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New Perspectives on Bahamian Geology: San Salvador Island, Bahamas

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ABSTRACT

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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, morphostratigraphy, 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 acid racemization (AAR) ratios. Such a multi-method approach was successfully used to chart the depositional history of Bermuda (HEARTY *et al.*, 1992), but the geologic

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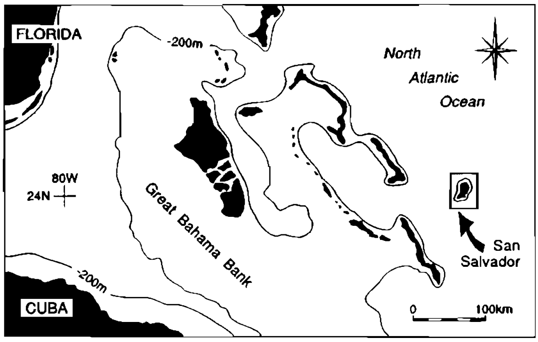


Figure 1. Map showing location of San Salvador Island, Bahamas.

histories of the two islands are diverse in many ways (HEARTY, 1992).

Field Techniques

Geomorphology and Morphostratigraphy

Major landforms were mapped by using 1:25,000 topographic charts, air photos and information gleaned from previous field investigations. Field sites were selected (Figure 2) on the basis of their volumetric and geomorphic importance to the accretion of the island, and of course, their accessibility. The relative ages of landforms on San Salvador were assessed in light of the fundamental principles of superposition and juxtaposition, but in a lateral accretionary sense (off and onlapping), rather than a vertical, stratigraphic one (Figure 3).

Two basic concepts guide our relative-age interpretations. First is a model of lateral accretion (VACHER, 1973), namely that islands grow by addition of sediment on their margins. The second concept applies to catenary ridges and their anchoring headlands, where the anchors are, logically, older than the ridges connecting them (GARRETT and GOULD, 1984). Combining both models suggests that the more seaward of two parallel ridges is the younger, except in examples where it is breached. The younger event then results in catenary ridges between and landward of the remnants of the older ridges (Figure 3, D3). It is also possible to rank the relative age of carbonate landforms based on the degree of preservation of primary morphology, cavernous weathering, the thickness of calcretes and the development of soils (BIRKELAND, 1974).

Physical Stratigraphy

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.

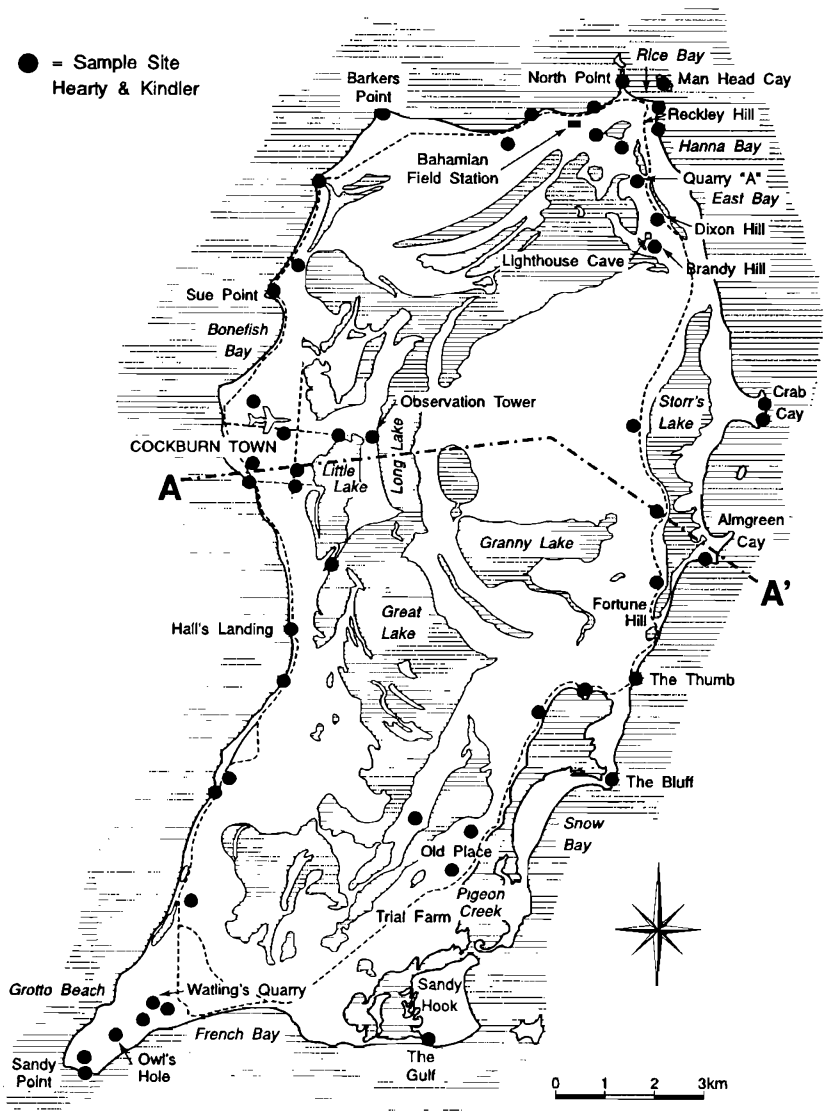


Figure 2. Map of San Salvador Island showing locations of sample sites. Line A–A′ shows the location of the profile in Figure 6.

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 Phil-

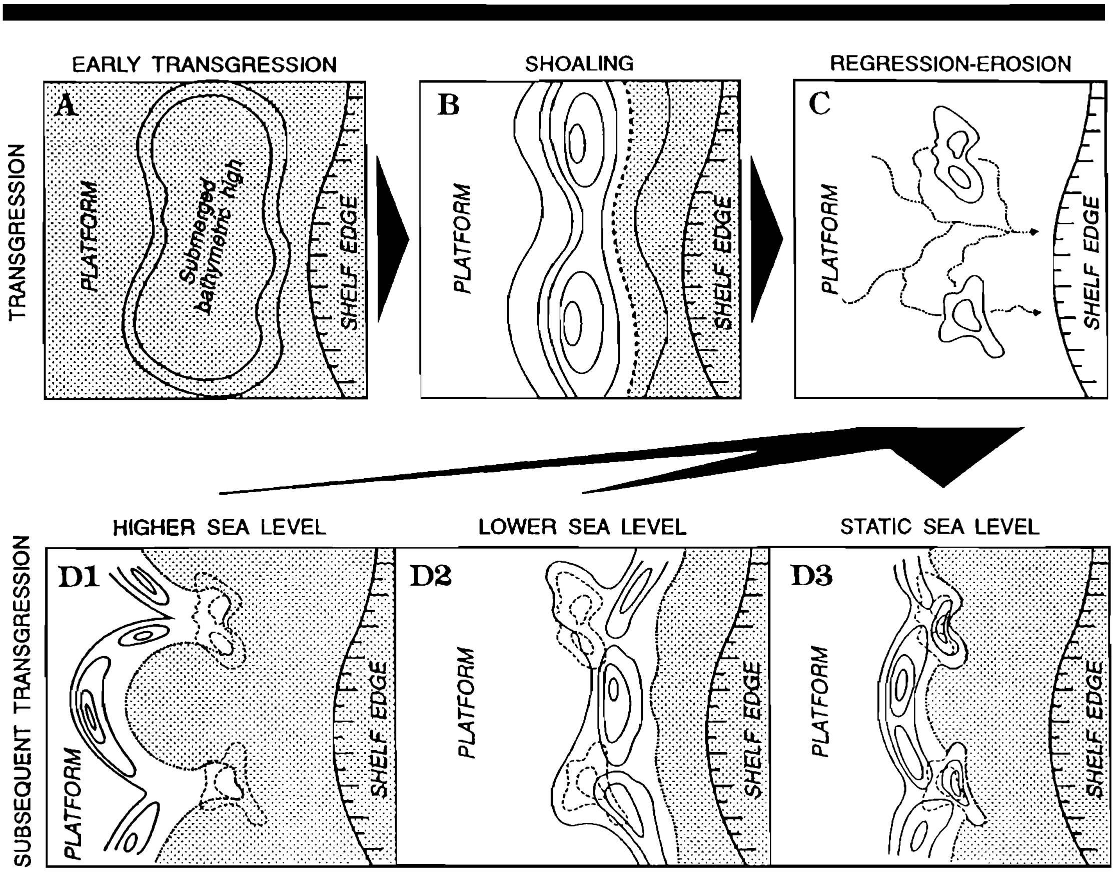


Figure 3. Series of maps showing sequence of sea-level fluctuations and resulting changes in island formation (event-response model). Given the development of topographic highs during earlier cycles (boxes A through C), subsequent sea levels that are: higher (box D1), will result in catenary ridges far inland from the original highs and generally will be associated with higher percentages of ooids; lower (box D2), will result in sublinear skeletal sediment ridges seaward of the original highs; or static (box D3), will result in catenary ridges subparallel and inland of the highs.

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, cross-cutting 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

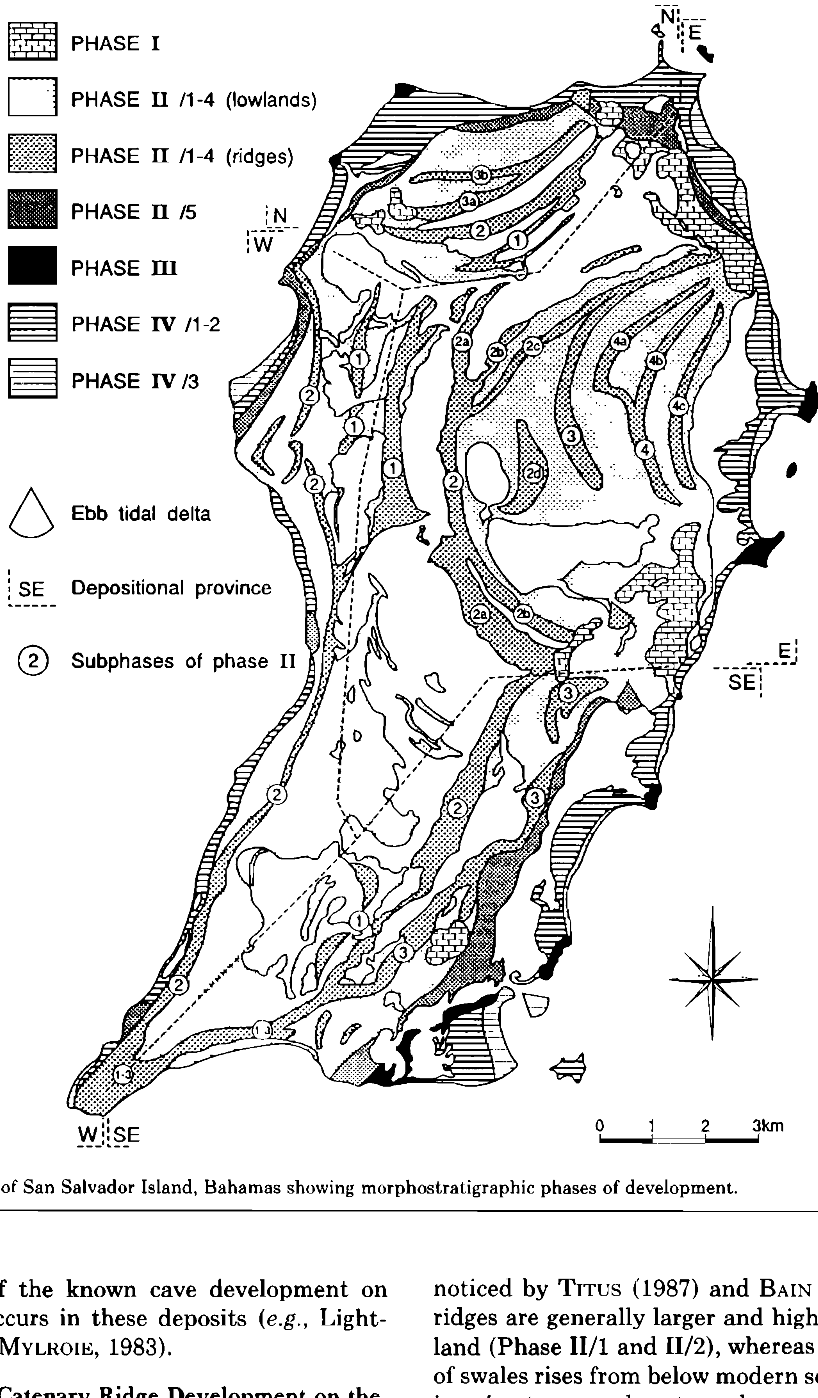


Figure 4. Map of San Salvador Island, Bahamas showing morphostratigraphic phases of development.

significant of the known cave development on the island occurs in these deposits (*e.g.*, Lighthouse Cave; MYLROIE, 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 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 I/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 I/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.*

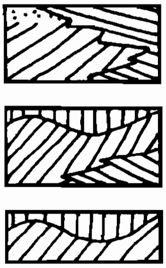
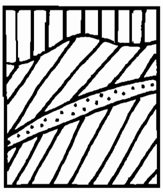
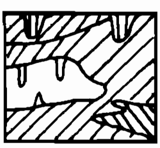
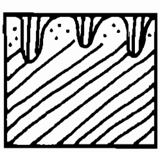
LOG	ROCK UNIT		PHASE	SETTING	PETROLOGY	A/I	AGE (yBP)
	**RICE BAY FORMATION** (Holocene)	East Bay Mb.	IV/3	soil eolian marine	skeletal	0.09	
		Hanna Bay Mb.	IV/2	soil eolian marine	skeletal/ooidal	0.19	3,200 (14C)
		North Point Mb.	IV/1	soil eolian	ooidal/peloidal	0.24	5,300 (14C)
PALEOSOL							
	**ALMGREEN CAY FORMATION** (Late Sangamonian)	Upper Mb.	III/2	eolian	skeletal	0.32	
				protosol			>63,000 (AAR)
		Lower Mb.	III/1	eolian	skeletal	0.28	
PALEOSOL							
	**GROTTO BEACH FORMATION** (Sangamonian)	Fernandez Bay Mb.	II/5	eolian marine	ooidal/peloidal	0.43	120,000 (AAR)
		Cockburn Town Mb.	II/4	protosol marine (reef)	skeletal	0.48	123,000 (U/Th)
			II/3		ooidal		
		French Bay Mb.	II/2	eolian	ooidal	0.56	135,000 (AAR)
			II/1		ooidal		
PALEOSOL							
	**FORTUNE HILL FORMATION** (Mid-Pleistocene)		I/2	protosol eolian ? marine	skeletal/peloidal	0.68	<205,000 (AAR)
PALEOSOL							
	**OWL'S HOLE FORMATION** (Mid-Pleistocene)		I/1	protosol eolian	skeletal	1.06	<385,000 (AAR)

Table 2. *Stratigraphic nomenclature of Quarternary rock units on San Salvador Island.*

	Carew & Mylroie, 1985	Titus, 1987	This study
HOLOCENE	**Rice Bay Fm.** Hanna Bay Mb. North Point Mb.	**Rice Bay Fm.** No members	**Rice Bay Fm.** East Bay Mb. Hanna Bay Mb. North Point Mb.
WISCONSINAN		**Granny Lake Oolite** **Dixon Hill Ls**	
SANGAMONIAN	**Grotto Beach Fm.** Dixon Hill Mb. Cockburn Town Mb. French Bay Mb.	**Grotto Beach Ls**	**Almgreen Cay Fm.** **Grotto Beach Fm.** Fernandez Bay Mb. Cockburn Town Mb. French Bay Mb.
PRE-SANGAMONIAN	**Owl's Hole Fm.**	Unnamed	**Fortune Hill Fm.** **Owl's Hole Fm.**

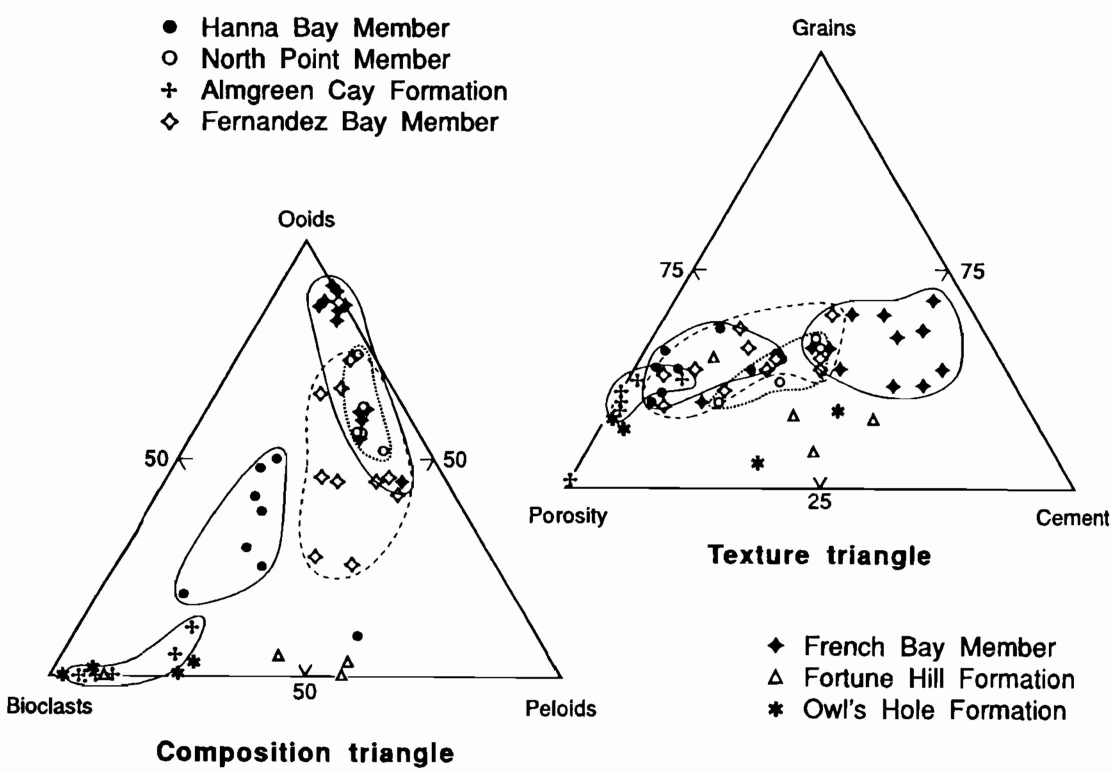


Figure 5. Triangular diagrams showing petrographic characteristics of the Quaternary units.

Table 3. *Whole-rock amino acid racemization (AAR) A/I 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.*

FM	LOC.	COMPOSIT.	MEAN A/I	AGE
Modern beach sediments				
0028-A	CM1	peloidal/ooidal	0.089 (1)	
0028-B	TT1	skeketal	0.073 (1)	
0028-C	SP1	peloidal/ooidal	0.111 (1)	
0028-D	GH1	skeletal	0.090 (1)	
0028-E	GH2	skeletal	0.081 (1)	
UT54-A	HB2F	skeletal	0.116 (1)	
Rice Bay Formation				
Hanna Bay Member				
UT55-A	HB2B	skeletal	0.189 (2)	3,200
North Point Member				
UT58-A	NP4	ooidal/peloidal	0.238 (2)	5,200
Almgreen Cay Formation				
Upper Member				
0021-B	TB1C	skeletal	0.333 (1)	
0022-B	AC1C	skeletal	0.312 (1)	
Lower Member				
0021-A	TB1A	skeletal	0.283 (1)	
0022-A	AC2A	skeletal	0.284 (1)	
Grotto Beach Formation				
Fernandez Bay Member				
0014-C	CTD1d	ooidal/peloidal	0.432 (1)	
0018-	VH1A	ooidal	0.445 (2)	
0019-A	TG1A	ooidal/peloidal	0.413 (1)	
0024-A	FS1A	ooidal/peloidal	0.408 (2)	
0026-A	QA1A	ooidal/peloidal	0.414 (1)	
0027-B	FQ1	ooidal/peloidal	0.438 (1)	
0027-C	PC1	ooidal/peloidal	0.343 (1)	
0027-A	OP1	ooidal	0.439 (1)	
Cockburn Town Member				
0014-	CT	skeletal	0.480 (2)	123,000
French Bay Member				
0014-D	CT4	ooidal	0.550 (1)	
0017-A	CW2A	ooidal/peloidal	0.352 (1)	
0017-B	CW2B	ooidal/peloidal	0.546 (1)	
0019-B	TG1CE	ooidal/peloidal	0.494 (2)	
UT59	WQ1C	ooidal	0.549 (2)	
0012-	OT1	ooidal/peloidal	0.460 (4)	
0013-	OT3	ooidal	0.474 (2)	
0015-A	FB4A	ooidal	0.576 (1)	
0015-B	FB4C	ooidal	0.469 (1)	
0016-	OH3	ooidal	0.511 (1)	
0023-E	TD3	ooidal/peloidal	0.465 (1)	
0025-B	LC2	ooidal/skeletal	0.477 (1)	
0025-C	LC3	ooidal/skeletal	0.474 (1)	
0026-B	QC1	ooidal/skeletal	0.482 (1)	
0026-C	QD1	ooidal	0.556 (1)	
0026-D	QN1	ooidal	0.576 (1)	
Fortune Hill Formation				
0020-A	TT1	skeletal/peloida	0.680 (1)	
0025-A	LC4	skeletal/peloida	0.680 (2)	
			0.52 (1) l. c.	
Owl's Hole Formation				
0016-A	OH1A	skeletal	0.50 (1) l. c.	
0016-B	OH1A	skeletal	0.46 (1) l. c.	
UT60-A	WQ1A	skeletal	1.140 (1)	
UT60-B	WQ1A	skeletal	0.976 (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 calcrete is capped by a skeletal grainstone 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);

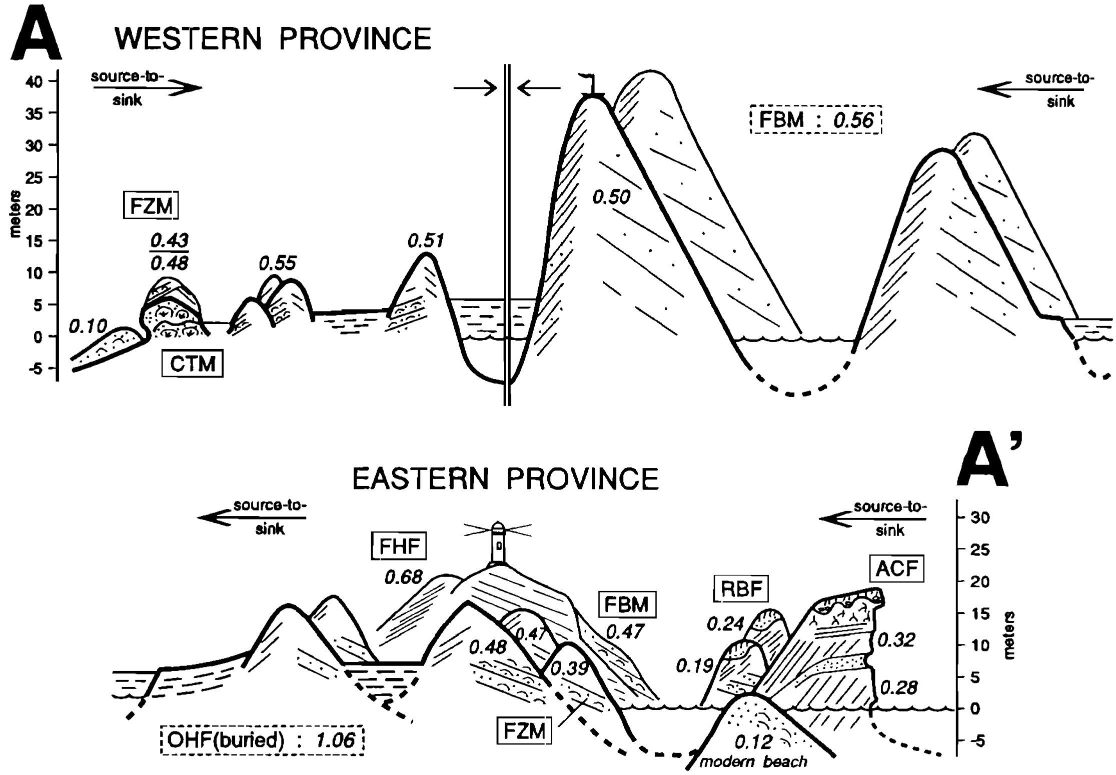


Figure 6. Topographic profile and stratigraphic cross section constructed along the west to east line A–A' shown in Figure 2. Full line-framed, abbreviated formation names indicate locations of the rock-unit type sections; broken line-framed abbreviations signify type section is off the profile.

(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

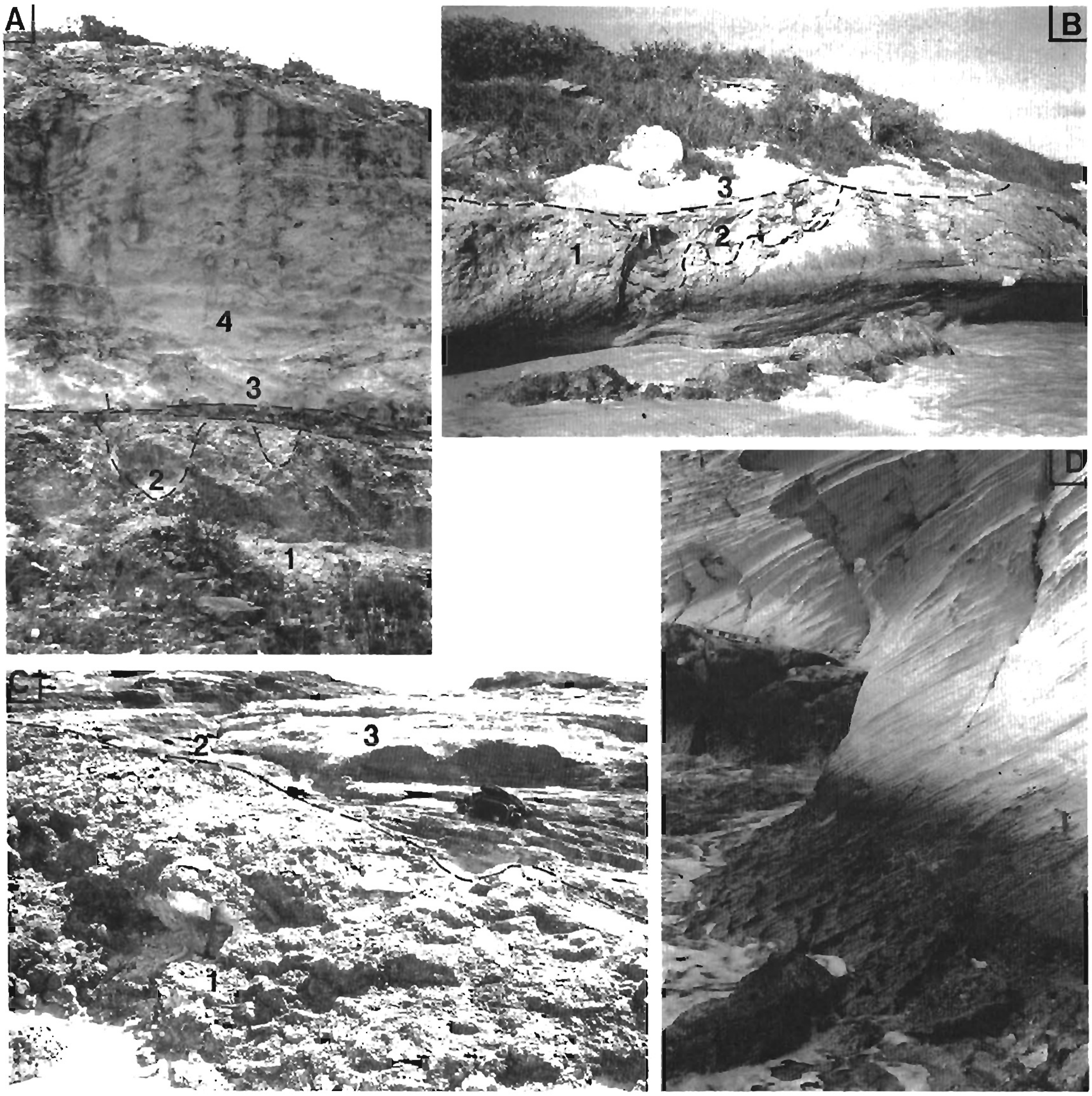


Figure 7. Photos of important outcrops on San Salvador Island. (7A) Watling's Quarry: (1) Owl's Hole Fm.; (2) Protosol at top of Owl's Hole Fm.; (3) Terra rossa paleosol; (4) Eolianites of French Bay Mbr. of Grotto Beach Fm. (7B) The Thumb: (1) Skeletal eolianites of Fortune Hill Fm.; (2) Thick calcretes (>15 cm); (3) Eolianite of unknown age. (7C) Cockburn Town reef: (1) Lower Cockburn Town Mbr. reef facies dated at 123,000 years; (2) Unconformity; (3) Upper Fernandez Bay Mb. (7D) Almgreen Cay Mbr. with skeletal eolianites dipping below present sea level.

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/1) clearly belongs to the French Bay Member because of its morphostratigraphic position, similar petrology and amino-acid ratios. No data support a penultimate interglacial age of this ridge as proposed by Foos and Muhs (1991).

The Cockburn Town Member (CTM, Phase II/?2-4). The physical, chronometric and biostratigraphic 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 average 0.48 (n = 2), whereas marine shells yield ratios of 0.86 for *Lucina pennsylvanica,* 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 between 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 contemporaneous 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 unconformably overlain by a shallowing-upward sequence displaying subtidal, beach and eolian deposits (White *et al.*, 1984) (Figure 7C). Similar marine and eolian deposits are exposed at several locations around the island (*e.g.*, Old Place, Victoria and Reckley Hills, Grotto Beach, Fernandez Bay (type locality)) and represent the most seaward extension of Phase II ridges. They are composed of well-lithified medium to coarse grained calcarenites containing a mixture of thinly coated ooids, peloids and bioclasts, and are bound by coarse sparry cement.

All FZM sites have A/I ratios that average 0.41 ± 0.04. If we exclude from the average two *Halimeda*-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 better lithified than is the younger North Point oolite.

The FBM and the FZM of the Grotto Beach Formation probably represent the two separate highstands of sea level that have now been identified at the beginning of the last interglacial (isotopic Substage 5e; Johnson, 1991). We have also observed a disconformity *within* the reef throughout the famous exposure at Cockburn Town. Evidence 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, Almgreen 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 reefal 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 (Muhs *et al.*, 1990). It is composed of weakly cemented, yellowish grainstones, that contain as much as 85% of bioclastic grains (mollusks and coral fragments, benthic forams, bryozoan and algal debris) that have retained their original mineralogy. Finely crystallized 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 paleosol comprising extensive rhizoliths, laminar calcrete and a breccia horizon (Beier, 1987).

AAR ratios (mean whole-rock values of 0.29) suggest a considerably younger age for the Almgreen 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 (Substage 5a) at around 85,000 years ago, much like 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 ^{14}C 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 protosol 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 ^{14}C 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.

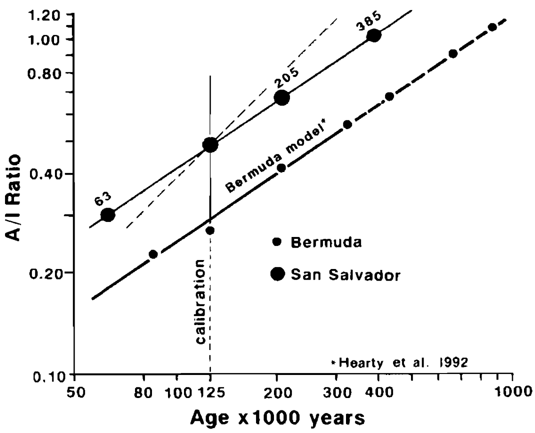


Figure 8. Kinetic curves constructed from U-series and amino acid data from Bermuda (heavy line) and San Salvador (dashed and solid thin lines). The Bermuda whole-rock curve serves as a kinetic model for San Salvador whole-rock data. The unequal temperature history at the two sites is manifest in the A/I differential 125,000 year U-series calibration at both sites. The solid thin line represents a first-order comparison of San Salvador data to the Bermuda model, whereas the dashed line is a more realistic version that considers the effect of interglacial warmth on the kinetics of the curve. Age estimates are approximate.

Cliffs are developing on some areas of the ridge, particularly on the east coast. This erosional pattern signals a reversal of the progradational trend that resulted in the formation of the ridge, and it also may represent a continued rise of sea level during the present time.

DISCUSSION OF THE WHOLE-ROCK AMINO ACID DATA

In San Salvador Island, five aminozones are distinguished. Aminozones A, C, E, F and G are tied to deposits of the Holocene, the late last interglacial, the peak last interglacial, and two middle Pleistocene events (Figure 8). The whole-rock ratios of 0.48 from the Cockburn Town reef are unambiguously equated to an average U-series age of about 123,000 years (CHEN *et al.*, 1991), while an island-wide range of 0.56 to 0.42 (n = 34) for Aminozone E is representative of the entire peak last interglacial period (perhaps from 135,000 to 120,000 years) between French Bay and Fernandez Bay depositional times.

By direct comparison of the whole-rock data from San Salvador and Bermuda (see HEARTY *et al.*, 1992), correlated via Aminozone E at 123,000 years, we have *estimated* the ages of Pleistocene deposits. Aminozone C (Almgreen Cay Fm.; 0.29 ± 0.02) is calculated to be about 62,000 years old. However, because no high sea level is globally recognized at this time, it is reasonable to assume that the Almgreen Cay Formation is somewhat older and is probably correlated with the Southampton Formation in Bermuda at 85,000 years old (VACHER and HEARTY, 1989). Amino acid ratios also suggest that two separate middle Pleistocene deposits are present, but a limited number of samples discourage precise age interpretations.

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 II/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 II/3–4 (Figure 9) appear to be contemporaneous with the Cockburn Town reef, whereas Phase II/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-

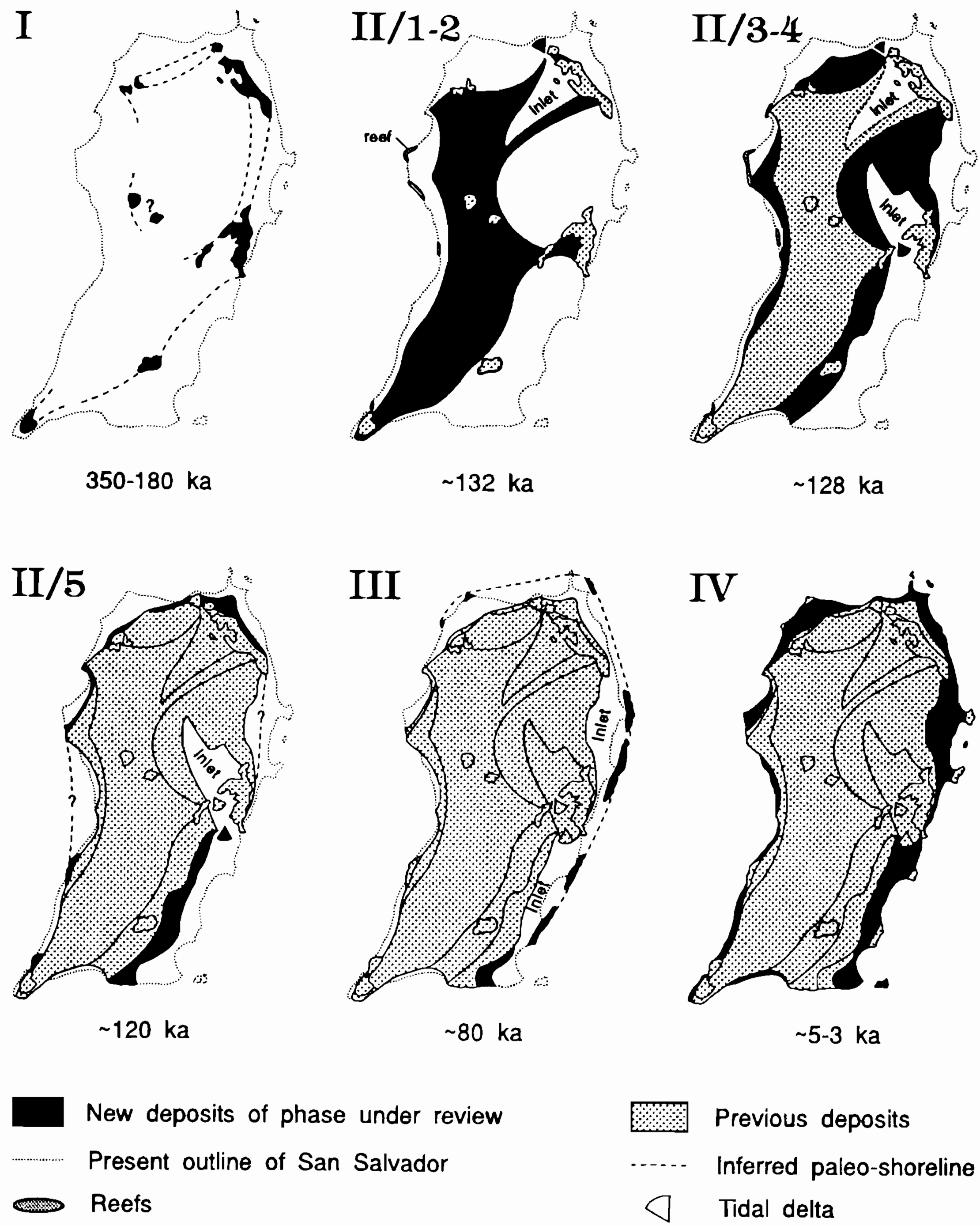


Figure 9. Series of maps showing the geological evolution of San Salvador between the middle Pleistocene and the present.

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 ^{14}C 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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