1997

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Recommended Citation

PROCEEDINGS OF THE 8TH SYMPOSIUM
ON THE GEOLOGY OF THE BAHAMAS AND
OTHER CARBONATE REGIONS

May 30 - June 3, 1996

Edited by
James L. Carew

Bahamian Field Station
San Salvador, Bahamas
1997

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ABSTRACT

Our field studies indicate that 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 the Devil's Point reef on Great Inagua, and produced erosional breaks in the reefal sequences elsewhere. Minor red caliche developed during the low stand, and the erosional surfaces were bored by sponges and bivalves and encrusted by serpulids. The erosional surfaces were subsequently recolonized by corals of younger interglacial age. These later reefal deposits form the base of a shallowing-upward sequence that developed during the rapid fall of sea level that heralded the onset of Wisconsinan glacial conditions. Petrographic studies reveal a diagenetic sequence which 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 less than 1,500 years 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 supports a variable climate for the last interglacial, in contrast to what is widely believed to be the stable climates of the Holocene interglacial.

INTRODUCTION

Bank-barrier and patch coral reefs flourished on the Bahamian islands of San Salvador and Great Inagua (Figure 1) during the last interglacial – variously known as substage 5e of the marine isotope record, 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 (Figure 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. Petrologic 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 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 petrologic work. Recent evidence from ice-core data and pollen studies of lake sediments indicates that the last interglacial was an interval of extreme climate fluctuations. 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 the validity of this concept in the light of our
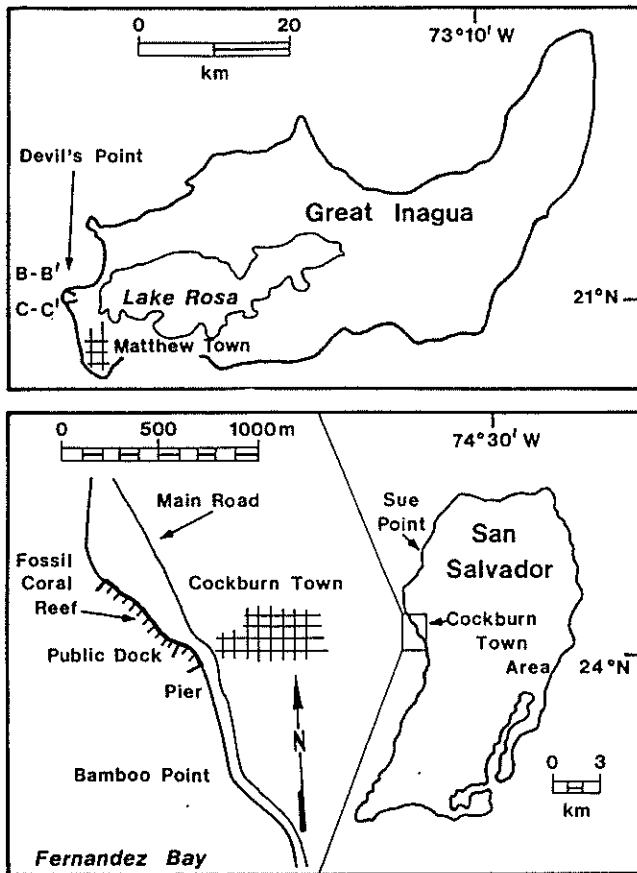
Figure 2. Map showing the location of the Devil's Point fossil reef on Great Inagua Island, and the Cockburn Town and Sue Point fossil reefs on San Salvador Island.

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 (Figures 4A, B). Corals beneath the erosional surface are truncated, in some cases including the lithophagid borings within the corals (Figure 4C). Elsewhere the erosion surface itself was bored by sponges, and subsequently these borings were encrusted by corals (Figure 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 (Figure 5A, B), which in some places has been removed by subsequent

erosion to reveal cavity floors, walls, and roofs that have sponge and bivalve borings and serpulid encrustations (Figure 5C). Red paleosols overlying the fissures and the infilling subtidal calcarenites (Figure 5D) prove the Pleistocene age of these features. In some fissures, the red paleosol unconformably overlies an earlier generation of red caliche that lines fissure walls and the adjacent 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 crops out 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 following the sea-level lowstand recorded at the Devil's Point and Cockburn Town fossil bank-barrier reefs. The oldest dated corals from this reef are a *Montastrea annularis* (122.9±1.9 ka) and *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 entire last interglacial, and evidence for the mid-Sangamon lowstand may be absent from some of them. This 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 developmental stages of the reef (Chen et al., 1991; Curran et al., 1989). Two of the topographic and geologic profiles from our previous work provide important information regarding the timing of formation of the wave-cut surface. Profile B-B' is from the locality where the photographs shown in Figure 3 were taken. It reveals that the
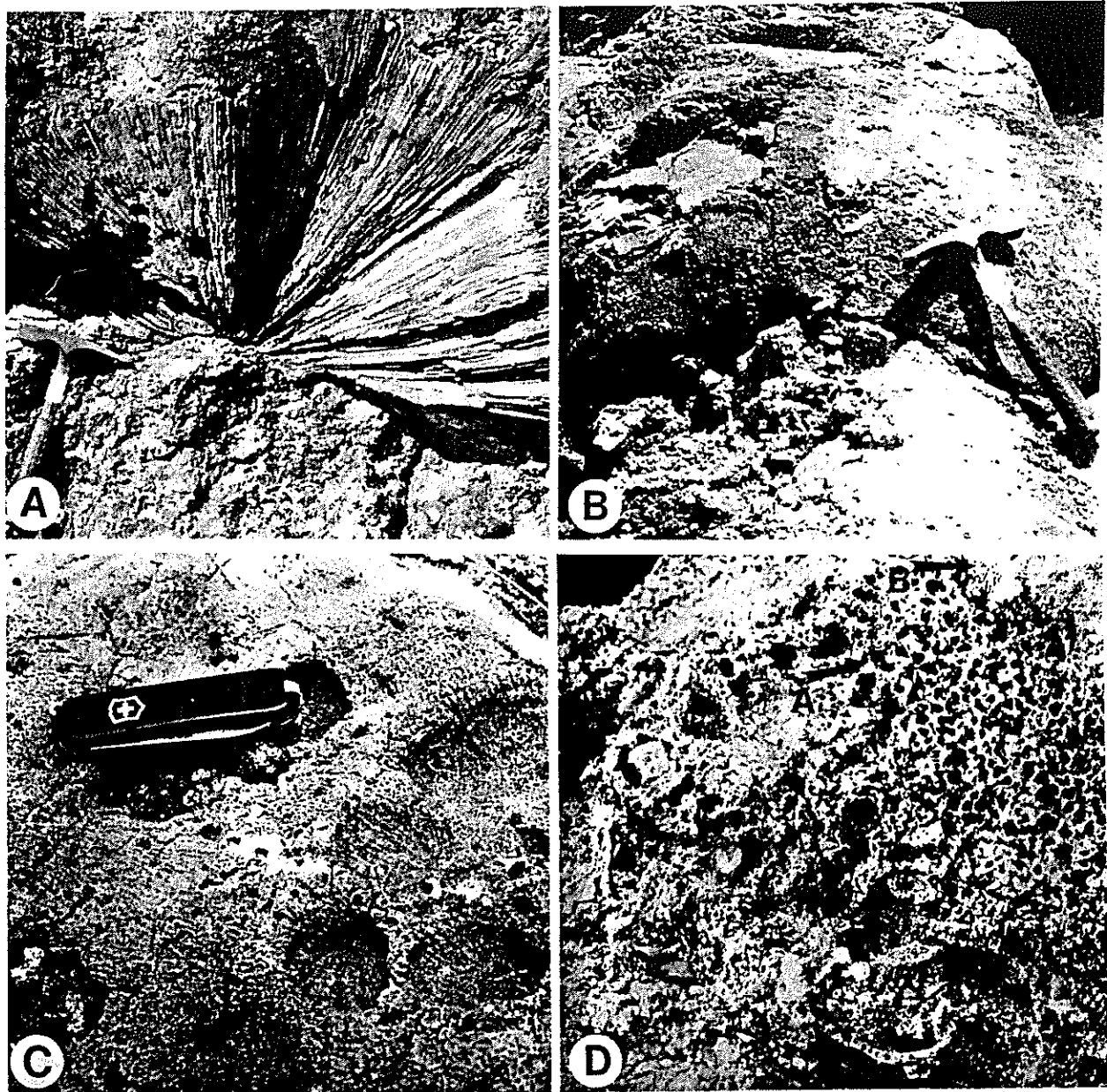
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Figure 4. Geology at Cockburn Town fossil reef. A) Diploria strigosa fossilized in growth position on the erosional surface that developed during the mid-Sangamonian sea-level lowstand. B) Montastrea annularis fossilized in growth position on the erosional 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).

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

Profile C-C' illustrates a locality where a fully developed and extraordinarily well-preserved coral patch reef overlies the erosion surface (Figure 7). An *Acropora cervicornis* sample from below the erosion
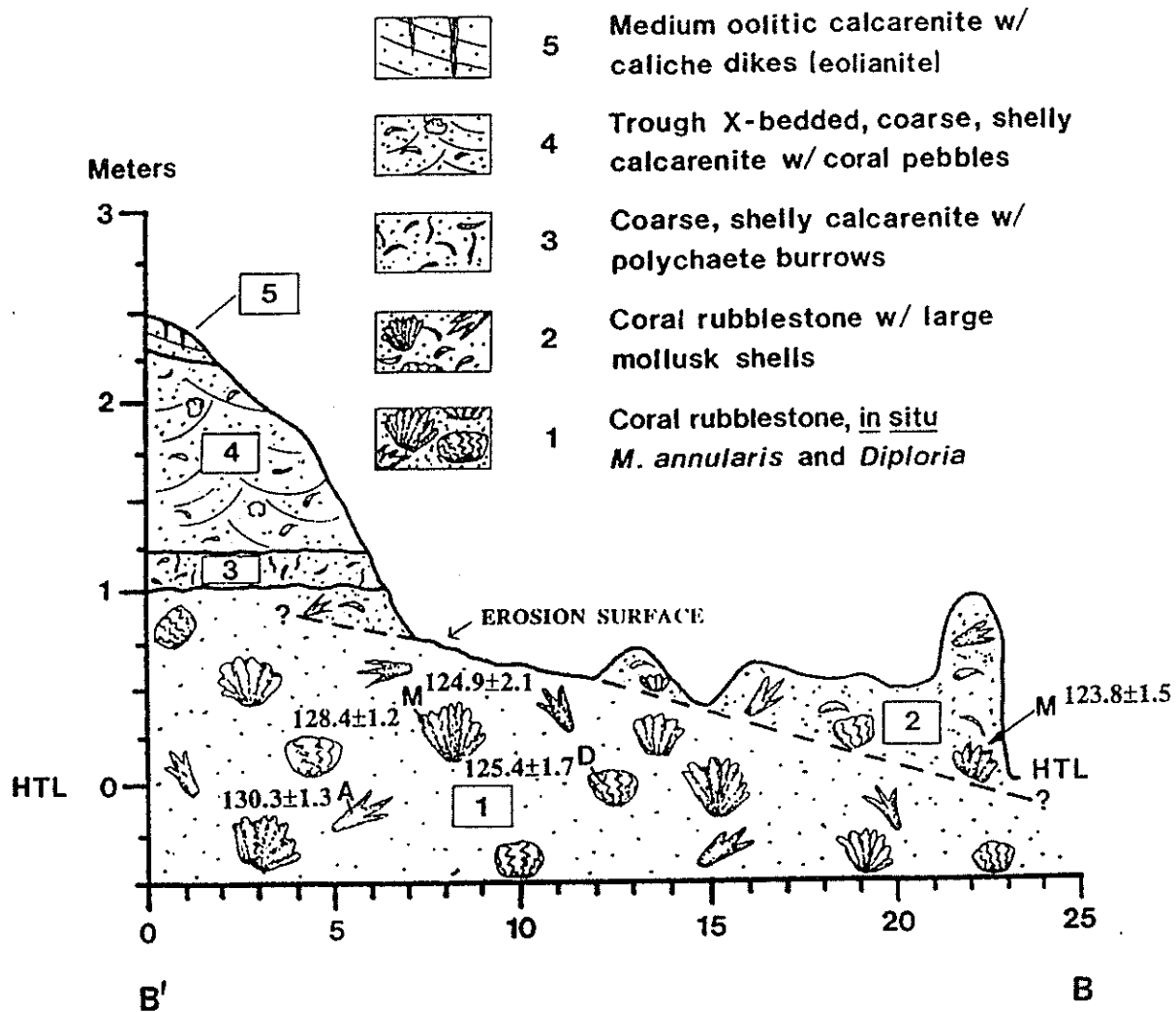
Meters

5 Medium oolitic calcarenite w/ caliche dikes (eolianite)

4 Trough X-bedded, coarse, shelly calcarenite w/ coral pebbles

3 Coarse, shelly calcarenite w/ polychaete burrows

2 Coral rubblestone w/ large mollusk shells

1 Coral rubblestone, in situ *M. annularis* and *Diploria*

Figure 6. Profile B-B', Devil's Point fossil reef. U-Th ages shown adjacent to sampled corals. A = Acropora cervicornis; M = Montastrea annularis; D = Diploria strigosa.

The Cockburn Town Reef Erosional Event

Profile C-C' of our earlier work (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 (Figure 8). 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 single specimen of *A. palmata* collected 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.

Other dated corals from the Cockburn Town fossil reef aid in determining the age of the sea-level lowstand. A sample of *Acropora palmata* from above the erosional surface at profile D-D' has an age of 124.0±1.6 ka. No dated corals are presently available from below the erosional surface at this locality. A *Montastrea annularis* associated with a group of corals with even younger ages, from the former outcrop above the erosion surface at the northern end of the reef, has an age of 124.2±1.3 ka. An *Acropora cervicornis* sample associated with a group of even older corals from below the erosion surface has an age of 125.3± 2.0 ka (Chen et al., 1991).
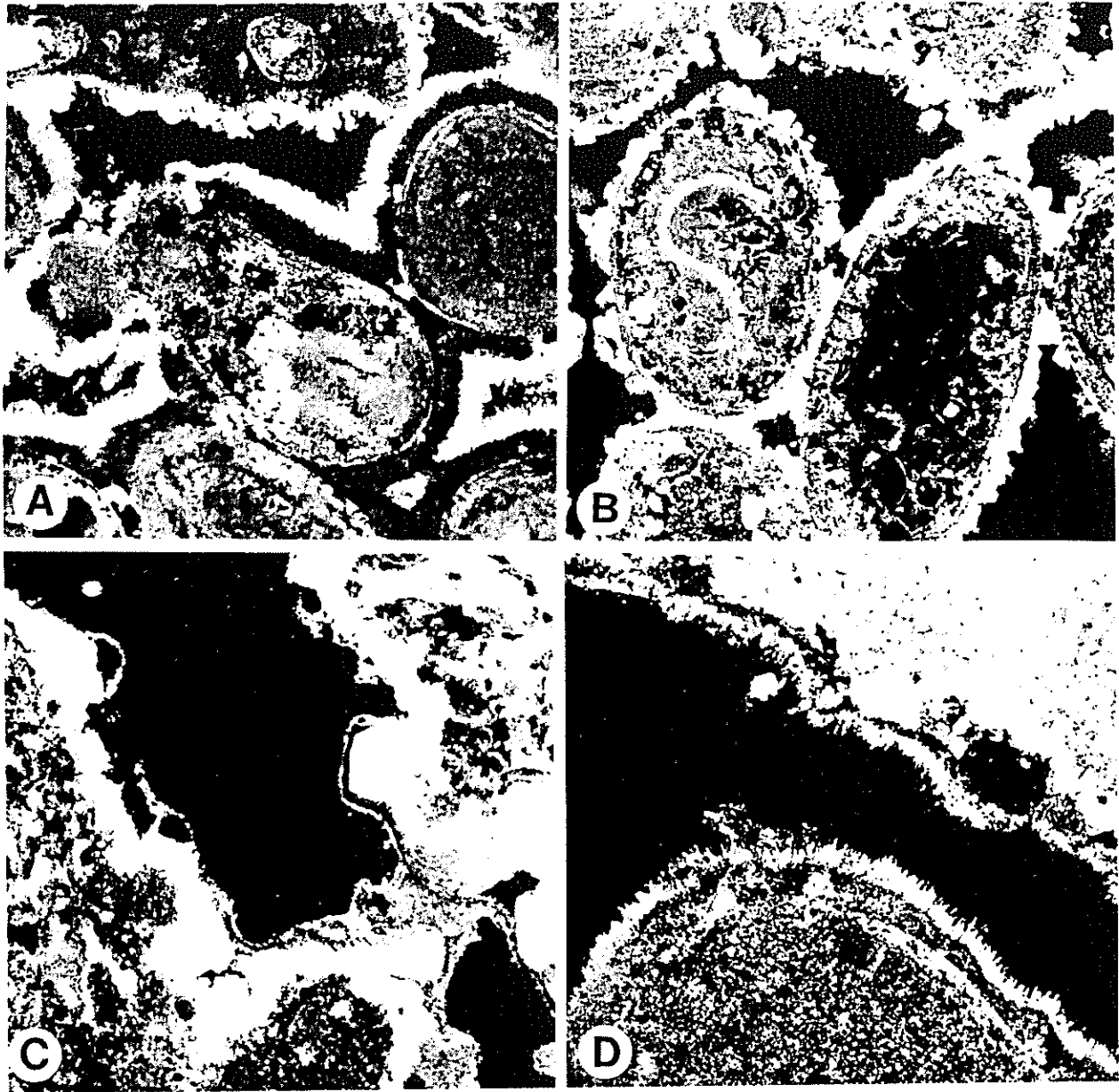
Figure 9. Photomicrographs under crossed polarizers of samples from Devil's Point fossil reef. All widths of view = 2 mm. A) Early marine high-Mg calcite and aragonite cements followed by sparse non-marine sparry calcite cement. B) Sparse early marine cements followed by abundant non-marine vadose sparry 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.

calcite cements. The grainstone shown in Figure 9B has a similar overall sequence but the amount of early marine cement is much less and the rock is cemented largely by vadose fresh-water spar. In contrast, the cement sequence seen in the rock shown in Figure 9C is reversed. That rock is largely cemented by an early non-marine isopachous calcspar with a small amount of later, irregularly distributed, marine high-Mg calcite and subsequent
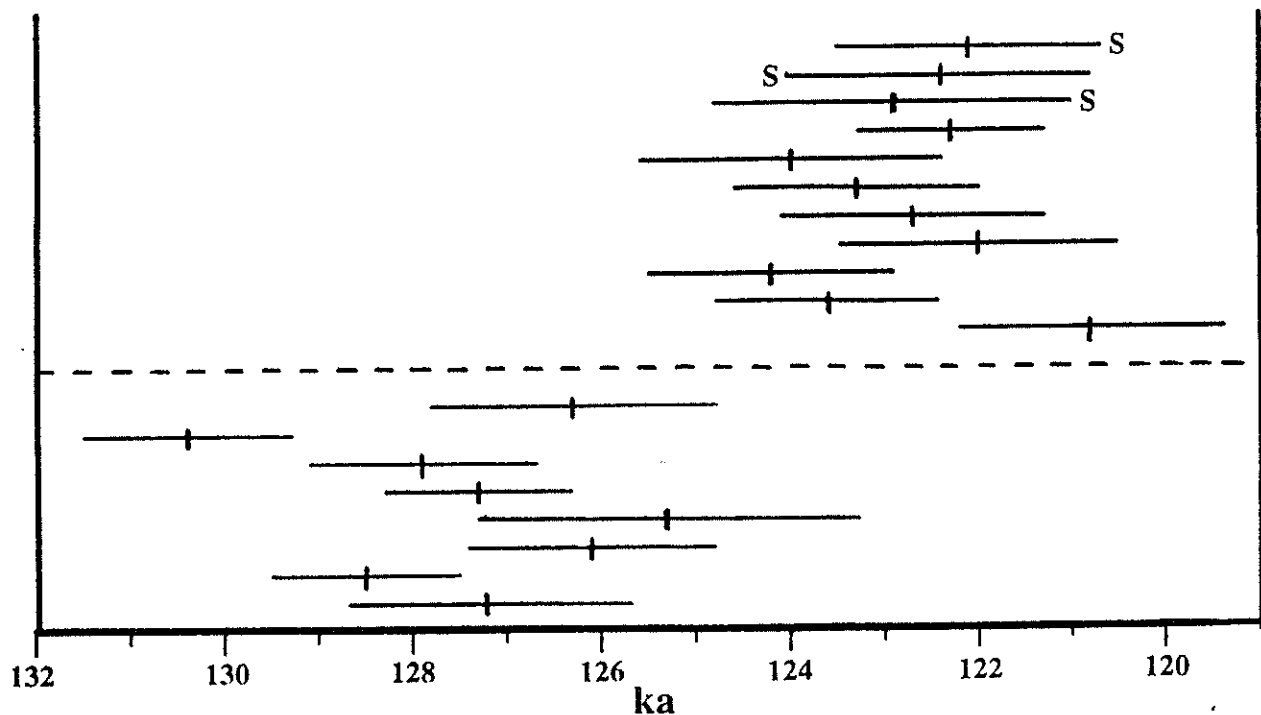
Figure 11. Compilation of U-Th ages of corals that are not shown in Figure 10. S = corals from the Sue Point fossil reef; unlabelled ages are of corals from the Cockburn Town fossil reef; dashed line represents the erosional surface.

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. 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 of 1.1 ka from 124.9 to 123.8 ka. Data from Figure 11, which represent dated corals that have a known relationship to the erosion surface, but lack the vertical juxtaposition, indicate a time window for the regression-lowstand-transgression sequence of 1.1 ka from 125.3 to 124.2 ka. Combining these data yields two possible endmember values: a narrow temporal window of 0.7 ka from 124.2 to 124.9 ka, or a broad window of 1.5 ka from 123.8 to 125.3 ka.

Rates of Sea-level Change

Prior to the regression to the lowstand,

sea level 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 regression/transgression episode. 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 with their borings, encrustations, and thin caliche linings requires that the lowstand existed for a significant fraction of the time interval. Table 1 shows the rate of sea-level change required for the narrowest and widest time intervals for the regression/transgression cycle, assuming various durations of lowstand needed to form the wave-cut platform.

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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 an 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 propose 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 refer 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 regresssion of Hearty and Kindler (1995). In a more recent paper, Neumann and Hearty (1996) focus mainly on evidence for a rapid rise and subsequent fall of sea level at the end of the last interglacial. However, they infer that sea level for most of the interglacial remained near 2 m above present, interrupted only by a short-lived, sea-level regression of approximately 1.5 m at approximately 125 ka. The timing of this event appears to be constrained largely by data from Chen et al. (1991).

Interesting information is presented by Precht (1993) based on studies of reefal facies of the Falmouth Formation in Jamaica. Presently, this information is published only in the form of an abstract, which makes it difficult to evaluate. 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 parasequnce 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 from the last interglacial period recorded elsewhere. Figure 12 is based on data presented in GRIP members (1993), and shows measured changes in $d^{18}O$ of the portion of the Greenland ice core that formed during the last interglacial, and the calculated temperature fluctuations based on the isotope data. As this ice core data yields the best presently available

minor fluctuations, for a little more than a millenium. This warming trend coincides with evidence of a rapid rise in sea level seen in the fossil reefs, and the 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 the Bahamian fossil reefs indicate that sea level, and accompanying coral growth, was higher than present levels at that time.

The reason for the discordance between evidence of rapidly rising sea level in the Bahamas 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, then temperatures rose rapidly during the last 1000 years (Field et al., 1994). This corresponds more closely to the ice-core data than to our sea-level history. Interestingly though, the 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 level identified from the Bahamian reefs is the global norm. Hollin (1980) proposed that some polar ice masses could pass a critical limit and then surge into the oceans, and 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.

In a 500 year span between 119 and 118 ka, the ice-core data show that temperatures in Greenland fell approximately 9°C to a level ~5°C below average Holocene values. This timing corresponds to the record

from the Bahamian coral reefs where the youngest known coral dates to 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 warm episode at ~115 ka when temperatures reached approximately 4°C above the Holocene average for a short interval, before falling to the glacial values 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 onto the sands of the terminal shallowing-upward sequence.

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 131-125 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 phase of reef development 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 fresh-water diagenesis. Sea level fell during the interval 125-124 ka to about current sea 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

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