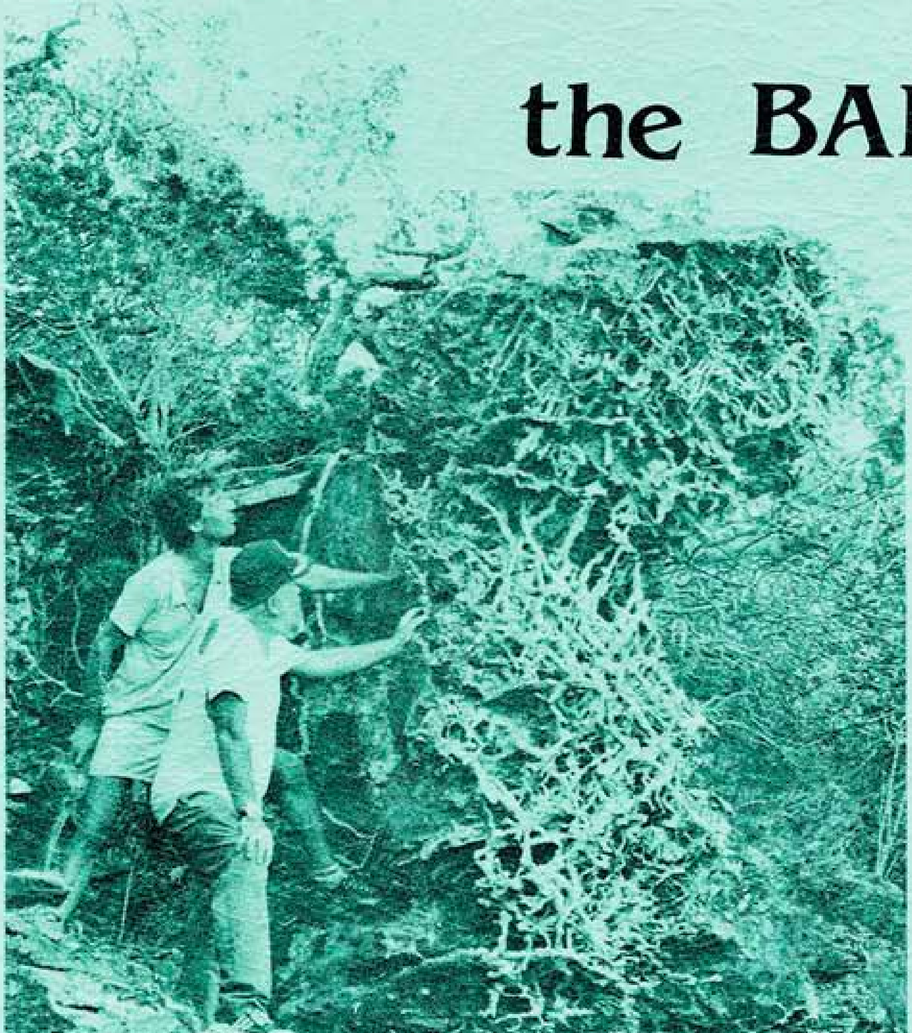

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EPISODES OF BANKTOP GROWTH RECORDED IN PERIPLATFORM SEDIMENTS AND THE CHRONOLOGY OF LATE QUATERNARY FLUCTUATIONS IN SEA LEVEL

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Abstract

Geochemical and sedimentological examination of cores from the periplatform environment of Northwest Providence Channel, Bahamas provides a record of banktop responses to late Quaternary fluctuations of sea level. During lowstands of sea level, the periplatform sediment is dominated by planktonic deposition of calcitic foraminifera and coccoliths. Aragonitic sediment includes Sr-poor aragonite from pteropods, and a small amount of Sr-rich aragonite of shallow-water origin is derived from the portion of the steep bank margins within the photic zone. When highstands of sea level flood carbonate platforms, the area available for production of shallow-water carbonate increases enormously. A pulse of shallow-water sediment is produced and provides sediment not only to the shallow lagoons and to intertidal and supratidal tidal flats, but also to the periplatform environment. These pulses of banktop production are recorded in the periplatform sediments as abrupt increases of aragonite overlying the calcite-rich sediment deposited during lowstands. A gradual decline in the amount of shallow-water sediment deposited in the periplatform environment may indicate the growth of effective barriers to off-bank transport on the bank margins. In addition, as the lagoons fill and become more shallow, a decrease in benthic productivity may accompany more variable salinities and temperatures.

By extrapolating rates of accumulation determined from C-14 dating of the uppermost highstand and lowstand modes of deposition, the chronology of late Quaternary fluctuations of sea level has been determined.

Introduction

There is abundant evidence that many fluctuations in sea level have occurred during the Quaternary. Some very good records of late Pleistocene and Holocene fluctuations in sea level have been interpreted from studies of elevated reef terraces, oxygen isotope analyses of deep-sea cores and studies of speleothems in Bermuda and the Bahamas. However, considerable uncertainty exists regarding the timing, durations and amplitudes of highstands of sea level. This study presents a record of the timing and durations of highstands of sea level based on examination of periplatform deposition.

Previous Work

Elevated Reefs: Isotopically dated coral reef terraces on tectonically active (emerging) coastlines provide estimates of the timing of highstands of sea level. However, highstands which are of short duration may not be preserved, and superposition of highstands of different amplitudes complicate interpretation of the stratigraphy and isotopic dates. There is also the assumption that tectonic uplift has been continuous and at a constant rate. In general, however, the careful research in New Guinea, Barbados and Haiti provides one of the best records of fluctuations in sea level during the late Pleistocene (Bloom, et al., 1974; Fairbanks and Matthews, 1978; Aharon, 1983; Dodge, et al., 1983). In the Bahamas, exposed, in situ reef material has been isotopically dated and confirms that a single highstand or multiple highstands of sea level affected the Bahamas between 115,000 and 130,000 years before present (Neumann and Moore, 1975).

Oxygen Isotope Analysis: Oxygen isotope analyses of planktonic foraminifera from deep-sea cores provide an estimate of changes of ice volume which are then related to fluctuations in sea level (Shackleton, 1967). However, variations in the water temperature at the time of calcification, specimen age and life habits, and diagenesis on the sea floor and in the sediment column can significantly alter the $\delta^{18}O$ signal from foraminifera. Kennett (1982) and Matthews (1984) review these concerns. The most widely used method for assigning an absolute chronology to the fluctuations in $\delta^{18}O$ has been interpolation from a major magnetic anomaly or from a biostratigraphic control point (Shackleton and Opdyke, 1973; Thierstein, et al., 1977). Use of oxygen isotopic ratios of planktonic foraminifera in deep-sea cores can provide a complete record of sea-level fluctuations, not just highstands. Each meter of sea-level fluctuation changes the $\delta^{18}O$ value by about 0.011 ppt (Matthews, 1984).

Speleothems: Speleothem growth is a subaerial process which is interrupted when a highstand of sea level floods the cave. Evidence of marine conditions retained within speleothems includes marine borings and encrusting worm tubes (Carew and Mylroie, 1983) and aragonite rinds (Harmon, et al., 1978). Isotopic dating of the laminae deposited before and after evidence of marine conditions can provide a time and duration of highstands of sea level.

Periplatform Sediments: Periplatform environments are areas of carbonate accumulation located on the deep flanks of carbonate platforms. This enormous wedge of carbonate sediment is a mixture of bank-derived and planktonic-derived sediment (Schlager and James, 1978; Mullins and Neumann, 1979; Boardman and Neumann, 1984).

Kier and Pilkey (1971) examined cores from Tongue of the Ocean, Bahamas and reported layers of aragonitic needle-rich sediment alternating with calcitic, coccolith-rich sediment. They proposed that during highstands of sea level, the banks are submerged and off-bank transport of aragonitic, needle-rich sediment occurs; whereas during lowstands of sea level, only planktonic deposition is possible.

Alternative explanations of the layers of aragonite-rich sediment and aragonite-poor sediment include periodic emplacement of aragonite-rich layers by turbidity currents (Lynts, et al., 1973) and dissolution cycles which selectively dissolve aragonite (Droxler, et al., 1983). Droxler, et al. (1983) purposefully selected a core site which was removed from effects of turbidity currents yet close enough to the platform margin to record any signal of off-bank transport of sediment accompanying highstands of sea level. This excellent study revealed alternating aragonite-rich and calcite-rich layers of sediment which apparently support the idea that periplatform sediments record sea-level events. However, their analysis of the data is that the most recent increase of aragonite occurred prior to the possible time of flooding of the banktop. They suggest that selective dissolution of aragonite during glacial periods produces aragonite-poor zones. Although the peaks in the aragonite cycles are related to climate, they are not caused by pulses of bank-derived sediment being swept off the platform during highstands of sea level. The core used by Droxler, et al. (1983) was recovered from 1062 meters and could have been affected by fluctuation in ocean chemistry. However, the source of the high concentrations of aragonite is not explained by selective dissolution.

Purpose of this Research: The purpose of this paper is to demonstrate that the periplatform environment contains a record of continuous planktonic deposition punctuated by deposition of bank-derived sediment during highstands of sea level. In addition to determining the relative chronology of highstands of sea level, absolute ages and durations of the highstands can be determined by extrapolating rates of sedimentation determined for the upper portion of the core to the entire core.

Methods

A piston core (11.7 meters long) was recovered from an intercanyon high area, 675 m deep, in Northwest Providence Channel (Fig. 1). This core site was specifically chosen because it is:

1. removed from effects of turbidity currents,
2. above the zone of oceanic dissolution cycles,
3. close enough to the periplatform environment to receive and record the effects of highstands of sea level.

Subsamples were extracted every 10 cm, and the sediment was soaked in clorox to remove organic matter, rinsed and wet-seived to separate the mud fraction (<62um).

Previous studies on the geochemistry and sedimentology of

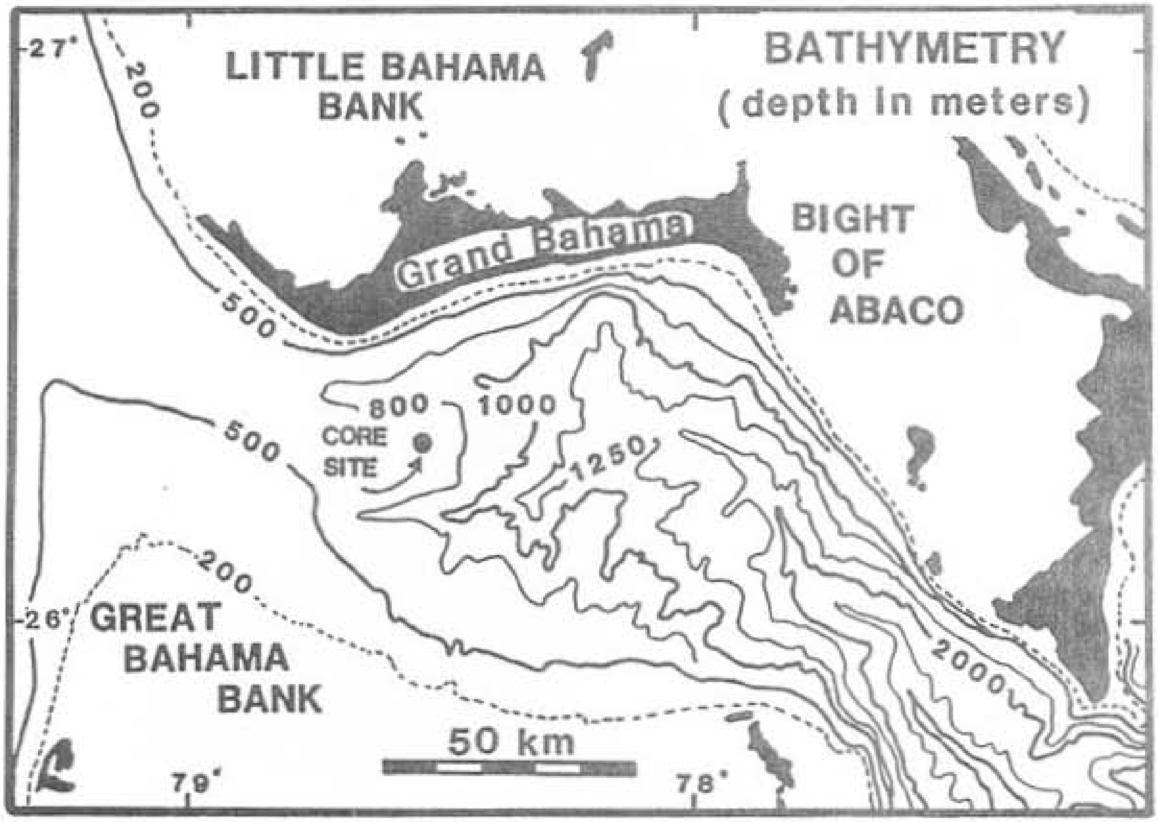


Figure 1: Bathymetry of Northwest Providence Channel and location of core.

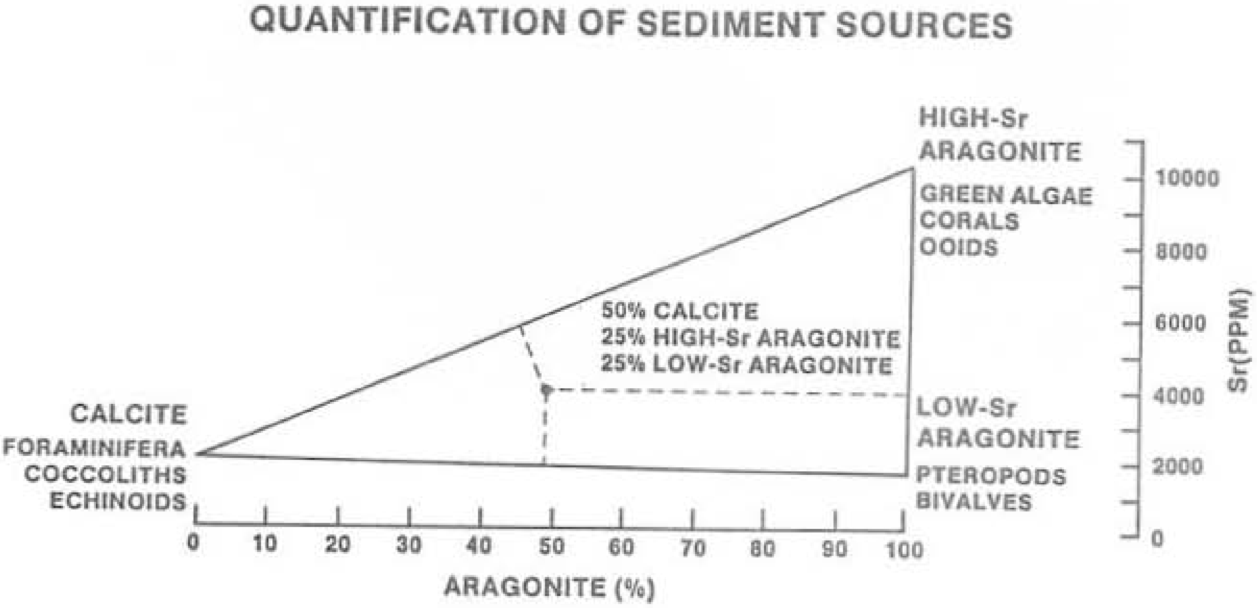


Figure 2: Geochemical distinctions can be made to separate and quantify the sources of periplatform sediment.

surface sediment from Northwest Providence Channel indicate that the clay-sized fraction is the best fraction to distinguish bank-derived from ocean-derived sediment (Boardman and Neumann, 1984). Both aragonite and strontium are determined in order to estimate the relative proportions of bank-derived sediment and sediment derived from open-ocean sources. Bank-derived sediment contains aragonite with 7500 to >10,000 ppm Sr substituting for Ca (e.g. green algae, corals, ooids, cements); while planktonic-derived sediment is dominated by calcite and aragonite with 1000-2000 ppm Sr substituting for Ca (e.g. pteropods). Figure 2 shows how these distinctions can be made and relative proportions determined.

Percent aragonite and percent total calcite are determined in the clay-sized fraction by X-ray diffraction using ratios of intergrated peak counts and comparing them to standard curves of biogenic carbonates (Neumann, 1965; Boardman, 1978). For aragonite concentrations between 30 and 80 percent, the precision (one standard deviation) for this analysis is 1.6 percent. The precision deteriorates as the concentration of aragonite decreases below 30 percent.

Strontium in the clay-sized fraction is determined by atomic absorption. Weighed samples are dissolved in HCl (10%), filtered (0.45μm MilleporeR), diluted to a constant volume and run in triplicate. Calibration solutions are prepared with identical concentrations of Ca and HCl to minimize matrix effects. Precision (one standard deviation) is 42 ppm Sr.

Results

Synchronous fluctuations of aragonite and strontium occur in the clay fraction of the core (coefficient of correlation = 0.9). Aragonite varies from 18 percent to 90 percent, and Sr varies from 2300 ppm to 10,000 ppm (Fig. 3).

When the data are plotted using aragonite and Sr as the two axes (Fig. 4), it is seen that most of the sediment samples are within the ternary diagram created by the three end-member geochemistries and are mixtures of high-Sr aragonite and calcite. Low-Sr aragonite is of less importance. Using Figure 4, the relative proportions (%) of calcite, high-Sr aragonite and low-Sr aragonite can be determined. The distribution of these geochemical signatures within the core show that high-Sr aragonite and calcite are most abundant and have pronounced peaks and valleys (Fig. 5).

Discussion

Origin of Cycles of Aragonite

The main cause of the fluctuations in aragonite is the input of bank-derived high-Sr aragonite during times when highstands of sea level were high enough to flood the platforms. Consideration of the geochemistry of the sediments and the sedimentary budget of lagoons supports this conclusion.

Geochemistry: The methods used in this study are specifically designed to permit a geochemical interpretation of the origin of aragonite to Northwest Providence Channel (Fig. 2).

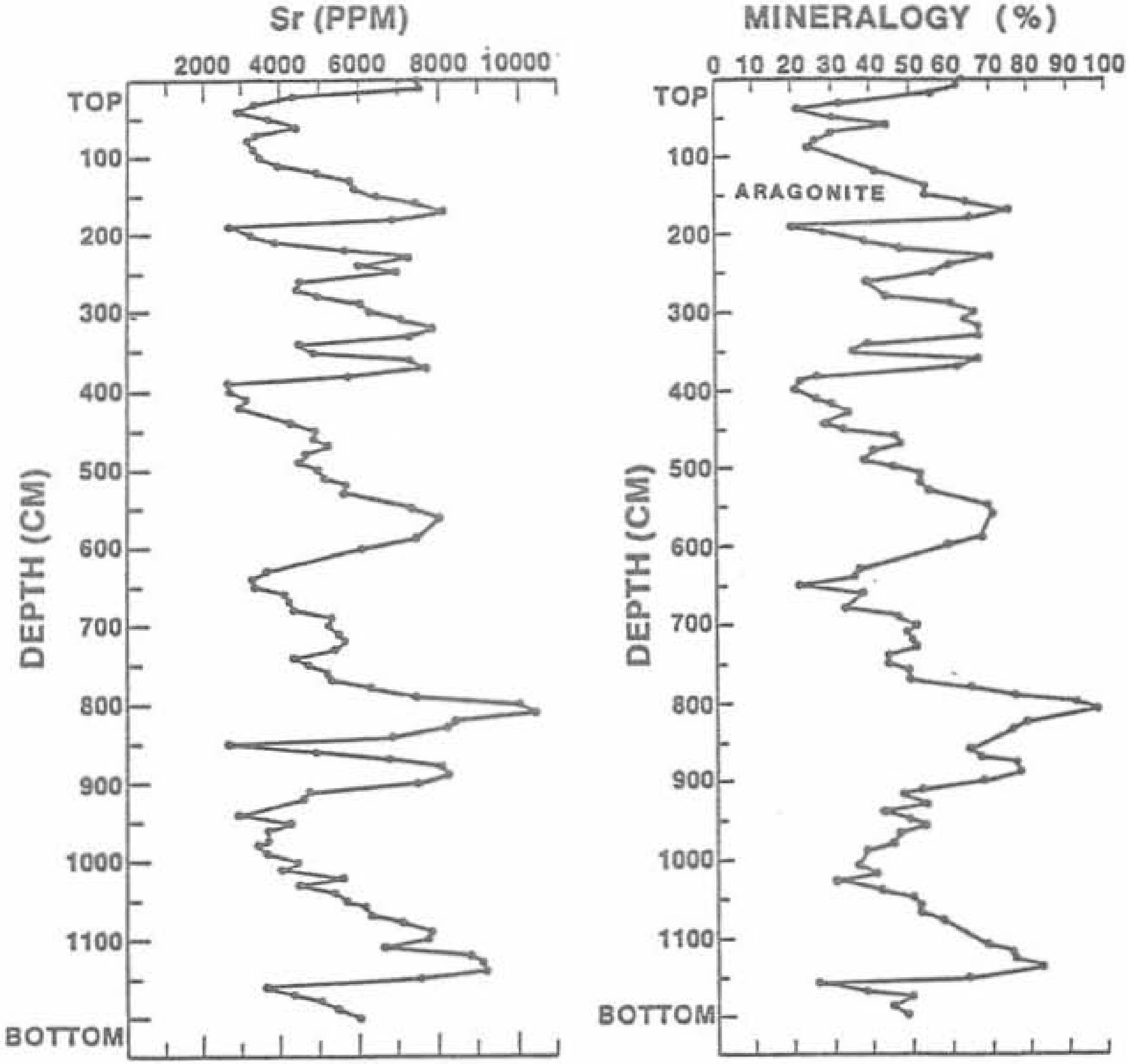


Figure 3: The distributions of strontium and aragonite with depth in the core are synchronous (r = .9)

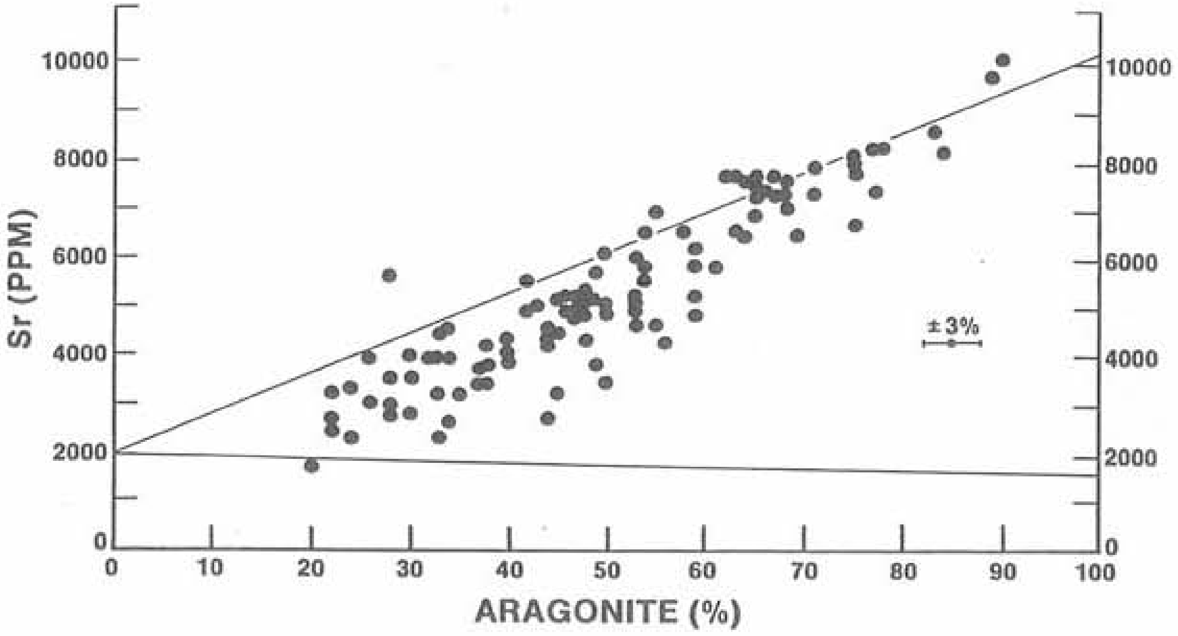


Figure 4: The relative proportions of the sources of sediment to Northwest Providence Channel can be determined using the method outlined in Fig. 2. Most of the sediment samples lie along a mixing line between high-Sr aragonite sources and calcite sources. Low-Sr aragonite is of minor importance.

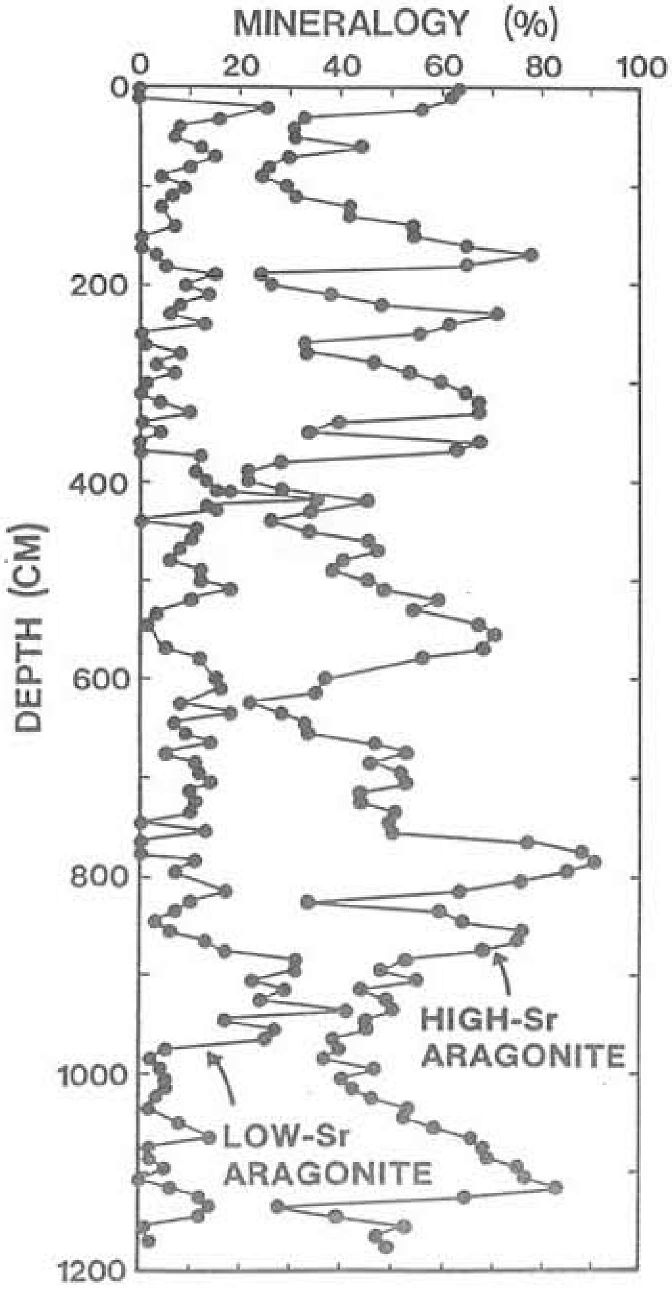


Figure 5: Pronounced peaks and valleys are evidenced in the distribution of high-Sr aragonite (and calcite) with depth in the core. The low proportions of low-Sr aragonite do not contain variations which mimic the variations in high-Sr aragonite.

Of crucial importance is the bimodal distribution of Sr in all naturally occurring carbonate (Bathurst, 1975). All naturally occurring calcite and molluscan aragonite contain low concentrations of strontium (<2000 ppm). The only source of high concentrations of strontium in naturally occurring carbonates is in aragonite from corals, green algae, ooids and shallow-water aragonite. The aragonite cycles cannot be caused by fluctuations in the productivity of pteropods (a planktonic mollusc which secretes an aragonitic skeleton). Pteropods secrete aragonite with a low content of Sr (about 1500 ppm); whereas the cycles of aragonite are created by the high-Sr variety of aragonite (Fig. 5). Thus, the geochemistry of the sediment indicates a shallow-water origin of the aragonite cycles.

Budget: The prolific sediment production by green algae when lagoons are flooded is known to be more than sufficient to account for all the aragonite sediment accumulating within lagoons (Neumann and Land, 1975; Stockman, et al., 1967). This overproduction helps build tidal flats and is exported from the lagoon to the periplatform environment. The overproduction from the Bight of Abaco accompanying the Holocene rise in sea level has been measured (100×10^{10}kg; Neumann and Land, 1975) and compares very well with the quantity of sediment derived from Bight of Abaco found in Northwest Providence Channel (70×10^{10}kg; Boardman and Neumann, 1984). Thus, the mineralogy, Sr concentration, and budget calculations support a bank-derived source of aragonite as the major cause of the Holocene signal.

Downslope gravity movement such as a turbidity flow is also an unlikely cause of these fluctuations. The site of this core is a large intercanyon plateau, and downslope gravity movements would probably be channeled via the canyon system within Northwest Providence Channel (Fig. 1). While we do not deny the importance of turbidity currents in carbonate margins and seaways (Crevello and Schlager, 1980; Rusnak and Nesteroff, 1964; Mullins and Neumann, 1979), careful selection of a core site can eliminate or minimize their importance (e.g. Droxler, et al., 1983).

Model: The model proposed by Kier and Pilkey (1971) predicts high concentrations of bank-derived aragonite during highstands and no bank-derived aragonite during lowstands of sea level with no in-between values of bank-derived aragonite. The signal of high-Sr aragonite found in this core is more complicated (Figs. 5 & 6). First of all, we do not see a box-shaped curve of bank-derived aragonite. Instead we find sharp increases in aragonite (from 15% to 65% within 40 cm of deposition) followed by a more gradual decline to 15% high-Sr aragonite (during 80 cm of deposition). Secondly, the quantity of high-Sr aragonite does not decrease to zero, but usually reaches a low value of about 15% high-Sr aragonite.

A reasonable explanation for this signal of bank-derived aragonite is that when sea level first floods the banktops, lagoon production begins and any overproduction is transported off the banktop without hinderance (Fig. 7a). After a few thousand years, reefs, sand shoals and islands develop on the margins (e.g. Joulter's Cay north of Andros Island; Harris, 1979)

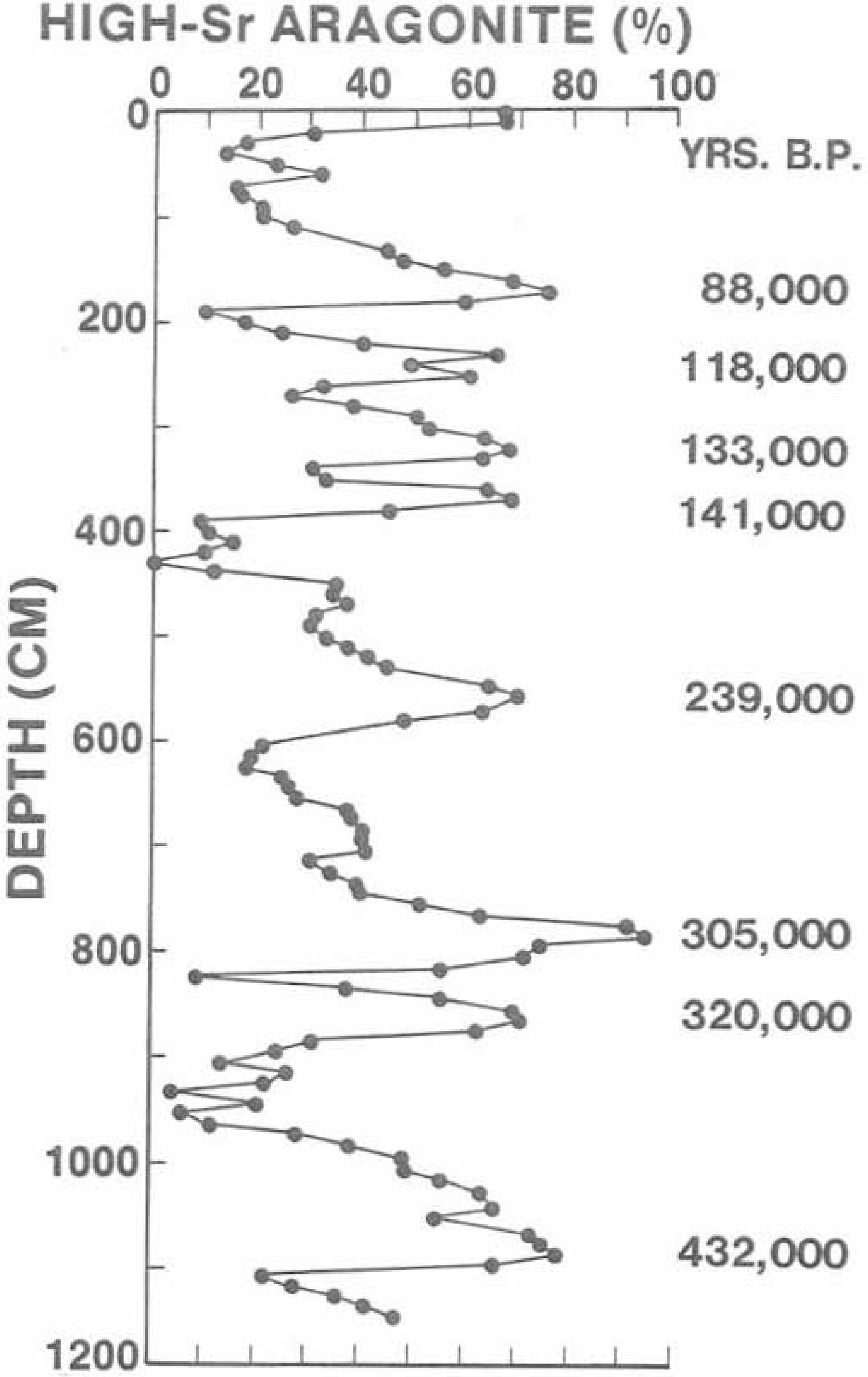
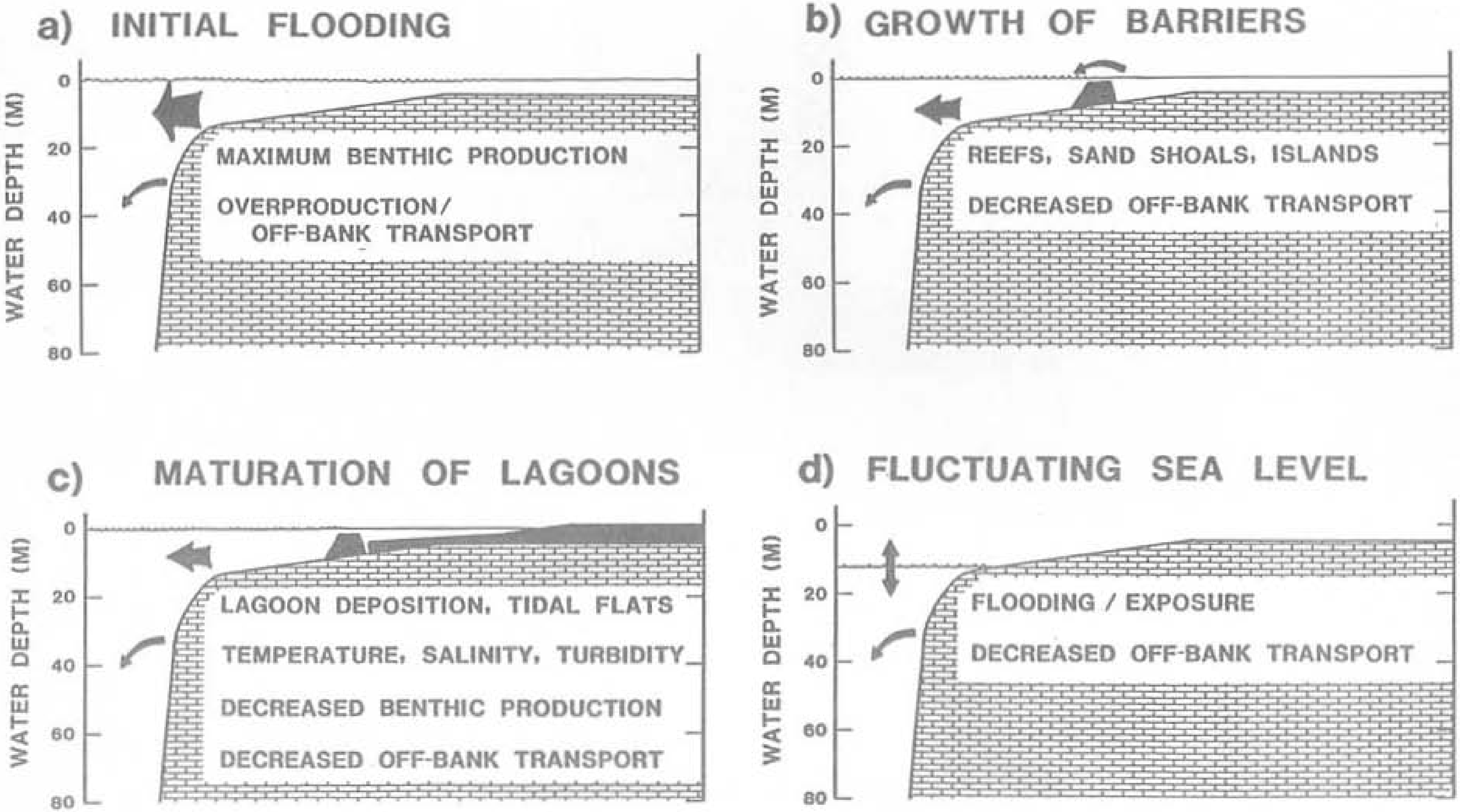


Figure 6: The signal of high-Sr aragonite records the inital flooding of the banktops (maximum values of sea level) banktop evolution (gradual declines of aragonite) and lowstands of sea level (minimum values of aragonite). The numbers at the right are the years (B.P.) when the inital flooding occurred. These dates are determined from extrapolation of sedimentation rates determined by C-14 analyses of the upper portion of the core.



a) INITIAL FLOODING

b) GROWTH OF BARRIERS

c) MATURATION OF LAGOONS

d) FLUCTUATING SEA LEVEL

Figure 7: Banktop processes resulting from fluctuations of sea level. a) during initial flooding, offbank transport is greatest, b) barrier development restricts offbank transport, c) lagoon productivity may decrease because of decreasing size of the lagoon and changes in salinity, turbidity or temperature, d) fluctuating sea level may lead to decreased sediment production.

and should obstruct the offbank transport of lagoonal sediment (Fig. 7b). Several other processes may act to limit the production of carbonate sediment. Restricted circulation resulting from the growth of barriers at the margins and/or lagoon infilling may cause the lagoonal environment to become less hospitable to carbonate production. Also tidal flats may grow laterally and diminish the area for benthic production of carbonate. These processes on the bank tops may act to reduce the production and off-bank transport of sediment to the periplatform environment and cause the gradual decline in the accumulation of bank-derived aragonite seen in the core (Fig. 7c). It is also possible that rapid fluctuations of sea level exposed and flooded the banktops causing a reduction in the production and off-bank transport of sediment (Fig. 7d). Bioturbation of the upper 5-10 cm of sediment would obscure high-frequency changes in sediment geochemistry.

The presence of some high-Sr aragonite during the times when the banktops were subaerially exposed is not unexpected because benthic production of high-Sr aragonite should continue along the steep margins of the platforms (e.g. Moore, et al., 1976).

Rebuttal to Dissolution Cycles: Dissolution cycles (Droxler, et al., 1983) cannot be of major importance to these fluctuations. This core is recovered from a relatively shallow water depth (675 meters), and during times of lowered sea level, when Droxler, et al., (1983) propose selective dissolution of aragonite occurs, this core would have been located in water depths around 550 meters. It is unlikely that the depth of undersaturation with respect to aragonite in the Atlantic Ocean has been that shallow. The depth of saturation in the western North Atlantic is presently 1000 meters (Berner, 1977) and the aragonite lysocline pccurs between 3000 and 3500 meters (Milliman, 1977).

Additional evidence that selective dissolution of aragonite is not a major factor in these cycles is that the minor fluctuations in the vertical distribution of low-Sr aragonite are not synchronous with the fluctuations of high-Sr aragonite (Fig. 5). It is unlikely that the solubility of high-Sr aragonite (1.0 mole % $SrCO_3$) is significantly higher than the solubility of low-Sr aragonite (0.2 mole % $SrCO_3$). And besides, where could the high-Sr aragonite originate which would then be selectively dissolved? We see little support for the process of selective dissolution in this core.

The signal of high-Sr aragonite (Fig. 6) is a record of highstands of sea level. This record results from the addition of lagoonal sediment to the continuous deposition of planktonic sediment in the periplatform environment. It is a primary depositional signal and is not a result of dissolution cycles nor of turbidity current emplacement.

Chronology of Highstands of Sea Level

To determine the chronology of highstands of sea level in this core, we have used C-14 ages from the upper portion of the core to compute sedimentation rates which are then applied to the entire core to assign ages to each highstand of sea level. This extrapolation requires that sedimentation processes are predictable and understood.

Our model of late Pleistocene deposition in the periplatform environment demands that deposition rates be higher during periods of highstands of sea level when the banktops are additional sources of sediment and should decrease as the amount of bank-derived sediment transported to the periplatform site decreases. Thus, the deposition rate should vary between a low value during lowstands and a high value during the initial flooding of the banktops and should be a direct reflection of the amount of high-Sr aragonite in the periplatform sediment.

This reasoning was checked by comparing the quantity of bank-derived sediment (derived from Bight of Abaco) which is presently found in Northwest Providence Channel (Boardman and Neumann, 1984). For a core in Northwest Providence Channel near Bight of Abaco, they determined (from C-14 ages) that the rate of deposition for sediments containing approximately 80% bank-derived material (i.e. 4 parts bank-derived plus 1 part planktonic-derived) is about 5 times greater than the deposition rate of sediment containing very little bank-derived material.

The rate of deposition (determined by three C-14 analyses of bulk samples) for sediments dominated by high-Sr aragonite in the piston core used in the present study is 9.4 cm/1000 years. This rate of deposition is similar to the rates of deposition determined for the aragonite-dominated sediments of other areas in Northwest Providence Channel (Boardman, 1978; Boardman and Neumann, 1984) and for other areas in the Bahamas (Droxler, 1984, figure 51a). Additional support for this average deposition rate comes from a separate study of a box core recovered from a nearby area. In this box core, the rate of deposition of silt-sized material averages 8.9 cm/1000 years and of clay-sized material is 16.2 cm/1000 years. The textures of both the piston core and the box core are dominated by silt-sized material.

The rate of deposition (based on 2 C-14 analyses) for sediments dominated by planktonic sources is 0.8 cm/1000 years. This rate is on the low end of the range of 16 rates of deposition (0.7 - 3.2 cm/1000 years) determined from "glacial" sediments (Droxler, 1984, figure 51a).

Thus the rate of deposition at this site is 9.4 cm/1000 years during the initial stage of a highstand when the input of high-Sr aragonite is high (69.5 percent) and 0.8 cm/1000 years during lowstands when the input of high-Sr aragonite is low (~13 percent). As the sea floods the banks or as the banktops attain an equilibrium to a stillstand by barrier development and/or lagoon maturation (Fig. 7), intermediate inputs of high-Sr aragonite are expected, and intermediate rates of deposition should occur. If this relationship remains true thoughout the core, the quantity of high-Sr aragonite can be used to estimate the rate of deposition at every point in the core, and the time and duration of highstands of sea level can be estimated.

<u>Chronology of Highstands:</u> The chronology of highstands determined in this manner is shown in Figure 6. It should be remembered that the absolute elevation of these highstands is not known. We only know that each highstand of sea level measured by

a peak in the amount of high-Sr aragonite was high enough to flood the lagoons, i.e. at least as high as 2 or 3 meters below present sea evel.

This chronology compares well with chronologies from elevated reef terraces, speleothems and oxygen isotope curves from planktonic foraminifera. There are some differences however.

Comparison to Elevated Reefs: The chronology of elevated reef terraces is determined by isotopic dating of reef material which has undergone constant uplift (Mesolella, et al., 1969; Bloom, et al., 1974; Stearns, 1978; Dodge, et al., 1983) and indicates that highstands of sea level occurred around 82,000 B.P. and 105,000 B.P. and were much lower than modern sea level (-13 to -45 meters and -8 to -43 meters, respectively). The data presented in this report show that these highstands did reach to within 2 or 3 meters of the present-day level in the Bahamas.

Several researchers recognize three highstands between 105,000 and 140,000 years B.P. Although there is some disagreement as to the exact time of these highstands, one of them is thought to have been higher than present sea level by several meters (Usually the highstand at 125,000 years B.P. is cited); whereas the other two highstands are thought to be lower than present sea level. Our data suggests that all three highstands were near to or higher than present sea level. This is in agreement with a study of elevated reefs from the Bahamas in which dates range from 100,000 to 145,000 years B.P. (Neumann and Moore, 1975).

Comparison to the Record of Oxygen Isotopes: The chronology of the deep-sea oxygen isotope curve is created by interpolation from the Brunhes-Matuyama magnetic reversal (700,000 years B.P.) to the present assuming uniform rates of deposition (Shackleton and Opdyke, 1973). The curves of $\delta^{18}O$ generally show three peaks during stage 5 (5e, 5c and 5a), the oldest of which (5e) is 128,000 years B.P. Peaks 5c and 5a are not as high as 5e and suggests that these later highstands were not as high as present sea level. This interpretation is not supported by the present study. In addition, the deep-sea isotope record shows only one poorly developed highstand (stage 3) between stage 5 and today which occurs at 64,000 years B.P. However, our data (and data from elevated reefs) clearly shows a highstand of sea level around 80,000 years B.P.

Comparison to Speleothems: Speleothem data from Bermuda (Harmon, et al., 1978) indicates that at least two highstands of sea level occurred (125,000 and 97,000) prior to the present highstand. Data from a speleothem on San Salvador (Carew and Mylroie, 1983) suggests that a highstand of sea level existed sometime between 47,000 and 35,000 years ago. Our data provides minimal support for a highstand in this time interval. A minor peak of high-Sr aragonite (at 60 cm in the core) is dated at 37,000 years B.P.

Conclusions

Highstands of sea level are recorded in periplatform sediments when large quantities of bank-derived sediment (high-Sr aragonite) are swept off the banktops and deposited in the periflatform environment. Each highstand is recorded as a peak of high-Sr aragonite. By applying sedimentation rates determined from the top of the core to the entire length of the core, a chronology of these highstands has been determined and compares well with the chronology of highstands determined from elevated reefs, the deep-sea oxygen isotope record and speleothem data.

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