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Brian White
Smith College

H. Allen Curran
Smith College, acurran@smith.edu

Mark A. Wilson
The College of Wooster

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BAHAMIAN CORAL REEFS YIELD EVIDENCE OF A BRIEF SEA-LEVEL LOWSTAND DURING THE LAST INTERGLACIAL

[1]Brian White, [1]H. Allen Curran, and [2]Mark A. Wilson
[1]Department of Geology, Smith College, Northampton, MA 01063
[2]Department of Geology, The College of Wooster, Wooster, OH 44691

ABSTRACT: The growth of large, bank-barrier coral reefs on the Bahamian islands of Great Inagua and San Salvador during the last interglacial was interrupted by at least one major cycle of sea regression and transgression. The fall of sea level resulted in the development of a wave-cut platform that abraded early Sangamon corals in parts of the Devil's Point reef on Great Inagua, and produced erosional breaks in the reefal sequences elsewhere in the Devil's Point reef and in the Cockburn Town reef on San Salvador. Minor red caliche and plant trace fossils formed on earlier interglacial reefal rocks during the low stand. The erosional surfaces subsequently were bored by sponges and bivalves, encrusted by serpulids, and recolonized by corals of younger interglacial age during the ensuing sea-level rise. These later reefal deposits form the base of a shallowing-upward sequence that developed during the rapid fall of sea level that marked the onset of Wisconsinan glacial conditions. Petrographic studies reveal a diagenetic sequence that supports this sea-level history. Preservation of pristine coralline aragonite, coupled with advances in U/Th age dating, allow these events in the history of the reefs to be placed in a precise chronology. We use these data to show that there was a time window of 1,500 years or less during which the regression/transgression cycle occurred, and that rates of sea-level change must have been very rapid. We compare our results with the GRIP ice-core data, and show that the history of the Bahamian coral reefs indicates an episode of climate variability during the last interglacial greater than any reported in what is widely believed to be the more stable climate of the Holocene interglacial.

INTRODUCTION

Bank-barrier and patch coral reefs flourished on the Bahamian islands of San Salvador and Great Inagua (Fig. 1) during the last interglacial - variously known as substage 5e of the marine isotope scale, the Sangamon of North America, and the Eemian of Europe. We have conducted detailed field studies of fossil reefs near Devil's Point on the west coast of Great Inagua, and of the Cockburn Town and Sue Point fossil reefs on the west side of San Salvador (Fig. 2) in order to determine their geologic history, particularly with respect to sea-level events. These three fossil reefs are the largest currently documented from the Bahamas. Petrographic studies have been used to determine the diagenetic history of these reefs as it relates to the sea-level changes that have affected them.

Advances in the dating of aragonite using TIMS U/Th

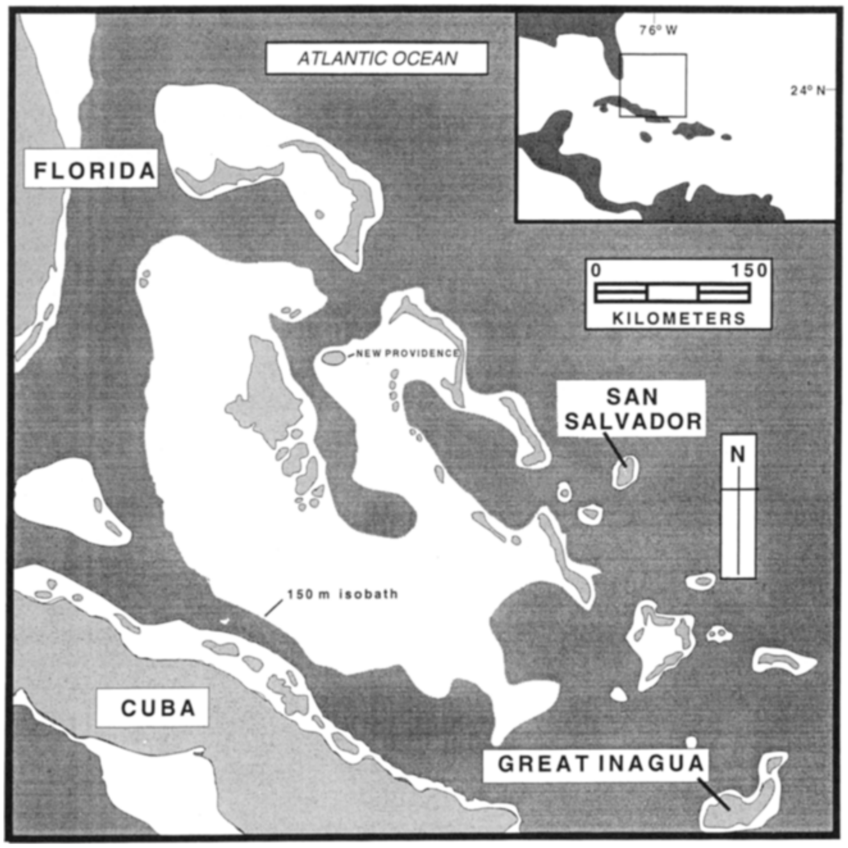

Figure 1. Location of Great Inagua and San Salvador islands, Bahamas.

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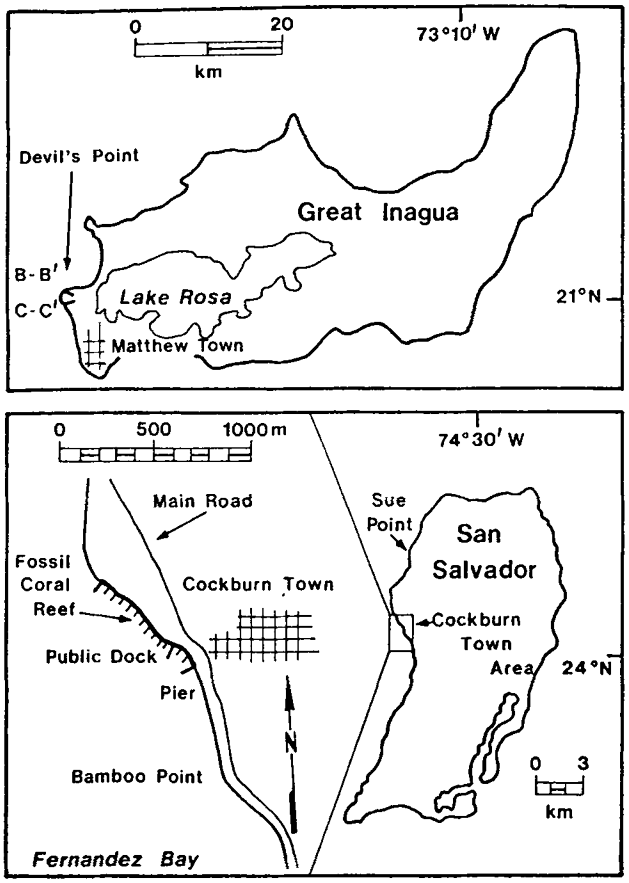

Figure 2. Location of the Devil's Point fossil reef on Great Inagua Island, and the Cockburn Town and Sue Point fossil reefs on San Salvador Island.

analyses, coupled with the preservation of pristine aragonite in fossil corals from these reefs, allows us to create a comprehensive chronology for the sequence of events revealed by the detailed field and petrographic work. The methods and results of the age dating and the overall stratigraphic setting of the sampled corals were presented in Chen et al. (1991). The presence of a wave-cut surface within parts of the Devil's Point reefal sequence also was noted. Subsequent detailed field studies on Great Inagua and San Salvador revealed the widespread occurrence of an erosional surface within the reefal sequences. In the case of the Cockburn Town fossil reef, these later studies were facilitated by new exposures created during the construction of a marina.

Recent evidence from ice-core data, pollen studies of lake sediments, and data from benthic foraminifera and stable isotopes indicates that the last interglacial included one or more episodes of extreme climate fluctuation. This is a controversial conclusion, as the last interglacial has hitherto been considered to have had a stable and equable climate, based in large part on comparison with the Holocene (Broecker 1994; Dowdeswell and White 1995). We explore this issue in the light of our detailed sea-level history with its precisely determined chronology.

FIELD EVIDENCE

Devil's Point Fossil Reef

A well-developed wave-cut platform within the Sangamonian sequence at Devil's Point (Fig. 3A) provides the most prominent field evidence for a fall and subsequent rise of sea level during the last interglacial. Corraded surfaces of large coral heads of *Montastrea* and *Diploria* fossilized in growth position (Fig. 3B) suggest removal of several decimeters of the coral head tops. Other field evidence shows that the wave-cut platform developed during the Pleistocene, and that it is not a modern or Holocene feature. In places, the platform surface has rhizomorphs, the fossilized traces of terrestrial plants, directly on top of planed-off corals (Fig. 3C). Elsewhere, coral rubblestone, collapsed but essentially in place coral debris (Curran and White 1985; White and Curran 1987), overlies the wave-cut surface (Fig. 3D). These deposits commonly extend vertically into a shallowing-upward sequence of strata deposited during the transition from marine subtidal to non-marine eolian deposition resulting from the regression caused by the onset of Wisconsinan glaciation (White and Curran 1987, 1995) (see also later discussion of profile B-B' Figure 6). Laterally, the sea-level fall is represented by an irregular erosional surface upon which a well-preserved coral patch reef of Sangamon age is preserved (see later discussion of profile C-C' Devil's Point Figure 7).

Cockburn Town Fossil Reef

Although lacking a distinct wave-cut platform, many other features found in the Cockburn Town reef were formed during a sea-level lowstand that interrupted the growth of the reef. Corals are preserved in growth position on an undulating erosional surface that is interpreted as equivalent to the wave-cut platform in the Devil's Point reef (Figs. 4A and 4B). Corals beneath the erosional surface were truncated, in some cases including the lithophagid borings within the corals (Fig. 4C). Elsewhere the erosion surface itself was bored by sponges, and subsequently these borings were encrusted by corals (Fig. 4D).

Fissures, erosional channels, and small caves formed during the sea-level lowstand, and they cut through both *in situ* corals and associated lithified subtidal sediments. Some of the channels are wider in the lower part, thereby forming overhung cavities. These cavities and openings were subsequently filled by subtidal sediments (Figs. 5A and 5B), which in some places have been removed by subsequent erosion to reveal cavity floors, walls, and roofs that have sponge and bivalve borings and serpulid encrustations (Fig. 5C). Red paleosols overly the fissures and the infilling subtidal calcarenites (Fig. 5D). Following the physical stratigraphy of Carew and Mylroie (1995a) such paleosols mark the boundary between the Pleistocene and Holocene, and prove the Pleistocene age of these features. In some fissures the red paleosol unconformably overlies an earlier generation

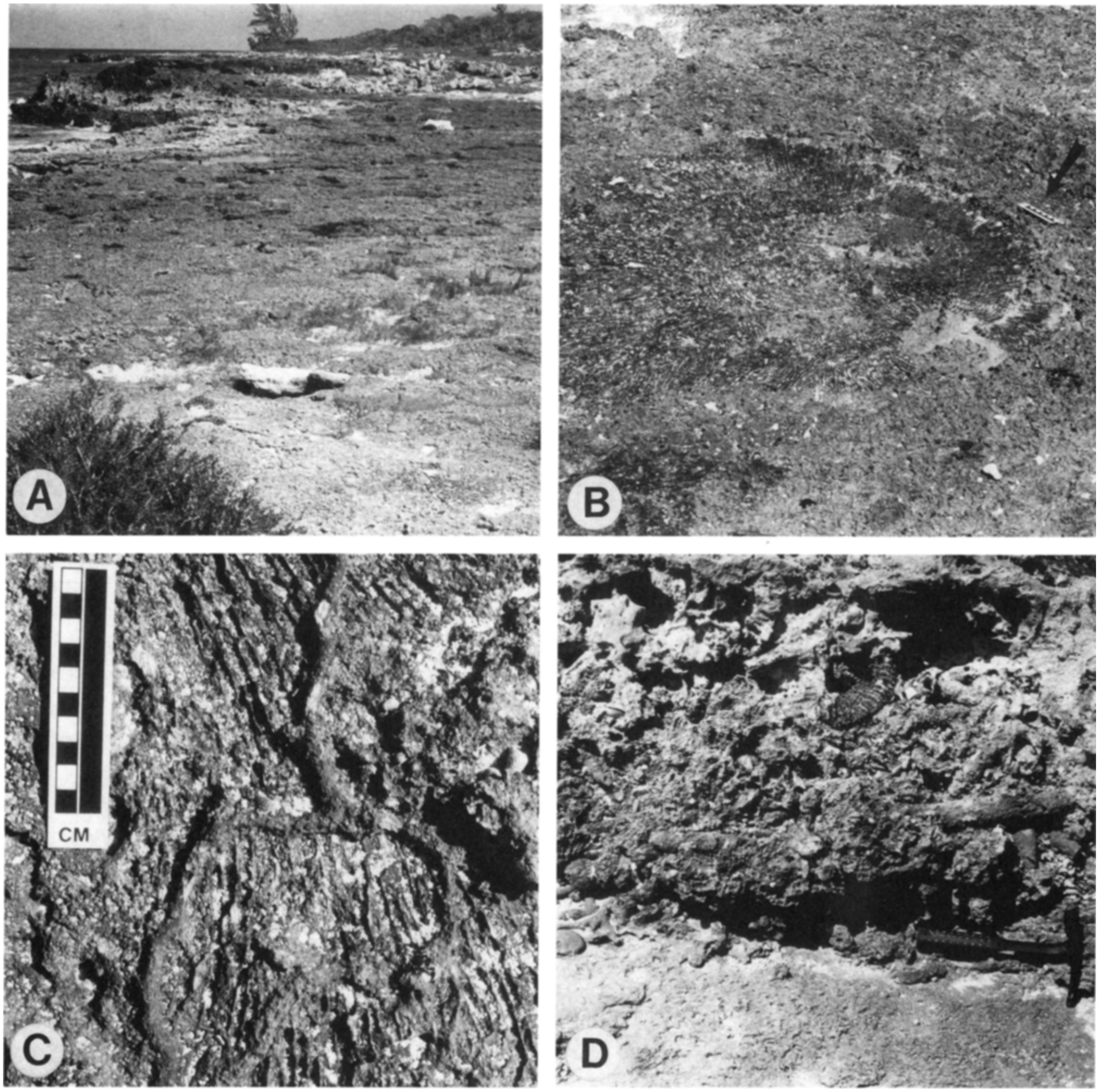

Figure 3. Geology at Devil's Point fossil reef, Great Inagua Island. A) General view of the wave-cut platform that formed during the mid-Sangamonian sea-level lowstand. B) Planed-off coral heads exposed on the wave-cut surface. Arrow points to 10 cm scale. C) Rhizomorphs (fossilized plant traces) on the wave-cut surface showing that it is not a modern erosional feature. D) Coral rubblestone that forms the basal layer of a shallowing-upward sequence which accumulated above the wave-cut surface during the second Sangamonian sea-level highstand.

of red caliche that lines fissure walls and the adjacent fissure-filling subtidal calcarenites that were deposited in the interval between the two soil-forming episodes. This first generation of paleosol/caliche provides additional evidence for a brief sea-level lowstand during the overall development of the reef.

Sue Point Fossil Reef

A well-preserved fossil patch reef is exposed along the coast north of the Cockburn Town reef (White 1989). No wave-cut platform or erosional surface interrupts the reefal sequence, suggesting that this reef may have developed only during the later interglacial sea-level highstand following the sea-level lowstand recorded at the Devil's Point and Cockburn Town fossil bank-barrier reefs. This interpretation is supported by the fact that the oldest dated corals from this reef are a *Montastrea annularis* (122.9±1.9 ka) and a *Diploria strigosa* (122.4±1.6 ka) (Chen et al. 1991). This suggests that not all Bahamian fossil coral reefs were in existence throughout the last interglacial and evidence for the mid-Sangamon lowstand

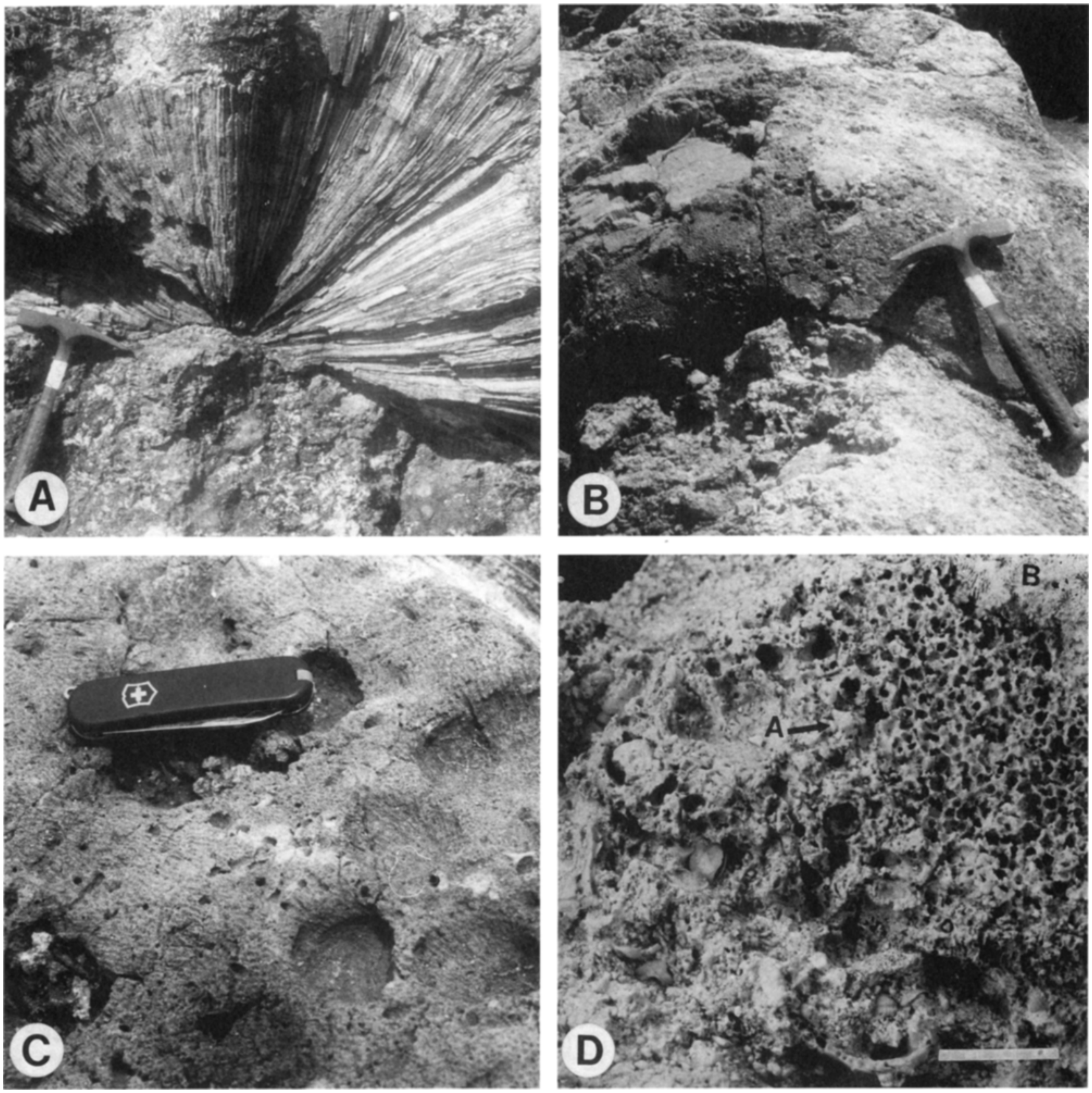

Figure 4. Geology at Cockburn Town fossil reef, San Salvador Island. A) Diploria strigosa fossilized in growth position on the erosional surface that developed during the mid-Sangamonian sea-level lowstand. B) Montastrea annularis fossilized in growth position on the erosional surface that developed during the mid-Sangamonian sea-level lowstand. C) Lithophagid borings into Montastrea annularis truncated by the erosion surface. D) Sponge borings (A) in the erosion surface partly covered by encrusting coral (B). Scale bar = 4 cm.

may be absent from some of them. For example, the reefs described by Halley et al. (1991) may have formed only during the younger Sangamon sea-level highstand. Such restricted duration may be the case for patch reefs to a greater extent than for the more substantial bank/barrier reefs.

URANIUM/THORIUM DATING OF FOSSIL CORALS

The Devil's Point Reef Wave-cut Platform

Mass spectrometric analysis of pristine coral aragonite from the Devil's Point fossil reef allowed precise age determination of the reef (Chen et al. 1991). Two of the topographic and

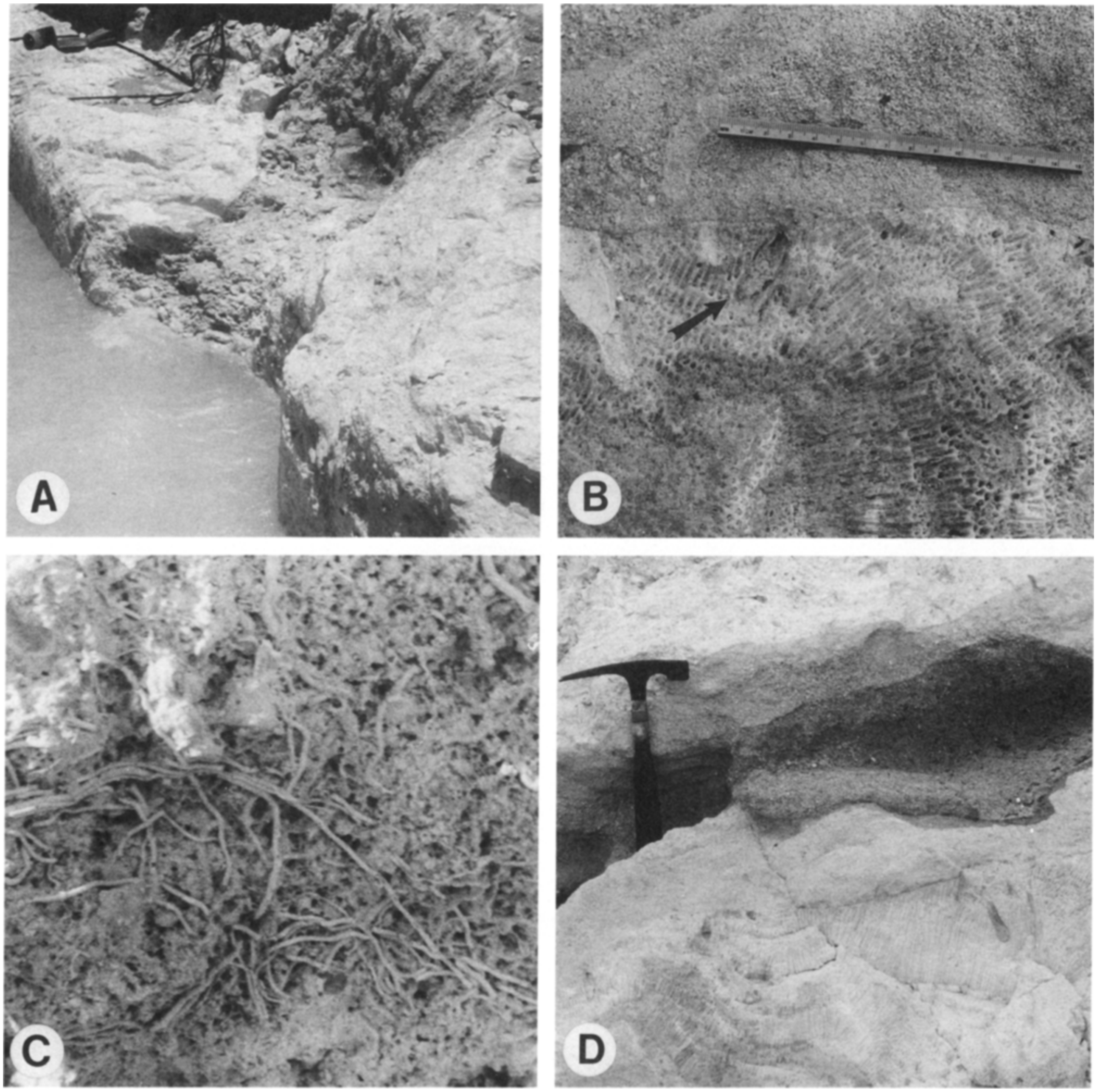

Figure 5. Geology at Cockburn Town fossil reef, San Salvador Island. A) Small, sediment-filled cave exhumed by marina construction work. Width of filled fissure is ~50 cm. B) Horizontal surface view of fissure showing truncated Montastrea annularis and lithophagid boring (arrow). Fissure was subsequently infilled with marine calcarenites. Scale = 15 cm. C) Serpulid tubes encrusting the wall of an exhumed fissure. Tubes are ~ 2 mm in diameter. D) Part of a fissure with paleosol overlying the fissure fill of marine calcarenites.

geologic profiles from Chen et al., (1991) have been modified to incorporate more recent field observations and to provide important information regarding the timing of formation of the erosional surface.

Profile B-B' (Figs. 2 and 6) is from the locality where the photographs shown in Figure 3 were taken. Here the wave-cut surface is underlain by *in situ* corals, and is overlain by coral rubblestones of collapsed but unabraded and pristine coral fragments, which form the lower layer of a shallowing-upward sequence. Such pristine preservation requires that corals be rapidly removed from the taphonomic environment (Greenstein and Moffat 1996). The following coral ages were obtained from samples collected below the erosion surface: *Acropora palmata*, 130.3±1.3 ka; *Diploria strigosa*, 125.4±1.7 ka; *Montastrea annularis*, 128.4±1.2 and 124.9±2.1 ka. One sample of *Montastrea annularis* from above the surface has an age of 123.8±1.5 ka. All coral ages

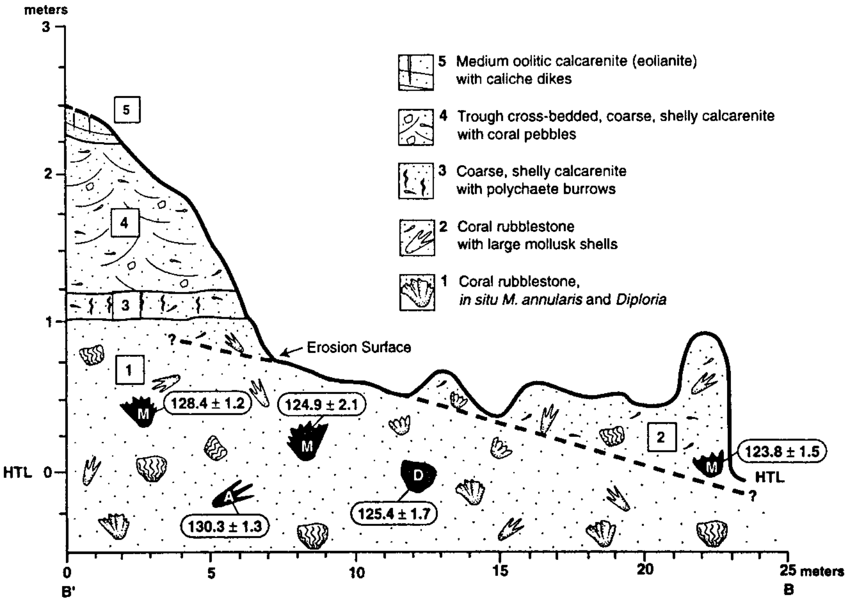

Figure 6. Profile B-B', Devil's Point fossil reef, Great Inagua Island. U-Th ages shown adjacent to sampled corals. A = Acropora cervicornis; M = Montastrea annularis; D = Diploria strigosa. Modified from Chen et al. (1991).

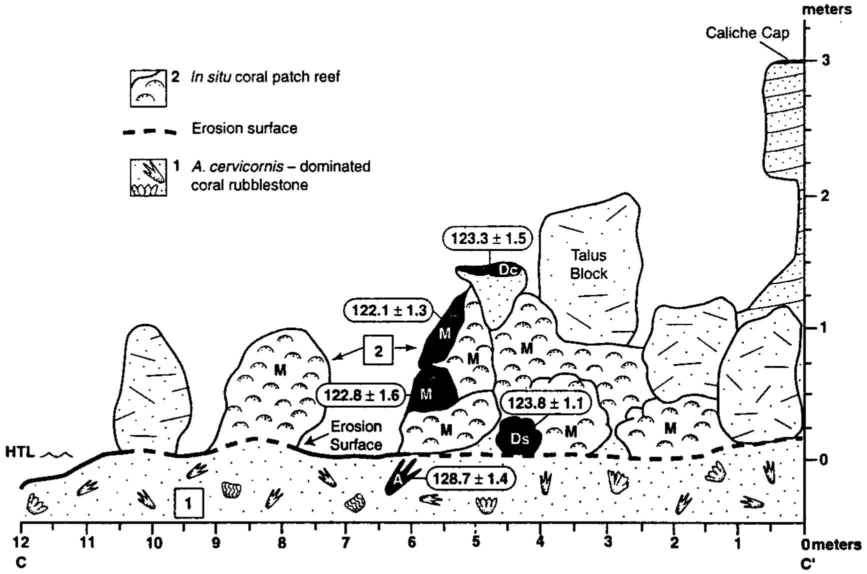

Figure 7. Profile C-C', Devil's Point fossil reef, Great Inagua Island. U-Th ages shown adjacent to sampled corals. A = Acropora cervicornis; M = Montastrea annularis; Ds = Diploria strigosa; Dc = D. clivosa. Modified from Chen et al. (1991).

and comprehensive documentation of relevant geochemical and analytical data are presented in Chen et al. (1991).

Profile C-C' (Figs. 2 and 7) illustrates a locality where a fully developed and extraordinarily well-preserved coral patch reef overlies the erosion surface. An *Acropora cervicornis* sample from below the erosion surface has an age of 128.7±1.4 ka. Corals from above the erosion surface gave the following ages: *Diploria strigosa*, 123.8±1.1 ka; *D. clivosa*, 123.3±1.5 ka; *Montastrea annularis*, 122.8±1.6 ka and 122.1±1.3 ka. Combining data from the two profiles gives a range of coral ages from below the erosion surface of 130.3±1.3 to 124.9±2.1 ka, and from above the surface the range is 123.8±1.5 to 122.1±1.3 ka.

The Cockburn Town Reef Erosional Event

Profile C-C' (Fig. 8) modified from our earlier work on San Salvador (Curran and White 1985) illustrates the most complete set of data for establishing the age of the erosional surface found in the Cockburn Town reef. The following coral ages were obtained from three samples of *Acropora palmata* collected below the erosion surface: 132.6±1.3 ka, 125.5±1.4 ka, and 125.3±1.7 ka. A specimen of *A. palmata* collected

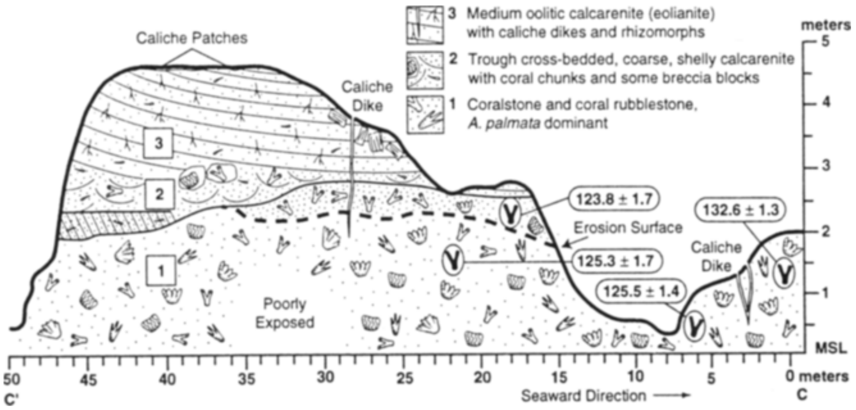

Figure 8. Profile C-C', Cockburn Town fossil reef, San Salvador Island. U-Th ages shown adjacent to sampled corals (all *<u>Acropora palmata</u>). Modified from Chen et al. (1991).*

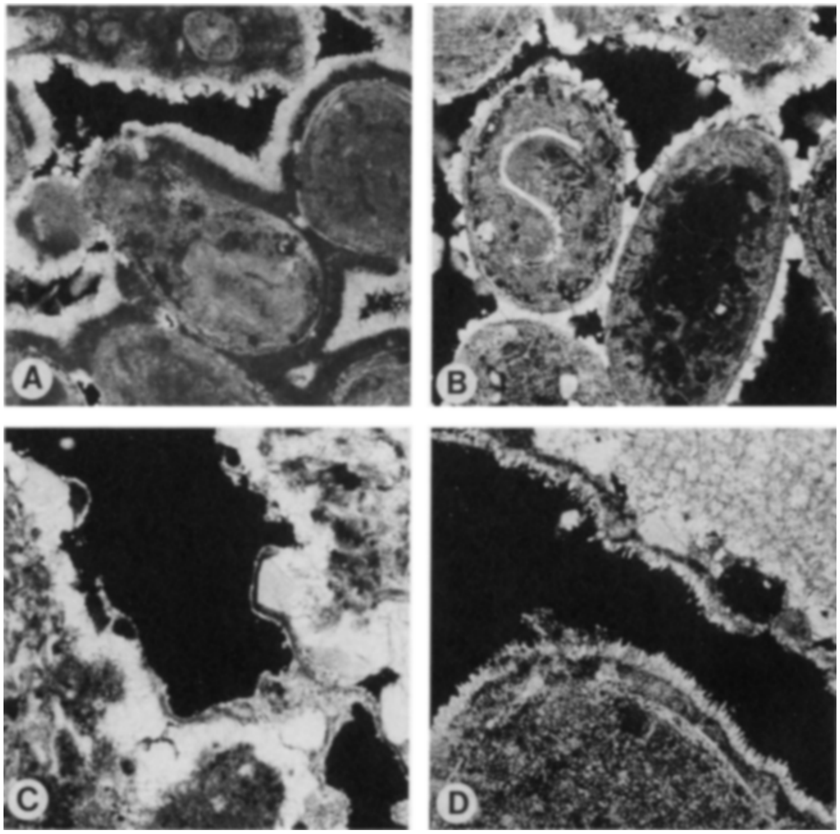

Figure 9. Photomicrographs under crossed polarizers of samples from Devil's Point fossil reef, Great Inagua Island. All widths of view = 2 mm. A) Early marine high-Mg calcite and aragonite cements followed by sparse non-marine sparry calcite cement. B) Sparse early marine cements followed by abundant non-marine vadose sparry calcite cement. C) Early non-marine isopachous sparry calcite cement followed by sparse marine high-Mg calcite and aragonite cements. D) Sparse, early non-marine isopachous sparry calcite cement followed by well-developed, isopachous marine high-Mg calcite and aragonite cements.

from above the erosion surface has a U-Th age of 123.8±1.7 ka (Chen et al. 1991, includes all analytical data). This gives a range of coral ages from below the erosion surface of 132.6±1.3 to 125.3±1.7 ka, and from above the surface a single age of 123.8±1.7 ka.

PETROGRAPHIC EVIDENCE

Changing sea levels may expose nearshore reefs and associated subtidal grainstone facies to a sequence of diagenetic environments, each of which may leave a distinctive imprint that creates a record of these changes in

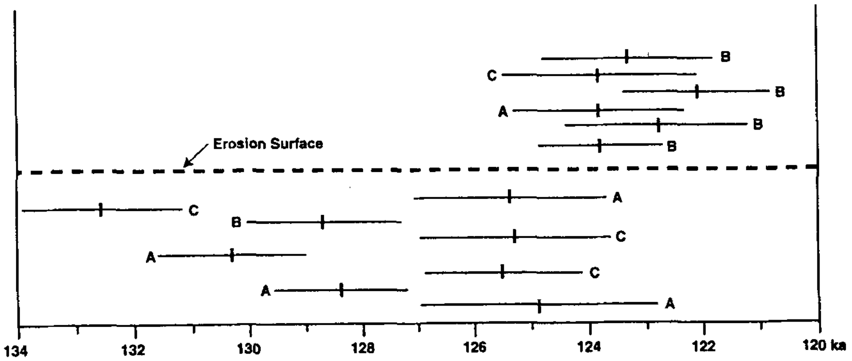

Figure 10. Diagram showing the U-Th ages of corals in relation to the erosional surface that formed during the mid-Sangamonian sea-level lowstand. A = corals from B-B' Devil's Point fossil reef; B = corals from C-C' Devil's Point fossil reef; C = corals from C-C' Cockburn Town fossil reef; dashed line represents the erosional surface. Horizontal scale in thousands of years before present. No vertical scale implied. Stratigraphic location of the dated corals is shown in Figures 6, 7, and 8.

environment. Figure 9A shows a grainstone with a sequence of earlier marine cements consisting of micritic high-Mg calcite followed by aragonite. Also present are later sparry calcite cements typical of meteoric, non-marine diagenetic environments in unburied Quaternary limestones. The grainstone shown in Figure 9B has a similar overall sequence but the amount of earlier marine cement is much less and the rock is cemented largely by non-marine calcspar with a patchy distribution typical of a vadose zone. The cement sequence is reversed in the rock illustrated by Figure 9C, with the rock being largely cemented by an earlier non-marine isopachous calcspar with a small amount of later, irregularly distributed, marine high-Mg calcite and subsequent aragonite. A more completely developed sequence of later marine cements is illustrated in Figure 9D where early isopachous to patchy non-marine calcspar is followed by isopachous marine high-Mg calcite and aragonite. Using the well-established principles of cement stratigraphy (Meyers 1974), we can deduce a sequence of diagenetic environments from marine to non-marine and then a return to marine. This cement sequence indicates that an interval of sea-level lowstand occurred during the diagenetic history of these rocks and that sea level fell far enough to expose reefal and associated rocks to the freshwater phreatic and vadose environments.

DISCUSSION

Timing of the Sea-level Excursion

A compelling body of field and petrographic evidence shows that the development of coral reefs on Great Inagua and San Salvador islands during the Sangamon interglacial was interrupted by a fall of sea level that exposed the reefs and associated sedimentary facies to non-marine conditions. Sea level prior to the fall was at least 4 m higher than the lowstand level. Subsequently, sea level rose to approximately +6 m and the reefs flourished once again.

Corals from beneath and above the erosion surface produced during the lowstand are exposed in close vertical proximity along profiles B-B' (Fig. 6) and C-C' (Fig. 7) at the Devil's Point reef and C-C' (Fig. 8) at the Cockburn Town reef. Uranium-thorium ages of corals from these localities are shown in Figure 10. In attempting to evaluate all of our data from a geological perspective we have tended to follow the common practice of focusing on the central tendency of the age data (see for example Chen et al. 1991; Carew and Mylroie 1995a; Eisenhauer et al. 1996). Our interpretations are constrained by the known rock record, and we are impressed by the relationships between the clustering of dates in relationship to their stratigraphic source. Failure to follow this multifaceted approach leads to geologically absurd conclusions, for example placing younger rocks beneath an erosional disconformity and older ones above it. Following these techniques the data from Figure 10, which represent situations where dated corals are in vertical juxtaposition from beneath and above the erosion surface, indicate a time window for the regression-lowstand-transgression sequence in the range of 1.1 to 1.5 ka.

Rates of Sea-level Change

Sea level prior to the regression to the lowstand was a minimum of 4 m above present sea level and the ensuing transgression raised sea level to 6 m above present sea level (Curran and White 1985). During the lowstand, sea level fell to approximately present sea level (Curran et al. 1989). Thus a total change of sea level of 10 m occurred during the fall and subsequent rise. To abrade the broad wave-cut platform present at the Devil's Point reef site and to remove several decimeters of coral rock during this abrasion, sea level must have been maintained at the lowstand level for a significant, but unknown, part of this interval. Similarly, development of the various erosion cavities and thin caliche linings requires that the lowstand existed for a significant fraction of the time interval. Table 1 shows the average rate of change required for cycles of sea-level fall and rise of 1.1 and 1.5 ka duration assuming various periods of lowstand.

Table 1. Calculated average rates of sea-level change for the mid-Sangamon fall and rise of sea level, assuming various durations for the lowstand and using two estimates (1100 and 1500 years) derived from data of Figure 10 for the length of the sea-level cycle.

Lowstand duration in yrs.	1100 yrs. - mm/yr.	1,500 yrs. - mm/yr.
100	10.0	7.1
200	11.1	7.7
300	12.5	8.3
400	14.3	9.1
500	16.7	10.0
600	20.0	11.1
700	25.0	12.5
800	33.3	14.3
900	50.0	16.7
1000	100.0	20.0
1100	-	25.0
1200	-	33.3
1300	-	50.0
1400	-	100.0

Non-reefal Evidence for Climatic Instability During the Sangamon

The Bahamas are generally regarded as lacking tectonic activity that would explain relative sea-level changes that occur in tandem over the whole archipelago (Carew and Mylroie 1995a, b). Such changes must be due to absolute changes in the volume of sea water, most likely caused by changes in terrestrial ice volume. By comparison with the generally stable climates of the Holocene, it was widely assumed that the last interglacial was also a period of stable climate. This stability was in sharp contrast to the 100 ka of the last glacial period when relatively stable climate periods lasting several millenia were disrupted by abrupt changes to radically different climate states that occured within a few decades (Broecker 1994). This view of stable climates during the last interglacial was called into question by ice-core data which showed that abrupt changes of temperature occurred in Greenland during that time (GRIP members 1993; Johnsen et al. 1995).

In a review of the Greenland ice-core data and the record of rapid climate changes, Dowdeswell and White (1995) comment that the terrestrial and marine records of the last interglacial give mixed signals. They concluded, somewhat cautiously, that the weight of evidence from the terrestrial and marine records suggests stable climate during the last interglacial. Not all of the evidence supports that conclusion, however. In a brief summary, Tzedakis et al. (1994) report that pollen data from Europe support the view that climatic fluctuations occurred during the Eemian. More detailed pollen data from annually laminated lake sediments in Germany, and peats from France, showed that the last interglacial climate was more unstable than the Holocene, and that at times, winter temperatures reached levels similar to those that occurred during glacial periods (Field et al. 1994). Magnetic susceptibility, pollen, and organic carbon records from maar lakes that formed in explosive volcanic craters in the Massif Central of France show two periods of rapid cooling during the last interglacial that coincide with colder periods indicated by the GRIP ice-core data (Thouveny et al. 1994). Seidenkrantz et al. (1995) presented data on the abundance of benthic foraminiferal species found in two cores of marine shelf sediments from Denmark. They interpret their data as indicating two cooling events during the last interglacial, that they correlate with colder intervals indicated in the GRIP ice-core data. Furthermore, these authors conclude that climatic change was rapid, on the scale of decades or centuries. Recently, Seidenkrantz and Knudsen (1997) presented a detailed analysis of benthic foraminifera from one of these cores that supports their earlier conclusions. Thus, the known signatures of climatic instability during the last interglacial extend from Greenland to Europe and are, in fact, believed to be global (Broecker 1994).

Sangamon Climate Instability and Sea-level Changes

Literature survey.-- The evidence indicates that rapid changes of temperature of several degrees Celsius occurred on a decadal time scale during the last interglacial, producing a variety of signatures recorded in several parts of the globe (Broecker 1994). The question arises whether such temperature changes would also cause rapid changes in the volume of terrestrial ice and attendant rapid changes in sea level. Based on stratigraphic studies of carbonate rocks on Oahu, Hawaii, Sherman et al. (1993) reported two distinct sea-level highstands during the last interglacial. However, their age dating had wide error bars that fell within the general age range of the last interglacial, but were not accurate enough to subdivide it. More recent studies by Muhs and Szabo (1994) of uranium-series dating of the Waimanalo Formation on Oahu do not support the double sea-level highstand, and they concluded that Oahu and similar tectonically active Pacific islands are unsuitable as reference points for determining last interglacial highstands.

Precisely dated corals from a core through fossil reefal deposits in the Houtman Abrolhos islands off the tectonically passive coast of Western Australia give some information about sea-level changes and elevations during the last interglacial (Eisenhauer et al. 1996). Sea level rose steadily from ~4 m below present around 134 ka, passed present level between 130 and 127 ka, and reached a maximum of at least 3.3 m above present at ~124 ka. Sea level fell below present datum at ~116 ka. Eisenhauer et al. (1996) found no evidence of intra-interglacial fall of sea level, but they state that the resolution of their data would limit the duration of any such undetected regressions to 1.0 ka, or less.

Based on the island geology of Bermuda and The Bahamas, Hearty and Kindler (1995) developed a chronology for sea-level highstands for the past 1.2 Ma. For the last interglacial, they proposed two highstands separated by a regression that lasted from approximately 128 to 123 ka based on protosols that lie between the marine deposits of the two highstands. They referred to Chen et al. (1991) in pointing out that coral reefs grew during the earlier oscillations. However, corals presently *in situ* above present sea level also are reported by Chen et al. (1991) from much of the time interval represented by the proposed lowstand of Hearty and Kindler (1995). In a more recent paper, Neumann and Hearty (1996) focused mainly on evidence for a rapid rise and subsequent fall of sea level at the end of the last interglacial. However, they inferred that sea level for most of the interglacial remained near 2 m above present, interrupted only by a short-lived, sea-level fall of about 1.5 m at approximately 125 ka. The timing of this event appears to be constrained largely by data from Chen et al. (1991). To explain bioeroded notches at 6 m above present sea level, Neumann and Hearty (1996) invoked a rapid rise of sea level from + 2 to + 6 m at the end of the interglacial and a highstand that lasted only a few hundred years. This interpretation was questioned by Carew (1997) who stated that the postulated rate of notch formation is much too high and that the notches could not have been formed in a few hundred years, and by Mylroie (1997) who reinterpreted the notches as the eroded remnants of flank margin caves. Regardless, such caves also would need much longer than a few hundred years to form. Our work on the fossil reefs indicates that sea level was at or close to the + 6 m level for several thousand years from about 124 ka to approximately 119 ka. This provides sufficient time for both notch and cave formation but obviates the need for invoking a very rapid rise in sea level close to the end of the interglacial.

Interesting information is presented by Precht (1993) based on studies of reefal facies of the Falmouth Formation in Jamaica. According to Precht (1993), the Falmouth Formation comprises two shallowing-upward parasequences that represent reefal development during two separate sea-level highstands of substage 5e. Uranium-series dating of aragonitic corals suggests that the lower parasequence corresponds to a sea-level highstand at 134-127 ka, and the upper sequence to a highstand at 124-119 ka.

The evidence from this study.-- The combination of excellent exposures of some Bahamian fossil coral reefs and associated facies, detailed field work, the preservation of pristine coral aragonite, and breakthroughs in U/Th age dating techniques creates an opportunity to compare evidence of sea-level changes in the Bahamas, with climate changes recorded elsewhere from the last interglacial period. Figure 11 is based on data presented in GRIP members (1993), and shows measured changes in $\delta^{18}O$ of the portion of the Greenland ice core that formed during the last interglacial, and the calculated temperature fluctuations based on the isotope data. Because these ice core data yield the best presently available information about the duration and timing of climate fluctuations during the Eemian, we use this diagram to discuss the results of our work on sea-level changes recorded in Bahamian fossil coral reefs, in the context of temperature fluctuations recorded in Greenland ice.

One of the main features of the ice-core record for the last interglacial is rapid, and commonly significant, temperature fluctuations. However, some general trends can be discerned. From a low of approximately 10°C below average Holocene temperatures around 142 ka, a general warming trend brought temperatures above Holocene levels by approximately 133 ka. These warmer conditions continued as a general trend of temperatures approximately 4°C above Holocene values until 126 ka, when a rapid cooling began. This period of higher temperatures coincides quite well with the first stage of coral growth in the Bahamian reefs which extended from 132-125 ka. Rapid cooling events punctuated this early last interglacial warm period, although the most severe of these pre-date the oldest corals yet found in the Bahamian reefs that we have studied. A short-lived cold spell, some time between 129 and 128 ka, brought temperatures approximately 2°C below Holocene values. We have found no record in the Bahamian reefs of this cold spell, but it is possible that any effects are beyond the resolution of field studies in a complex reef facies.

The ice-core data show a major fall in temperature of

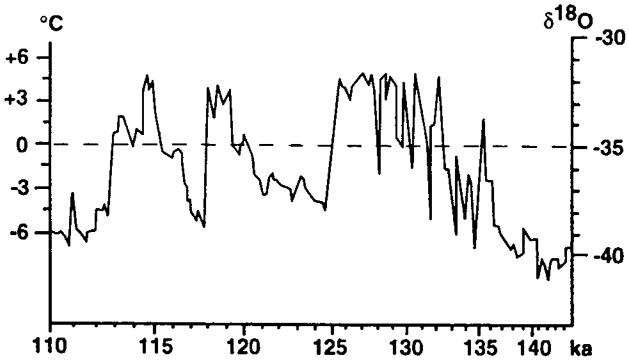

Figure 11. Temperature data spanning the last interglacial based on oxygen isotope data from a Greenland ice core. Dashed line represents average Holocene temperature. Redrawn from data in GRIP members, 1993. Horizontal scale is non-linear.

approximately 9°C from 126 to 125 ka, just prior to the dramatic fall in sea level recorded in the Bahamian reefs beginning at approximately 125 ka. The most reasonable conclusion from these data is that this major cooling led to greatly increased snowfall and the rapid increase in the accumulation of land-based ice.

Following 125 ka, a slow warming is indicated by the ice core data, but average Holocene temperature values were not reached until approximately 121 ka. Temperatures then rose quickly to approximately 4°C above Holocene levels, where they remained, with minor fluctuations, for a little more than a millennium. In the fossil reefs discussed in this paper this warming trend coincides with a rapid rise in sea level and re-establishment of the coral reefs and the second stage of their growth, which lasted from 124-119 ka. Although the general trends of warming climate, rising sea level, and regrowth of corals are coincident, there are discrepancies in the magnitude of these events. The ice-core data show that temperatures in Greenland remained below Holocene values for much of this interval, whereas sea level and accompanying coral growth in the Bahamian reefs was higher than present levels.

The reason for the discordance between rapidly rising sea level and slowly rising temperatures in Greenland is not known. However, some speculations are possible. Pollen data from Germany and France show that the average mean temperature of the coldest month remained low and relatively stable during the latter part of the last interglacial before rising rapidly during the last 1000 years (Field et al. 1994). This corresponds more closely to the ice-core data than to the Bahamian sea-level history. Summer temperatures remained relatively high during this period, suggesting a more extreme seasonality than is presently experienced. The rate of increase in mean annual temperatures in the higher latitudes of the Northern Hemisphere may have lagged behind the average global increase, perhaps due to the lack of penetration by relatively warm oceanic currents. In this scenario, the low Northern Hemisphere temperatures are anomalous and the rapidly rising sea levels identified from the Bahamian reefs are the global norm. Hollin (1980) proposed that some polar ice masses could pass a critical limit and surge into the oceans, and thus cause rapid sea-level rise. It is possible that such events occurred during the early stages of the warming in the latter part of the last interglacial, and accelerated the rate of sea-level rise.

The ice-core data show that temperatures in Greenland fell approximately 9°C in a 500-year span between 119 and 118 ka to 5°C below average Holocene levels. This timing corresponds to the record from Bahamian coral reefs with the youngest known coral being 119.9±1.4 ka. The excellent state of preservation of Bahamian coral reefs has been attributed to rapid burial by the entombing sands of a shallowing-upward sequence resulting from rapid sea-level drawdown beginning at about 119 ka (White et al. 1984; White and Curran 1995). This interpretation has been supported by the recent taphonomic studies of the Cockburn Town fossil reef by Greenstein and Moffat (1996).

The Greenland ice-core data show one more warmer episode that occurred around 115 ka when temperatures reached approximately 4°C above the Holocene average for a short interval, before falling to the glacial levels that persisted until the Holocene. No corals of this age are known from the Bahamian fossil reefs that we have studied, nor are any corals found encrusting the terminal shallowing-upward sequence sands.

CONCLUSIONS

1. Bahamian coral reefs on San Salvador and Great Inagua islands developed during two stages within the last interglacial separated by a short-lived sea-level lowstand.

2. The first stage of reef growth occurred during the interval 132-125 ka when Greenland ice-core data indicate that temperatures were generally about 4°C higher than the average for the Holocene. Sea level during this first reef development phase was at least 4 m above present.

3. According to ice-core data, temperatures fell approximately 9°C during the interval 126-125 ka. This corresponds to a rapid sea-level fall that interrupted coral growth and led to a period of erosion in the earlier reef, and to an episode of freshwater diagenesis. Sea level fell during the interval 125-124 ka to about the current level, at rates probably significantly in excess of 10 mm per year.

4. After 124 ka, sea level rose rapidly to a maximum of 6 m above present, and coral reef growth was renewed. This second phase of reef growth lasted from 124-119 ka. Although the ice-core data indicate a slow warming during this second interval of reef development, the extent of the warming seems insufficient to explain the magnitude and high rate of sea-level rise. The reason for this discrepancy is unknown. Warming in Greenland may have lagged the global rate due to its isolation from warming ocean currents, perhaps due to the kinds of longitudinal shifts in ocean circulation patterns described by Johnsen et al. (1995).

5. A rapid cooling of approximately 9°C beginning at 119 ka coincides with a very rapid fall in sea level beginning shortly after 119 ka. This fall was due to an early phase of ice volume increase that marked the beginning of the Wisconsinan glacial stage. Falling sea level led to the rapid burial of the coral reefs in regressive facies sands and to their excellent preservation.

6. A brief return to temperatures up to 4°C higher than Holocene values is indicated by ice core data at around 115 ka. If this led to a sea-level highstand higher than present we have detected no impact in the Devil's Point and Cockburn Town reefs. The ice-core data show no other time between 115 ka

and the beginning of the Holocene when temperatures approached the Holocene average.

7. Our data support the concept that the last interglacial climate was subject to rapid and significant fluctuations in temperature that had dramatic effects on sea level, which in turn affected the development of coral reefs.

8. Marked changes of sea level appear to have separated two intervals of several millenia duration when sea level was higher than present and reef growth flourished.

9. The frequency of sharp temperature fluctuations shown by the ice-core data is greater than that reflected in the observed effects in the coral reefs of sea-level changes. Whether this means there were no effects on sea level or the reefs, or that the effects are too subtle for present methods of analysis to discover, is unknown.

10. Based on the record of the last interglacial, there can be no assurance that dramatic temperature fluctuations and changes in relative sea level will not occur during the remainder of the present interglacial.

11. As the changes of sea level during the last interglacial most likely are due to changes in the volume of land-based ice, it is wrong to think of interglacials as being free of ice sheets. Perhaps terminology misleads us and the terms glacials and interglacials might be better changed to greater glacials (i.e., hyperglacials) and lesser glacials (i.e., hypoglacials) respectively.

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