New Perspectives on Bahamian Geology: San Salvador Island, Bahamas

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ABSTRACT


Using San Salvador Island, Bahamas, as an example, this paper demonstrates that the stratigraphy of the Bahamas is much more complex than the three-unit column proposed in earlier works. It further provides new insights into the growth and evolution of carbonate islands.

Despite its 700-plus islands and enormous platform area, the surficial geology of the Bahamas has been largely neglected. Using a multiple-method approach combining geomorphology, sedimentology, petrography and amino acid racemization data, we have identified nine lithostratigraphic units representing the middle Pleistocene to the Holocene. These units, four of which are previously unrecognized, were deposited in shallow marine and eolian environments, and are generally bounded by soils. Their petrographic composition is dominated by either ooids or bioclasts.

By recognizing the overall patterns of ridge and shoreline development, a better understanding of the development of Bahamian-type carbonate islands is presented. Island growth ultimately depends on the geometry and energy conditions on the shelf. As the shelf narrows with island accretion, a concurrent decrease occurs in the amount of sediment manufactured, resulting in smaller volume landforms. Oolitic sediment deposition mainly occurs during early platform flooding when the shelf is open and energetic. Skeletal and peloidal sands assume subsequent dominance during marginal flooding events. Thus, some indication of relative sea-level intensity can be inferred from petrological evidence.

ADDITIONAL INDEX WORDS: Carbonate islands, eolian activity, marine environment, shoreline, coastal sediment, sea-level change, morphastratigraphy, amino acid racemization, Holocene.

INTRODUCTION

In a global scientific perspective, the Bahamian islands are relatively unknown. The Bahama Banks encompass over 700 islands ranging from hundreds to a few kilometers in length. Except for GARRETT and GOULD's (1984) important paper on New Providence Island, published literature dealing with the island geology of the Bahamian Platform (Figure 1) is scanty. Other papers (mostly available in the Proceedings volumes of the Bahamian Field Station, 1980–1992) have been site- or topic-specific thus leaving a large vacuum in our understanding of the overall surficial geology and processes involved in the formation of such islands. This paper tries to fill this gap in our knowledge and offers a framework for answering profound questions regarding the geological evolution of carbonate islands.

Over the past decade, the common stratigraphic view of San Salvador consisted of a three-part depositional history during the late middle Pleistocene, the late Pleistocene, and the Holocene (CAREW and MYLROIE, 1985). No doubt deposits from these events are present on most islands, but a three-part scheme is simplistic and, thus, is regionally inadequate to describe the geology of the Bahamas. As demonstrated in this paper, the stratigraphic history of San Salvador is much more complex than previously described, requiring some units to be eliminated, and others to be replaced in light of our results.

METHODS

Single methodological approaches are inadequate to resolve the complex history of San Salvador or other carbonate islands. Thus, a variety of subdisciplines and techniques were utilized to decipher the geologic history including geomorphic mapping, physical stratigraphy, petrographic analysis, and amino acidracemization (AAR) ratios. Such a multi-method approach was successfully used to chart the depositional history of Bermuda (HEARTY et al., 1992), but the geologic
Each of our selected study sites (solid circles in Figure 2) was described and sampled. Measured sections were constructed in order to portray the anatomy of island’s landforms. Field observation of sedimentary structures and trace fossils played an important role in the interpretation and reconstruction of depositional environments.

Laboratory Techniques

Aminostratigraphy (Amino Acid Racemization or AAR)

Marine shells, land snails (*Cerion* sp.) and whole-rock samples were analyzed for their amino-acid composition. But because of the scarcity of mollusk shells in most of the rock units on San Salvador, primarily whole-rock alloisoleucine/isoleucine (A/I) ratios were used to support our geologic correlations. As recently reiterated from Bermuda (Hearty et al., 1992), each type of sample material racemizes at a different rate: wholerock the slowest; *Glycymeris* and *Cerion* at moderate rates; and *Lucina* the fastest, such that coeval whole-rock and *Cerion* samples have significantly different but consistent values. Recent radiometric dating of San Salvador deposits at a number of given locations (Carew and Mylroie, 1987; Curran et al., 1989; Chen et al., 1991) was helpful to establish direct ties between AAR ratios and absolute ages (for example, Cockburn Town reef at 123,000 yr equal to A/I of 0.48). This calibration allowed absolute age estimates to be made on deposits younger and older than the peak of the last interglacial age.

The theory underlying the AAR method is explained by Hare and Mitterer (1967, 1969), whereas the guidelines and applications are reviewed in Miller and Brigham-Grette (1989). Applications and methodological considerations related to this study are contained in Hearty et al. (1986), Hearty (1986), and Hearty et al. (1992). Only HPLC-derived, peak height A/I ratios are used in this study.

Aminostratigraphy is not new to San Salvador, however. Attempts were made in the early 1980’s to use AAR on *Cerion* land snails to decipher the ages of the deposits (Carew et al., 1984). But because we use exclusively whole-rock ratios instead of *Cerion* in this study, a discussion of the utility of the land snails for AAR is irrelevant to this paper.
Sedimentary Petrology and Mineralogy

Samples were impregnated with blue epoxy, thin-sectioned and analyzed qualitatively and quantitatively under a petrographic microscope. Point-counting (Chayes, 1956) was made following revisions by Halley (1978), Harrel (1981) and Flügel (1982). Two 350-grain counts were performed on each thin-section in order to calculate the relative percentages of grains, cements, and primary and secondary porosity. Among the grains, we tabulated peloids, aggregates, lithoclasts, true as well as superficial ooids (Illing, 1954), and finally, five types of bioclasts: algae, coral and mollusk fragments, benthic foraminifers and other miscellaneous bioclasts. Detailed grain counts are available upon request.

Two samples per unit were X-rayed in a Phi-
ips-Norelco XRG 3000 X-ray diffractometer using Ni-filtered Cu radiation. Goniometer scans were conducted from 31° to 25° (2θ) at a speed of 1° per minute to identify the main carbonate minerals.

RESULTS
The Morphostratigraphy of San Salvador Island

On the basis of the model in Figure 3, crosscutting relationships and the relative maturity of ridges, we have identified four major phases of landform development on San Salvador (Figure 4). These depositional phases (I through IV) are subdivided into numbered ridges in Figure 4 (1 through 4, 1 being the oldest). Bifurcations of numbered ridges are labeled “a” through “c”, “a” being the oldest.

Phase I—The Ancient Landscape

This oldest known generation of rocks outcropping on San Salvador is both buried (e.g., Phase I/1 at Owl’s Hole and Watling’s Quarry (Figure 2)) and exposed in moderate-elevation (25 m), morphologically-mature landforms, from which all primary morphology has been lost to erosion, collapse and weathering (e.g., Dixon Hill and Fortune Hill on the Atlantic side of the island, Phase I/2). Phase I deposits essentially form the corners of San Salvador and all subsequent phases are tied to or modified by these “anchors”. The most
significant of the known cave development on the island occurs in these deposits (e.g., Lighthouse Cave; MYLRoen, 1983).

Phase II—Catenary Ridge Development on the Ancient Landscape

Present-day San Salvador Island is dominated by Phase II catenary ridges (Figure 4). As already noticed by TITUS (1987) and BAIN (1991), these ridges are generally larger and higher farther inland (Phase II/1 and II/2), whereas the elevation of swales rises from below modern sea level in the interior to several meters above present datum between coastal ridges.

Deposits of the western and northern provinces form a 25 km-long ridge from Sandy Point to
Reckley Hill. It is deflected at Cockburn Town and Sue Point, where obscured anchors are suspected to exist. This continuous ridge represents a stable shoreline on the more tranquil side of San Salvador. Bifurcations of the ridge near Cockburn Town indicate a migrating spit or headland (Figure 4). Cockburn Town reef (Carew and Mylroie, 1985; Curran et al., 1989; Chen et al., 1991) may have developed offshore during much of early Phase II, but clearly anchors late Phase II events (II/4 and II/5).

Phase III—Eastern Ridge/Bluff Formation

Phase III deposits form high promontories on the eastern margin of San Salvador and include (from north to south) Man Head Cay, Crab Cay, Almgreen Cay, The Bluff, the ridge south of Snow Bay, and the ridge behind Sandy Hook ending at The Gulf. They lie seaward of all other ridges and form the anchors for subsequent catenary development. Their position very near the platform margin may suggest that they were formed when sea level was below present datum.

Phase IV—Subrecent Catenary Development

Phase IV is represented around nearly the entire circumference of San Salvador and forms catenary ridges on anchors of all previous phases. The ridges are generally low and simple compared to those of Phase II landforms. Three subphases have been identified on the northeast extension of the island near the Bahamian Field Station. The Phase IV/2 builds large semi-consolidated dune ridges along the eastern shoreline that are catenary on Phase III promontories. A large prograding sequence of beach ridges is present at Sandy Hook and significant spit development occurs at Sandy Point in the southwest. Phase IV strandplains are also apparent at Bonefish Bay and at Barkers Point.

STRATIGRAPHY, PETROLOGY AND AMINOSTRATIGRAPHY OF SAN SALVADOR

Vertical successions of rock units are rare on San Salvador, thus a system of stratigraphic classification was used (Table 1) that combines geomorphic, sedimentological, petrological and geochemical (AAR) data. Five formations, each capped by a paleosol, are recognized and are correlated to the geomorphic phases described in the previous section (Figure 4).

Four of the rock units listed in Table 1 (Fortune Hill Fm., Almgreen Cay Fm. with upper and lower members, the Fernandez Bay Mb., and East Bay Mb.) are newly named here and have been added to previous schemes (Table 2). These and the already named rock units are distinguished mainly by their sedimentologic, petrologic and geochemical characteristics. The ternary diagrams in Figure 5 describe the composition and grain characteristics of each of the units. Figure 6 ties the geomorphology and stratigraphy of an island cross-section to the AAR ratios (Table 3) from the units.

The Owl’s Hole Formation

The Owl’s Hole Formation (OHF, Phase 1/1) is exposed in a solution pit at Owl’s Hole, at Watling’s Quarry (Figure 7A) and Grotto Beach. It is composed of well-lithified but poorly cemented bioclastic grainstones. On the basis of the occurrence of steep eolian foresets (Carew and Mylroie, 1985; Stowers et al., 1989) and the presence of numerous bioclasts typical of a high-energy marine environment (e.g., red algae and coral fragments), we interpret this unit as an ancient dune bordering an exposed shoreline. Finely crystallized sparry cement, mostly found at grain contacts, confirms this interpretation and may further indicate diagenesis under an arid or a semi arid climate (Ward, 1973).

The large proportion of low-Mg calcite within samples and high whole-rock AAR ratios (1.06 at Watling’s Quarry, Tables 2 and 3) support the interpretation of a middle Pleistocene interglacial age (Stowers et al., 1989; Hearty and Kindler, 1991) attributed to the Owl’s Hole Formation.

OHF rocks are more lithified than the younger bioclastic grainstones composing the Almgreen Cay Formation and the Hanna Bay Member. In thin-section, grains are more altered by recrystallization and leaching than are their younger equivalents and they commonly display planar and interpenetrating contacts, indicating incipient compaction.

The Fortune Hill Formation

The Fortune Hill Formation (FHF, Phase 1/2) at its type locality of the same name, and at Dixon-Brandy Hills exhibits mature landforms with extensive karst and cavernous weathering. Because of the general absence of lower bounding marine deposits, it appears that much of the Fortune Hill eolianites were deposited at a time when sea level was near but slightly below present. Thick calcretes (>15 cm) and oolites yielding Grotto
Table 1. Composite stratigraphy of Quaternary rocks units of San Salvador Island. Log key: leftward dipping lines, eolian facies; rightward dipping lines, marine facies; vertical lines, paleosol; dots, protosol; fan-shaped dashes, reef facies.

<table>
<thead>
<tr>
<th>LOG</th>
<th>ROCK UNIT</th>
<th>PHASE</th>
<th>SETTING</th>
<th>PETROLOGY</th>
<th>A/I</th>
<th>AGE (yBP)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>RICE BAY FORMATION</td>
<td>East Bay Mb.</td>
<td>IV/3</td>
<td>eolian soil</td>
<td>skeletal</td>
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<td></td>
<td></td>
<td>Hanna Bay Mb.</td>
<td>IV/2</td>
<td>eolian soil</td>
<td>skeletal/ooidal</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Holocene)</td>
<td></td>
<td>marine soil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>North Point Mb.</td>
<td>IV/1</td>
<td>eolian soil</td>
<td>ooidal/peloidal</td>
<td>0.24</td>
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<td>PALEOSOL</td>
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<td>Upper Mb.</td>
<td>III/2</td>
<td>eolian</td>
<td>skeletal</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>ALMGREEN CAY FORMATION</td>
<td></td>
<td></td>
<td>protosol</td>
<td></td>
<td>&gt;63,000 (AAR)</td>
</tr>
<tr>
<td></td>
<td>(Late Sangamonian)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Mb.</td>
<td>III/1</td>
<td>eolian</td>
<td>skeletal</td>
<td>0.28</td>
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<tr>
<td></td>
<td>GROTTO BEACH FORMATION</td>
<td>Fernandez Bay Mb.</td>
<td>II/5</td>
<td>eolian marine protosol</td>
<td>ooidal/peloidal</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>(Sangamonian)</td>
<td>Cockburn Town Mb.</td>
<td>II/4</td>
<td>marine protosol</td>
<td></td>
<td>123,000 (U/Th)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II/3</td>
<td>(reef)</td>
<td>skeletal</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>French Bay Mb.</td>
<td>II/2</td>
<td>eolian</td>
<td>ooidal</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II/1</td>
<td>eolian</td>
<td>ooidal</td>
<td></td>
</tr>
<tr>
<td>PALEOSOL</td>
<td>FORTUNE HILL FORMATION</td>
<td></td>
<td>I/2</td>
<td>protosol</td>
<td>skeletal/peloidal</td>
<td>0.68</td>
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<td></td>
<td>(Mid-Pleistocene)</td>
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<td></td>
<td>eolian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PALEOSOL</td>
<td>OWL'S HOLE FORMATION</td>
<td></td>
<td>I/1</td>
<td>protosol</td>
<td>eolian</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>(Mid-Pleistocene)</td>
<td></td>
<td></td>
<td>skeletal</td>
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Table 2. Stratigraphic nomenclature of Quarternary rock units on San Salvador Island.

<table>
<thead>
<tr>
<th></th>
<th>Carew &amp; Mylroie, 1985</th>
<th>Titus, 1987</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HOLOCENE</strong></td>
<td>Rice Bay Fm.</td>
<td>Rice Bay Fm. No members</td>
<td>Rice Bay Fm. East Bay Mb. Hanna Bay Mb. North Point Mb.</td>
</tr>
<tr>
<td></td>
<td>Hanna Bay Mb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North Point Mb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WISCONSINAN</strong></td>
<td>Granny Lake Oolite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dixon Hill Ls</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SANGAMONIAN</strong></td>
<td>Grotto Beach Fm. Dixon Hill Mb.</td>
<td>Grotto Beach Ls</td>
<td>Almgreen Cay Fm.</td>
</tr>
<tr>
<td></td>
<td>Cockburn Town Mb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>French Bay Mb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PRE-SANGAMONIAN</strong></td>
<td>Owl's Hole Fm.</td>
<td>Unnamed</td>
<td>Fortune Hill Fm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Owl's Hole Fm.</td>
</tr>
</tbody>
</table>

- Hanna Bay Member
- North Point Member
- Almgreen Cay Formation
- Fernandez Bay Member

**Composition triangle**

**Texture triangle**

Figure 5. Triangular diagrams showing petrographic characteristics of the Quaternary units.
Table 3. Whole-rock amino acid racemization (AAR) All data corresponding to rock units from San Salvador Island. Note that in nearly all cases, whole-rock ratios occur in the same stratigraphic order as that established by field studies. Mean ratios from each formation and member are available in Table 1.

Beach age A/I ratios cap the FHF on the eastern flank of Dixon and Fortune Hills. At The Thumb (Figure 7B), the thick post-FHF calcite is capped by a skeletal grainerstone of uncertain age. Limestone samples collected within Lighthouse Cave and at The Thumb are well lithified and contain a large quantity of reef-associated bioclasts (i.e., red algae and coral debris). The occurrence of such bioclasts along with land snails, fresh-water cement and steep foresets leads us to consider that this unit is made up of ancient eolian ridges deposited along a high-energy, reef-bordered coastline much like today's setting.

The Fortune Hill Formation presents marked petrographic and sedimentological similarities with the older Owl's Hole Formation. However, it yields much lower whole-rock A/I ratios (average: 0.68), shows less compaction features and is more peloidal than the latter. FHF rocks are clearly better lithified and less porous than the bioclastic calcarenites deposited during younger events. Further analyses are required to resolve this question.

Stratigraphic Position of the Dixon Hill Rocks

Dixon Hill and associated landforms were originally interpreted (Titus, 1984; Carew et al., 1984; Carew and Mylroie, 1985; Mylroie and Carew, 1988) as the expression of a late Sangamonian highstand ("Dixon Hill Member" dated at ca. 70,000 yr). For the following reasons, we place them at an older position in the stratigraphic column within the middle Pleistocene (Hearty and Kindler, 1991; Kindler and Hearty, 1992):

1. Deposits at Dixon Hill and Fortune Hill clearly form anchors for the catenary ridges of the Grotto Beach Formation (Sangamonian) and thus must predate them;
2. Dixon Hill and equivalents display a greater maturity of landform than the ridges between them;
3. Cave development (e.g., Lighthouse Cave) is greater within Dixon Hill than anywhere else on the island (Mylroie, 1983);
(4) Both Dixon Hill and Fortune Hill had to be present in order to form the eastern margin of the Sangamonian tidal channels observed to the south of Granny Lake and to the east of Dixon Hill (HINMAN, 1980; THALMAN and TEETER, 1983; NOBLE et al., 1991);

(5) The petrography of Dixon Hill samples suggests an age much older than that proposed by CAREW et al. (1984);

(6) At Quarry A, deposits onlapping the eastern flank of Dixon Hill have yielded both 140 ka U-series ages (CAREW and MYLROIE, 1987) and 0.48 A/I ratios (Table 3); the underlying FHF rocks must then necessarily be older than these deposits;

(7) The AAR ratios from Dixon Hill and Fortune Hill indicate a pre-Sangamonian age (Table 3).

The Grotto Beach Formation

The French Bay Member (FBM, Phase II/1-4). The French Bay Member is a well-lithified and well-sorted oolitic calcarenite and volumetrically represents the most extensive rock body on San Salvador. Thickly coated ooids and widespread fresh-water sparry cement are characteristic of these limestones.

The bulk of the French Bay Member was deposited in a subaerial environment, indicated by well-preserved dune and swale morphology, large-scale eolian cross-stratification, rhizoliths and discontinuous structureless protosols (upper unit in Figure 7A). Subtidal and beach deposits can also be observed up to an elevation of + 7 m. The former are characterized by small-scale trough cross-bedding, herring-bone structures, slumped
beachrock blocks, callianacid burrows and fossil sand-waves. The latter typically display >1 m high planar cross-beds dipping at various oblique angles to the coastline.

Amino-acid analysis on whole-rock samples from the type locality yielded an A/I ratio of 0.56 (n = 3) that is consistent with an early last interglacial age (compared to calibrated whole-rock ratios at Cockburn Town reef; next section).

Observation Tower ridge (Phase II/I) clearly belongs to the French Bay Member because of its morphostratigraphic position, similar petrology
and amino-acid ratios. No data support a pen-
ultimate interglacial age of this ridge as proposed

The Cockburn Town Member (CTM, Phase II/3-2-4). The physical, chronometric and biostrati-
graphic characteristics of the Cockburn Town reef
are available in Curran and White (1984), Carew
et al. (1984), Curran et al. (1989) and Chen et al.
(1991). The most notable outcrops are found
at Grotto Beach, Hall’s Landing, Cockburn Town
Pier and Sue Point. Reef matrix at Cockburn Town
surprisingly reveals numerous thinly coated ooids.

At the type locality whole-rock A/I ratios av-
erage 0.48 (n = 2), whereas marine shells yield
ratios of 0.86 for Lucina penna brianica, 0.80 for
Glycymeris, and 0.72 for Barbatia, all of which
equate with U-series ages on in situ corals of about
123,000 YBP (Chen et al., 1991).

Although no clear stratigraphic relationship be-
tween the Cockburn Town reef and the French
Bay Member has yet been established, whole-rock
ratios from both units indicate that the FBM (0.56
at French Bay ridge) is generally older than the
CTM (0.48). However, the span of coral ages from
the Cockburn Town reef (130–119 ka; Chen et al.,
1991) could indicate that reef growth was con-
temporaneous with at least a significant part of
FBM interval.

The Fernandez Bay Member (FZM, Phase II/5).
At Cockburn Town, the CTM reef facies is un-
conformably overlain by a shallowing-upward se-
quence displaying subtidal, beach and eolian de-
posits (White et al., 1984) (Figure 7C). Similar
marine and eolian deposits are exposed at several
locations around the island (e.g., Old Place, Vic-
toria and Reckley Hills, Grotto Beach, Fernandez
Bay (type locality)) and represent the most sea-
ward extension of Phase II ridges. They are com-
posed of well-lithified medium to coarse grained
calcarenites containing a mixture of thinly coated
ooids, peloids and bioclasts, and are bound by
course sparry cement.

All FZM sites have A/I ratios that average 0.41
± 0.04. If we exclude from the average two Hal-
imeda-rich samples from the north end of Pigeon
Creek that yield very low ratios (0.34), the average
becomes more precise (0.43 ± 0.02; n = 8). This
ratio translates to an age of a few thousand years
less than that of the underlying Cockburn Town
Member.

FZM rocks contain more bioclasts than does
the French Bay Member and lack the thickly coated
ooids typical of this unit. They are clearly bet-
ter lithified than is the younger North Point oo-
ite.

The FBM and the FZM of the Grotto Beach
Formation probably represent the two separate
highstands of sea level that have now been iden-
tified at the beginning of the last interglacial (iso-
topic Substage 5e; Johnson, 1991). We have also
observed a disconformity within the reef through-
out the famous exposure at Cockburn Town. Ev-
idence of a double transgression during Substage
5e has been signaled in New Guinea (Aharon,
1983), the Mediterranean Basin (Hearty, 1986,
1987; Miller et al., 1986), and the southeast U.S.
Coastal Plain (Hollin and Hearty, 1990).

The Almgreen Cay Formation

The Almgreen Cay Formation (ACF, Phase III)
forms high promontories (e.g., the Bluff, Almg-
reen Cay (type locality) and Crab Cay) on the
eastern headlands and northern points-of-land
(e.g., Barkers Point) of San Salvador Island. It is
bounded in some localities at the base by reeal sediments (exposed best at Crab Cay) associated
with ca. 135,000 year U-series dates (Carew et al.,
1984), and at the top by terra rossa paleosol that
presumably accumulated from Saharan dust
during glacial lowstands (Muhls et al., 1990). It is
composed of weakly cemented, yellowish grain-
stones, that contain as much as 85% of bioclastic
grains (mollusks and coral fragments, benthic for-
rums, bryozoan and algal debris) that have re-
tained their original mineralogy. Finely crystal-
ized equant spar ("grain-skin cement"; Land et al.,
1967), occurring at grain contacts and as non-
isopachous rims, suggests that diagenesis of the
ACF took place in the fresh-water vadose zone
under a dry climate (Ward, 1973). ACF limestones
were deposited in an eolian setting when sea level
was lower than it is today, as demonstrated by the
large eolian foresets dipping systematically below
modern datum (Figure 7D). A complex protosol containing Cerion and pisoliths separates the formation into two members. The
upper one is covered by a thick and complex pal-
eosol comprising extensive rhizoliths, laminar
calcrite and a breccia horizon (Beier, 1987).

AAR ratios (mean whole-rock values of 0.29)
suggest a considerably younger age for the Almg-
reen Cay Formation as compared with the 123,000
year old Cockburn Town Member (A/I = 0.48).
These values require the ACF eolianites to date
from the end of the last interglacial period (Sub-
stage 5a) at around 85,000 years ago, much like

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the Southampton Formation eolianites of Bermuda (Vacher and Hearty, 1989; Hearty et al., 1992). This age would also imply a correlation with uplifted coral reefs in this age range from Barbados (Bender et al., 1979) and New Guinea (Bloom et al., 1974).

ACF limestones are more friable than the older bioclastic calcarenites forming the core of San Salvador (OHF and FHF). They also differ from the younger Hanna Bay Member by the absence of beach deposits and by having a finer sparry cement.

The Rice Bay Formation

The North Point Member (NPM, Phase IV/1). The North Point Member is best represented at the northern end of San Salvador but also has been identified at a few localities along and off the eastern shoreline of the island (CAREW and MYLROIE, 1985). It is composed of well-sorted moderately lithified grainstones that predominantly contain superficial ooids (> 50%), whereas peloids and bioclasts are poorly represented. The constituent grains are bound by low-Mg calcite and meniscus cements indicative of a fresh-water vadose environment. Aragonite needles commonly are superimposed on the calcite cements where the North Point rocks crop out in the modern intertidal zone (White and White, 1990). The NPM was deposited in a subaerial environment when sea level was lower than it is today, as demonstrated by the numerous eolian sedimentary structures (White and Curran, 1985, 1988) dipping below present datum. The North Point eolianite is capped by an orangish-tan sandy paleosol containing pisoliths and abundant terrestrial snails (Cerion sp.). This soil is deeply developed in dune swales. The grain composition of the paleosol is similar to that of the underlying limestone.

Amino-acid analyses on whole-rock samples yield an average A/I ratio of 0.24 that is in agreement with the 5,345 YBP whole-rock 14C age reported by CAREW and MYLROIE (1987) for the same unit. An A/I ratio of 0.25 was measured on deeply-buried (>1 m) Cerion shells from the overlying paleosol. These ratios accurately reflect the pre-modern age of the termination of the depositional phase, at least several thousand years ago.

The North Point limestones differ from the aforementioned Pleistocene oolites (FBM and FZM) being less well lithified, by their more pristine sedimentary structures (White and Curran, 1988) and by the absence of calcrete-infilled root molds.

The Hanna Bay Member (HBM, Phase IV/2). The Hanna Bay Member is composed of a weakly cemented yellowish limestone that forms small ridges and sea cliffs that are anchored on the North Point Member and Pleistocene headlands. The lower part of the unit shows flat beds dipping seaward, coarse shell layers and intertidal fenestrae indicative of a beach environment, whereas the upper part is characterized by large-scale eolian stratification and land-crab and cluster burrows (White and Curran, 1985, 1988). The Hanna Bay Member contains a weak protocons and is capped locally by a Cerion-rich complex paleosol showing a dark brown organic-rich lower horizon, that has yielded Lucayan artifacts. HBM limestones are made of mostly skeletal grains and peloids. Benthic forams (Homotrema rubrum, Miliolidae, Soritidae), red and green algae fragments and mollusk debris are most abundant among the bioclasts. The grains are bound by low-Mg calcite cement that is common in the beach facies but virtually absent from the eolianites.

Whole-rock A/I ratios of the Hanna Bay calcarenites average 0.19, which average is compatible with the 3,210 YBP whole-rock 14C age obtained by CAREW and MYLROIE (1987). Land snails from the overlying brown soil yield values of 0.11 that clearly support a non-modern age of the soil. HBM eolianites differ from older bioclastic units (ACF, OHF, FHF) by their common association with beach facies and their relatively high proportion of superficial ooids. Poor lithification and numerous pink Homotrema grains are helpful criteria for distinguishing this unit from the FZM of the Grotto Beach Formation.

The East Bay Member (EBM, Phase IV/3). A coastal beach/dune ridge of submodern age, anchored on the HBM and covered by heavy overgrowth of woody vegetation, represents the newly named East Bay Member. The stratigraphic relationship to the precursory Hanna Bay Mb. is clearly exhibited at Hanna Bay on the south end of the type HBM outcrop. The EBM is capped by a thin and slightly tan-brown colored soil with abundant Cerion fragments. The petrology of the unit is similar to that of the Hanna Bay Member from which it appears to be largely recast. Soil development on the ridge is restricted to some minor coloration and organic accumulation that is due to decay of litter in the uppermost A horizon.
The depositional history of San Salvador

Phase I deposition (Figure 9/I) probably initiated during Stages 7 to 9 (180,000 to 380,000 years ago). A somewhat younger Phase I sequence began with the development of a small ridge on the eastern margin of the island, followed by the larger and more seaward ridges of Dixon and Fortune Hills. Clearly Phase I has several ridges representing minor or major fluctuations of sea level during that interval. Smaller nodes also developed on the western, less energetic shorelines.

In early Sangamonian time, very large ooid dunes (French Bay Mb. of the Grotto Beach Fm.) started to form after initial flooding, but before sea level reached its present elevation (Phase III 1-2; Figure 9), which is indicated by the flooded swales between the interior ridges. The platform was then very wide and probably not rimmed by reefs. Later, as sea level kept rising to nearly 7 m (FBM) and the shelf narrowed due to ongoing progradation, the ridges became lower, and swale elevations rose to above the modern datum. Ridges 11/3-4 (Figure 9) appear to be contemporaneous with the Cockburn Town reef, whereas Phase 11/5 (Fernandez Bay Mb.) could indicate either progradation over the reef or, as we prefer, a subsequent, late rise of sea level.

Phase III landforms (Almgreen Cay Formation) were emplaced mainly along the eastern shoreline during the late Sangamonian (around 85 ka) when sea level was slightly below its present stand (Figure 9/III). The sea then retreated off the bank for the duration of the last glacial period (80,000 to 12,000 years). We found no evidence supporting a 40,000 to 50,000 year old highstand (based on a single U-dated speleothem) as proposed by Mylroie and Carew (1988).

Phase IV (Figure 9/IV) of the Holocene in-
Figure 9. Series of maps showing the geological evolution of San Salvador between the middle Pleistocene and the present.
cludes three intervals of deposition represented by the North Point (around 5,300 YBP), Hanna Bay (around 3,000 YBP) and East Bay (? 1,000 YBP) Members of the Rice Bay Formation. These ridges, like the Phase III ridges, are best developed on the eastern shoreline and are catenary on the Phase III and older anchors. Petrographic differences between middle (NPM) and upper Holocene units (HBM, EBM) appear to be related to a change in the rate of sea-level rise some 3,500 years ago (Kindler, 1991, 1992).

CONCLUSIONS

Our analysis of the island of San Salvador reveals a geomorphic history defined by four phases (I–IV) that are represented by a suite of shallow marine and terrestrial facies (Table 1). AAR estimated ages place the Phase I deposits at greater than 180,000 years, Phase II deposits at the last interglacial centered on 123 ka, but ranging from 135,000 to 120,000 years ago. Phase III deposits occurred at around 85,000 years ago. Phase IV deposits are 14C dated at <5,300 YBP.

Like Bermuda, San Salvador provides a model for deposition on stable carbonate-platform islands. The growth of the islands occurs by lateral accretion and is dependent on the sea level, the configuration of the platform, the geometry of the shelf margin, and the orientation of sediment-transport sources.

Carbonate islands originate by shoaling during stormy periods when sediments blanketing the platform first accumulate as shoals, and progressively emerge into beach ridges and dunes. During low stands, dune deposits indurate and form nucleation points or anchors for subsequent deposition during high sea levels.

Ooid formation and deposition occur early in major transgressive cycles (e.g., French Bay and North Point Mbs.) while skeletal and peloidal sediment dominates later in the cycle (Almgreen Cay Fm. and Hanna Bay Mb.). This transition is apparently tied to the growth of reefs around the island inhibiting the flow of deep, cool and carbonate-saturated waters onto the shelf.

The lateral growth of San Salvador and other islands on carbonate platforms is self-regulating: the greater the lateral growth, the smaller the source area for sediment production that is required for growth. San Salvador appears to have nearly completed its lateral growth, and subsequent growth (which would be mainly vertical) would require accommodation through subsidence, a new orientation of storm tracks, or a significantly higher sea level in order to overstep the high ridges surrounding the island. Lateral growth of the island ceases at a time when the shelf becomes too narrow and steep to sustain the formation and landward transport of sediments.

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LITERATURE CITED


