PROCEEDINGS

OF THE THIRD SYMPOSIUM

ON THE GEOLOGY OF THE BAHAMAS

Editor

H. Allen Curran

Production Editor

Donald T. Gerace

Sponsored by CCFL Bahamian Field Station

June 6 - 10, 1986

Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

Articles in this volume should be cited as follows:

Author(s), 1987, Article title, in Curran, H.A., ed. Proceedings of the Third Sympoisum on the Geology of the Bahamas: Fort Lauderdale, Florida, CCFL Bahamian Field Station, p. xx-xx.

ISBN 0-935909-24-9

Printed by Don Heuer in the U.S.A.

A REFINED GEOCHRONOLOGY FOR SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

Uranium/Thorium isotopic age determinations on numerous fossil reef corals on San Salvador, Bahamas suggest that reef growth, and the requisite high stand of sea level, was either continuous on the island from about 150,000 years ago to approximately 100,000 years ago, or separate high stands took place around 140,000, 125,000 and 105,000 years ago. Uranium/Thorium analyses on speleothems provide evidence for an additional high stand of sea level on San Salvador about 49,000 years ago.

Radiocarbon isotopic ages from whole-rock analyses indicate significant carbonate production on the San Salvador platform at 5,300 and 3,200 years ago. The deposition of the 5,300 year-old carbonate allochems into existing eolian dunes took place when sea level was at least one meter below its present elevation. The 3,200 year-old sediment was deposited in equilibrium with today's sea level. Very young (420 years old) sediment has been deposited and weakly cemented in intertidal through back-beach dune settings.

Amino acid racemization analyses of *Cerion* sp. suggest that there was substantial eolianite formation on San Salvador around 100,000+, 85,000, and less than 6,000 years ago. Additionally, there is reason to believe that widespread development of paleosol/calcrete was centered around 15,000 years ago. A single radiocarbon date on a caliche pisolite layer is consistent with that assumption.

Paleomagnetic analyses of fossil paleosols indicate that the oldest rock exposed in the Bahamas is found near the southern coast of San Salvador. That paleosol possesses a reversed remnant magnetism; therefore, the paleosol and underlying eolianite must be older than 700,000 years.

INTRODUCTION

Geologic investigation of Bahamian islands provides incomparable insight into the deposition, modification, and preservation of carbonate sediments. Because of their tectonic stability, they also yield direct evidence for Quaternary sea level high stands that were near or above that of the present. The study of the geology of San Salvador Island is particularly informative, and at times perplexing, for the small size and isolation of the San Salvador platform places severe constraints on the carbonate system. With variation in sea level the size of the platform does not change significantly, and, unless sea level is high enough to flood the platform, the carbonate "factory" is not in operation. Thus, carbonate deposition of any sort is an indication of marine flooding of the platform. When sea level is below the platform, only erosional processes and the formation of karst and paleosols occurs.

The small isolated platform of San Salvador places limits on such things as fetch, sediment production, rainfall catchment, freshwater lens size and development, and karst processes among others. We must be able to account for all that we find here, within the limited system that can occupy the platform. The variability and complexity of the modern sediments, geology, and karst development of this island also can be used to shed light on the interpretation of pre-Quaternary carbonate rocks.

Unravelling the chronology of events

represented in the rock record of San Salvador Island, Bahamas (see Index Map 1) has been a continuing research effort. Earlier discussions of the geochronology of San Salvador have been reported in Carew (1983a,b), Carew and Mylroie (1983), Carew and others (1984), and Mylroie and others (1985). Those previous reports were largely based upon amino acid racemization of *Cerion* sp., and limited Uranium/Thorium isotopic age determination on corals and speleothems. Carew and Mylroie (1985) provided more geochronologic data in the context of a discussion of the stratigraphy and depositional history of San Salvador. This paper presents a concise discussion of the geochronology data for San Salvador, as it is currently known.

THORIUM 230/URANIUM 234 AGE DETERMINATIONS

Fossil Corals

Thirteen (13) Uranium-series isotopic age determinations on fossil coral have been conducted (Table 1). Those isotopic ages range from 171,000 to 103,000 years. The 171,000 year age is from a sample of *Diploria strigosa* from the rubble facies of the Cockburn Town reef (see Index Map 2) described in detail by Curran and White (1984, 1985) and White and others (1984). The *in situ* corals from the Cockburn Town reef (Lamont samples #1654c and 1974b) indicate that the reef framework was built in conjunction with the relatively well established +6m Sangamon high stand of about 125,000 years ago; which correlates with the oceanic ^{18}O substage 5e of Shackleton and Opdyke (1973). The presence of the older coral in the Cockburn Town rubble facies may be explained by reference to the Cockburn Town fossil reef as it is today. Toward the northern end of the outcrop a coral-boulder rubble deposit is currently forming. That deposit contains both modern coral and eroded fossil coral boulders. We suggest that 125,000 years ago a similar deposit incorporated material from an older (171,000 years) fossil reef that was then being eroded. From that it may be extrapolated that San Salvador experienced a platform flooding event around 170,000 years ago.

The remaining coral ages range from 146,000 to 103,000 years ago. Considering the one-sigma errors (see Table 1) these dates can be incorporated into one broad smear of ages, or may be segregated into three distinct groups that may represent separate sea level high stands and coral reef growth-episodes at about 140,000, 125,000, and 105,000 years ago (Fig. 1). Continuing analysis of coral from San Salvador, and elsewhere in the Bahamas, will hopefully resolve this dilemma.

Speleothems

Several stalagmites, situated at present sea level, have been removed from Lighthouse Cave beneath Dixon Hill in northeastern San Salvador (see Index Map 2). U-series ages have been determined from two of the specimens that contain clean unaltered calcite layering (see Table 2). The upper four dates in Table 2 are from one stalagmite that contains a layer of serpulid worm tube encrustation assigned to *Filograna* sp. (H. Zibrowius, personal communication, 1986) between the older (49,000 years) and younger (37,000 years) ages. The lower two dates (Table 2) are from the central portion of a 70 cm tall stalagmite. This specimen also contains a serpulid encrustation between the dated layers (70,000 and 48,000 years).

The conclusions that can be reached from these data are as follows. (1) The Dixon Hill eolianite that contains the cave must have been deposited prior to 70,000 years ago. (2) A high stand of sea level, sufficient to place a freshwater lens at an elevation several meters above present sea level, must have occurred before 70,000 years ago, because the solutional cave existed and speleothem growth began at least 70,000 years ago. Cave development may have been syngenetic with the high sea stand that produced the sediment for the eolianite deposition. (3) A later sea level high stand is required for the serpulid encrustations. The data are consistent with a single high stand about 49,000 years ago, or one between 48,000 and 70,000 and one between 37,000 and 49,000 years ago.

RADIOCARBON ANALYSES

Eight (8) radiocarbon ages have been determined from whole-rock samples from San Salvador (Table 3). These data indicate

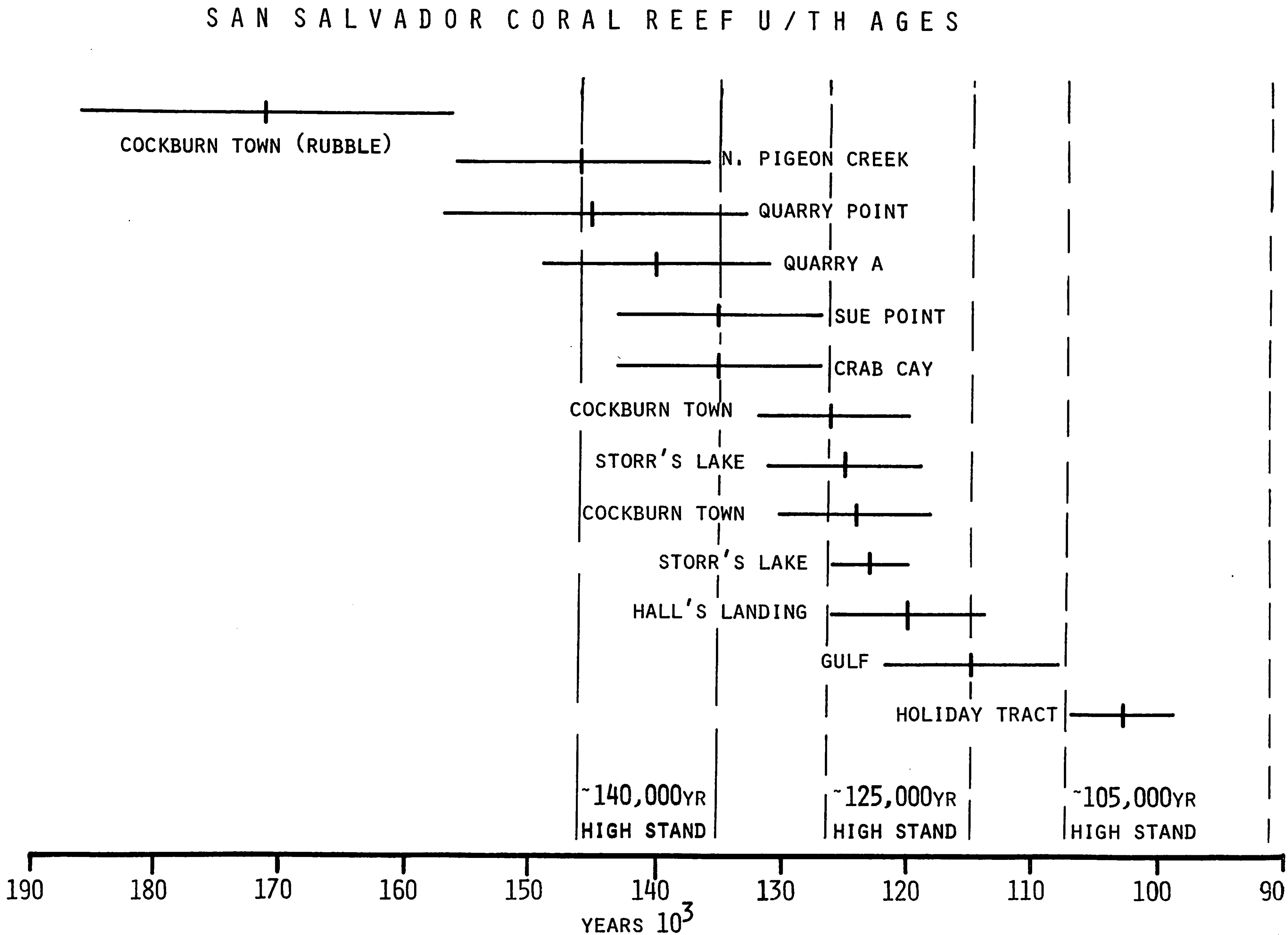

Fig. 1. San Salvador coral reef U/Th ages with one-sigma error bars.

TABLE 1. SAN SALVADOR CORAL AGES

#	Lamont #	Locality	Species	Uppm	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	Age x 10^3	% Aragonite
U/Th 84-2	1619B	Quarry Pt.	*A. palmata*	3.26±.08	1.10±.01	0.75±.03	145±12	100%
U/Th 84-1	1619A	Cockburn Town (Rubble)	*D. strigosa*	2.78±.08	1.16±.02	0.82±.03	171±15	100%
R-84-6	1619C	Sue Pt.	*M. annularis*	1.99±.05	1.11±.02	0.72±.02	135+8	100%
SS-85M-18	1654e	Pigeon Cr.	*M. annularis*	2.69±.07	1.13±.02	0.76±.02	146±10	100%
SS-85M-23	1654i	Quarry A	*Diploria* sp.	3.24±.10	1.11±.025	0.74±.02	140±9	100%
SS-85M-4	1654b	Gulf	*Diploria* sp.	3.12±.08	1.11±.02	0.66±.02	115±7	100%
SS-85M-20	1654f	Holiday Tract (T. Hanna)	*Diploria* sp.	3.06±.07	1.11±.02	0.62±.02	103±4	100%
SS-85M-21	1654g	Storr's Lake	*M. annularis*	2.29±.05	1.10±.015	0.69±.02	125±6	100%
SS-85M-22	1654h	Storr's Lake	*M. annularis*	2.45±.06	1.12±.02	0.69±.02	123±3	100%
SS-85M-10	1654d	Hall's Landing	*Diploria* sp.	2.87±.07	1.12±.01	0.68±.02	120±6	100%
SS-85M-9	1654c	Cockburn Town	*Diploria* sp.	2.55±.07	1.11±.02	0.70±.02	126±6	100%
SS-86-1	1674a	Crab Cay	*M. annularis*	2.95±.08	1.10±.02	0.72±.02	135±8	100%
SS-86-3	1674b	Cockburn Town	*Diploria* sp.	2.97±.08	1.13±.02	0.69±.02	124±6	99%

TABLE 2. RESULTS OF U-SERIES AGE ANALYSES ON SPELEOTHEMS FROM LIGHTHOUSE CAVE, SAN SALVADOR, BAHAMAS

Sample	Material	U (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$*	Age ($\times 10^3$ years $\pm$ 1σ error)
MGS-81159	stalagmite, 16 cm above serpulid layer	0.52±0.009	1.135±0.021	>1000	0.288±0.008	37 ± 1
MGS-81158	stalagmite, 4 cm above serpulid layer	0.41±0.011	1.195±0.038	>1000	0.286±0.014	36 ± 2
MGS-81155	stalagmite, 20 cm above base	0.34±0.008	1.130±0.030	>1000	0.377±0.014	51 ± 2
MGS-81151	stalagmite, 7 cm above base	0.30±0.007	1.058±0.028	14±2.0	0.351±0.014	47 ± 2
MGS-446	stalagmite, 5 cm above base	0.399±0.008	1.116±0.027	8.2±1.2	0.481±0.024	70 ± 5
MGS-445	stalagmite, 16 cm above base	0.438±0.006	1.065±0.162	53±16.1	0.360±0.010	48 ± 1.7

*The half-lives used for ^{234}U and ^{230}Th were 2.48×10^5 and 7.52×10^4 years.

TABLE 3. SAN SALVADOR RADIOCARBON DATES

LOCALITY	DATE yBP	UNCORRECTED DATE yBP
North Point	5345 ± 125	
North Point	5360 ± 110	
Hanna Bay	3470 ± 80	3210 ± 80
Snow Bay	3300 ± 50	3100 ± 50
Singerbar Point	3040 ± 90	2870 ± 90
Barker's Point	420 ± 70	360 ± 70
Bluff (up. Pisolite)	14,286 ± 210	12,870 ± 210
Lighthouse Cave	>50,000	

the following. (1) It confirms that the eolianite in which Lighthouse Cave was formed is greater than 50,000 years old (the upper limit of the radiocarbon method). (2) The pisolitic caliche soil horizon exposed near the top of the Bluff (see Index Map 2) was formed about 14,000 years ago. This is consistent with the interpretation of some amino racemization data in the next to youngest "amino group" discussed later in this paper (refer to Table 4). (3) The remaining dates indicate that there was significant carbonate allochem production on the San Salvador platform about 5,300 years ago; that sediment was deposited in terrestrial dunes that extend at least one meter below present sea level. Thus, the dunes were deposited at a time when sea level was at least a meter below its present position. A second pulse of sediment production occurred about 3,200 years ago, and that sediment was deposited as intertidal, beach, and back-beach dune facies congruent with modern sea level.

Along the north coast between Singer Bar (Dump) Point and Barker's Point (see Index Map 2) there are rocks that are assigned to intertidal through back-beach dune facies that consist of sediment dated at 420 years old. This relatively recent depositional event may be related to changes in the wave dynamics of Graham's Harbor (see Index Map 2). This may be due to reef growth to wave base along the northeastern margin of the platform, or to erosional changes in the pre-existing cays and/or peninsula in Graham's Harbor. Could it be related to the supposed post-Columbus breaching of North Point that produced Cut Cay?

AMINO ACID RACEMIZATION

Over the past five (5) years we have been enlarging the number of amino acid racemization analyses of *Cerion* sp. from eolianites and paleosols on San Salvador. With the increasing number of data points the complexion of the chronologic interpretation has changed. From more than 50 analyses that have been conducted, the twenty-four (24) samples shown in Table 4 comprise those that show a high degree of reproducibility and no evidence of contamination. Based upon *Cerion* D/L leucine ratios, the samples fall into five (5) "amino-groups". The ages assigned to those groups have a fair amount of uncertainty, and are the least precise of our geochronologic data.

Table 4 provides three (3) possible alternative age assignments. If one accepts the correlation of *Cerion* data to *Chione cancellata* from the Cockburn Town fossil

TABLE 4. SAN SALVADOR AMINO ACID DATA
CERION D/L LEUCINE RATIOS

D/1 0 - 0.10	D/L 0.15 - 0.30	D/L 0.35 - 0.50	D/L 0.50 - 0.60	D/L 0.62 - 0.72
C-84-8 Clearpond	C-1 Sandy Point	C-84-20, Bluff, Low Piso	C-9 Lighthouse Cave	C-10 Crab Cay
	C-3 Sandy Point	C-84-32 Old Place	C-18 Lighthouse Cave	C-12 Almgreen Cay
	C-83-4 High Cay	C-0 Rocky Point	C-17 Conch Point	C-13 Watling's Quarry
	C-83-5 High Cay		C-84-29 N. Altar Cave	C-14 Watling's Quarry
	C-84-1 Cut Cay			C-83-2 Bluff
	C-84-2 Hanna Bay			C-84-12 Fr. Bay Road Cut
	C-84-7 S. of R.R.			C-84-28 Watling's Quarry
	C-84-24 Almgreen Cay			
	C-84-30 S.W. Low Cay			
AGES ASSIGNED IF USE *CERION* TO *CHIONE* CORRELATION WITH COCKBURN TOWN REEF AS 125,000 YEARS OLD (D/L 0.5-0.6 = ^{18}O Substage 5a)				
0 - 1,000	8,000 ± 5,000	60,000 ± 10,000	80,000 ± 10,000	100,000 ± 25,000
MAXIMUM AGES IF ASSIGN D/L 0.5-0.6 AN AGE OF 125,000 YEARS (^{18}O Substage 5e)				
<5000	15,000 to 20,000	80,000	125,000	150,000 to 200,000
MAXIMUM AGES IF ASSIGN D/L 0.5-0.6 AN AGE OF ~100,000 YEARS (^{18}O Substage 5c)				
<5000	5,000 to 10,000	70,000	100,000	125,000

reef as described in Carew and others (1984), then the "amino group" with D/L = 0.5-0.6 is assigned an age of 80,000 ± 10,000 years. Based on that assumption, we have previously suggested that the eolianites that enclose Lighthouse Cave are about 85,000 years old (Carew and Mylroie 1983, 1985; Carew and others, 1984). However, should the above assumptions provide to be incorrect, the alternative ages shown at the bottom of Table 4 are both plausible and reasonable. In each case the sea level high stands necessary for the deposition of the eolianites can be correlated with an ^{18}O substage.

An examination of the samples that fall in the D/L = 0.15 to 0.3 "amino group" reveals that it consists of two types of *Cerion* accumulations; ones disseminated within eolianites, and ones in which *Cerion* are associated with paleosol development. The age of the disseminated *Cerion* can be interpreted as 3,000 to 6,000 years and thus are consistent with the C_{14} dates obtained on the same or similar deposits (i.e. Rice Bay Formation of Carew and Mylroie, 1985). Likewise, the samples associated with paleosols can be interpreted as about 13,000 years old and thereby are in the same range as the C_{14} date for the upper pisolite at The Bluff (see Table 3). We further suggest that those data may support the hypothesis that rapid denudation of San Salvador, and extensive development of paleosol, occurred during the latest Wisconsinan sea level low stand.

PALEOMAGNETIC ANALYSES

Paleosol/calcrete samples from fifteen (15) different localities on San Salvador have been analyzed for their remnant magnetism. The results indicate that, with a single exception, all are normally polarized and are thus indistinguishable on that basis. Based on our stratigraphic work, and interpretation of the amino acid data, we believe that those fourteen (14) paleosols are among those formed about 15,000 years ago.

However, after AF and thermal demagnetization, triplicate samples from the paleosol near the base of the Owl's Hole solution pit near Sandy Point on San Salvador (see Mylroie, 1983, for location and discussion) yield a predominantly reversed polarity. The samples retained that reversed magnetic polarity through a range of temperatures. This reversed magnetism is the result of an *in situ* chemical event, and there is no plausible secondary source of reversal. These results suggest that this paleosol has an original reversed magnetic polarity with a chemically induced normal polarity overprint. These data, first reported in Mylroie and others (1985), indicate that this paleosol and the eolianite underlying it are at least 700,000 years old, as that is the minimum age of the Matuyama reversed polarity epoch. As such these rocks are the oldest surface rocks yet discovered in the Bahamas. On-going analysis of the paleosol exposed in Watling's Quarry (Sandy Point Plantation Quarry, see Index Map 2) may show that it is also reversed, as the petrology of the underlying and overlying rocks is identical to that at Owl's Hole.

We are aware that more recent short duration magnetic reversals have been reported in the literature (e.g. Denham and Cox, 1971; Harrison, 1974, Kukla, 1977; Smith and Foster, 1969), but it is estimated that the probability that these samples reflect a geomagnetic excursion during the Brunhes normal epoch is no better than 1 in 40 (Barton, personal communication, 1985). Additionally, the probable early Sangamonian age of the eolianite overlying the Owl's Hole paleosol, and the one in Watling's Quarry, make correlation of this reversed event with the Blake event, or any more recent short duration magnetic reversal, unlikely.

SUMMARY

A compilation of these several varieties of geochronologic data gathered on San Salvador has yielded a detailed history of San Salvador Island. This history has been discussed in Carew and Mylroie (1985), and has resulted in the stratigraphy proposed in that paper.

Briefly, the geologic history of San Salvador can be summarized as follows. However, it should be noted that continued data gathering may yield results that will alter these interpretations.

At some time prior to 700,000 years ago San Salvador Island existed as exposed eolian ridges, not dissimilar to those at present. Terrestrial erosional processes resulted in the reversely magnetized Owl's Hole paleosol. Except for an apparent platform flooding event indicated by the 171,000 year-old coral in the rubble facies of the Cockburn Town reef, there is no known record of subsequent geologic deposits on San Salvador prior to the deposition of reefs through eolianites associated with the Sangamon interglacial sea level high stand (Grotto Beach Formation of Carew and Mylroie, 1985). At this time we cannot determine whether there was one long high stand from about 150,0000 to 100,000 years ago, or up to three separate high stand events. We are continuing with fossil reef investigations in an effort to resolve this question.

To account for the deposition of the Dixon Hill eolianite and/or the solutional formation of Lighthouse Cave, we have proposed a later sea level high stand at about 85,000 years ago (Carew and others, 1984; Carew and Mylroie, 1985). Regardless of the scenario for the ultimate origin of the cave, it had formed and was dry by at least 70,000 years ago, as speleothem growth had been initiated by that time.

The presence of serpulid worm tube encrustation within two stalagmites collected at sea level from Lighthouse Cave requires at least one mid-Wisconsinan sea level high stand at nearly the same elevation as present sea level. The most reasonable time for that event is approximately 49,000 years ago.

Some of the amino acid racemization data and one C_{14} age suggest to us that rapid island denudation and paleosol formation may have been coincident with the latest Wisconsinan glacial advance and sea level depression about 15,000 years ago. Subsequently sea level rose toward today's position. Considering C_{14} data, about 5,300 years ago substantial sediment was being produced as the ocean flooded the San Salvador platform. Some of that sediment was eventually blown into eolianites along the eastern margin of San Salvador (North Point Member of Carew and Mylroie, 1985). Because those eolianite deposits dip steeply below present sea level they must have been formed when sea level was at least one meter below its present position, but clearly on the platform.

The C_{14} data also indicate that a large volume of sediment with an average age of approximately 3,200 years was produced on San Salvador. Those sediments have been deposited in geologic settings in equilibrium with present sea level (Hanna Bay Member of Carew and Mylroie, 1985). One very young date from rocks exposed on the north coast indicates that sediment only a few hundred years old has been deposited in a variety of coastal facies; and reported cases of historical objects cemented into beach rock (Adams, 1983) show that the process is on-going.

ACKNOWLEDGMENTS

We extend our thanks to Don and Kathy Gerace and the staff of the CCFL Bahamian Field Station for their continuing support of our research. Funds for sample analyses have also been provided by the Southern Regional Education Board, Murray State University, Mississippi State University, and the College of Charleston Foundation. Sample analyses have been provided by: John Wehmiller, University of Delaware, amino acid analyses; Richard Lively, Minnesota Geological Survey, speleothems; John Goddard, Lamont-Doherty Geological Observatory, corals; Charles Barton, Australian Bureau of Mineral Resources, paleomagnetic analyses; Sam Valastro, Radiocarbon Lab, University of Texas at Austin. We also than Joan Newell for word processing.

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