PROCEEDINGS OF THE 9th SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
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Production Editors:
Matthew A. Reece
Laurel L. Powers

Bahamian Field Station, Ltd.
San Salvador, Bahamas
1999

Front Cover: Lee-side exposure of a fossil parabolic dune viewed from the Grahams Harbour side (west) of North Point, San Salvador, Bahamas. These Holocene carbonate eolianites have been assigned to the North Point Member of the Rice Bay Formation (Carew and Mylroie, 1995). The eolian cross-stratification dips below present sea level, proving that late Holocene sea-level rise is real. Top of the dune is about 7 meters above the sea surface. Photo by Al Curran.

Back Cover: Dr. Noel P. James of Queen's University, Kingston, Ontario, Canada, keynote speaker for this symposium. Noel is holding a carving of a tropical fish created by a local artist and presented to him at the end of the symposium. Photo by Al Curran.

Printed in USA by

ISBN 0-935909-67-2

A REVIEW OF THE LAST INTERGLACIAL SEA-LEVEL HIGHSTAND (OXYGEN ISOTOPE SUBSTAGE 5e): DURATION, MAGNITUDE, AND VARIABILITY FROM BAHAMIAN DATA

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ABSTRACT

Based on data obtained from the geologic record in the Bahamas, the last interglacial sea-level highstand (oxygen isotope substage 5e) seems to have lasted 10-15 ka, centered at approximately 125 ka ago, and sea level reached a maximum elevation of about +6 m. The initial data regarding the onset and termination of the highstand came from alpha count Uranium-series dates from presumed in situ fossil corals, which yield dates consistent only with stage 5 (Carew and Mylroie, 1995a). More precise dates obtained by mass spectrometry (Chen et al.,1991) constrain the time of reef growth to the substage 5e highstand. Reef growth occurred over approximately 13 ka, from 132 ka to 119 ka ago.

The highest reported in situ elevation of a fossil reef in the Bahamas is +3 m, which indicates the minimum height of the substage 5e sea-level highstand. Isostatic subsidence of the Bahamas has been reported as 1-2 m/100ka, so the current elevations of fossil reefs may be consistent with a highstand of +6 m. The elevations of flank margin caves also support a +6 m position for the substage 5e highstand, as the caves formed in a fresh-water lens floating on marine water. The phreatic roofs of these caves range up to +6 m, which is consistent with cave development in a fresh-water lens whose upper surface was slightly above a +6m sea level, with subsequent subsidence of 1-2 m over 125 ka. It has also been suggested that the substage 5e highstand contained a minor regression at approximately 125 ka. Possible evidence for this regression is provided by data from fossil reefs (White et al., 1998), sedimentary structures (Hearty and Kindler 1995), and caves (Mylroie et al., 1991). More controversial is a recent proposal that, during the majority of the substage 5e highstand, sea level was at approximately +2 m (excepting the regression at 125 ka), with an abrupt rise to +6 m for only approximately 1 ka at about 120 ka ago, followed by a precipitous decline (Neumann and Hearty, 1996). This hypothesis is contrary to other data which requires sea level to be at 4-6 m both before and after the 125 ka regression.

INTRODUCTION

The Bahamian Archipelago has long been recognized as one of the great carbonate provinces of the world, and has been host to numerous studies of carbonate deposition, karst processes, and Quaternary sea level history (Carew and Mylroie, 1997 and references therein). The debate about sea level in the Quaternary began in part because of work done in the 19th century in the Bahamas (Sealey, 1991), when Pleistocene fossil coral reefs were first recognized above modern sea level. The tectonic stability of the Bahamas has made it an excellent location in which to examine the effects of glacio-eustasy (Carew and Mylroie, 1995a), and has been able to provide a stable counterpoint to the record provided by uplifted islands such as Barbados. Studies of surficial geology were sparse in the Bahamas until the opening of the Bahamian Field Station (BFS) on San Salvador Island in the early 1970's. For more than 25 years, the BFS has supported a wealth of geologic inquiry that has produced significant advances in our understanding of Late Quaternary sea level (Carew and Mylroie, 1995a,b, 1997 and references therein).

LATE QUATERNARY SEA-LEVEL CHRONOLOGY

Early Fossil Coral Work

By the end of the 19th century, geologic investigators had realized that the fossil coral reefs found above modern sea level in the Bahamas were most likely produced by a past interglacial sea-level highstand. There was ample continental evidence, especially bone deposits from Great Britain, that the last interglacial had been warmer than the current one (Tratman, 1975). The development of the Uranium-series method for dating of deposits in the 1960's allowed the fossil corals of the Bahamas to be dated, provided that the corals were still aragonitic and had not yet inverted to calcite (aragonite inversion to calcite results in open-system conditions, and loss of reliability of the dates). The earliest work on Bahamian fossil corals, from the Berry Islands in the northwest Bahamas, was that of Broecker and Thurber (1965), which was redone by Broecker and Van Donk (1970). Those early results indicated that the last interglacial extended from 113 +/- 12 to 127 +/- 7 ka (Broecker and Van Donk, 1970). Those data fit well with the oxygen isotope sea-level curves being generated at that time (Shackleton and Opdyke, 1973), which called for a sea-level highstand, oxygen isotope substage 5e, that lasted for about 10,000 to 15,000 years, centered at about 125,000 years ago.

Following upon that initial work was a larger-scale survey of Andros Island, Grand Bahama Island, Moore's Island, New Providence Island, and the Berry Islands by Neumann and Moore (1975). That study yielded dates ranging from a low of 94 +/- 8 ka on the Berry Islands to a high of 146 +/- 9 ka on New Providence Island. Given the relatively large error bars on alpha count dates, it was unclear at the time whether the ages represented a long highstand during the last interglacial, or perhaps more than one highstand during the overall oxygen isotope stage 5 (i.e., substage 5a circa 85 ka, substage 5c circa 105 ka, and the "traditional" substage 5e circa 125 ka, see Figure 1a).

Beginning in the late 1970's work began on the dating of fossil coral reefs in the southeastern Bahamas, through the auspices of the BFS. Dates later reported by Carew et al. (1987) and Carew and Mylroie (1995a) showed a pattern similar to that previously found. Their dates gave a similar large spread, from San Salvador Island (103 +/- 4 to 146 +/- 10 ka), Rum Cay (130 +/- 8 ka), and Great Inagua Island (124 +/- 6 to 147 +/- 6 ka). Those numbers were important for several reasons. First, the northwestern Bahamas are subject to a much wetter climate than the southeastern Bahamas, and therefore diagenetic processes are believed to operate much faster in the northwestern Bahamas (Beach, 1995). There was concern that the early coral dating was on corals with some calcite inversion, which might have caused the "spread" in the dates. Second, the northwestern Bahamas are on a few very large banks next to a passive continental margin, whereas the southeastern Bahamas are small, isolated banks near the plate boundary between the Caribbean plate and the North American plate. It was initially thought possible that tectonics could be active in the southeastern Bahamas, and the corals

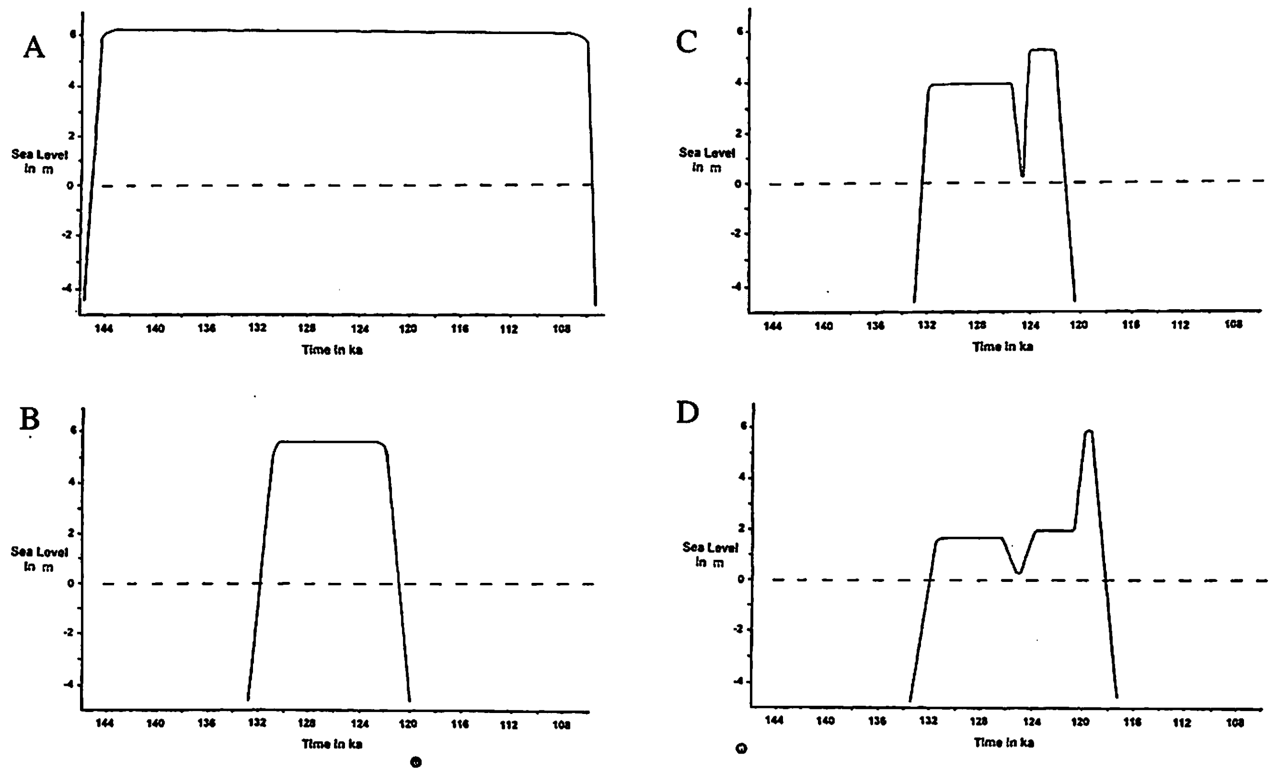

Figure 1: A diagrammatic representation of the changes in the sea-level curve for the last interglacial (oxygen isotope substage 5e) highstand. A - The initial curve based on alpha-count Uranium-series dates; B - The modified curve after application of the TIMS technique; C - A refined curve after combining detailed outcrop study with TIMS dates; D - A proposed curve refinement that is not supported by existing data.

would therefore show very different ages. The data shows that this latter concern is unwarranted (Carew and Mylroie, 1995a).

Later Fossil Coral Work

The major problem with the coral dates produced in the 1970's and 1980's was their lack of precision. The Uranium-series isotopes were measured by counting the alpha particles emitted from purified samples, the alpha energy spectra being different for each isotope. To successfully assess the ratio of isotopes, the counting must be done for long periods of time, commonly weeks, and even then, only a fraction of the isotopes are actually counted. The large error bars produced by the technique were the result. In addition, large samples were necessary, restricting the number of growth layers that could be assessed in a given sample.

In 1987, a Penrose Conference was held at the Bermuda Biological Station (Carew et al., 1987) to focus on the question of sea level history during the late Quaternary. One of the participants, Gerry Wasserberg of the California Institute of Technology, presented information on how a new technique, now known as thermal ionization mass spectrometry (TIMS), could provide a much higher degree of precision for Uranium-series dating of corals, and therefore address some of the problems with the large error bars associated with alpha-count dates. TIMS measures the number of atoms of different isotopes directly, and a greater precision can be obtained from much smaller samples. Collaboration soon began between Wasserberg's lab and Allen Curran and Brian White of Smith College, who re-visited and re-sampled two classic fossil reef locations on San Salvador Island and one on Great Inagua Island. Their results showed a much tighter spread of dates, from 120.7 +/- 1.5 to 132.6 +/- 1.3 ka on San Salvador, and 122.1 +/- 1.3 to 130.3 +/- 1.3 on Great Inagua (Chen et al., 1991). The dates all fell within the range of the alpha count dates done earlier by a variety of workers (Carew and Mylroie, 1995a). However, these new data indicated that the substage 5e sea-level highstand of the last interglacial had a maximum duration of probably only 13,000 years (Figure 1b).

LATE QUATERNARY SEA-LEVEL MAGNITUDE

The question of the timing of the last interglacial sea-level highstand appears to have been answered, but there is still some debate about the maximum elevation that highstand reached. The fossil reefs on San Salvador Island and Great Inagua Island are very well preserved. It has been argued that this excellent preservation is the result of extremely rapid sea level fall at the end of substage 5e (Neumann and Hearty, 1996), but we have argued that only entombment in sands prior to sea level fall, most likely by a storm event, could provide such widespread and detailed preservation (Carew and Mylroie, 1995b, 1997). Whatever the reason for the excellent preservation, the outcome is twofold: first, the fossil corals still contain their primary aragonite, important for Uranium-series dating; and second, many fossil corals are in growth position, which means their position can provide information about minimum sea level elevation.

The elevations of the coral reefs that have been TIMS dated on San Salvador Island and Great Inagua Island are well known (White et al., 1998, and references therein). These fossil reefs have corals in growth position up to 3 m above modern sea level. In the absence of uplift tectonics, such an elevation requires that sea level was at least 3 m above modern level when the corals were alive. Given that the corals were not obligated to grow to sea level, the actual sea level position could have been higher, therefore the 3 m elevation is a minimum.

While the Bahamas are tectonically stable, they are undergoing isostatic subsidence. The currently accepted subsidence rate, from a variety of authors using different techniques, is 1-2 m/100ka (Carew and Mylroie, 1995a and references therein). Therefore, given the age of oxygen isotope substage 5e as 119-132 ka, a subsidence of 1 to 2 m is expected. Accounting for that subsidence would place the fossil corals, when they were alive, at a minimum elevation of 4-5 m above current sea level. So, a sea level of +6 m is in agreement with the fossil coral data.

A second line of evidence supports the contention that the oxygen isotope substage 5e sea-level highstand peaked at approximately +6 m. Flank margin caves develop at the distal margin of the fresh-water lens in response to mixing dissolution in that environment (Mylroie and Carew, 1990, 1995; Mylroie, et al. 1995). The margin of the fresh-water lens is a proxy for sea level; therefore the position of flank margin caves from the last interglacial is a measure of past sea-level position. Analysis of currently subaerial flank margin caves shows that they commonly have phreatic roofs up to elevations of 6 m above modern sea level. Given that the fresh-water lens can extend slightly above sea level, especially during high recharge events (1-2 m above sea level), the cave roofs are in the position expected for a +6 m sea level, given later isostatic subsidence (Carew and Mylroie, 1995a). The ages of the caves can be demonstrated by U/Th analysis of their included speleothems. These cave deposits are all less than 119,000 years in age, which is consistent with development of the caves during the oxygen isotope substage 5e sea-level highstand, and not an earlier highstand (Carew and Mylroie, 1995a).

A BRIEF LOWSTAND WITHIN THE LAST

INTERGLACIAL SEA-LEVEL HIGHSTAND

As our understanding of the duration and magnitude of the last interglacial sea-level highstand (oxygen isotope substage 5e) was refined, some workers uncovered evidence that within that highstand there was a brief excursion of sea level downward to perhaps modern level. The best data come from the detailed elevation studies and TIMS Uranium-series dates from the fossil reefs of San Salvador and Great Inagua islands (White et al., 1998), as follows. In those reefs, an erosion surface is found within the fossil coral stratigraphy. The TIMS dates indicate that the sea level excursion occurred about 126-125 ka ago and lasted for up to 1,500 years. Diagenetic data also support subaerial exposure of the older corals (132-125 ka) at that time. The elevation data suggest that the magnitude of the sea-level highstand prior to the excursion was +4 m, and rose to +6 m afterward (Figure 1c).

Hearty and Kindler (1995) also suggested, from protosols found between marine deposits, that there had been a sea-level excursion during oxygen isotope substage 5e. Their timing of the event disagrees with that of White et al., (1998), and they have no absolute age data of their own. Nonetheless, the Hearty and Kindler (1995) observations support the initial contention that there was a sea-level lowstand excursion during oxygen isotope substage 5e.

Further observations supporting a sea-level lowstand excursion during substage 5e come from Hunts Cave on New Providence Island. Garrett and Gould (1984) reported dissolved flowstone in the cave; this observation was confirmed and documented by Mylroie et al.(1991) at an elevation of 4-6 m above modern sea level. The dissolved flowstone was interpreted by Mylroie et al.(1991) as follows: The subaerial flank margin caves of the Bahamas formed during oxygen isotope substage 5e, as earlier sea-level highstands were either not high enough (oxygen isotope stage 7) or were too long ago (stage 9 or 11) to leave the caves above modern sea level, given isostatic subsidence. Therefore Hunts Cave must have formed during oxygen isotope substage 5e. In order for the flowstone to have been deposited, the cave had to be at least partially drained. This draining phase could not be the result of the termination of substage 5e, because later the cave was flooded and the flowstone was partially dissolved (along with adjacent roof rock) in the phreatic environment, an event that could not have occurred after the end of substage 5e. Mylroie et al.(1991) invoked a sea-level lowstand excursion in the middle of substage 5e to explain the observations. The Mylroie et al.(1991) data lack absolute dates from the flowstone, and an alternative hypothesis, condensation corrosion in the vadose zone, could account for the dissolved flowstone (see Frank et al., 1998 versus Tarhule-Lips and Ford, 1998).

Three separate lines of evidence seem to indicate that there was a brief sea-level lowstand excursion approximately in the middle of the last interglacial (oxygen isotope substage 5e). The data from White et al. (1998) is most compelling, as a result of the high-precision absolute dates that fix their interpretation.

AN ALTERNATIVE HYPOTHESIS

Neumann and Hearty (1996) offer an alternative hypothesis for some of the fine structure in the oxygen isotope substage 5e sea-level highstand. They suggest that the early portion of the substage 5e highstand was at only +2 m above modern level for most of its duration, with a subsequent lowstand excursion as previously described, with a dramatic and sudden rise to +6 m for only hundreds of years before falling precipitously at about 119 ka (Figure 1d). The timing of their events is drawn entirely from the data of Chen et al. (1991). The key piece of evidence in the Neumann and Hearty (1996) hypothesis is a feature on Little Sale Cay interpreted by them as a bioerosion notch. However, in our opinion, this notch is most likely a breached flank margin cave (Mylroie and Carew, 1991; Mylroie 1997). The Neumann and Hearty (1996) interpretation has been questioned in the literature (Carew, 1997; Mylroie, 1997; White et al., 1998) and the ideas have not received any support in the scientific community. Both the fossil coral reef data of White et al. (1998), and the cave data of Carew and Mylroie (1995a), both of which are tied to absolute dates, require a sea level elevation well above 2 m for the first half of oxygen isotope substage 5e. Both data sets require sea level at +6 m for a significant period of time (i.e. at least several thousand years) for the second half of the substage. The current model for the formation of banana holes in the Bahamas (Harris et al., 1995) also requires that sea level during oxygen isotope substage 5e follow the White et al., (1998) model. The alternative hypothesis of Neumann and Hearty (1996) has no apparent support in the existing data base from the Bahamas.

CONCLUSIONS

The scientific community's understanding of the duration, magnitude and variability of the last interglacial sea-level highstand (oxygen isotope substage 5e) has been continually refined over the last three decades. Today, the data suggest that the highstand lasted from about 132 ka to about 119 ka. It had a maximum magnitude of approximately +6 m above current sea level for much of its duration. The data indicate that there was a brief excursion of sea level that produced a modest lowstand which lasted approximately a thousand years centered about 125 ka ago. The highstand is now seen as asymmetrical, rising to at least +4 m prior to 125 ka, and rising to about +6 m afterwards. An alternative hypothesis that sea level was at only +2 m for most of the highstand, with a brief precipitous rise to, and fall from, +6 m about 120 ka is not supported by the field evidence.

The increased resolution of the details of the substage 5e highstand is the result of application of new techniques, such as TIMS dating, and detailed field work and surveys, as demonstrated by the work of White et al. (1998). Information from other fields, such as the use of cave data (Carew and Mylroie, 1995a), has been helpful in corroborating the fossil coral data.

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