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THE LATE QUATERNARY EVOLUTION OF SURFACE ROCKS ON SAN SALVADOR ISLAND, BAHAMAS

Hearty, P.J. Department of Geology, University of South Florida, Tampa, FL 33620*

Kindler, P., Département de Géologie et de Paléontologie, Université de Genève, 1211 Genève 4, Switzerland

Schellenberg, Stephen A., Department of Geology University of South Florida, Tampa, FL 33620

ABSTRACT

This study combines several methods of investigation in order to trace the late Quaternary evolution of San Salvador Island. An overall pattern of island growth is observed that can be explained in the context of sea-level changes and sedimentary dynamics. This work together with previous studies identify the main depositional units which are: (1) the Owl's Hole Fm; (2) the Fortune Hill Fm; (3) the multiple oolitic ridges of the Grotto Beach Fm; (4) the Almgreen Cay Fm; and (5) the Rice Bay Fm. Cerion faunas from the younger formations display unique morphology and thus are useful as a field stratigraphic tool.

Some generalizations can be drawn on the nature of the processes governing the formation of sediments on the shelf, and their deposition as beach or dune ridges. Early interglacial, total-flooding transgressions result in the formation of ooids. But as the shelf narrows by progradation, the output of the "carbonate factory" diminishes resulting in smaller landforms and a tendency toward non-oolitic sediments. The petrology of the sediments is thus integrally related to the amplitude of the transgression and evolution of the shelf bathymetry.

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*Current address: College of the Bahamas, P.O. Box N4912, Nassau, Bahamas

INTRODUCTION

Save for Garrett and Gould's (1984) important paper on New Providence Island, published literature dealing with the evolution of Bahamian islands is scanty considering their vast area and large number of islands. Most published studies concentrate on discrete sites or topics rather than on a regional perspective. In an effort to supplement our current Bahamian database, a synthesis of San Salvador's geology is presented here which includes: (1) a refined and more detailed geomorphic framework; (2) a revised stratigraphic column; (3) a biostratigraphy of Cerion morphologies; and (4) a sea-level history. In this paper, our effort is only to present an overview of island growth, and not to provide a detailed history or contest the geology of individual sites.

METHODS

Single methodological approaches are insufficient to resolve the complex history of San Salvador or other carbonate islands. Thus, a variety of subdisciplines and techniques are used to decipher the geologic history (Hearty et al., 1992; Vacher et al., in press) in San Salvador.

Field techniques

Geomorphology and morphostratigraphy. Major landforms were mapped by using 1:25,000 topographic charts, air photos and information from previous publications (cited and discussed below). The relative ages of landforms on San Salvador were assessed in light of the fundamental principle of superposition, but in a lateral accretionary sense (off and on-lapping), and catenary ridge/anchor relationships (Garrett and Gould, 1984).

Physical stratigraphy. Over 50 study sites were described, and sampled (Figure 1) for petrographic and biostratigraphic analyses (Cerion land snails). Field observations of sedimentary structures and trace fossils were recorded at each site.

Laboratory techniques

Aminostratigraphy (Amino acid racemization or AAR). Whole-rock samples were analyzed for their amino acid composition (alloisoleucine/isoleucine or A/I) and were used to support geologic correlations. Methodological considerations pertaining to whole-

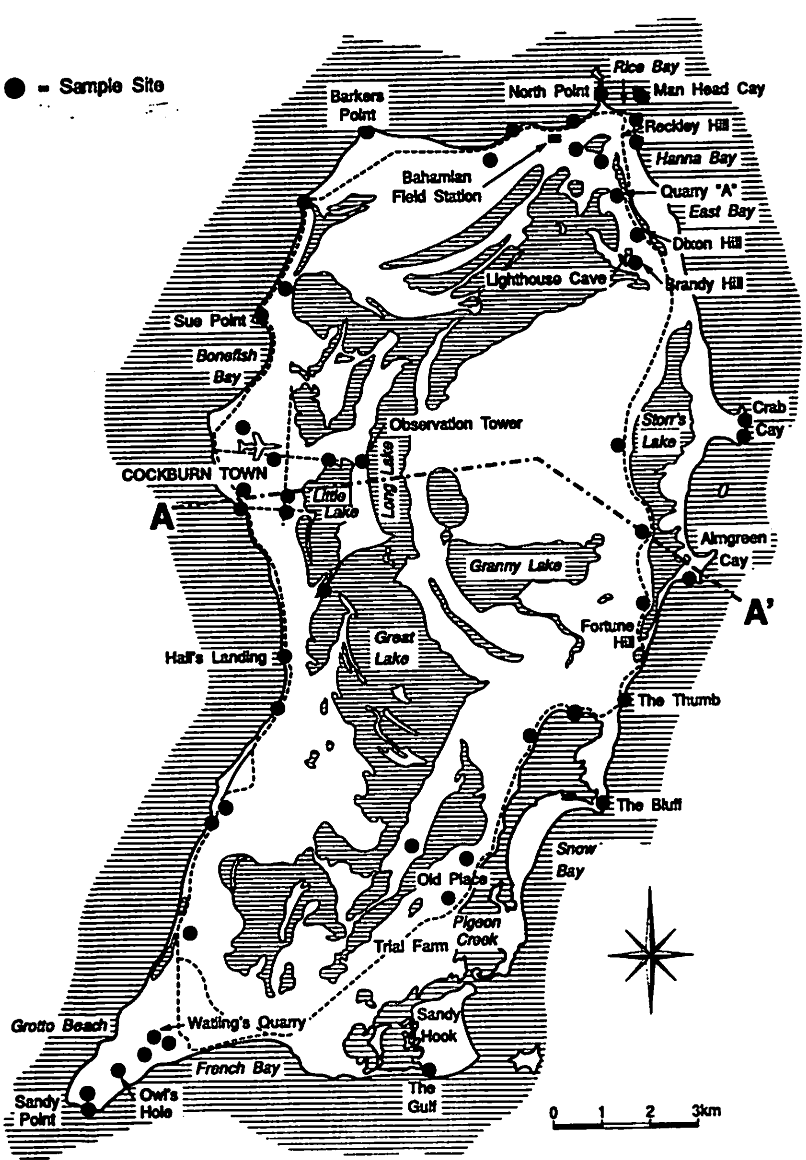


Fig. 1 -- Map of San Salvador Island showing locations of sample sites. Line A-A' marks the location of the profile in Figure 4.

rock analyses are contained in Hearty et al. (1992).

AAR 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 primarily whole-rock ratios in this study, a discussion of the utility of Cerion for AAR is largely irrelevant to this paper.

Sedimentary petrology and mineralogy. Two 350-grain counts were performed on each of nearly 50 thin-sections 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. Detailed grain counts (too extensive for this publication) are available upon request from PK.

Cerion biostratigraphy. The sample population consists of all individuals which display features of terminated growth and those lacking signs of major shell repair (e.g. following crab or hutia predation). *Cerion* growth halts at an ontogenetic stage well marked by an abrupt change to a negative coiling translation and the secretion of a thickened, definitive apertural lip (Gould and Woodruff, 1986). By utilizing only those individuals fulfilling both requirements, results from the subsequent analysis of the sample population would best reflect a normal, adult *Cerion*.

For each valid specimen, twenty variables were measured via fifty-three morphologic landmarks on a video data acquisition system (VDAS) (Schellenberg and Hearty, 1991; submitted). Morphometric variables for Cerion were developed by Gould and co-workers (Gould et al., 1974; Gould & Paull, 1977; Gould & Woodruff, 1978). In addition, VDAS usage allows area-based measurements of specimens. All statistical analyses were performed at USF using the IBM SYSTAT Version 4 statistical package.

RESULTS

Morphostratigraphic Phases

We have identified four major phases of ridge development on San Salvador (Figure 2) (Hearty and Kindler, 1991; 1993). Because they are often complex, these depositional phases (I through IV) are subdivided into numbered ridges (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

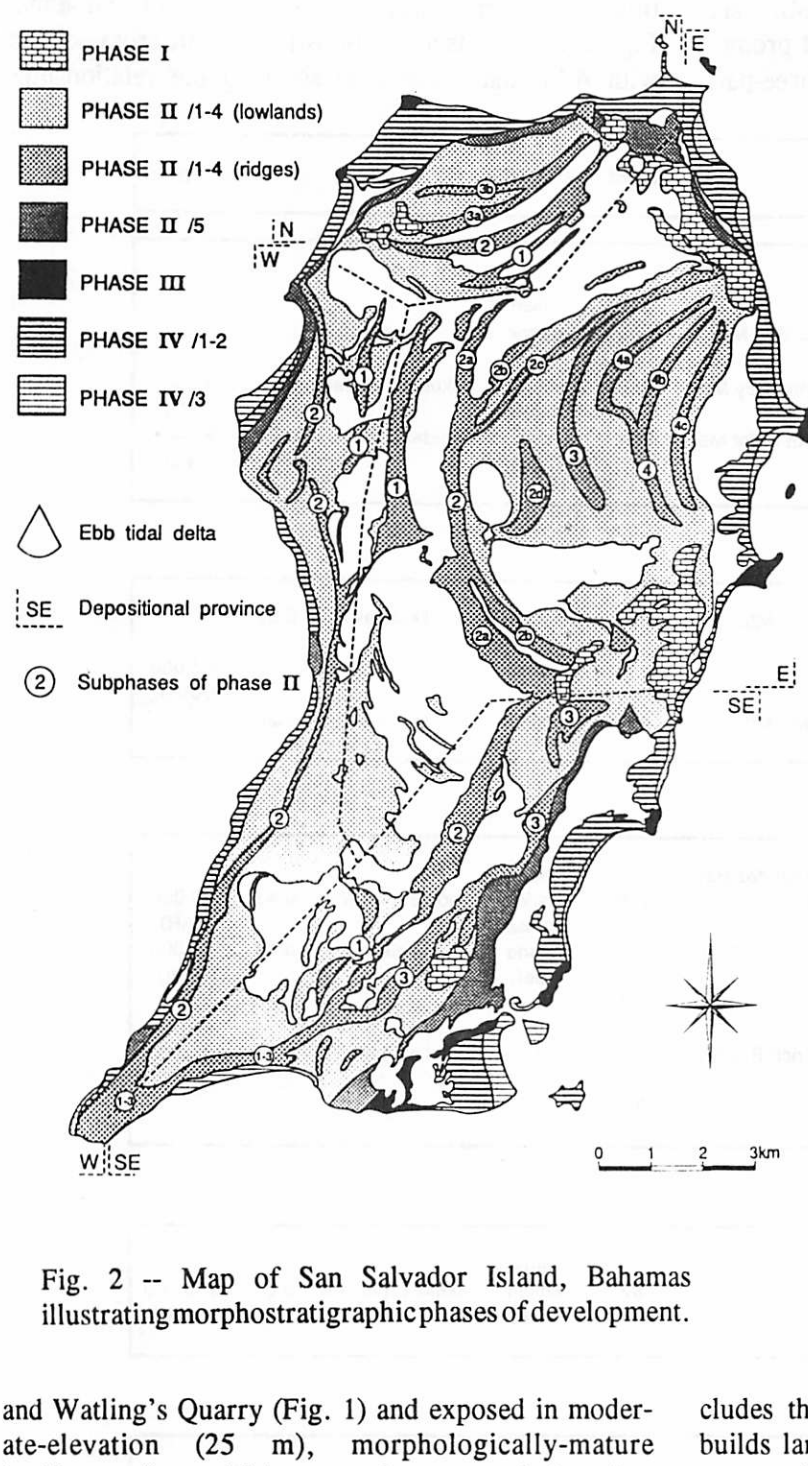


Fig. 2 -- Map of San Salvador Island, Bahamas illustrating morphostratigraphic phases of development.

and Watling's Quarry (Fig. 1) and exposed in moderate-elevation (25 m), morphologically-mature landforms, from which most 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). The most significant of the known cave developments 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 at least four (II/1, 2, 3, and 4) Phase II catenary ridges (Fig. 2). Bain (1991) observed that 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.

Beach ridges of the western and northern provinces form an extensive (25 km-long) linear feature extending from Sandy Point to Reckley Hill. Bifurcations and subdivisions of the ridge occur landward of the Cockburn Town reef which dates from the last interglacial (cf. Chen et al., 1991). An offshore feature during the bulk of the Phase II deposition, the reef is ultimately buried by Phase 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 west of Sandy Hook. Phase III ridges lie seaward of all other ridges and form the anchors for Phase IV catenary development.

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. Three subphases have been identified on the northeast extension of the island near the Bahamian Field Station. Phase IV/1 includes the North Point ridge. Phase IV/2 and IV/3 builds large semi-consolidated dune ridges along the eastern shoreline that are catenary on Phase III promontories. Phase IV strandplains are also apparent at Bonefish Bay, Sandy Hook and near Barkers Point.

Lithostratigraphic and Aminostratigraphic Sequence

Five formations, each capped by a paleosol, are recognized and are correlated to the geomorphic phases described in the previous section (Figure 2).

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 (Hearty and Kindler, 1993) and prompt some revision (Table 2) of the current three-part stratigraphy (Carew and Mylroie, 1985; 1987). The ternary diagrams in Figure 3 summarize the composition and grain characteristics of each of the units. Figure 4 presents a morphostratigraphic cross-section with AAR data (Table 3) showing the relationships

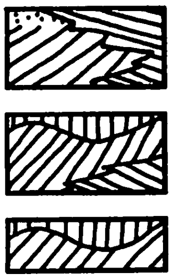
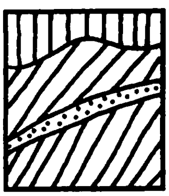
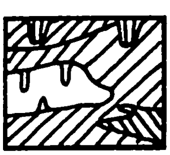
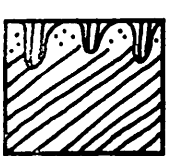
LOG	ROCK UNIT		PHASE	SETTING	PETROLOGY	A/I	AGE (yBP)
	**RICE BAY FORMATION** (Holocene)	East Bay Mb.	IV/3	soil eolian marine	skeletal	0.09	
		Hanna Bay Mb.	IV/2	soil eolian marine	skeletal/ooidal	0.19	3,200 (14C)
		North Point Mb.	IV/1	soil eolian	ooidal/peloidal	0.24	5,300- (14C)
PALEOSOL							
	**ALMGREEN 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)	Femandez Bay Mb.	II/5	eolian marine	ooidal/peloidal	0.43	120,000 (AAR)
				protosol			
		Cockburn Town Mb.	II/4	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 1 – Composite stratigraphy of Quaternary rock 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. Carbon-14 and U-series ages are cited in the text.

	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.

Table 2 -- Previous and proposed (this study) stratigraphic nomenclature of Quaternary rock units on San Salvador Island.

Beach. It is composed of well-lithified but often leached 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 as discussed by Ward (1973).

among the major units reviewed below.

The Owl's Hole Fm (OHF, Phase I/1) (Carew and Mylroie, 1985) is exposed in a solution pit at Owl's Hole, at Watling's Quarry (Fig. 1) and Grotto

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 middle Pleistocene age attributed to the OHF (Hearty and Kindler, 1991; 1993).

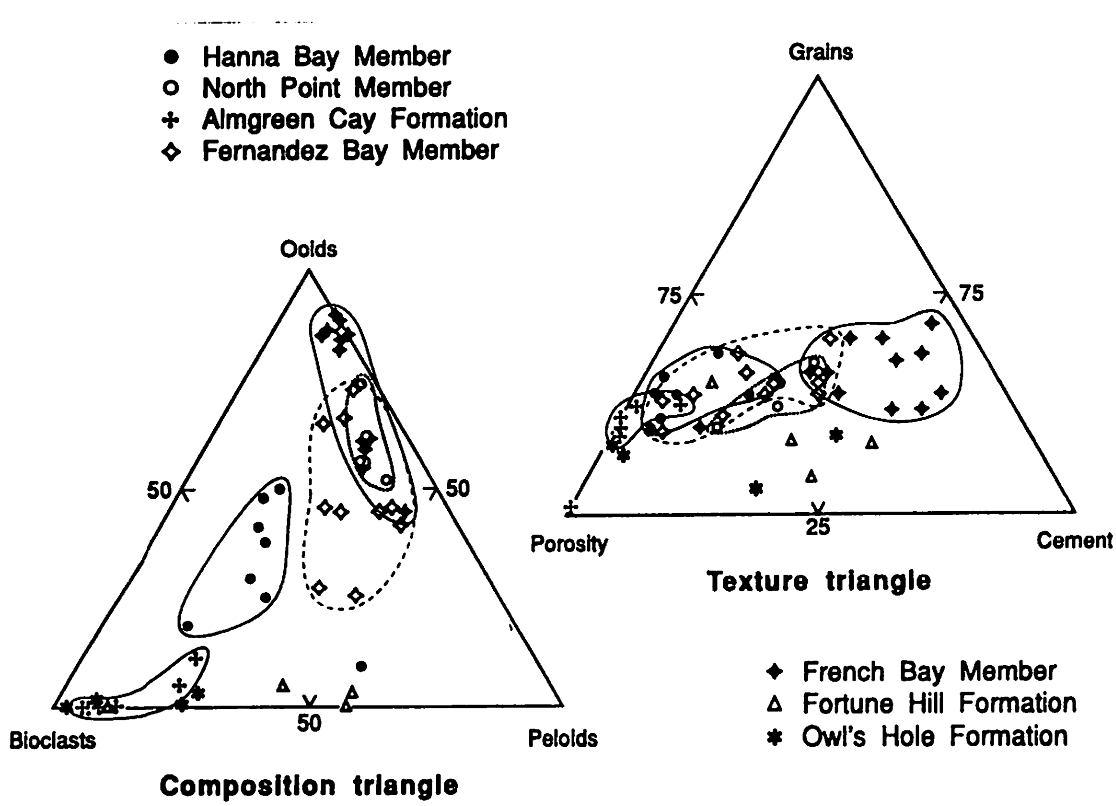


Fig. 3 -- Ternary diagrams presenting petrographic characteristics of the Quaternary units.

We have observed that OHF rocks are more lithified than the younger bioclastic grainstones composing the Almgreen Cay Fm and the Hanna Bay Mb. 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 Fm (FHF). At its type locality at Fortune Hill (best exposed at The Thumb) and at Dixon-Brandy Hills, the FHF (Phase I/2) exhibits imposing, mature landforms with extensive karst and cavernous weathering. At The Thumb, the FHF is capped by a thick calcrete (> 15cm), which in turn is overlain by a petrologically identical skeletal/peloidal grainstone. The occurrence of reef-associated bioclasts along with land snails, fresh-water cement and steep foresets in Lighthouse Cave lead us to consider this unit as ancient eolian ridges deposited along a high-energy, reef-bordered coastline much like today's setting.

FHF rocks are clearly better lithified and less porous than the bioclastic calcarenites deposited during younger events. The FHF presents marked petrographic and sedimentological similarities with the older OHF. However, it yields some considerably lower whole-rock A/I ratios (average: 0.68 vs. 1.06 in OHF), shows less compaction features and is more peloidal than the latter. Further amino acid analyses of well-preserved samples are required to further resolve the question of age of these units.

The 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 Mb"). For the following reasons, we place them at an older position (i.e. FHF) within the middle Pleistocene (Hearty and Kindler, 1991; 1993; Kindler and Hearty, 1992): (1) deposits at Dixon Hill and Fortune Hill form anchors for the catenary ridges of the Grotto Beach Fm (Sangamonian) and thus must

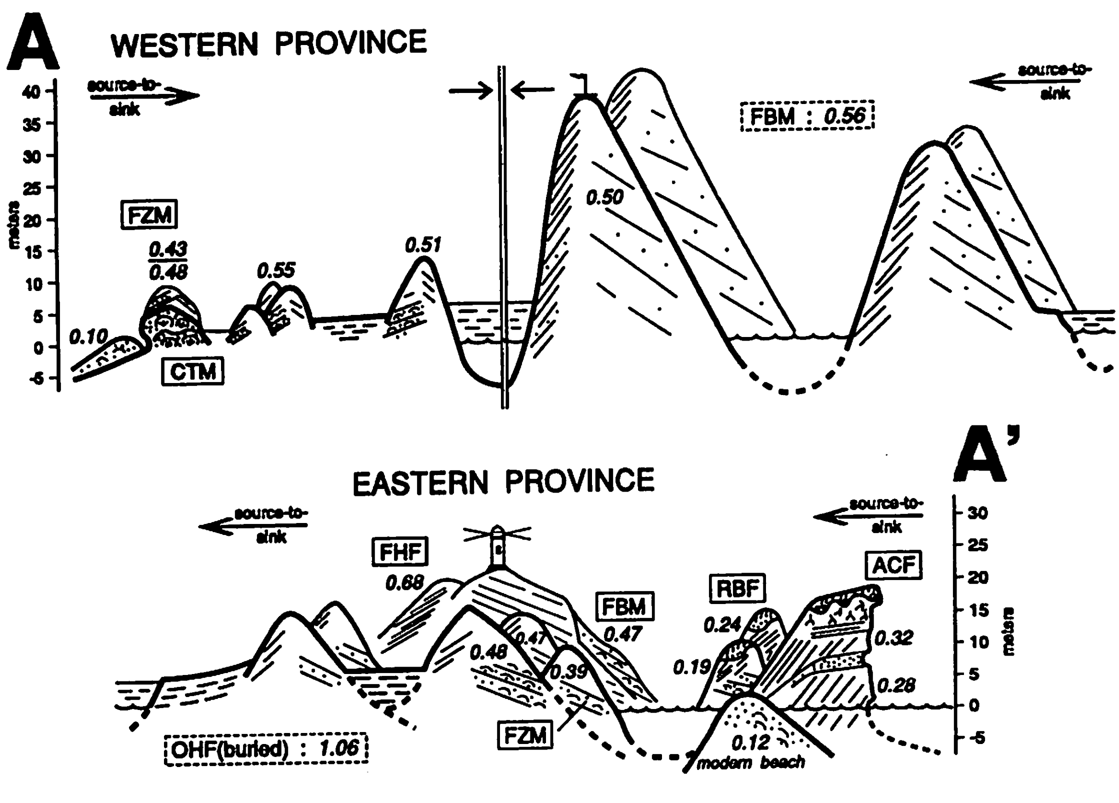


Fig. 4 -- Topographic profile and stratigraphic cross section constructed along the west to east line A-A' of Figure 1. Full line-framed, abbreviated formation names (see text) indicate locations of the rock-unit type sections; broken line-framed abbreviations signify type section is off the profile. FBM type locality at Watling's Quarry; OHF type locality at Owl's Hole.

predate them; (2) Dixon Hill and equivalents display a greater landform maturity (well-developed paleosols, calcrete, caves (Mylroie, 1983) and karst) than the ridges between them; (3) 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 west of Dixon Hill (Hinman, 1980; Thalman and Teeter, 1983; Noble et al., 1991); (4) at Quarry A, deposits onlapping the eastern flank of Dixon Hill have yielded both 140 ka U-series ages (Carew and Mylroie, 1987) and 0.47 A/I ratios (Table 3 and Figure 4). Thus, the underlying FHF (A/I = 0.68) rocks must be older (Table 3); and (5) the degree of cementation of Dixon Hill samples (Fig. 3) suggests an age much older than 70 ka.

The Grotto Beach Fm. The French Bay Mb (FBM, Phase II/1-4) 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 Mb was deposited in a subaerial environment, indicated by well-preserved

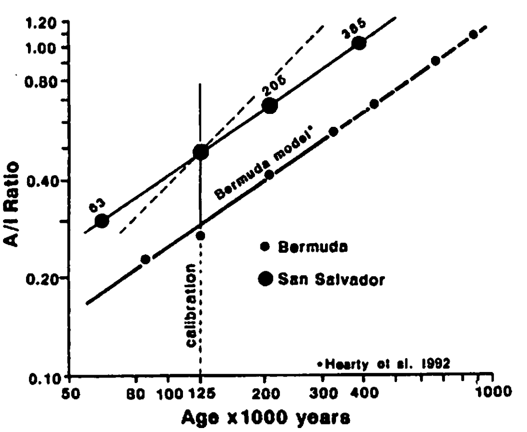
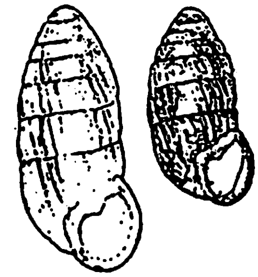
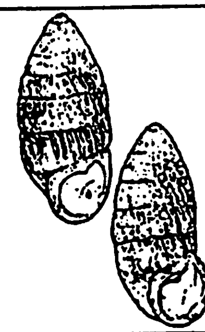
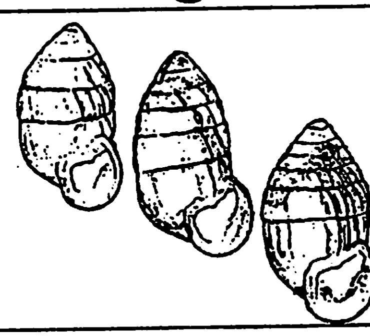
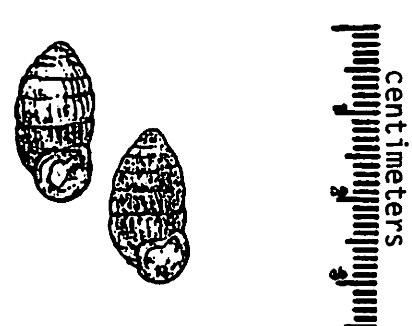


Fig. 5 -- Kinetic curves constructed from U-series and amino acid data from Bermuda (heavy line) and San Salvador (dashed and solid thin lines). The large solid points are mean A/I ratios of the Pleistocene formations discussed in this study. The Bermuda whole-rock A/I curve (small points) serves as a partially calibrated kinetic model for San Salvador whole-rock data. The unequal temperature history at the two sites is manifest in the A/I differential 125 ka U-series calibration at both sites. The solid lines represent a first-order comparison between San Salvador data and the Bermuda model, whereas the dashed thin line is a more realistic curve that considers the effect of interglacial warmth on the kinetics of racemization.

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)	

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 the lithostratigraphy. Average ratios from each formation and member are available in Table 3. Radiometric ages and statistics associated with A/I data are presented in the text. (l.c. = low concentration of amino acids in samples.)

FORMATION Members	WHOLE-ROCK* A/I (total)	CERION FAUNA (morphology)
MODERN BEACH SEDS	0.093	
North Point		
Crab Cay		
RICE BAY FM		
ˉsoil		
East Bay mbr		
soil		
Hanna Bay mbr	0.189	
soil		
North Point mbr	0.238	
ALMGREEN CAY FM		
soil		
Upper member (eol)	0.32	
protosol		
Lower member (eol)	0.28	
Man Head Cay (ACF) Cerion		
GROTTO BEACH FM		
soil		
Fernandez Bay mbr	0.43	
Cockburn Town mbr		
marine	0.48	
protosol		
local unc		
French Bay mbr	0.51	
?soil?		
upper eol		
protosol		
lower eol	0.56	

*Whole-rock statistics contained in text.

Table 4. Biostratigraphy of Cerion faunas, source stratigraphic units, and average whole-rock amino acid ratios from San Salvador Island.

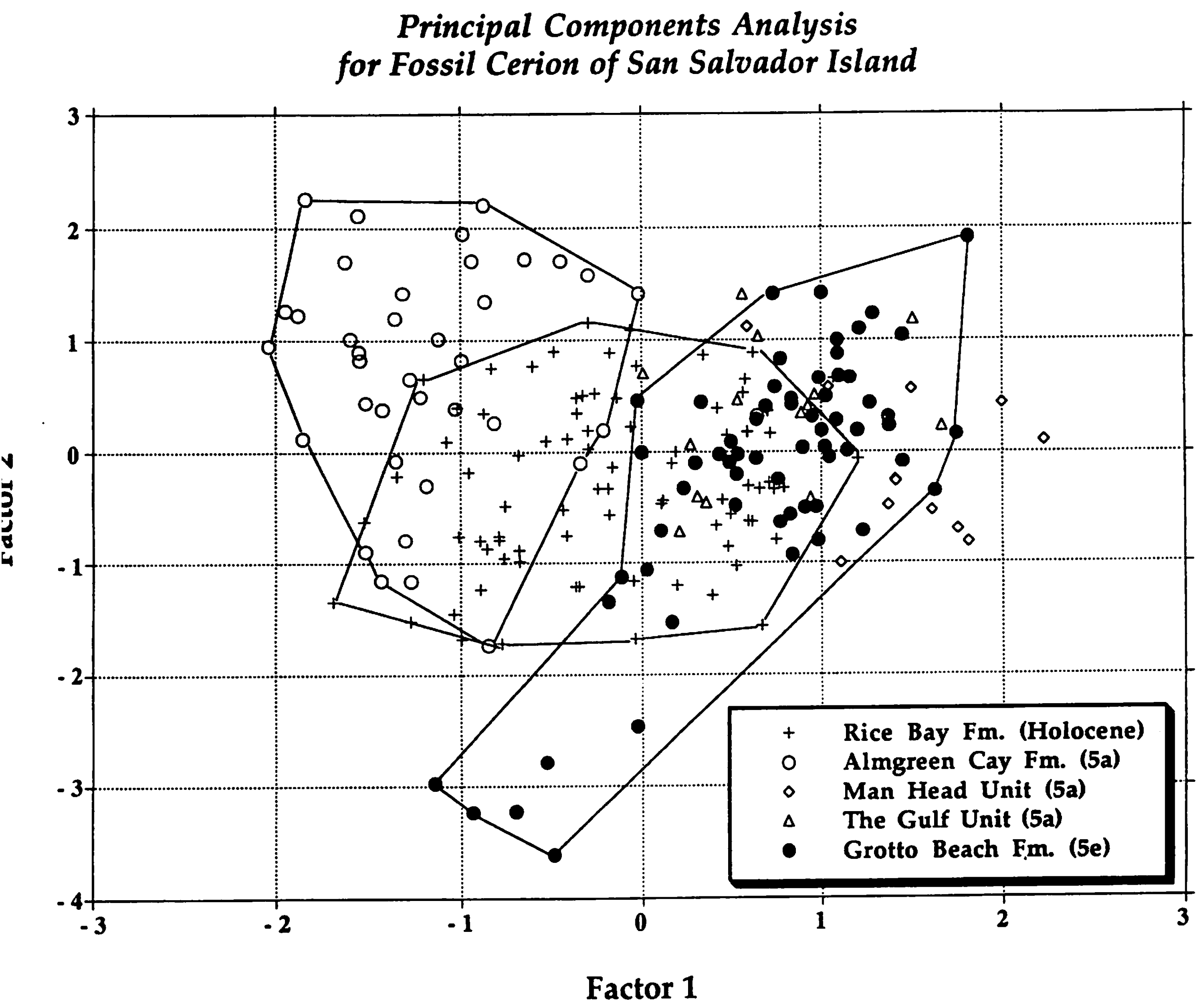


Figure 6. Principal components analysis (PCA) factor scores 1 versus 2 for Cerion. Petrological data equates Man Head Cay with the Almgreen Cay Formation and The Gulf with the Fernandez Bay Member of the Grotto Beach Formation. Thus, Man Head Cay Cerion are the only ACF sample to plot within the GBF cluster.

dune and swale morphology, large-scale eolian cross-stratification, rhizoliths and widespread structureless protosols. Subtidal and beach deposits can also be observed up to an elevation of $\geq$+8m (at Causeway Rd south of Cockburn Town). The former are characterized by small-scale trough cross-bedding, herring-bone structures, slumped beachrock blocks, callinacid burrows and fossil sand-waves at French Bay.

Amino-acid analysis on whole-rock samples from the FBM type locality at French Bay ridge (including Watling's Quarry) yielded an A/I ratio of 0.56 $\pm$0.01 (n=3), consistent with an early last interglacial age (Table 3). The faster racemizing Cerion from a protosol at Watling's Quarry average 0.69 $\pm$0.03 (n=3). Observation Tower ridge (Phase II/1) is correlated with FBM due to its morphostratigraphic position, oolitic petrology, and equivalent AAR ratios. None of our data support a proposed middle Pleistocene age (Foos and Muhs, 1991) of Observation Tower ridge.

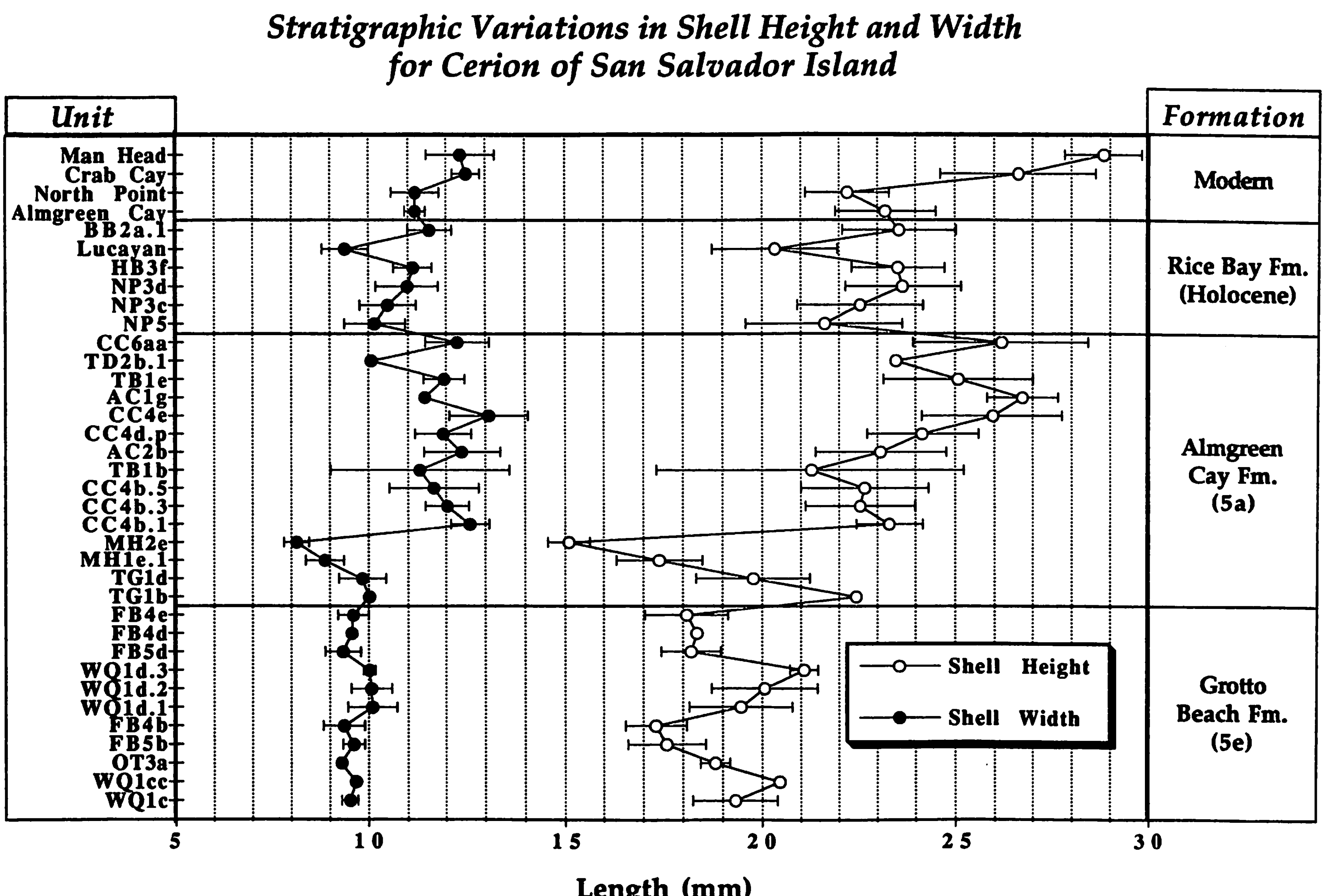


Figure 7. Stratigraphic variation in shell height and width by unit and formation. With the exception of modern samples, all values are plotted in approximate stratigraphic position.

Almgreen Cay Formation	Grotto Beach Formation	Rice Bay Formation
Late Last interglacial	Peak Last Interglacial	Holocene
(~ 100 - 80 ka)	(~ 135 - 120 ka)	(< 5 ka)
Shell Height = 23.83 mm ± 2.09	Shell Height = 19.05 mm ± 1.56	Shell Height = 22.05 mm ± 2.06
Shell Area = 208.81 ± 30.23	Shell Area =136.38 ± 17.95	Shell Area = 166.67 ± 27.32
Axial Ribs = 1.29 ± 1.88	Axial Ribs = 5.13 ± 0.85	Axial Ribs = 5.71 ± 0.77

Figure 8. A summary of morphometric characteristics of Cerion land snails from the three youngest formations in San Salvador. Snails from stratigraphic units can be differentiated based on increasing size (Grotto Beach, Rice Bay, Almgreen Cay), and on the degree of ribbyness (Almgreen Cay = non-ribby; Rice Bay and Grotto Beach = highly ribbed).

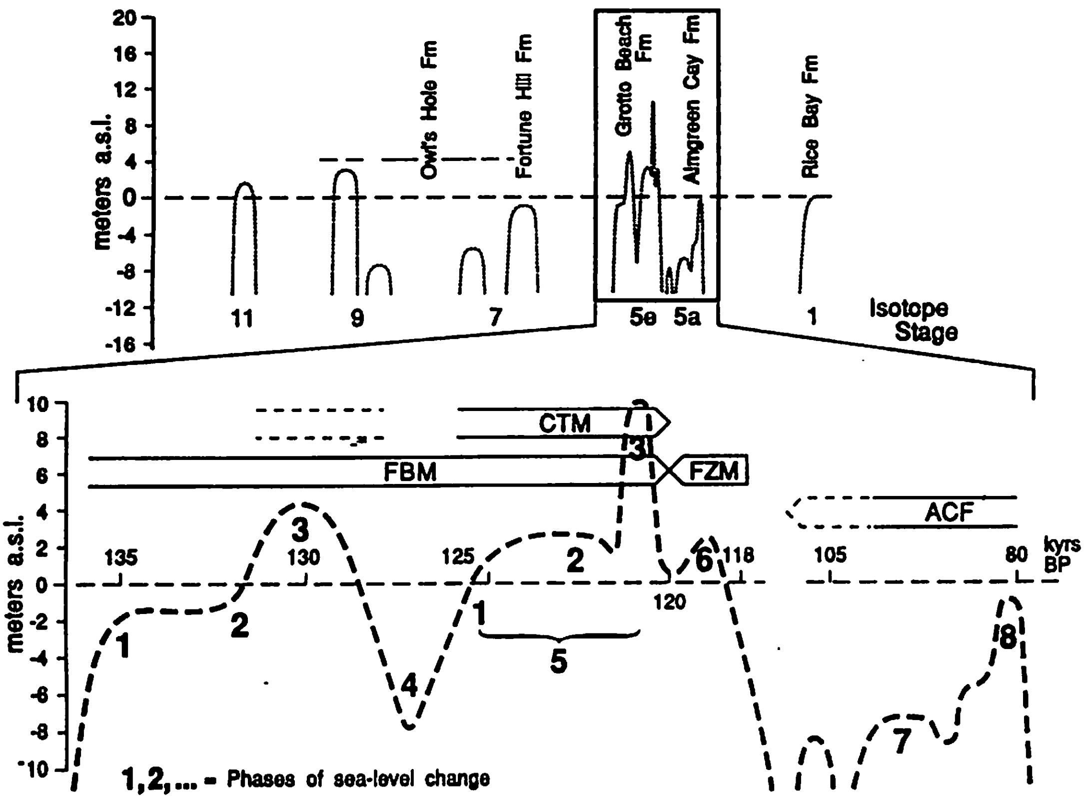


Figure 9. Late Quaternary sea-level curve inferred from stratigraphic and chronometric data presented in this paper. The elevation of the mid-5e regression (#4) is inferred.

The Cockburn Town Mb (CTM, phase II/?2-4). The character of the Cockburn Town reef is well documented (see Chen et al., 1991 for citations). The reef matrix at Cockburn Town surprisingly yields numerous thinly-coated ooids.

At Cockburn Town reef whole-rock A/I ratios average 0.48 ±0.00 (n=2) which equate with in situ corals dated at 123 ka (Chen et al., 1991). Although no clear stratigraphic relationship between the CTM and the FBM 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 offshore reef growth was synchronous with at least part of FBM (see Sea-Level History).

We have observed a disconformity within the reef throughout the famous exposure at Cockburn Town. Stratigraphic evidence of a double transgression during Substage 5e has been signaled elsewhere (see Hollin and Hearty, 1990 for discussion). A minor regression (-8m to -10m?) of a few thousand years may also be represented by island-wide protosols observed in Bermuda (Hearty et al., 1992) and in FBM outcrops.

The Fernandez Bay Mb (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). 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.

The 10 FZM sites average 0.41 ±0.04 (Table 3). 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 suggests a somewhat younger age than the underlying CTM.

FZM rocks contain more bioclasts than the FBM and lack the thickly coated ooids. Also, they are clearly better lithified than the younger North Point oolite.

The Almgreen Cay Fm (ACF, Phase III) forms high promontories (e.g., the Bluff, Almgreen Cay (type locality) and Crab Cay) on the eastern headlands of San Salvador Island. The ACF with its upper and lower members is commonly bounded at its base by reefal sediments (exposed best at Crab Cay) associated with ca. 135 ka U-series dates (Carew et al., 1984), and capped by terra rossa paleosol. Both members are composed of weakly cemented, yellowish grainstones, that contain as much as 85% of well-preserved bioclastic grains of primary mineralogy. Finely crystallized equant spar, occurring at grain contacts and as nonisopachous rims, ("grain-skin cement"; Land et al., 1967), suggests that diagenesis of the ACF took place in the fresh-water vadose zone under a dry climate (cf. Ward, 1973). The ACF was deposited in an eolian setting with sea level lower than today as demonstrated by the large eolian foresets which systematically dip below the modern datum. An extensive protosol containing Cerion and pisoliths separates the formation into two members. The upper member is capped by a complex protosol and a red paleosol.

Whole-rock AAR ratios (0.30 ±0.03 (n=4)) suggest a considerably younger age for the ACF as compared with the average 123 ka old (Chen et al., 1991) Cockburn Town Mb (A/I = 0.48).

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 Mb by the absence of beach deposits and by having a finer sparry cement.

The Rice Bay Fm - North Point Mb (NPM, Phase IV/1). In addition to the type section, the NPM has been identified at a few localities around 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 less represented. The thinly-coated ooids may have formed on the broad shelf, northwest of the present deposits. Petrological and sedimentological characteristics have been previously discussed (White and White, 1990; White and Curran, 1985; 1988). The NPM is capped by an orangish-tan sandy soil deeply developed in dune swales, containing pisoliths and Cerion landsnails.

A/I ratios in whole-rock samples average 0.24 ±0.01 (n=2), coherent with a 5,345 YBP whole-rock ^{14}C age (Carew and Mylroie, 1987). Cerion average 0.25 ±0.01 (n=2) from the overlying soil.

The NPM differs from other oolites (FBM and FZM) being less lithified, having more pristine sedimentary structures (White and Curran, 1988) and by the absence of calcrete-infilled root molds.

The Hanna Bay Mb (HBM, Phase IV/2) is composed of a weakly cemented yellowish limestone that forms small ridges and sea cliffs that are anchored on the NPM and Pleistocene headlands. The HBM contains both dune and beach facies (Carew and Mylroie, 1985; White and Curran, 1985, 1988). It is also capped locally by a Cerion-rich soil showing a dark brown, organic-rich lower horizon, that has yielded Lucayan artifacts. HBM limestones are generally made of skeletal grains and peloids. The grains are bound by low-Mg calcite cement that is common in the beach facies but virtually absent from the eolianites.

HBM whole-rock A/I ratios average 0.19 ±0.02 (n=2), which is compatible with the 3210 YBP whole-rock ^{14}C age obtained by Carew and Mylroie (1987). However, the sizable percentage of ooids

(~30%) probably reworked from the NPM (Kindler and Hearty, 1992), could generate slightly "old" ^{14}C and AAR ages. Cerion snails from the overlying soil yield a youthful average A/I of 0.11 ±0.03 (n=2).

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 (probably derived from the destruction of the NPM). Poor lithification and numerous pink Homotrema grains are helpful field criteria for distinguishing this unit from the FZM of the Grotto Beach Fm.

The East Bay Mb (EBM, Phase IV/3) is a coastal beach/dune ridge of submodern age, anchored on the HBM and covered by moderately thick overgrowth of woody vegetation. At the type locality in East Bay south of Hanna Bay (Fig. 1 and 2), the newly named EBM is catenary on the HBM headlands demonstrating its younger age. The EBM is capped by a thin and organically enriched, tan-brown soil with abundant Cerion. The petrology of the unit is similar to that of the HBM from which it appears to be largely recast.

DISCUSSION OF THE WHOLE ROCK AMINO ACID DATA

On San Salvador Island, Aminozones named A, C, E, F and G are tied to the Holocene (A), the late last interglacial (C), the early last interglacial (E), and two middle Pleistocene events (F and G) (Table 1). The whole-rock ratios of 0.48 from the Cockburn Town reef are equated to a U-series age of 123 ka, while an island-wide range of 0.56 to 0.43 (n = 34) for Aminozone E is representative of the peak last interglacial period (135 ka to 120 ka) between FBM and FZM times.

By direct comparison (Figure 5) of the whole-rock data from San Salvador and Bermuda (Hearty et al., 1992), correlated via U-series ages of 125 ka, we have estimated the ages of Pleistocene deposits. These are minimum age estimates for A/I ratios younger than 125 ka, and maximum ages for older ratios since the slope of the San Salvador curve would tend to be greater (dashed line in Figure 5) due to its warmer climate (Hearty and Aharon, 1988). Thus, the minimum age of Aminozone C (ACF; 0.30 ±0.02) is 63 ka. The ACF presumably equates with the Southampton Fm in Bermuda at 85 ka (Vacher and Hearty, 1989) based on its morphostratigraphy and its post-5e AAR ratios. Whole-rock ratios also suggest middle Pleistocene aminozones are ≤385 ka and ≤205 ka, but a limited number of well-preserved samples inhibit precise age estimates.

BIOSTRATIGRAPHIC SUPPORT OF THE LITHOSTRATIGRAPHY

We have observed abundant fossil *Cerion* in the terrestrial Quaternary deposits of San Salvador Island that appear, through time, to have varied rapidly enough in morphology to provide a useful tool for stratigraphic correlation (Schellenberg and Hearty, 1991; submitted). Morphologic changes in *Cerion* (n=306) were measured from 13 distinct stratigraphic units (Table 4).

Univariate, ANOVA, K-mean, cluster and factor analyses reveal the major discriminating factors to be general body size and degree of axial ribbing. Factors 1 and 2 are based primarily on size and ribbing characteristics, and when plotted (Figure 6) indicate the differences between Grotto Beach and Almgreen Cay snails are significant, while Rice Bay snails overlap both groups.

Cerion groups are distinguished first, on the basis of size, and secondly, on the basis of ribbyness. *Cerion* from the Grotto Beach Fm (Figures 7 and 8) are smaller and possesses a high degree of ribbing. ACF Cerion have less axial ribbing and a wide morphologic variation. Holocene *Cerion* are heavily ribbed, intermediate in size, and originate from deposits without a capping paleosol. The profound differences between GBF and ACF snails provide further support for their independent formational status.

SEA-LEVEL HISTORY

A sea-level scenario for San Salvador Island is presented in Figure 9. It begins with the Owl's Hole and the Fortune Hill Fms that may have occurred within the same interglacial, but are separated by a significant amount of time according to the AAR ratios. OHF and FHF sea-level elevations remain uncertain but are certainly near present on the basis of the interior position of their ridges. AAR ratios equate FHF with the Belmont Fm of Bermuda which is tied to a sea level of ca. 2.3m (Hearty et al., 1992).

The last interglacial transgression is characterized by oolitic limestones, reefs, and an oscillating, high sea level (Figure 9). In order for multiple ridges to occur during the same interglacial period, a mechanism is required that accounts for 1) the sediment buildup offshore, and 2) the energy to transport the sediments to land. The high inner ridges of San

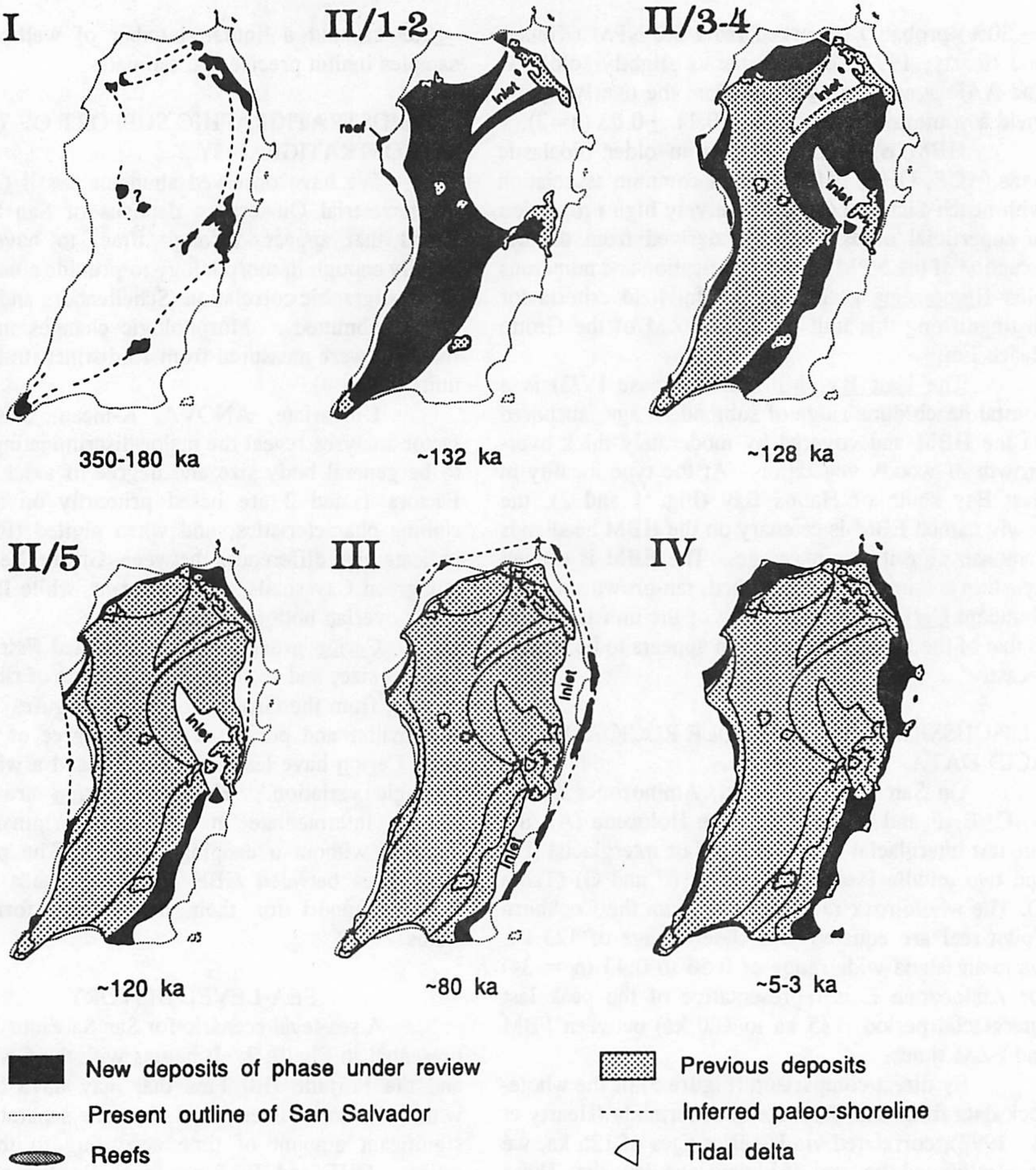


Fig. 10 -- Series of maps showing the geological evolution of San Salvador between the middle Pleistocene and the present.

Salvador certainly reflect active production of sediment due to the extensive shelf width. Shoreline progradation and concomitant reduction of shelf area controlled subsequent landform size (ridges progressively smaller seaward) and petrographic composition (reduction in percentage of ooids toward the coast). This transition occurred during the last interglacial sea-level highstand and illustrates the importance of the degree of platform flooding as a controlling factor of the petrography of Bahamian surficial deposits (Kindler and Hearty, 1992). An inferred last interglacial sea-level scenario (Figure 9) is as follows: (1) post-glacial rise of sea level onto the exposed, broad shelf; (2) formation of ooids during stable seas circulating across shallow platform areas (eg. Joulter Cays, Harris, 1979); (3) rise of sea level providing energy to transfer sediments landward into ridges (Phase II/1-2?); (4) a several meter fall of sea level to stimulate a brief dune buildup (on steeper coasts) followed by protosol formation and slope erosion; (5) repeat of 1, 2, and 3 (Phase II/2-4?); (6) minor stillstand (Phase II/5) at approximately 2.5m (FZM). The close of Stage 5 (5c - 5a) signaled a rise of sea level at a lower-than-present datum (7) for some time forming ACF (Phase III), with perhaps a final rise to near present (8) as observed in Bermuda (Vacher and Hearty, 1989). Our views on Holocene sea level depositional mechanisms correspond to those discussed in Kindler (1991; 1992). Landscape evolutionary snap-shots occurring as a result of sea-level changes are presented in Figure 10.

DISCUSSION

Bermuda and San Salvador share similarities and differences (Hearty, 1992) but nonetheless provide examples of the growth of stable carbonate-platform islands. This growth occurs mainly by lateral accretion (Vacher, 1973), and is dependent on sea-level elevation, antecedent topography, and the orientation and geometry of the shelf margin.

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. Hurricanes provide the primary sediment transport mechanism contributing to the growth of Bahamian islands.

Ooid formation occurs during major transgressive cycles where platform flooding is extensive (e.g., FBM) while skeletal and peloidal sediment are tied to platform-marginal flooding events (e.g. ACF). Stage 5e demonstrates that through progradation, the sediment type evolves from oolitic (FBM) to peloidal/bioclastic (FZM) as the shelf narrows.

The lateral growth of Bahamian islands on carbonate platforms appears to be self-regulating: the greater the lateral growth, the smaller the source area for sediment production that is required for growth, hence, smaller ridges through time. The growth ceases when the shelf becomes to steep and narrow to sustain the manufacture and transport of sediments.

CONCLUSIONS

1) Four geomorphic phases (I through IV), each with subdivisions (1-5; a-d), are distinguished (Fig. 2).

2) The middle Pleistocene rock record is represented by the Owl's Hole and Fortune Hill Fms but further study is required to firmly resolve the question of age of these units.

3) The last interglacial period (sensu lato) comprises the multiple ridges and reefs of Grotto Beach Fm and the newly named Almgreen Cay Fm. The East Bay Mb has been added to the Holocene nomenclature.

4) Cerion landsnail morphology provides biostratigraphic support for lithologic and aminostratigraphic correlations.

5) Extensive or complete flooding of the platform results in ooid formation while marginal flooding results in predominantly bioclastic sediment formation.

6) Considering that globally high sea level is the primary mechanism for island growth, we suggest that Bahamian islands, as well as other stable, carbonate landscapes have experienced parallel and synchronous growth periods during the Quaternary.

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