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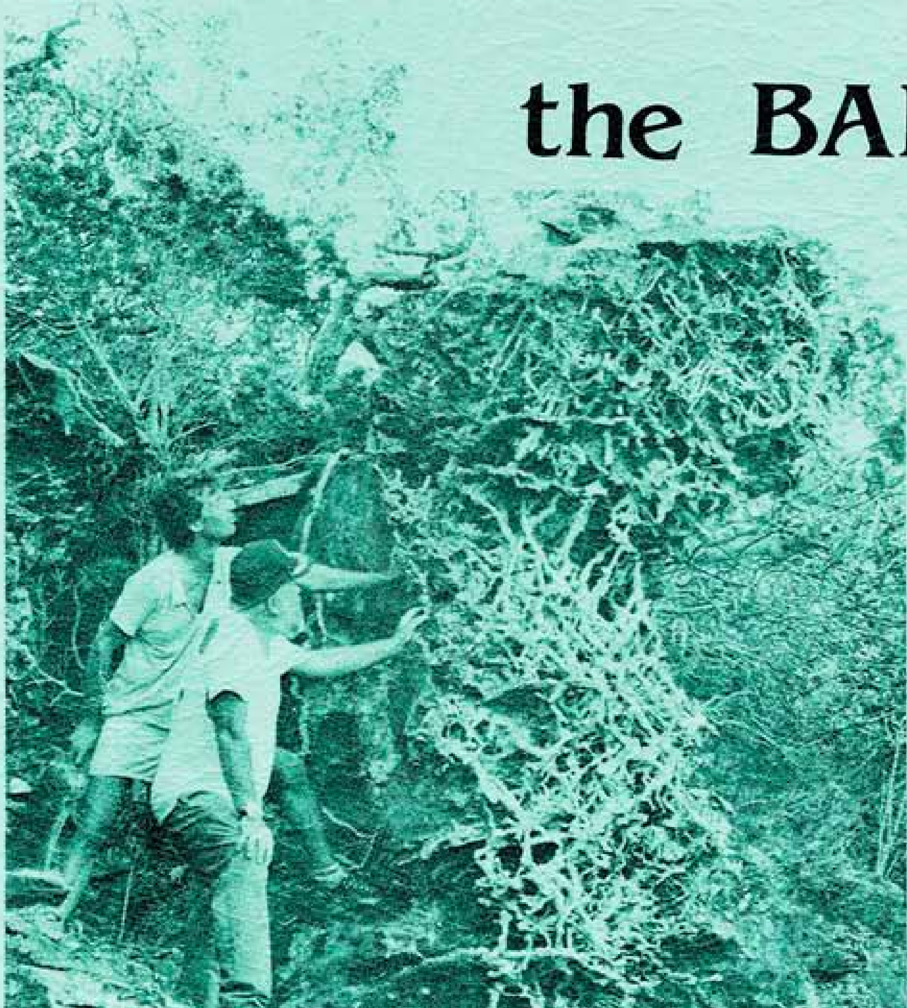

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ESTIMATES OF LATE PLEISTOCENE SEA LEVEL HIGH STANDS FROM SAN SALVADOR, BAHAMAS

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Abstract

Analyses of a series of integrated solution conduits and emergent reef deposits on San Salvador, Bahamas provides evidence for a significant re-evaluation of sea level fluctuations during the last 125,000 years. Amino acid racemization and Uranium-series dating of fossil molluscs, corals, and speleothems have established a chronology for the deposition of the sedimentary rock units in which the conduits are formed, the deposition of the exposed reef, and minimum time for cave formation and the timing of changes in internal cave conditions.

The elevation of a 125,000 year old reef on San Salvador, as well as published information on the Bahamas in general, makes it evident that no tectonic uplift, and little, if any, subsidence has taken place during the time in question. The isolated position and small size of the island and its associated submarine platform, regardless of sea level elevation, combined with its low relief and uniform lithology dictate that sea level and water table must be intimately linked.

An extensive eolian calcarenite with an amino acid racemization age of 70,000 ± 20,000 years contains horizontal solution conduits up to 50 square meters in cross section. Uranium-series age dates from a stalagmite collected in growth position from one of those conduits indicates that major growth episodes occurred at 49,000 ± 2,000 and 37,000 ± 2,000 years ago. On a tectonically stable platform such as San Salvador Island, the geologic features and ages are direct evidence of changes in Late Pleistocene sea level. During the time interval of 90 to 70 ka (kilo anni; thousand years) sea level below -2 meters is required for the deposition of the eolian calcarenite that extends to at least that elevation. The younger solution conduits within the calcarenite are evidence that sea level later became high enough to support a freshwater lens which formed the conduits that have phreatic solutional ceiling features that extend to +7 meters. Dated speleothem material reveals that sea level had fallen below -1 meters by 49,000 years ago. Marine deposits within the stalagmite require that sea level be at or above present elevation in the 49 ka to 37 ka time span. These data from San Salvador appear to settle a long-standing debate concerning a high sea level stand during the mid-Wisconsinan (Thom, 1973; Bloom, 1983b).

(Thom, 1973; Bloom, 1983b).

Introduction

Current estimates of Late Pleistocene high sea level stands have been derived in part from data obtained on Barbados and New Guinea, where tectonic activity has raised dateable reef horizons into the terrestrial sampling range (Fairbanks & Matthews, 1978; Bloom, et al., 1974). Those techniques require assumptions on rates of uplift that are difficult to substantiate. Indirect evidence of high sea level stands have also been obtained from geochemical analyses of deep-water cores taken off the Bahama Banks (Boardman, et al., 1983; Boardman, this volume), wherein pulses of aragonite-rich presumed shallow-water material washed into deep basins are used as evidence that the bank platforms were transgressed by high sea levels at those times; however, others interpret the data differently (Droxler, et al., 1983). Oxygen isotope data from deep sea cores and other geologic sources are also commonly used to provide indirect evidence of sea level (Broecker & Van Donk, 1970; Emiliani, 1972; Shackleton & Matthews, 1977; etc.). The interpreters of Pleistocene sea level changes must deal with the possibility that ice sheet growth and recession, and consequently sea level fall and rise, can occur quite quickly and precipitously (Bloom, 1983a; Mercer, 1978). This raises the possibility that short term sea level excursions may escape the resolving power of most current investigative techniques, especially if the excursion is continuous and does not stabilize at a single elevation or set of elevations for significant time intervals.

To address this problem, novel techniques have been applied to San Salvador Island, Bahamas (Carew & Mylroie, 1983). The data discussed herein have been calibrated by proven methods on well-established portions of the Late Pleistocene sea level curve, then applied to portions of the curve where the situation is less well-understood. In particular, the data have bearing on a recently described sea level high at aproximately 80 ka (Cronin, et al., 1981; Boardman, et al., 1983), and the much-discussed sea level high of approximately 40 ka (Thom, 1973; Bloom 1983b). In addition to our work which requires a high sea stand at approximately 40 ka, study of Norwegian glacial stratigraphy has led to the recognition of a middle Weichselian ice-free period called the Ålesund Interstadial (Mangerud, 1981a,b). The deposits indicative of that ice-free interval are dated at approximately 40 ka to 47 ka.

San Salvador Island, Bahamas was selected for a study of Late Pleistocene sea levels because it is part of the Bahamas trend, which has been tectonically stable over the time frame pertinent to this investigation (Mullins & Lynts, 1977). In addition, the island is an isolated, steep-walled platform that would exhibit a minimal change in size over the generally accepted range of Pleistocene sea level excursions. This is an important parameter in providing boundary conditions on the solution conduit development within the island (Mylroie, 1978; 1980; 1983; Carew, Mylroie, & Lively, 1982). San Salvador is a platform of shallow-water carbonates that extend at least 3 km down to what is interpreted as an original pervasively basalt intruded continental-fragment, or original basaltic volcanic peak (Mullins & Lynts, 1977). A living fringing reef and narrow lagoonal facies are active today, and these grade onshore into beach rock with occasional fossil reefs. This marine sequence interfingers with extensive eolian calcarenite deposits which have a current vertical extent of 38 m. Paleosols cut across both terrestrial and marine deposits. The island has an extensive surface and subsurface karst, most of which is currently inactive. The conclusions reached concerning sea level high stands are based largely on data derived from the study of two significant geologic features on San Salvador; a fossil reef, and a large solution conduit system. In Cockburn Town, on the west side of San Salvador, an emergent fossil reef (with elevations up to 4 m above present sea level) parallels the coast for over 700 meters. Samples of the corals Acropora cervicornis and Diploria strigosa and the bivalve mollusc Chione cancellata were collected for dating by amino acid racemization and Uranium-series methods.

Solution conduits are found at many localities on the island, the most significant being Lighthouse Cave, beneath Dixon Hill in the northeast portion of the island. Lighthouse Cave is a well-developed solutional network with passages ranging from 0.5 square meters to 50 square meters. It is developed in eolian calcarenites that extend to at least -2 m, and phreatic (sub-water table or tube-full) development extends from +7 m elevation to at least -2 m. Samples of the wallrock and the contained fossils of the pulmonate gastropod Cerion sp. were collected for amino acid analyses, and speleothems were removed for Uranium-series dating. The stalagmites analyzed were taken from growth position on the floor of a portion of the cave system that is flooded by marine water. The base of the stalagmites (which grow only under subaerial conditions) is inundated by the water even at low tide.

The Johnson Sea-Link submersible has been used to examine the near-vertical submerged wall of the island at the southwestern end. A well developed reef-constructive terrace or wave-cut platform is found at some localities at a depth of -55m and must have been formed during a still-stand in sea level at the -50 to -55m position. At -105m a number of wave-cut notches and overhangings, and a number of large horizontal solution conduits that open onto the island wall are indicative of a past sea level at that elevation. One major solution conduit was located at -125m. Solution conduits at preferred horizons in a uniform lithology argue for a still-stand in sea level at those horizons for a time period of a least a few thousand years. These features may be indicative of events during the maximum sea level lowering of the Late Wisconsinan and its subsequent rise to present elevation, or they may reflect the effects of older glacial stages. The usefulness of the submersible data on low sea level still-stands is limited by our present inability to date the features, and therefore fit them into the Pleistocene sea level chronology of San Salvador Island (Carew & Mylroie, 1984).

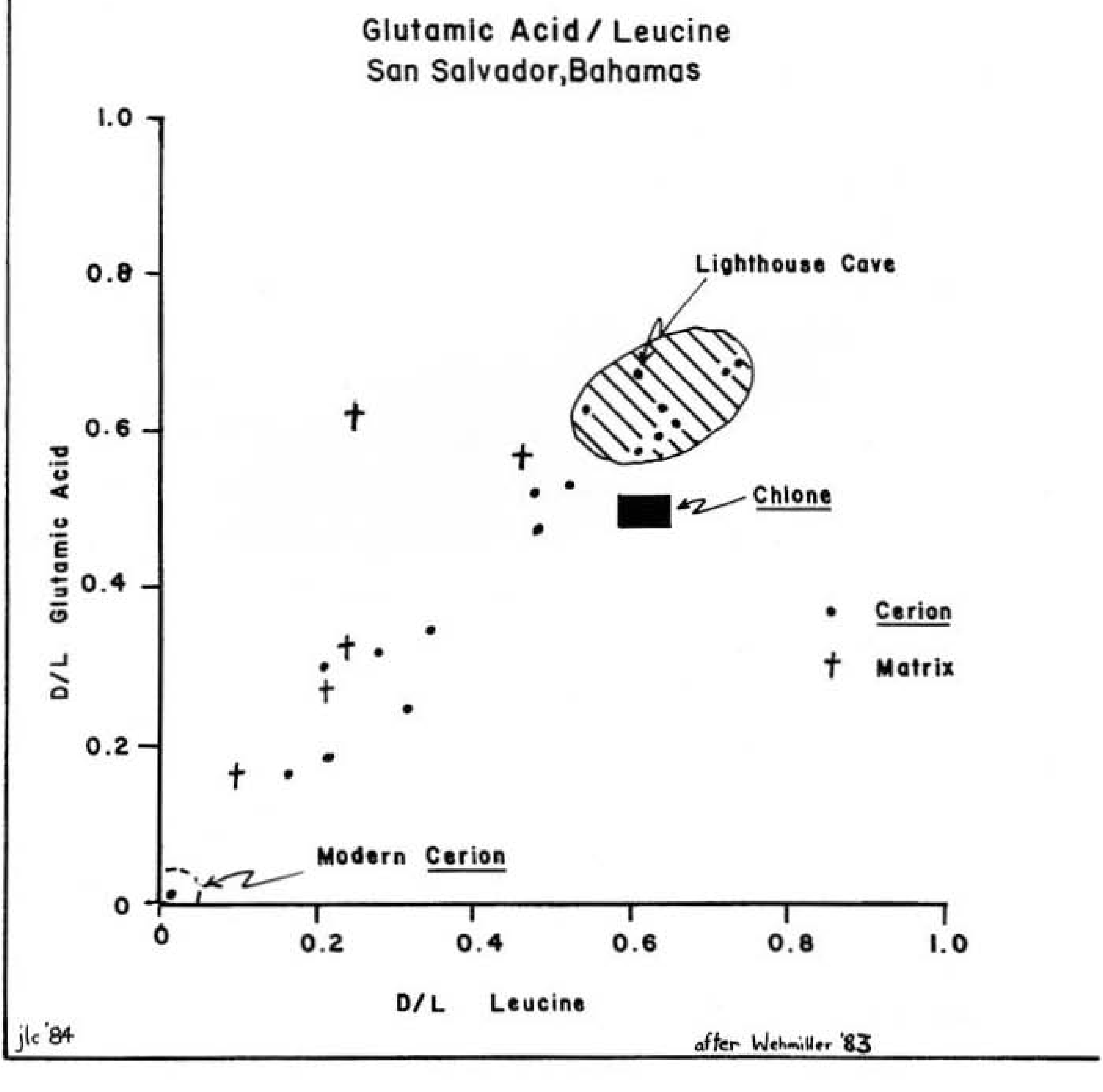
Amino Acid Analyses

Analyses of the enantiomeric (D/L) ratios of six amino acids in the total hydrolyzates of *Cerion* sp. and *Chione cancellata* samples have been conducted by gas chromatographic procedures described elsewhere (Wehmiller & Emerson, 1980; Wehmiller, 1982). Two *Chione* from the Cockburn Town reef and 16 *Cerion* samples from various calcarenite dune sites (including the cave wall at Lighthouse Cave) have been studied (Carew, 1983a,b). Because many of the *Cerion* samples were chalky and poorly preserved, enantiomeric ratio analyses of some of the calcarenite matrices (usually nearly pure carbonate, consisting of ooids, forams and shell fragments) have also been performed in order to assess the magnitude of natural diagenetic contamination of the *Cerion* amino acids with those of the surrounding matrix.

Co-varying glutamic acid and leucine D/L values are plotted in Figure 1. Results for other amino acids (alanine, valine, proline, phenylalanine, and aspartic acid) show the same relative trends as seen in Figure 1, and are generally consistent with the intrageneric racemization trends observed in other molluscs (Lajoie, et al., 1980). The D/L glutamic acid values in *Cerion* appear slightly (ca. 15%) greater than would be expected from previous glutamic acid-leucine intrageneric observations (Lajoie, et al., 1980); it is not known whether this relationship is unique to *Cerion*, or whether it is a consequence of some thermal or diagenetic effect inherent to the deposits being studied. The relative racemization rates for different amino acids in the matrix samples are rarely different from those in the _Cerion_ (or in other molluscs), so these relative rates cannot, by themselves, be used in this case to identify contamination in the _Cerion_ results. However, for the following reasons we conclude that the most reliable _Cerion_ results are those in the shaded region of Figure 1: (1) most of these samples were mechanically sound and physically well preserved, while those with lower D/L values were chalky and poorly preserved; (2) highest D/L values most likely represent the least amount of contamination with either Modern (D/L = 0) or matrix (D/L = 0.2-0.3) amino acids; (3) most of the lower D/L values in _Cerion_ are quite similar to the matrix D/L values, implying that these poorly preserved samples contain primarily matrix amino acids; (4) precision of multiple analyses from single sites is generally poorer for those samples with lower D/L values than for those with the higher D/L values. The geologic setting and the history of the _Cerion_ samples does not preclude multiple ages and/or complex thermal histories as explanations for the wide range of observed D/L values, but at present we prefer to interpret the results of Figure 1 as being indicative of one major calcarenite dune-forming event, represented by D/L values of 0.623 $\pm$ 0.068 (leucine) and 0.622 $\pm$ 0.053 (glutamic acid). More data will probably permit greater resolution of this "event" into more discrete intervals of calcarenite dune formation.

Also shown in Figure 1 are the leucine and glutamic acid data for _Chione cancellata_ from the Cockburn Town fossil reef. These data are consistent with intrageneric trends for this genus

Figure I.



Glutamic Acid / Leucine
San Salvador, Bahamas
1.0
0.8
0.6
0.4
0.2
0
D/L Glutamic Acid
Lighthouse Cave
Chione
Cerion
Matrix
Modern Cerion
0
0.2
0.4
0.6
0.8
1.0
D/L Leucine
jlc '84
after Wehmiller '83

(Lajoie, et al., 1980) and also with results obtained by Belknap (1979) for Lucina from a nearby Uranium-series dated 130 ka reef site on Eleuthera Island, Bahamas.

The age of the most reliable Cerion samples constrains the maximum age of Lighthouse Cave itself or any freshwater deposits therein. The amino acid age estimate for these relies upon the assumption that the Chione samples from Cockburn Town reef are approximately 130,000 years in age, and that these data provide a kinetic calibration for local Effective Quaternary Temperatures (see Wehmiller, 1982 for discussion of effective temperatures). Furthermore, the Cerion results must be converted into "equivalent" Chione in order to apply any local kinetics calibrated in this manner. Based upon the aspartic acid/leucine ratio of 1.6 $\pm$ 0.3 observed in the Cerion samples, we conclude that Cerion is one of a group of "fast-racemizing" genera (Wehmiller, 1982), and that an approximate conversion of Cerion enantiomeric ratios to equivalent Chione values can be made using intergeneric relationships observed in co-existing samples of "fast-" and "slow-racemizing" molluscan genera in Pleistocene marine deposits elsewhere (Belknap, 1979; Lajoie, et al., 1980). Using the leucine non-linear kinetic model of Wehmiller and Belknap (1982, Fig. 8), the leucine "fast to slow" conversion of Lajoie et al. (1980, Fig. 4), and Cockburn Town reef Chione data as a local kinetic calibration, we propose an age of 70,000 $\pm$ 20,000 years for the group of the most reliable Cerion samples depicted in Figure 1. The uncertainty given for this age estimate is due to the combined effect of analytical imprecision and an assumed effective temperature uncertainty of $\pm$ 0.5 degrees Celsius. The use of linear kinetic models (see Wehmiller, 1982), other possible and reasonable intergeneric conversions, or other amino acids (e.g., glutamic acid in Figure 1) would not reduce the above age estimate and would not increase it above the age of the Chione samples from Cockburn Town reef.

Uranium-Series Analyses

The results of the Uranium-series age analyses are shown in Table 1. The dates on the two coral samples were obtained from Lamont-Doherty Geological Observatory through the assistance of John Goddard, using procedures described by Thurber, et al. (1965). Uranium contents were suitably high (2.9, 3.4 ppm) and 232Th activity was nil. However, both coral samples showed evidence of calcite recrystallization (see Table 1).

Our interpretation of the coral dates is that they are anomalously young due to recrystallization of aragonite to calcite, as the younger age of 90,000 $\pm$ 5,000 years is derived from the sample with the greater amount of recrystallization. With no evidence for Pleistocene tectonic uplift on the Bahama platform, and the amino acid racemization results on the Chione cancellata samples from the Cockburn Town reef in agreement with a 130,000 year age, we interpret the emergent reef to be the result of formation during the generally accepted 125 ka high sea stand. In order to remove the ambiguity from the coral dates, new samples that are free of calcite are being analyzed. However, the fact that the coral U-series ages do not precisely

Sample	Location	U (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Age ($\times10^3$ years B.P.± 1σ error)	Comments
1588A	emergent coral reef <u>Acropora</u> <u>cervicornis</u>	3.46±0.11	1.140±0.022	>1000	0.570±0.019	90 ± 5	15% calcite
1588B	emergent coral reef, <u>Diploria</u> <u>strigosa</u>	2.90±0.06	1.114±0.010	>1000	0.655±0.014	112± 6	7.5% calcite
MGS-81159	stalagmite 1, top, 16 cm above serpulid layer	0.52±0.009	1.135±0.021	>1000	0.288±0.008	37 ± 1	
MGS-81158	stalagmite 1, top, 4 cm above serpulid layer	0.41±0.011	1.195±0.038	>1000	0.286±0.014	36 ± 2	
MGS-81155	stalagmite 1, bottom half, 20cm above base	0.34±0.008	1.130±0.030	>1000	0.377±0.014	51 ± 2	
MGS-81151	stalagmite 1, bottom half, 7cm above base	0.30±0.007	1.058±0.028	14 ± 2	0.351±0.014	47 ± 2	
MGS-83312*	stalagmite 2, 20 cm above base	0.11±0.004	0.985±0.048	7 ± 1	0.195±0.013	24 ± 2	

Table 1. Results of U-series age analysis on corals and speleothems. The half-lives used for ^{234}U and ^{230}Th were 2.48×10^5 and 7.52×10^4 years. Ratios are activity ratios.

*The low $^{230}Th/^{232}Th$ activity ratio indicates possible detrital ^{230}Th contamination.

agree with the amino acid data does not detract from the speleothem and calcarenite results; it is only necessary that the reef be older than 100,000 years, which it clearly is.

The speleothem ages were determined by Lively, using the facilities at the Minnesota Geological Survey. The analytical procedures were modified from Thompson (1973). Ten to fifteen grams of calcite were dissolved in 8N HNO3 to which was added a $^{228}Th/^{232}U$ tracer. Ion exchange techniques isolated U and Th which were then separately evaporated onto stainless steel planchets from a TTA/benzene mixture. The activities of the U and Th isotopes were measured on an alpha spectrometer. Total counts under the ^{228}Th and the ^{232}U peaks were greater than 6,000. Because of lower counts under the sample peaks, the samples were counted for four to nine days. Chemical yields averaged 40% for Uranium and 53% for Thorium.

The results from the speleothems meet the requirements for reliable ages: (1) there is sufficent U (>0.1 ppm); (2) $^{230}Th/^{232}Th$ activity ratios are high, indicating that the measured ^{230}Th was produced by _in situ_ decay of ^{234}U and was not introduced as a detrital phase; (3) the ages are in the correct stratigraphic order, the oldest ages are in the bottom half of the stalagmite, the youngest ages are in the top; (4) the samples were collected from zones of laminated calcite which showed no signs of recrystallization or post-depositional alteration.

The Uranium-series speleothem age analyses (Table 1) indicate that deposition began approximately 49,000 ± 2,000 years ago. Sample #81151 was taken about 5 cm above the actual base of the stalagmite, at the first zone of clean, laminated calcite (see Figure 2). Approximately 10 cm above sample #81151, sample #81155 yielded an age of 51,000 ± 2,000 years. While the ages are slightly different, the one sigma errors on the ages overlap. This suggests that the depostion of calcite was rapid, making the time difference between the two samples difficult to resolve. Due to the one sigma error overlap, no significance is attached to the inversion in the ages, and an age of 49 ka ± 2 ka is assigned to the bottom half of the stalagmite.

It should be noted that each of the above mentioned samples was collected just above zones of layered, punky calcite containing shell fragments and worm tubes. It is apparent that the clear, well laminated calcite was deposited in an air filled passage. Mg/Sr analyses of the punky zones are indicative of brackish conditions during that deposition (M. Gascoyne, personal communications). We envision this as resulting from marine interference with the calcite deposition as a result of a near modern sea level elevation.

Within the upper part of the stalagmite, two samples about 10 cm apart were collected and dated. Sample #81158 yielded an age of 36,000 ± 2,000 years, and sample #81159 an age of 37,000 ± 1,000 years. Again, the one sigma errors overlap, suggesting rapid deposition over an interval of one to two thousand years. An age of 37 ka ± 2 ka is assigned to the upper half of the stalagmite. This part of the speleothem shows little if any evidence of marine interference and presumably represents the entry into a period when sea level was below -1 m. We are

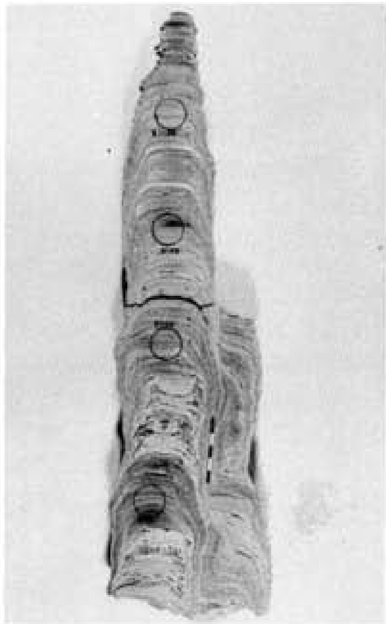
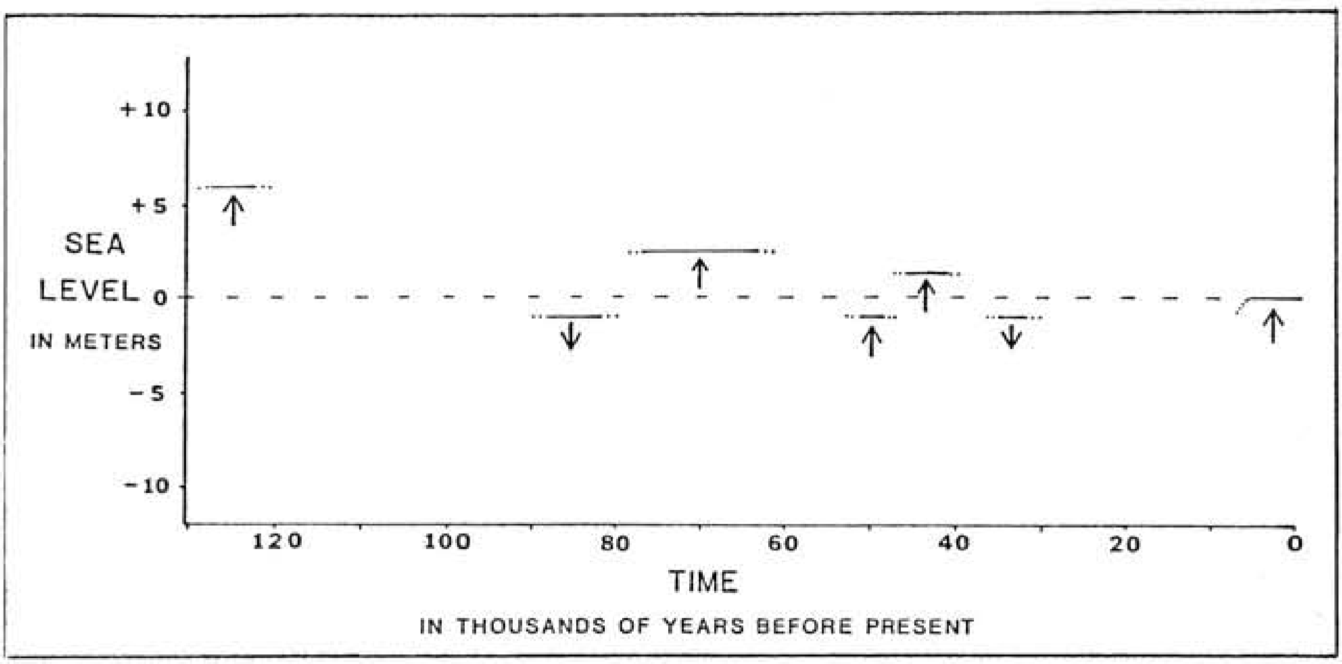


Figure 2. Longitudinal section of stalagmite 1, removed from the floor of Lighthouse Cave at -1 meters. Circles show U/Th sample localities. Bar scale in cm.

Figure 3. Constraints on sea level position over the last 130,000 years. Lines with upward pointing arrows indicate high sea level at or near the displayed elevation. Lines with downward pointing arrows indicate sea level somewhere below the displayed elevation.



not able to determine when the stalagmite stopped growing, as the top of the stalagmite is not present. It is apparent that when sea level rose to present day levels, the outer surface of the stalagmite began to redissolve.

The most significant feature of these stalagmite dates is the hiatus in deposition between 49 ka and 37 ka. It is particularly so when it is noted that both the bottom and top 20 cm portions were deposited within a few thousand years time. It is this hiatus in deposition combined with the marine overgrowth(s) which we feel provide the evidence for a high sea stand between 49 ka and 37 ka years. Sea water covering the stalagmite prevented further rapid growth and at the same time led to the deposition of a layer of marine overgrowth consisting of serpulid worm tubes. Whether or not the hiatus lasted 10,000 years we do not currently know. It is possible that with further analyses we may be able to narrow that time window.

Sample #83312 (Table 1), with a Uranium-series age of 24,000 ± 2,000 years is from 10 cm above the base of a large stalagmite (stalagmite #2) also from Lighthouse Cave. The $^{230}Th/^{232}Th$ activity ratio is low, making the 24,000 year age a maximum value because of an unknown amount of detrital ^{230}Th could be present. Combined with the low Uranium content and the possible detrital ^{230}Th this age is not considered reliable. Internally, the stalagmite shows evidence of recrystallization and possible post-depositional alteration. Some parts of the stalagmite also contain shells and possibly marine overgrowths. If these features are in fact marine, then the age of 24,000 years does not seem reasonable in view of the known low sea level during the late Wisconsinan. The most probable growth period for this sample is the end of the Wisconsinan and into the Holocene, when sea level was returning to present conditions.

Summary and Conclusions

The Cockburn Town reef on the west side of San Salvador can be correlated with Oxygen isotope substage 5e (Emiliani, 1972; Broecker & Van Donk, 1970), the Barbados III (Rendezvous Hill) reef (Fairbanks & Matthews, 1978), and other reported reef terraces of approximately 125,000 years ago (Neumann & Moore, 1975; Bloom, et al., 1974). The presence of this reef on San Salvador with a maximum elevation of approximately four meters above current mean sea level appears to confirm the tectonic stability of the island, as the 125 ka sea level is usually assumed to have been at approximately +6 meters. This suggests that if any vertical motion of the island has been experienced, it has been slight subsidence, as generally reported for the main Bahama platform (Mullins & Lynts, 1977). That means that any of our estimates for high sea levels are minima.

The base of stalagmites collected from the -1 m level of Lighthouse Cave date, by U/Th-series methods, at approximately 49 ka (Table 1). Clearly, the cave must be older than the subaerially formed stalagmites, but younger than the enclosing eolian calcarenite. That calcarenite, which extends to at least -2 m elevation, must have formed with sea level below present elevation. The water table must have reached to at least +7 m to develop the classic phreatic solution features of the walls and ceiling of the cave. The type of discharge provided by these solution conduits, coupled with the island's limited dimensions require that sea level must have been at or above its present position to place the freshwater lens above the +6 m elevation. The wall rock and stalagmite dates leave only the 80 ka to 50 ka time-window for this to occur. Recent advances in limestone solution kinetics (White, 1978; Palmer, 1981) suggest that a minimum time of 10,000 to 20,000 years is necessary for prodction of the conduit sizes observed. Undated conduits with solutional features exhibiting a similar range of elevation have been described from San Salvador, Andros, and New Providence Islands, Bahamas (Mylroie, 1978).

Between 49 ka and 37 ka the stalagmite from Lighthouse Cave ceased growth, and a layer of calcareous tubes were deposited on the stalagmite. Comparison of the ultra-structure of these tubes with those of modern serpulid worms and vermiform gastropods (J. Carter, personal communication) utilizing the scanning electron microscope reveals that they are indeed of serpulid origin. Serpulid growth in caves has been reported from Belize (Macintyre, et al., 1982). These tubes were later entombed within the stalagmite as growth of the speleothem continued after 37 ka. The deposition of subaerial stalagmitic material at -1 m at 49 ka indicates that the conduit was drained to at least that elevation, and by implication sea level must have been at least that low or lower. The serpulid overgrowth coupled with the cessation of growth between 49 ka and 37 ka requires a rise in sea level to at least its current elevation. The continued growth of the stalagmite after 37 ka indicates that sea level must have again fallen to at least -1 m.

The conclusions from our data are presented in Figure 3. The fossil reef and solution conduit elevations, and the requirements for their formation, argue for sea level to be in the +4 to +6 m range at both 125 ka and 80 ka-60 ka. Reported high sea level at approximately 80 ka (Boardman, et al., 1983; Cronin, et al., 1981) is of appropriate age. The deposition of the eolian calcarenite wall rock of the cave requires that sea level be below -2 m but above the bank edge at approximately 90 ka-70 ka. An age of 85 ka would be consistent with data for the eolian Southampton Formation of Bermuda (Harmon, et al., 1983). Sea level must have been at least at 0 m (current sea level) in the 50 ka-40 ka time range to account for the punky carbonate deposition in the lower half of the stalagmite, and for the serpulid worms to have lived, but below -1 m elevation for the remainder of the Late Pleistocene.

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