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Cover Photo: Outcrop showing Pleistocene soil profile,
caliche crust, and rhizocretions,
San Salvador, Bahamas.
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LATE QUATERNARY GEOLOGY OF SAN SALVADOR ISLAND, and the BAHAMAS

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ABSTRACT

The results of our investigation of the geology of San Salvador Island have led to: development of a physical stratigraphy that is applicable to San Salvador, and also throughout the Bahamas; establishment of a cohesive depositional model for San Salvador Island, and the Bahamas; and production of a geologic map of San Salvador Island.

The geological development of the current Bahamian islands has been in response to Quaternary glacio-eustatic sea-level fluctuations that have produced short-duration (~10,000-15,000 years) high-stand depositional packages associated with sea level rise (continental deglaciation) and marine transgression of the platform tops, a period of still-stand accumulation, and regressive-phase deposition as the platform tops are again subaerially exposed as sea level falls in response to increasing continental glaciation. Subaerial exposure, pedogenesis, and karstification are the dominant geological processes during stands of sea level below -10 meters relative to current sea level, and this occupies the majority of the late Quaternary. The geological record of the Bahamian islands consists of: eolian facies of high-stand deposits that formed prior to the last interglacial (i. e. oxygen isotope substage 5e), a full transgressive through regressive-phase sequence deposited during the last interglacial, and transgressive and still-stand phase deposits of the current interglacial (Holocene, stage 1). Only the marine deposits formed during the sea-level highstand associated with deep-sea oxygen isotope substage 5e are exposed subaerially in the Bahamas today.

The stratigraphic column and geologic map presented here reflect our current understanding of the late Quaternary rocks of San Salvador Island.

INTRODUCTION

We have investigated the late Quaternary geological history of San Salvador Island by field and petrologic study of: 1) coastal outcrops along the entire perimeter of the island, 2) all quarries and roadcuts, 3) all offshore cays, 4) measured sections up the flanks of numerous interior ridges, 5) the wall rock of many flank margin caves that penetrate horizontally into the interior of ridges, and 6) the wall rock of numerous pit caves that penetrate vertically into the ridges. In addition, in an attempt to develop a geochronological framework we have obtained $^{234}U/^{230}Th$ ages of *in situ* fossil corals and cave speleothems, radiocarbon ages of whole-rock samples, paleomagnetic analyses of eolianites and paleosols, and amino acid racemization analyses of fossil *Cerion* from eolianites and paleosols. We also have investigated the geology of numerous other Bahamian islands including: North and South Andros, Bimini, Eleuthera, Great Exuma, Great Inagua, Long Island, New Providence Island, and Rum Cay. We have published the results of our work, as it has developed, in the Bahamian Field Station Symposia on the Geology of the Bahamas series, in a variety of field guides (Carew and Mylroie, 1985, 1989, 1994a; Carew et al., 1992), and in several journal articles and books. To save space here we have limited citations, and urge the reader to consult our recent publications for a thorough list of pertinent references (Carew and Mylroie, 1995a, 1995b)

The results of our investigation of the geology of San Salvador and elsewhere in the Bahamas have led to: establishment of a physical stratigraphy based on the geology of San Salvador that is applicable throughout the Bahamas; development of a cohesive depositional model for the islands of the Bahamas; and production of a geologic map of San Salvador Island.

DEPOSITIONAL MODEL

The current Bahamian islands have developed in response to Quaternary glacio-eustatic sea-level fluctuations (Figure 1). The rocks of the Bahamian islands have been produced during the brief (~10,000-15,000 years) highstands of sea level that have flooded the bank tops. The depositional packages consist of facies deposited during sea-level rise (continental deglaciation) and marine transgression of the platform tops, followed by a period of still-stand accumulation, and finally regressive-phase deposition as the platform tops are again subaerially exposed as sea level falls in response to increasing continental glaciation (Carew and Mylroie, 1995a, 1995b) (Figure 2).

Subaerial exposure, pedogenesis, and karstification are the dominant geological processes during stands of sea level below -10 meters relative to current sea level. Based on our understanding of Quaternary sea-level history from deep-sea cores (e.g. Shackleton and Opdyke, 1973; Chappell and Shackleton, 1986; Shackleton, 1987) and other sources (e.g. Bloom et al., 1974; Chappell, 1974; Matthews, 1973), the Bahama banks and islands have been exposed about 10 times longer than they have been flooded. Figure 1 shows a representative deep-sea oxygen-isotope curve. Noting the value associated with today's highstand (Stage 1), and that a change of 0.1 per mil in delta ^{18}O is assumed to be equivalent to ~10 m change in sea level (Fairbanks and Matthews, 1978) it is evident that the Bahama banks have been subaerially exposed for the majority of the time.

The geological record of the Bahamian islands consists of: eolian facies of high-stand deposits that formed prior to the last interglacial (i. e. oxygen isotope substage 5e), a full transgressive through regressive-phase sequence deposited during the last interglacial, and transgressive and still-stand phase deposits of the current (Holocene, stage 1) interglacial (Carew and Mylroie, 1995a, 1995b). Because of the tectonic stability and slow isostatic subsidence of the Bahamas during the Quaternary (Carew and Mylroie, 1994c) only the marine deposits formed during the sea-level highstand associated with deep-sea oxygen isotope substage 5e (see Figure 1) are exposed subaerially in the Bahamas today.

STRATIGRAPHY

Relatively few stratigraphic columns have been proposed for the exposed rocks of

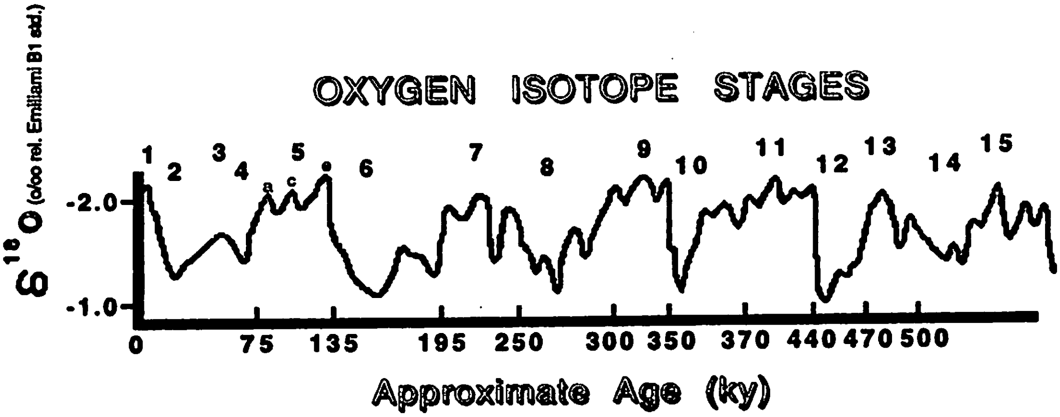

Figure 1. Graph of a representative deep-sea oxygen isotope curve for the past half million years (modified from Shackleton and Opdyke, 1973). Odd numbered stages are interglacials (sea-level highstands); even numbered stages are glacials (sea-level lowstands). Stage 1 is the present highstand; stage 2 is the Wisconsin lowstand estimated to have been at - 125 m; the acme of the stage 5 (substage 5e) sea-level highstand is estimated to have been at ~+ 6 m.

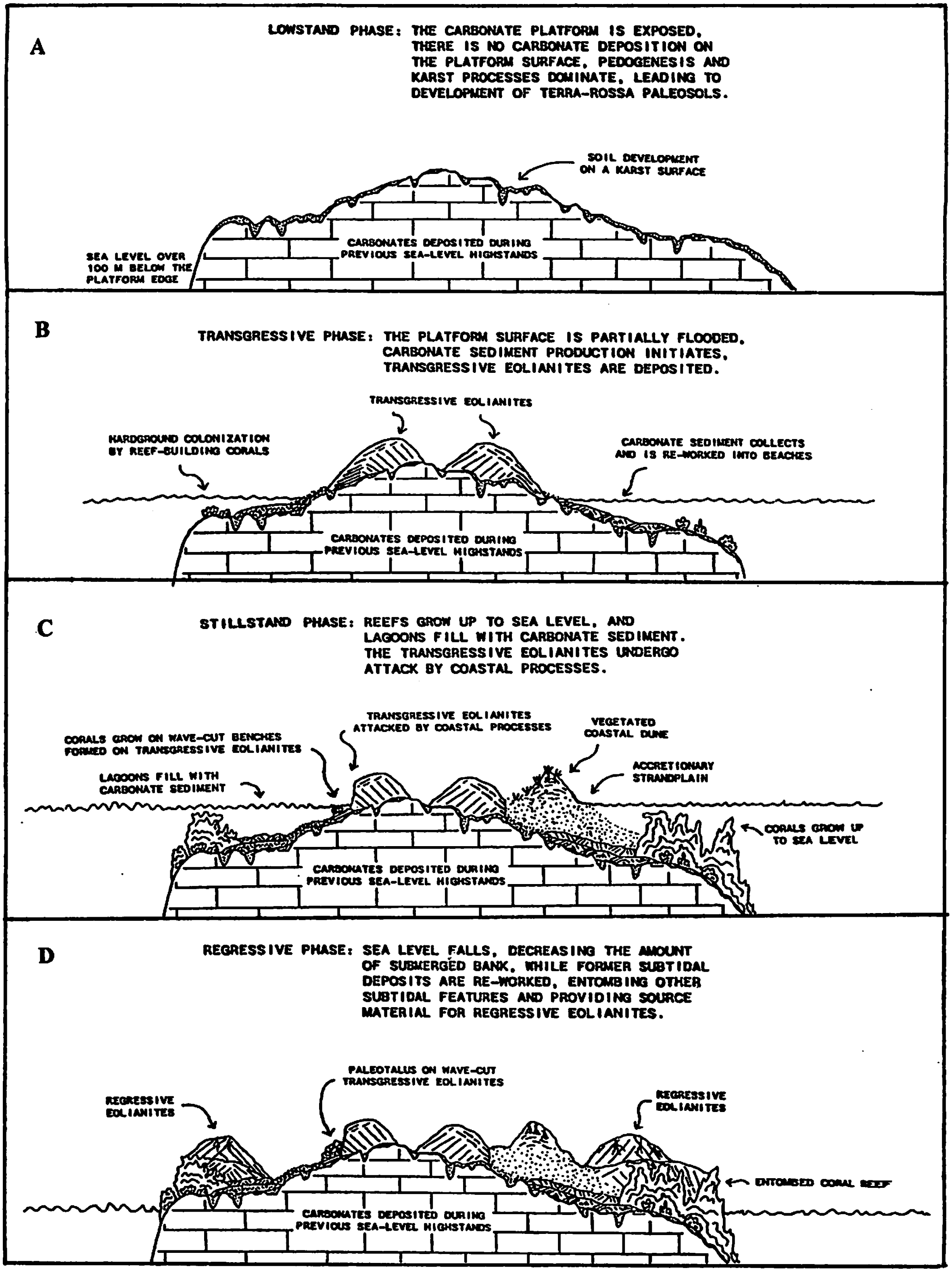

Figure 2. Illustration of the four stages of development of Bahamian Islands during each glacial/interglacial sea level fluctuation. During highstands the islands are the highest portions of the steep-walled banks with quasi-flat tops that are not inundated. During lowstands (below - 10 m) the entire platforms are the islands. (A) Lowstand phase - sea level > 10 m below present sea level, and only dissolution and pedogenesis are significant processes. (B) Transgressive phase - sea level is above - 10 m and the platform tops are being inundated by the sea as it rises to its acme. (C) Stillstand phase - sea level hovers around its maximum elevation (usually for ~ 10 ky to 15 ky) and reefs build-up and lagoons fill. (D) Regressive phase - sea level falls and eventually descends below the platform top.

Bahamian islands. Beach and Ginsburg (1980) assigned all of the late Pliocene through Quaternary rocks in the Bahamas to a single unit, the Lucayan Limestone, which extends back 2.6-2.7 million years (upper late Pliocene) (McNeill et al., 1988). Studies of the surface geology of San Salvador Island led to the abandonment of the Lucayan Limestone in favor of a more detailed set of units (Figure 3, Table 1). The first proposed stratigraphic column for the exposed rocks of a Bahamian island was that of Titus (1980). He interpreted the rocks as Pleistocene deposits that were laid down during sea-level regression from highstands. He made no suggestion concerning when in the Pleistocene they were deposited, and he indicated only that those units rested on pre-Pleistocene biomicrite. Study of the subsurface geology of the Bahamas indicates that such rocks (lowest Lucayan Limestone and unnamed units below) are at least 35 meters below present sea level on San Salvador (Supko, 1977; McNeill et al., 1988).

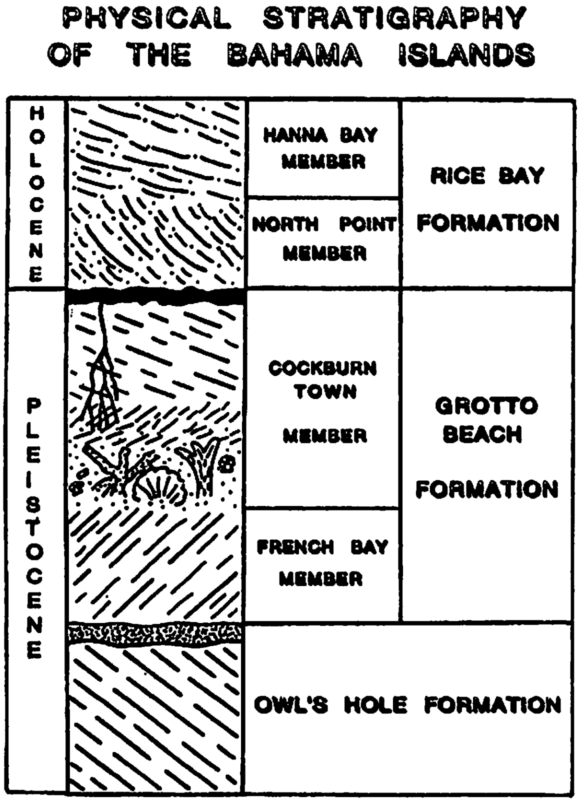

Figure 3. Lithostratigraphic column for San Salvador Island, and the bahamas (from Carew and Mylroie, 1995a). In the field, individual units are not necessarily seen stacked atop one another, but are often found lateral to one another. The thin stippled and black layers are terra rossa paleosols, and they separate deposits formed during separate glacio-eustatic sea-level highstands, but where there are no intervening deposits they may represent the total time of one or more complete glacio-eustatic sea-level cycles.

A few years later, Garrett and Gould (1984) published a detailed depositional history of New Providence Island, but they did not propose a physical stratigraphy. They proposed phases of deposition, but did not tie them to a precise chronology or stratigraphy. The following year, we (Carew and Mylroie, 1985) proposed a revision to the stratigraphy of San Salvador (Table 1) because we recognized that: (1) much of the rock assigned to the Grahams Harbour Limestone by Titus is Holocene rather than Pleistocene; (2) the rock cited by Titus as the type section for the Grahams Harbour Limestone does not correlate with the majority of rock assigned to that unit; (3) Titus had failed to recognize an older Pleistocene eolianite beneath the Grotto Beach Limestone at its type locality and elsewhere; (4) substantial portions of the rock record on San Salvador were deposited during the transgressive and stillstand phases of sea-level highstands, rather than only during the regression.

Later, Titus (1987) revised his stratigraphy to accommodate then-current information (Table 1). Later, we revised our stratigraphy because amino-acid racemization (AAR) data had been utilized to define parts of our previous stratigraphic column (Carew et al., 1992). Recently, through the use of morphostratigraphy and amino acid racemization data Hearty and Kindler (1993) proposed five additional stratigraphic units as a refinement to our 1985 stratigraphy (Table 1). Although their amino-acid zonation may be valid, none of the proposed new lithostratigraphic units can be recognized in the field, as they are based only on AAR data (Carew and Mylroie, 1994b, 1995c). Currently, the only workable, physical stratigraphy for San Salvador Island, and throughout the Bahamas, is that of Carew and Mylroie (1995a) (Figure 3, Table 1).

The late Quaternary stratigraphic column of the Bahamian islands consists of three major units (Figure 3). As each of these

Table 1. Comparison of stratigraphic columns proposed for San Salvador Island, and the Bahamas.

AGE	OXYGEN ISOTOPE STAGE	Titus 1980[1]	Carew and Mylroie 1985	Titus 1987	Hearty and Kindler 1993	Carew and Mylroie 1995a
HOLOCENE	1	"Recent sand"	Rice Bay Formation Hanna Bay Mbr North Point Mbr	Unnamed Holocene	Rice Bay Formation East Bay Mbr[2] Hanna Bay Mbr North Point Mbr	Rice Bay Formation Hanna Bay Mbr[3] North Point Mbr
PLEISTOCENE	3		Grotto Beach Formation Dixon Hill Mbr[2]	'Granny Lake' Oolite		(no deposits of these ages)
	5a	Grahams Harbour Limestone		Dixon Hill Limestone[2]	Almgreen Cay Formation[2] Upper Mbr Lower Mbr	
	5e	Grotto Beach Limestone	Cockburn Town Mbr French Bay Mbr	Grotto Beach Limestone	Grotto Beach Formation Fernandez Bay Mbr[2] Cockburn Town Mbr French Bay Mbr	Grotto Beach Formation Cockburn Town Mbr[4] French Bay Mbr
	7, 9, 11, or earlier		Owl's Hole Formation	Unnamed Pre-Sangamonian	Fortune Hill Formation[2] Owl's Hole Formation	Owl's Hole Formation[5]

[1] Titus recognized the Grahams Harbour and Grotto Beach limestones only as Pleistocene, and he considered them to lie on an unnamed pre-Pleistocene biomicrite.
[2] units identifiable only through amino acid racemization data
[3] includes all material assigned to East Bay Mbr by Hearty and Kindler, 1993
[4] includes rocks assigned to Almgreen Cay Fm and Fernandez Bay Mbr by Hearty & Kindler, 1993
[5] includes rocks assigned to Fortune Hill Fm by Hearty & Kindler, 1993

depositional packages is bounded by an unconformity that represents times of low sea level, they are allostratigraphic units (North American Commission on Stratigraphic Nomenclature, 1983). The oldest exposed surficial rocks in the Bahamas are assigned to the Pleistocene Owl's Hole Formation (Figure 2). This unit consists of eolianites capped by a terra rossa paleosol that is, in some places, overlain by younger Pleistocene deposits. The sea-level highstand(s) during which these older eolianites were deposited has not been conclusively established, but based on presumed isostatic subsidence rates, and the glacio-eustatic sea-level curve for the late Quaternary (Figure 1), they most likely represent deposition during one or more of oxygen isotope stages 7 (~220 ky), 9 (~320 ky), or 11 (~410 ky).

Overlying the Owl's Hole Formation is the Grotto Beach Formation which consists of transgressive-phase eolian deposits (French Bay Member), and terrestrial and marine stillstand-phase deposits plus regressive-phase beach and eolian deposits (Cockburn Town Member) formed during oxygen isotope substage 5e (~132 ,000 to ~119,000 years ago, Chen et al., 1991; 131,000 to 114,000 years ago, Szabo et al., 1994). This younger Pleistocene sedimentary package is usually sandwiched between terra rossa paleosols or calcretes. At many locations throughout the Bahamas, less complete depositional suites have been preserved from the substage-5e high stand, and in some cases only the eolianites can be seen.

Resting on the terra rossa paleosol that caps the Grotto Beach Formation there is an uppermost Holocene depositional unit (Rice Bay Formation) that consists of transgressive-phase eolianites (North Point Member) and stillstand-phase marine and eolian deposits (Hanna Bay Member) (Figure 3). As this tripartite stratigraphy of the Bahamas was initially developed through detailed study of the geology of San Salvador Island, the stratigraphic names are from locales there, and all type locations are on San Salvador, but the stratigraphy is applicable throughout the Bahamas.

GEOLOGIC MAP

Our geological map (Figures 4 and 5) presents data only from locales that we have observed and studied. Where extrapolation from known data would be required, we have chosen to refrain, and instead we depict those areas as undifferentiated. While some may find it unsatisfactory to designate substantial portions of the island as undifferentiated Pleistocene, we report the data as shown, because we have learned that to do otherwise is not valid. Other published maps contain significant errors because they relied on unsubstantiated extrapolation and/or inaccurate or unreliable data. Morphostratigraphic interpretation of the sequence of ridge emplacement is not reliable. Detailed sampling (using measured sections up

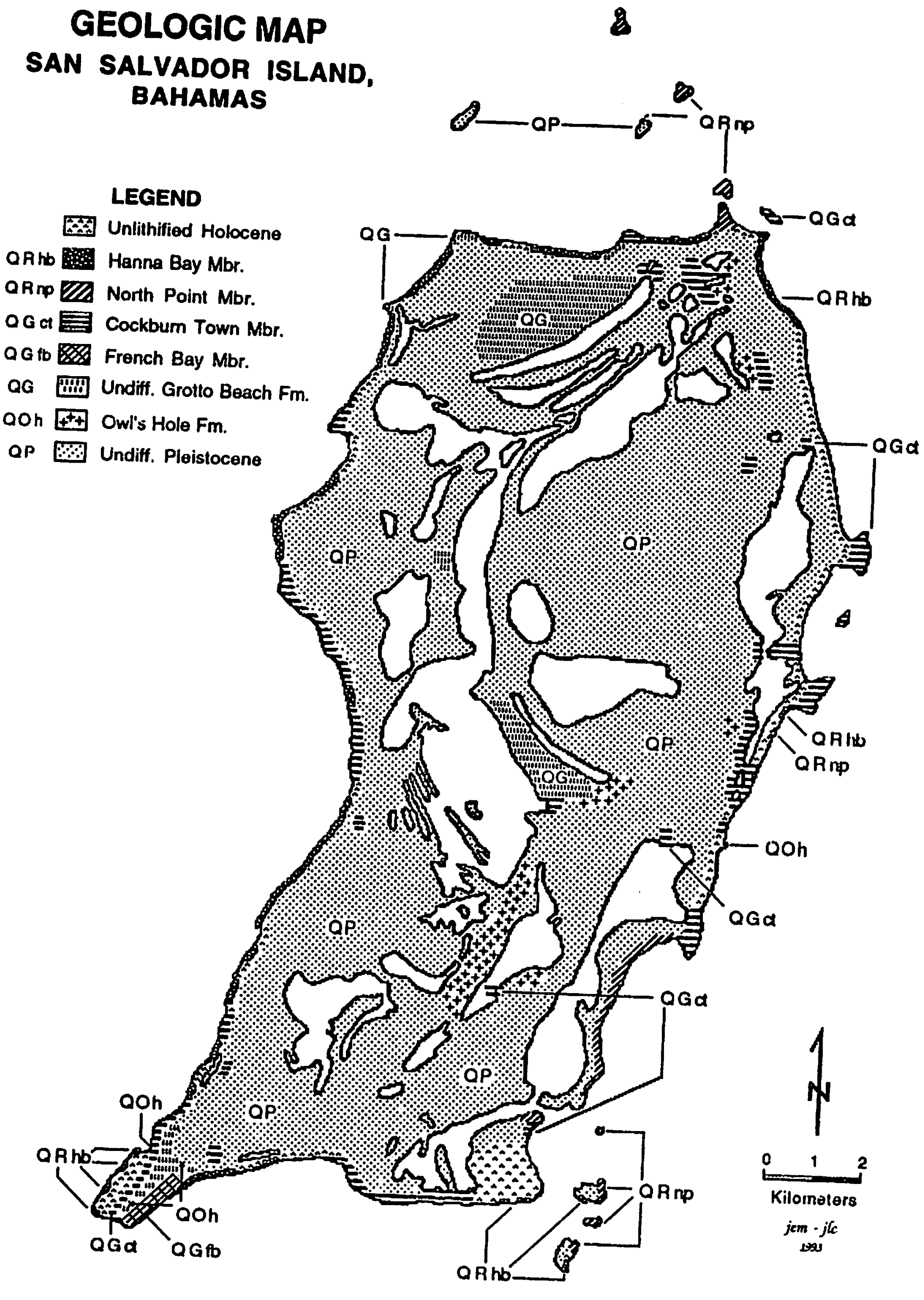

Figure 4. Geologic map of San Salvador Island (from Carew and Mylroie, 1995a). The patterns shown along the coast of the island represents the rock units exposed along that portion of the shore. The width of the pattern is necessary to depict the distribution of the various rock units, but does not necessarily reflect the actual inland distribution of those rocks. For example, in many places Pleistocene deposits are found immediately inland of Holocene outcrops that form a thin ridge along the shore. Because of the complexities that exist among paleosols and various deposits, much of the island is mapped as undifferentiated Pleistocene. Those rocks may belong to either the Owl's Hole Formation or Grotto Beach Formation.

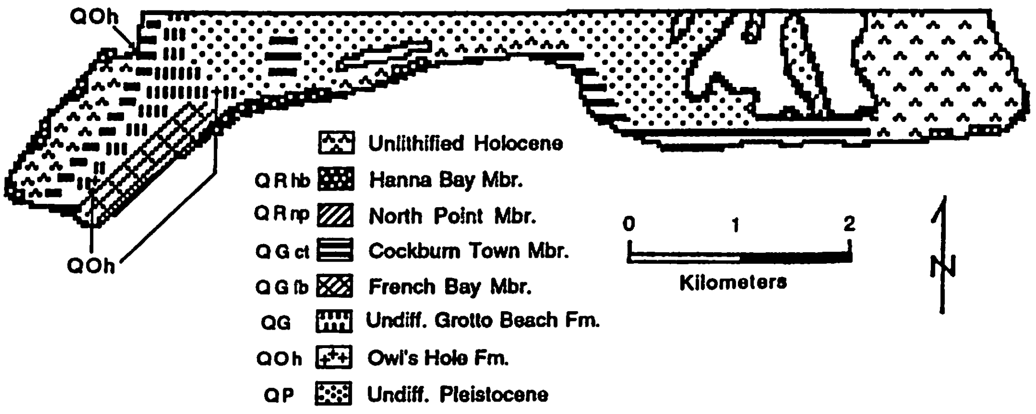

Figure 5. Enlargement of the south coast of San Salvador illustrating the complexity of the geology there, which may be hard to discern on Figure 4.

flanks of ridges, and from caves) has shown that many ridges consist of overlapping deposits from different interglacial highstands. Further, amino acid racemization analyses of *Cerion* and whole-rock samples yields estimates of age that are unreliable and cannot be used to support a stratigraphic interpretation that is otherwise unresolved. We have relied only on demonstrated field relationships to confirm stratigraphic relationships.

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