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Sea-Level Highstand Chronology from Stable Carbonate Platforms (Bermuda and The Bahamas)

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ABSTRACT

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A history of sea-level highstands representing the past 1.2 my is assembled from geological and geochronological data from Bermuda and the Bahamas. Outcrops of marine and eolian limestones exhibit sea-level indicators on tectonically stable islands. Because of the low-lying nature of the islands, they preserve a record of both highstand (limestone) and lowstand (paleosol) events. Geomorphology and sequence stratigraphy are critical for ranking deposit age, while U-series, amino acid racemization (AAR), electron spin resonance (ESR), and paleomagnetics have provided absolute and relative age estimates.

In Bermuda, two early Pleistocene marine sequences are estimated to be >700 ka and >880 ka. The younger of the two is associated with a +22 m marine terrace cut into the older Walsingham Fm, which exposes marine limestones at < +5 m a.s.l. During the latter half of the middle Pleistocene (Stages 11, 9, and 7; 500 to 180 ka), sea level rose above the present at least three times to approximately +4 m, +4 m, and +2.5 m, respectively. Stage 5e includes at least two major positive oscillations of sea level (early at +4 m and late at ≥ +6 m). The two 5e marine units are separated by an extensive, rubified protosol, interpreted as evidence of a minor regression (interstadial) of several thousand years. The late Sangamonian (Southampton Fm) is characterized by an extensive skeletal eolianite on high-energy shorelines, offlapped by a −1 m to +1 m marine deposit dated at *ca.* 85 ka. There is no evidence to support a Holocene sea level rising significantly above the present datum.

Unlike tectonic coastline and isotopic studies that require major assumptions of constant uplift and temperature/ice-volume/salinity in order to calculate ancient sea levels, precise elevations of paleo-seduced can be obtained from deposits on stable carbonate platforms. Regardless, the inexact models provided by deep-sea oxygen isotope and U-series dating of uplifted reef terraces are valuable to establish a framework for the timing, duration and relative magnitude of Quaternary high sea levels.

ADDITIONAL INDEX WORDS: *Sea level, marine limestone, islands, stratigraphy, amino acid racemization, electron spin resonance, paleomagnetics.*

INTRODUCTION

Many existing sea-level curves require either assumptions of constant uplift as in the case of New Guinea (BLOOM *et al.*, 1974) and Barbados (BENDER *et al.*, 1979) or temperature, ice-sea volume, and/or salinity calculations from oxygen isotopes measured on foraminifera in deep-sea cores (SHACKLETON and OPDYKE, 1973; CHAPPELL and SHACKLETON, 1986; SHACKLETON *et al.*, 1988). Ideally, to determine past sea-level highstands, littoral deposits from tectonically stable coastlines should be analyzed, eliminating the need for such assumptions.

Studies in Bermuda (LAND *et al.*, 1967; HARMON *et al.*, 1983; VACHER *et al.*, 1989; HEARTY *et al.*, 1992; MEISCHNER *et al.*, *in press*) and the Bahamas have advanced the ability to differentiate rock units of various ages and composition (HEARTY and KINDLER, 1993a,b; KINDLER and HEARTY, 1992, 1993). LAND *et al.* (1967) and HARMON *et al.'s* (1983) studies resulted in sea-level highstand curves compiled from the geological and geochronological evidence from Bermuda. VACHER *et al.* (1989) culminated 20 years of field studies by producing a geologic map of Bermuda. A summary of their findings and methods is available in VACHER *et al.* (*in press*). More recently, however, several advances in field and laboratory techniques (HEARTY *et al.*, 1992) have generated more data that have significantly revised the sea-level story in Bermuda. If we accept that U-series dates on tectonic coastlines and isotope records

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provide a reliable chronometric and amplitudinal framework for sea-level events, then placing sea-level deposits from stable carbonate platforms in such a framework becomes a more straightforward task.

Tectonic stability in Bermuda and the Bahamas is assumed from equal-age marine deposits that show no significant differences in elevation; both have apparently undergone similar, quiescent histories during at least the late Quaternary. Bermuda has deposits representing eustatic events of early, middle and late Pleistocene (VACHER *et al.*, 1989; HEARTY *et al.*, 1992), while the Bahamas emphasizes late-middle Pleistocene, late Pleistocene, and Holocene depositional records (CAREW and MYLROIE, 1985, 1987; CHEN *et al.*, 1991; LI *et al.*, 1989; HEARTY and KINDLER, 1993a,b; HEARTY *et al.*, 1993; NEUMANN and HEARTY, 1993, *in review*). Petrographic composition (oolitic *vs.* skeletal limestones) is clearly an important diagnostic feature related to the degree of platform flooding in the Bahamas (KINDLER and HEARTY, 1992, 1993). The reader is directed to these references for more detailed site and methodological information. Other sea-level curves from the Mediterranean (HEARTY, 1986) and southeast U.S. Coastal Plain (HOLLIN andHEARTY, 1990) provide additional support for the timing and the amplitude of sea level fluctuations.

Accurate paleo-sea-level benchmarks for Quaternary sea levels are important for many reasons: (1) to monitor the nature, magnitude and speed of climate and sea-level changes in the past; (2) to establish the concordance or discordance of astronomical, isotopic and climatic events; (3) to provide benchmarks from which the magnitude of uplift or subsidence in tectonically unstable zones can be calculated; and (4) to reduce the sole dependence on the Stage 5e, 125 ka, +6 m datum, which is of questionable validity.

GEOLOGICAL EVIDENCE FOR SEA-LEVEL HIGHSTANDS

The main objective of this paper is to review and summarize recent geological findings on the sea-level record, particularly as it relates to middle and early Pleistocene deposits on stable carbonate platforms. New data from Bermuda, and San Salvador, Eleuthera, and New Providence Islands, Bahamas have significantly revised existing curves. The geological approaches used for differentiating depositional events include geomorphic position of coastal ridges, sequence stratigraphy of marine and eolian deposits, petrographic composition, the degree of diagenesis of sediments, and development of soils and calcretes. Amino acid racemization data and published radiometric dates establish relative and absolute ages and confirm stratigraphic relationships. Later in this paper, stratigraphic and radiometric data are compared to deep-sea oxygen isotope records and U-series dated reef terraces on tectonic coastlines that offer a framework for the stable coastline data.

The Early Pleistocene

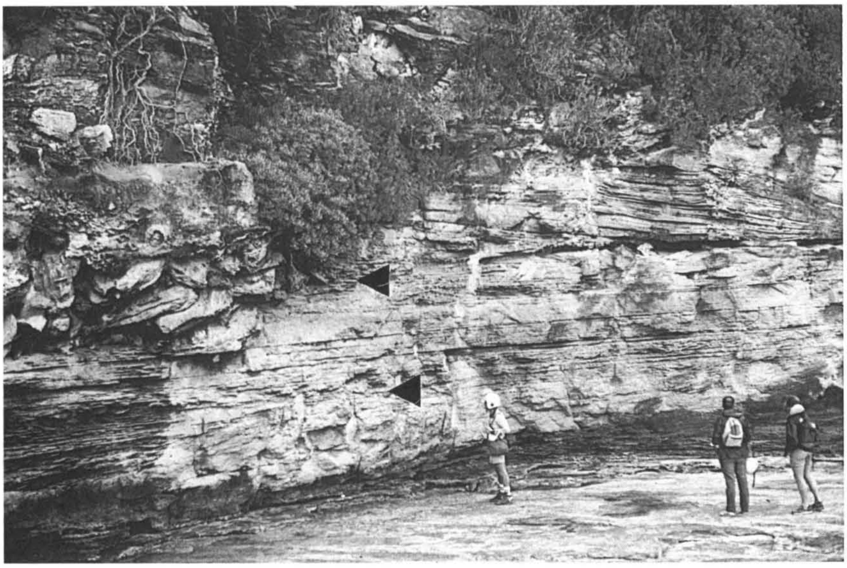
Bermuda

The Walsingham Formation's early Pleistocene age has long been suggested (LAND *et al.*, 1967) and recently confirmed by AAR (> 880 ka), ESR (>700 ka; HEARTY and VACHER, *in press*) and by reversed magnetic polarity (HEARTY *et al.*, 1992; HEARTY and KINDLER, 1993c; D.F. MCNEILL, *personal communication*). The extensively cavernous and largely eolianite outcrops of the Walsingham Fm around St. George's Island (Shore Hills Quarry, Stokes Point, and Mullet Bay) and in Government Quarry, are floored by low angle marine bedding at ≤+5 m (LAND *et al.*, 1967; VACHER, *personal communication*).

LAND *et al.* (1967) described a +22 m sediment-filled marine bench in Government Quarry (since completely removed) and attributed these deposits to the "Belmont Formation" (*sensu* BRETZ, 1960). Beach deposits from the +22 m level yielded AAR whole-rock age estimates of >700 ka (HEARTY *et al.*, 1992). Since this is a minimum age estimate, the deposits are probably early Pleistocene but post-dating the Walsingham Fm on which they are deposited.

BLACKWELDER (1981) similarly recognized an important early Pleistocene transgression to +25 m associated with the James City (North Carolina), Waccamaw (North and South Carolina), and Caloosahatchee Fms (Florida) along the southeast U.S. Coastal Plain. He/U ages from BENDER (1973; *unpublished*) place these deposits between 1.0 and 1.9 my. These early Pleistocene events were followed by a hiatus where coastal deposition did not apparently reach the present datum between 1.1 and 0.5 my.

In Bermuda, the Castle Harbour Geosol (VACHER *et al.*, 1989), a massive *terra rossa* paleosol developed on the deeply karstified surface of the



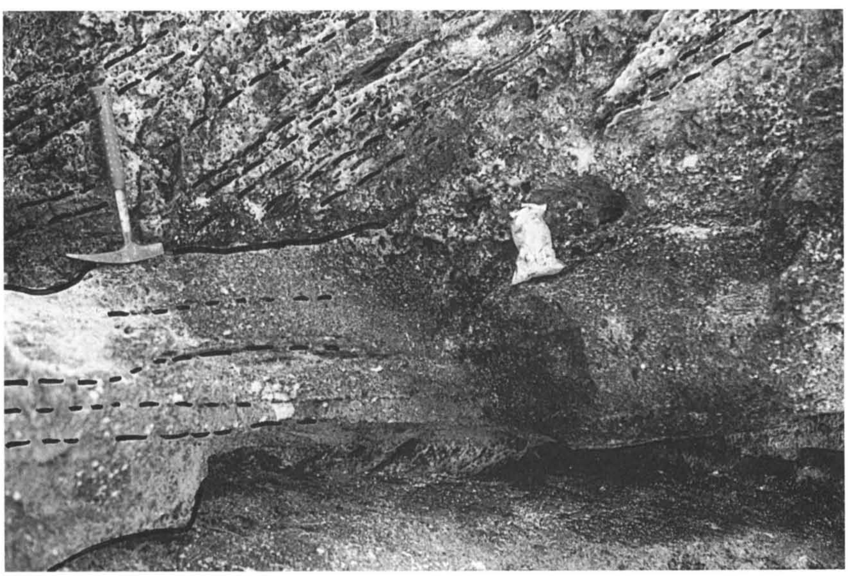


Figure 1. Photographs of the Hungry Bay section (A) on the south coast of Bermuda showing the sea level of the late Belmont Fm (arrow at +2.3 m), and the cliff cut in the section during the last interglacial (arrow at *ca.* +5.0 m). B is a photo of the Conyer's Bay section, Bermuda (see VACHER and HEARTY, 1989) showing beach deposits slightly above the present datum (high water at base of photo).

early Pleistocene Walsingham Fm represents this depositional hiatus separating the early and middle Pleistocene. In the Bahamas, well drillers recognize a highly-indurated, micritized surface on many islands at between −5 m and −20 m (E. RUSSELL, Freeport, Bahamas, *personal communication*), that may correspond to reversed paleomagnetism (Brunhes-Matuyama, 0.78 my) at similar depths on several islands (MCNEILL *et al.*, 1988; MCNEILL, 1989; MCNEILL, *personal communication*).

The Middle Pleistocene

Bermuda

The earliest appearance of the middle Pleistocene is at Bierman Quarry, the type locality of the Town Hill Fm (VACHER *et al.*, 1989). The Town Hill eolianites are divided into voluminous upper and lower members. These two units comprise nearly half of the volume of Bermuda implying events of considerable magnitude and duration. Marine deposits in the lower Town Hill occur at generally less than +5 m at Belmont Wharf (VACHER, *personal communication*) and along Front St. in Hamilton (Old Bus Garage). Upper Town Hill marine deposits occur at similar low elevations (< +5 m) at Whalebone Bay (MEISCHNER *et al., in press*), Devil's Hole (Harrington Sound), and at Red Hole (Paget Parish) (VACHER, *personal communication*). The upper and lower members of the Town Hill Fm have estimated AAR ages of 325–350 ka and 430–475 ka, respectively, and are thus correlated to Stages 9 and 11 (HEARTY *et al.*, 1992).

The Belmont Fm (Stage 7) is volumetrically less significant compared to deposits of Stages 9 or 5, intimating a shorter depositional interval on the shelf. Older Belmont eolianite ridges are positioned more interior on Bermuda, while younger south shore sites at Hungry Bay (Figure 1A) and Saucos Hill offer evidence of a Belmont sea-level higher than present at +2.3 m (HEARTY *et al.*, 1992). We have not observed the two higher-than-present Belmont sea levels, the earlier at ca. +1.5 m, and the latter at ca. +7.5 m identified by Meischner *et al.* (*in press*). The younger penultimate age of the late Belmont marine unit (average 204 ks) was confirmed by U-series (HARMON *et al.*, 1983), while AAR estimates for late and early Belmont are 190 ± 20 ka and 265 ± 30 ka, respectively (HEARTY *et al.*, 1992).

Bahamas, New Providence Island (Figure 2)

On New Providence Island, a basal unit in a quarry near Hunt's Cave predates the well known, more seaward penultimate interglacial ridges (GARRETT and GOULD, 1984). The lower unit (Figure 2A) is characterized by beach/dune facies in a highly-micritized oolitic limestone capped by a thick calcrete (> 25 cm) and a highly developed *terra rossa* paleosol. This "old oolite" at the northern margin of the quarry exposes beach facies with fenestrae at least +8 m a.s.l. No subtidal deposits are exposed in the section, but a conservative estimate of the actual sea level 3 m lower than highest fenestrae is reasonable, placing sea level of the old oolite at approximately +4 to +5 m. Because of its morphostratigraphic position landward of other middle Pleistocene dune ridges (GARRETT and GOULD, 1984; MUHS *et al.*, 1990), this unit must date from Stage 9 or older, perhaps Stage 11. GARRETT and GOULD (1984) did not recognize the old oolite at Hunt's Cave Quarry, a likely equivalent to the Town Hill Fm of Bermuda, perhaps because it was not exposed in the quarry during their studies over a decade ago.

Younger middle Pleistocene deposits in New Providence are the Blue Hill Ridge and the Water Works Ridges in Nassau (Figure 2B). The Blue Hill Ridge is deeply trenched by roadways at East Street and along Sir Milo Butler Road. Mainly forests are exposed in these half-kilometer cuts. Some horizontal and low-angle bedding is present at <+5 m, but no fenestral porosity (keystone vugs) has been observed. Morphostratigraphic position and facies relationships in the Blue Hill and Water Works Ridges are similar to those in the Belmont of Bermuda and the Fortune Hill Fm of San Salvador (HEARTY and KINDLER, 1993a,b).

MUHS *et al.* (1990) whole-rock U-series dated Blue Hill rocks at the East Street locality at 300 ka years, and a younger phase at Lyford Cay at 197 to 212 ka. Although the reliability of U-series dating of whole-rock limestones remains equivocal (KAUFMAN *et al.*, 1971), these ages generally support a pre-Sangamonian age of the Blue Hill and Water Works ridges (GARRETT and GOULD, 1984). The 300 ka date may be too old, and more likely the Blue Hill Ridge belongs to early Stage 7 (*ca.* 230 ka), while the Water Works Ridge (and lowest unit at Lyford Cay) phase would fit a late Stage 7 event. Unpublished whole-rock AAR ratios have confirmed the pre-Sangamonian age of these deposits.

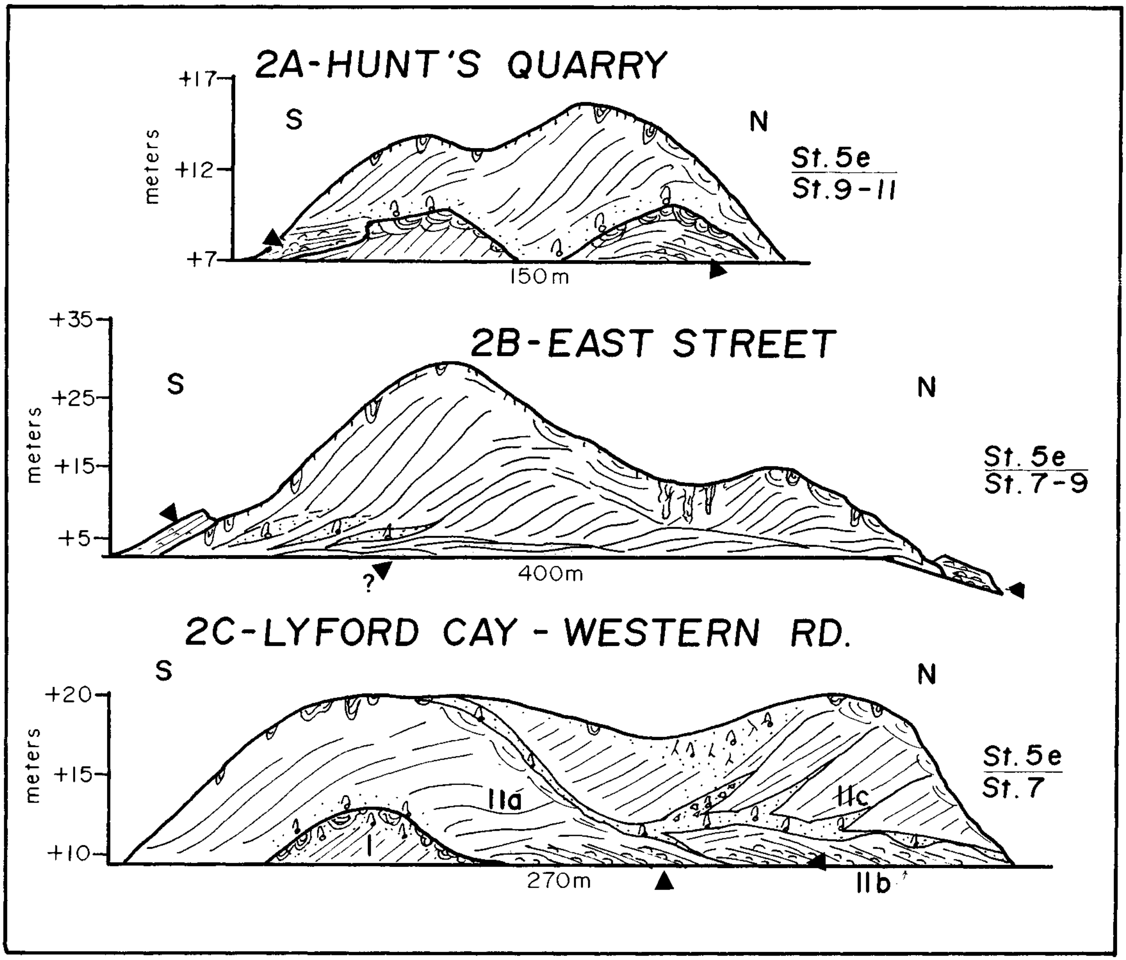


Figure 2. Stratigraphic sections from New Providence Island: A is of the Hunt's Cave Quarry with shoreline deposits in both the lower and the upper units. The older deposits are middle Pleistocene (Stage 9?) while the upper deposits are last interglacial (Stage 5e). B is a sketch of the East Street cut in central NPI. In addition to an abundance of foresets exposed, low-angle bedding is present at the base of the section, but keystone vugs were not observed. C is the Lyford Cay Western Road section (significantly revised from GARRETT and GOULD, 1984) showing at least two marine units low in the section, separated by an unconformity and reddish protosol. After the penultimate interglacial (I), three episodes of carbonate deposition bracketed by soils, occurred during the last interglacial: IIa = beach and dune; IIb = predominantly beach; and IIc = multiple penecontemporaneous pulses of eolian deposits.

Bahamas, San Salvador Island

Low angle bedding composed of very coarse, shelly sand is exposed near sea level in Lighthouse Cave in San Salvador Island. The Dixon Hill rocks that enclose Lighthouse Cave, formerly assigned an age of 70 ka (CAREW and MYLROIE, 1985, 1987), have been regrouped under the name, the Fortune Hill Fm (HEARTY and KINDLER, 1991, 1993a) in a middle Pleistocene position. These deposits are the latest of the penultimate interglacial and would thus correspond to the late Belmont Fm and the Water Works Ridge deposits of New Providence.

The Early Sangamonian

Bermuda

Both the north and south shores of Bermuda expose Sangamonian marine deposits that are grouped under the Rocky Bay Fm (VACHER *et al.*,

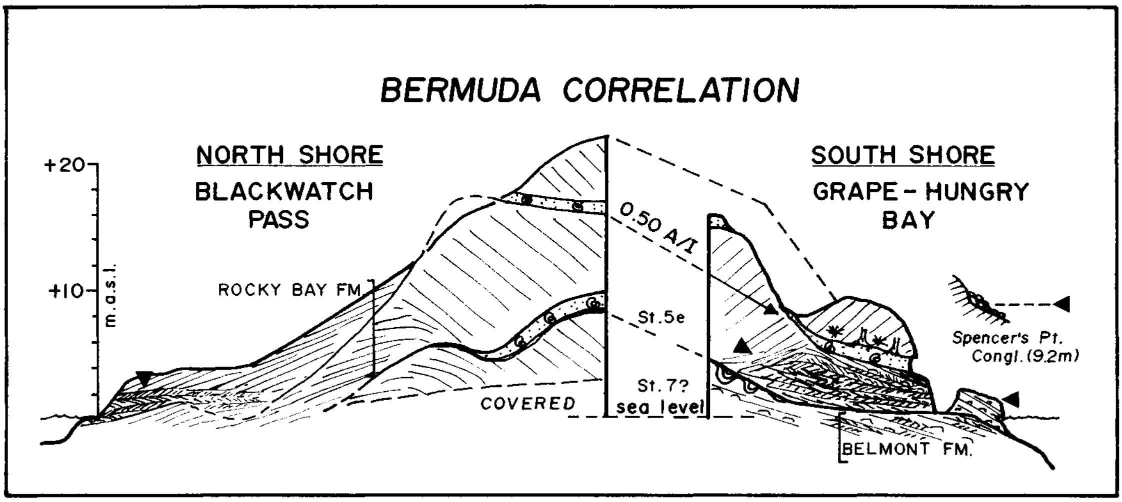


Figure 3. A proposed correlation between North and South Shore stratigraphic sections in Bermuda based on last interglacial stratigraphy and AAR ratios.

1989). However, it was unclear exactly what relationship existed between the rocks on the high-energy south shore and the low-energy north shore sites, particularly at Blackwatch Pass. Stratigraphy and 0.50 A/I ratios from the land snail *Poecilozonites* (HEARTY *et al.*, 1992), support a proposed correlation in Figure 3. The protosol bearing the *Poecilozonites* is recognized on the south shore as the Harrington soil and in the north as the upper protosol in Blackwatch Pass (Figure 3). Of the two early Sangamonian sea levels recognized in Bermuda, the early one rises to near +4.5 m at Rocky Bay, Grape Bay, and Hungry Bay (Figure 1A). The later one is associated with an ancient sea level +2.5 m on the north shore at Blackwatch Pass. An eolian facies of this unit caps the protosol at the crest of Blackwatch Pass and correlates with the smaller, coastal Pembroke dune at the type locality. At some point during isotope Substage 5e, probably late in the period, sea level rose again to between +5 and +10 m leaving conglomeratic deposits on older rocks at Spencer's Point. These deposits, previously identified as the Spencer's Point Fm (LAND *et al.*, 1967), have recently been attributed to the Rocky Bay Fm (HEARTY *et al.*, 1992).

The Bahamas, New Providence Island

At Lyford Cay (Western Road cut), two high marine oolites, whole-rock U-series dated at 128 ka and 117 ka, respectively, (MUHS *et al.*, 1990) are separated by a washed unconformity that translates upward into a well-developed protosol (Figure 2C). Both fenestral porosity and low-angle beach sets reach to above +8m elevation in the roadcut (see also GARRETT and GOULD, 1984) with the younger event (+8 m) being slightly higher than the older one (+5 m). The reddish protosol and calcrete represent a regression of some few thousand years. CHAPPELL and SHACKLETON (1986) estimated this regression to have fallen to at least −8 m around 124 ka. A third marine deposit, probably laid down during the latest regression from Substage 5e, outcrops on Lyford (or Simms) Cay to the north.

Bahamas—San Salvador Island

Like New Providence, San Salvador Island offers evidence of high Sangamonian deposits at +2 m to +4 m, at and landward of Cockburn Town Reef, and +7 m along Observation Tower Road (quarry midway between sea and observation tower). HEARTY and KINDLER (1993a) also identified younger regressive early Sangamonian beach deposits at *ca.* +2.5 m (Fernandez Bay Mb of the Grotto Beach Fm). The +2.5 m deposits may be the depositional "last gasp" of a declining energy threshold associated with falling sea level.

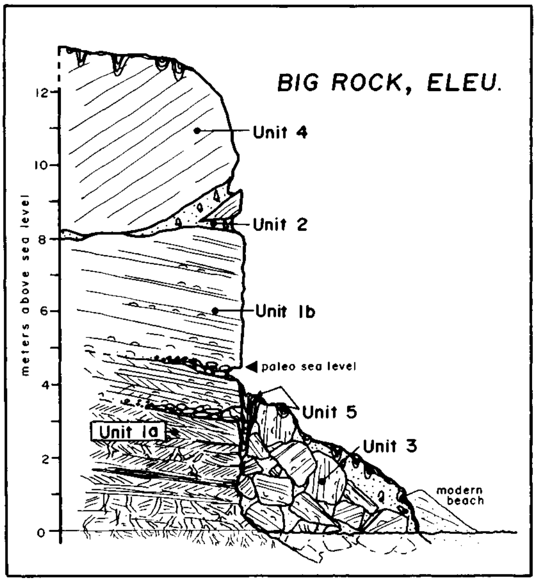


Figure 4. Stratigraphy of the Big Rock Section near Gregory Town, Eleuthera Island, Bahamas showing: Unit 1a = subtidal oolitic marine deposits up to +4.5 m; 1b = beach deposits; Unit 2 = protosol with *Cerion* land snails; Unit 3 = cliff talus eroded from Unit 1 during second transgression; Unit 4 = oolitic eolianites; and Unit 5 = capping protosol and *terra rossa* soil.

Bahamas—Eleuthera Island

The Big Rock Section, near Gregory Town (Figure 4) illustrates the complexity of the last interglacial. The lowest deposit (Unit 1) of the section is a shallowing-upward subtidal marine sequence (Unit 1a): at the base a heavily bioturbated zone, rising to herring-bone cross beds, and higher to tabular cross beds interrupted by beachrock conglomerate slumped into the subtidal. Interpreted sea level is at approximately +4.5 m. The subtidal sequence is overlain by a massive beach sequence over 3.5 m thick (Unit 1b). This sequence reflects the high-energy conditions of the open-Atlantic coastline of Eleuthera. A protosol with *Cerion* landsnails (Unit 2) capping the lower unit, indicates that carbonate deposition ceased for an extended period. Unit 3 is an indurated cliff talus, while Unit 4 is a thick eolianite above on Unit 2. A second protosol and a *terra rossa* paleosol (Unit 5) cap the sequence.

The Big Rock section reveals the following sequence: (1) transgression of sea level to +4.5 m; (2) formation of protosol during regression of sea level (the mid-interglacial regression must have been of sufficient time to allow for very complete induration of Unit 1 rocks); (3) sea-level rise causing erosion of the lower marine unit; (4) formation and deposition of capping eolianite with final early Sangamonian regression; (5) soil formation. Late Sangamonian skeletal eolianites lie a few hundred meters seaward of the early Sangamonian cliffs.

The Late Sangamonian

After the apparent deterioration of the climate at the close of Substage 5e, interglacial conditions were again achieved toward the end isotope Stage 5. There is abundant evidence from Bermuda (VACHER and HEARTY, 1989), Bahamas (HEARTY and KINDLER, 1993a,b), the Mediterranean basin (HEARTY, 1986), and the southeast Coastal Plain (SZABO, 1985; HOLLIN and HEARTY, 1990) that sea level rose sufficiently high during the late Sangamonian to flood platform margins, and to deposit sediments near the present coastline.

Bermuda

At Fort St. Catherine, HARMON *et al.* (1983) dated coral rubble from marine deposits on a platform slightly above present sea level at 85 ka. However, they interpreted these deposits as "cliff plasters" (*i.e.*, conglomerates deposited high above ambient sea level by storms), perhaps influenced by isotopic sea-level and tectonic coastline estimates which placed late Sangamonian (Substages 5c, and 5a) sea level at anywhere between −10 m to −20 m (SHACKLETON and OPDYKE, 1973; BLOOM *et al.*,1974; BENDER *et al.*, 1979).

Regarding Southampton eolian and marine deposits, VACHER and HEARTY (1989), and HEARTY *et al.* (1992) concluded that sea level indeed rose to between −1 m and +1 m, however briefly, between 75 ka and 85 ka (Substage 5a). Particularly convincing (VACHER and HEARTY, 1989), and contrary to the "cliff plasters" explanation is the presence of additional Southampton marine deposits at Conyer's Bay (Figure 1B), on the quiet, western lagoon-side of Bermuda where even raging storms could not generate much energy in the shallow water.

At both Fort St. Catherine and at Conyer's Bay, marine sediments offlap Southampton eolianites, indicating that the highest sea level must have occurred at the close of the depositional phase. Such a late, higher sea level may be explained by East Antarctic ice surge (MERCER, 1978; HOLLIN, 1980).

UNIBOOM data from the Bermuda platform (VOLLBRECHT, 1990) indicates that the island is surrounded by concentric, submerged Pleistocene eolianite ridges. These submerged ridges in the lower-energy North Lagoon, which are apparently younger than Substage 5e, may translate to subaerial eolianites on the high-energy south shore. To the north, the most seaward (eolian) ridge flattens at *ca.* −12 to −18 m. Coraliferous deposits from this zone provided U-series ages of 94, 98, 103 and 114 ka (VOLLBRECHT, 1990). A more platform-interior ridge intersects with island outcrops of the younger Southampton Fm dated at Conyers Bay and Fort St. Catherine at *ca.* 85 ka. Blueholes in the platform side of Eleuthera commonly have deep notches at −12 to −15 m. Substage 5c appears to have reached a maximum elevation of *ca.* −12 m during which (now submerged) dune ridges were built and notches were incised.

Bahamas, San Salvador Island

The Almgreen Cay Fm is correlated to the Southampton of Bermuda on the basis of morphostratigraphic position, proximity to the shelf edge, estimated age, and other characteristics discussed in HEARTY and KINDLER (1993a). The steeply-cliffed Almgreen Cay site exhibits distinctive lower and upper members separated by a well-developed protosol. The formation is capped by a complex, rhizomorph-rich zone and *terra rossa* soil, but displays no marine deposits. If thin, patchy marine deposits were laid down seaward of older eolianites, as at Conyer's Bay and Fort St. Catherine, Bermuda, the high-energy, open Atlantic setting of eastern San Salvador Island during the Holocene would unquestionably result in their expeditious removal.

The Holocene

The Holocene is scarcely represented in Bermuda by subaerial marine and eolian deposits but more abundantly so in the Bahamas. Stratigraphic equivalents of the North Point, Hanna Bay, and East Bay Mbs (CAREW and MYLROIE, 1985; KINDLER, 1992; HEARTY and KINDLER, 1993a) named in San Salvador Island are present on most islands. The early North Point member formed when sea level was several meters lower than today, while the Hanna Bay and East Bay Members equate with present sea level. Despite an active search over several years by the authors, there is no evidence for Holocene sea level rising above the present level in Bermuda or the Bahamas.

AMINOSTRATIGRAPHIC RECORD OF SEA-LEVEL CHANGES

U-series dates from last interglacial marine deposits constitute a "golden spike" along many coastlines of the world (KU *et al.*, 1974; BLOOM *et al.*, 1974; NEUMANN and MOORE, 1975; HARMON *et al.*, 1983; HEARTY *et al.*, 1986; HEARTY, 1991; CHEN *et al.*, 1991). Of equal importance to this study is the calibration for AAR ratios offered by these U-series dates. However, beyond the range of U-series, AAR is one of the only methods that can be used throughout the Quaternary for ranking and estimating the age of deposits.

The AAR method depends on the progressive decomposition of residual amino acids locked in carbonate matrices. While it has been demonstrated that a wide variety of shelled organisms (WEHMILLER *et al.*, 1988; MILLER and BRIGHAM-Grette, 1989) provide consistent results, it is also clear that whole-rock oolitic and skeletal limestones are equally suitable for correlation and age estimation (HEARTY, 1992; HEARTY *et al.*, 1992; HEARTY and KINDLER, 1993a).

An aminostratigraphic sequence in Italy (Table 1), based on the marine shell *Glycymeris*, is summarized in HEARTY *et al.* (1986), HEARTY (1986; 1987) and HEARTY and DAI PRA (1992). The early Pleistocene aminozones (mean A/I ratios from Table 1 in brackets) are represented by the Calabrian (Emilian) (A/I = 1.20) and the Sicilian (A/I = 1.00) Fms, the middle Pleistocene by three distinct units (A/I = 0.73, 0.61, 0.50), and the late Pleistocene by two depositional phases (A/I = 0.40, 0.30). Italian coastlines are tectonically active, however, so the aminostratigraphy is only useful in this case for reconstructing the number, timing and relative intensity of paleo sea-level events.

Along the southeast U.S. Coastal Plain, WEHMILLER *et al.* (1988) and HOLLIN and HEARTY (1990) distinguished similar AAR sequences (Table 1), although they were not in total agreement regarding some age interpretations.

In Bermuda (HEARTY *et al.*, 1992), whole-rock aminostratigraphy identifies two early Pleistocene aminozones (A/I = 1.11 and 0.92), three middle Pleistocene aminozones (A/I = 0.69, 0.56, 0.44), and two late Pleistocene aminozones (A/I = 0.27 and 0.23) (Table 1). The middle and late Pleistocene whole-rock aminozones are paralleled by aminozones determined from the land snail *Poecilozonites*. The early Pleistocene age of the Walsingham Fm is confirmed by reversed magnetic

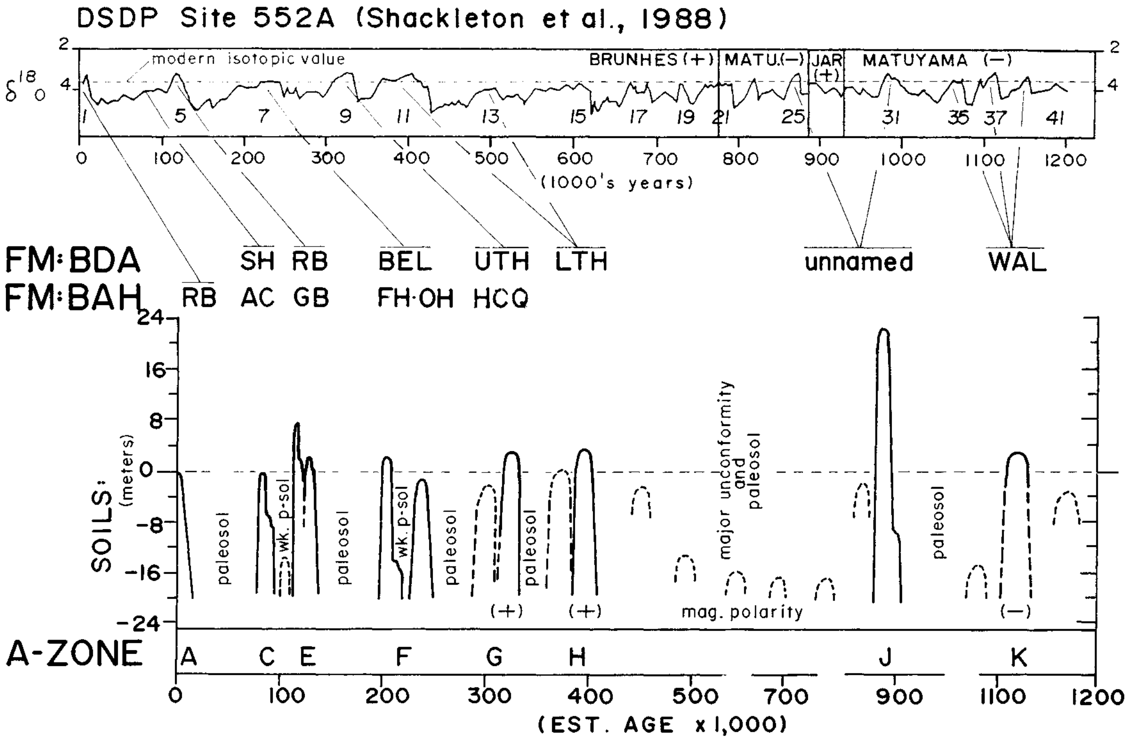


Figure 5. A. Oxygen isotope curve from DSDP site 552A (SHACKLETON *et al.*, 1988) showing interglacial excursions greater than or equal to the modern values. B. A proposed highstand sea-level curve for the Quaternary constructed from geological studies on stable carbonate platforms in Bermuda and the Bahamas. The chronology is derived from isotopic, U-series, paleomagnetic and AAR data.

polarity (HEARTY and KINDLER, 1993c; MCNEILL, *personal communication*), while early, middle and late Pleistocene aminozones are supported by electron spin resonance dates (HEARTY and VACHER, *in press*).

HEARTY and KINDLER (1993a) used whole-rock AAR ratios (Table 1) to confirm the stratigraphic sequence for San Salvador. The AAR data agree with available published radiometric data (CAREW and MYLROIE 1985, 1987; CHEN *et al.*, 1991) from the island. Mean whole-rock ratios for two middle Pleistocene, two late Pleistocene, and three Holocene units (including modern beach deposits) are, respectively, 1.06 and 0.68, 0.48 and 0.30, and 0.24, 0.19 and 0.09 (Table 1). The early Sangamonian average of 0.48 is subdivided into three separate aminozones with corresponding stratigraphic subdivisions at 0.50, 0.48, and 0.42.

In summary, aminostratigraphic records generated from marine deposits from widespread localities yield corresponding aminozones: two from the early Pleistocene, at least three from the later half of the middle Pleistocene, and a complex of several aminozones from the Sangamonian and Holocene.

INDEPENDENT SUPPORT FOR QUATERNARY HIGHSTAND EVENTS

The Deep-Sea Oxygen Isotope Record

Isotopic records from deep-sea cores (SHACKLETON and OPDYKE, 1973; SHACKLETON *et al.*, 1984, 1988; PRENTICE and MATTHEWS, 1988) reveal the more significant of glacial and interglacial events of the Quaternary (Figure 5A). Pleistocene interglacial stages with $\delta^{18}O$ values greater than the present include Stages 5e and 9, while Stages 7 and 11 generally lie nearer to the present Holocene value. Interglacial Stages 13 through 23 appear to fall short of the present isotopic datum

Table 1. *A comparison of amino acid racemization (AAR) ratios (mean, 1σ, and number of samples (N)) from Quaternary shoreline sequences in Bermuda, South Carolina, Italy and the Bahamas. There is a conspicuous gap in the AAR ratios between the early Pleistocene and the later middle Pleistocene that cannot be attributed to sampling bias (i.e., all observed marine deposits were sampled). This early-mid Pleistocene hiatus of 0.3 to 0.5 my has been discussed previously by* BLACKWELDER *(1981) and* HEARTY *et al. (1986). The AAR data indicated that marine sediments were deposited at or above present eight times during the Quaternary: twice during the early Pleistocene; three times during the later-middle Pleistocene; twice during the Sangamonian; and in several pulses during the present interglacial*

Bermuda[1] Poecilozonites	Bermuda[1] Whole-rock	South Carolina[2] Anadara sp.	Italy[3] Glycymeris	Bahamas[4] Whole-rock	Period	A-Zone
0.014 (1)	0.12 ± 0.01 (2)		0.12 ± 0.02 (4)	0.09 ± 0.02 (6) 0.19 ± 0.03 (2) 0.24 ± 0.01 (2)	Holocene	A
0.40 ± 0.04 (36)	0.23 ± 0.03 (3)	0.37 ± 0.02 (7)	0.29 ± 0.02 (11)	0.30 ± 0.02 (4)	late Pleis.	C
0.49 ± 0.03 (36)	0.29 ± 0.03 (12)	0.43 ± 0.05 (20)	0.39 ± 0.03 (56)	0.42 ± 0.03 (10) 0.48 ± 0.01 (2) 0.50 ± 0.04 (21)	late Pleis.	E
0.61 ± 0.05 (10)	0.49 ± 0.04 (11)		0.48 ± 0.02 (7)	0.68 ± 0.01 (3)	mid Pleis.	F
0.78 ± 0.04 (11)	0.56 ± 0.02 (11)	0.59 ± 0.08 (6)	0.58 ± 0.03 (33)	1.06 ± 0.12 (2)	mid Pleis.	G
0.91 ± 0.03 (9)	0.69 ± 0.01 (6)		0.73 ± 0.05 (3)		mid Pleis.	H
	0.92 ± 0.03 (5)	0.89 ± 0.06 (8)			early Pleis.	J
	1.11 ± 0.02 (3)	1.01 ± 0.07 (12)	1.10 ± 0.10 (12)		early Pleis.	K

Notes: 1 = HEARTY *et al.*, 1992; 2 = HOLLIN and HEARTY, 1990; 3 = HEARTY *et al.*, 1986 and HEARTY and DAI PRA, 1992; 4 = HEARTY and KINDLER, 1993a.

back to the early Pleistocene (Pre-Brunhes magnetochron; 0.78 my). Four interglacials during the early Pleistocene equal (Stages 31 and 35?) or exceed (Stages 25 and 37?), the Holocene isotopic value.

Thus, in terms of events greater than or equal to present recorded by deep-sea oxygen isotopes, it appears that a maximum of four occurred during the early Pleistocene, three to four during the middle Pleistocene, and at least two during the late Pleistocene. Ages (IMBRIE *et al.*, 1984) of these more significant events are: Stages 31–37: 0.99–1.10 my; Stage 25: (*ca.* 880 ka); Stage 11: 362–423 ka; Stage 9: 303–339 ka; Stage 7: 186–245 ka; and Stage 5: 71–128 ka. Stages 13–23 (478–~850 ka) represent a period of the Quaternary when interglacial isotopic values are consistently lower than present. In general, oxygen isotopes support the same sequence of highstand events identified and dated through geological and aminostratigraphic investigations on stable carbonate platforms.

QUINN and MATTHEWS (1990), through isotopic variations and subsidence models, interpreted subaerial exposure (glacial age) and flooding (interglacial) events from deep cores from Enewetak Atoll in the South Pacific. Their "best-fit" model identifies eight Quaternary flooding events; four occur between 100 and 400 ka and four between 0.8 and 1.6 my. A gap during which no flooding events are recorded lies between 0.4 and 0.8 my.

U-Series and ESR Dating on Tectonic Coastlines

Quaternary chronologies from uplifted reef tracts in New Guinea (BLOOM *et al.*, 1974; CHAPPELL, 1983) and Barbados (BENDER *et al.*, 1973, 1979; RADTKE *et al.*, 1988) confirm for the late-middle and late Pleistocene the concordance between isotopic and geochronometric techniques in determining high sea-level events. Unfortunately, U-series methods are only effective back to the late middle Pleistocene (< 350 ka) even under ideal conditions (EDWARDS *et al.*, 1987a,b), and regardless of the increased precision of measuring techniques, pristine *in situ* corals are a prerequisite for accurate dating.

A sea-level curve for the past 300 ka has been generated from studies in New Guinea (CHAPPELL, 1983; CHAPPELL and SHACKLETON, 1986). This curve shows highstands near to or higher than the present at around 330 ka, 215 ka, 135–120 ka (three peaks), and the Holocene. BLOOM *et al.* (1974) estimate middle Pleistocene sea level at 320 ka and 336 ka at about +4 m. Interpreted sea-level data from the Thorpe terrace in Barbadaos indicate +2 m sea level during an event dated around 220 ka (BENDER *et al.*, 1979).

Table 2. *A summary of sea-level highstand localities, elevations, and apparent ages from Bermuda and the Bahamas. Column 1 is a proposed correlation of sea-level highstands with the oxygen isotope record.*

Stage[1]	Age[2] (ka)	Elev[3] (m)	Localities[4]
		Holocene	
1	3–0	0	San Salvador, ELU, BAH
		Late Pleistocene	
5a	80–70	−1 to +1	Conyers Bay, Ft. St. Catherine, BDA
5e	133–118	+4 and +8	Hungry Bay, Grape Bay, Blackwatch Pass, BDA—Lyford Cay, NPI; Big Rock, ELU, BAH
		Late-middle Pleistocene	
7a	210–180	+2.5	Hungry Bay, Saucos Hill, BDA
7c	240–230	≤0	Older Belmont, BDA; Blue Hill, NPI, BAH
9	339–303	+4	Upper Town Hill (Whalebone Bay; Devil's Hole; Red Hole), BDA; Hunt's Quarry, NPI, BAH
11	423–362	+4	Lower Town Hill (Belmont Wharf; Front St.), BDA
		Early-middle Pleistocene and early Pleistocene	
13–23	850–478	<0	Major Unconformity (Castle Harbour Geosol), BDA
		Early Pleistocene	
25?	900–800	+22	Government Quarry, BDA
35–37	1,100–990	≤+5	Walsingham Fm (Shore Hills Quarry, Stokes Point, Mullet Bay), BDA

Notes: 1 = SHACKLETON and OPDYKE, 1973; SHACKLETON *et al.*, 1988; 2 = IMBRIE *et al.*, 1988; 3 = approximate sea-level elevation in meters above present sea level; 4 = Locations discussed in text; BDA = Bermuda (VACHER *et al.*, 1989; HEARTY *et al.*, 1992); BAH = Bahamas (NPI = New Providence Island; ELU = Eleuthera) (HEARTY and KINDLER, 1993a,b).

A QUATERNARY INTERGLACIAL SEA-LEVEL HISTORY

The Quaternary

An empirically-derived curve of Quaternary highstands is presented in Figure 5B. Correlation with the isotopic stages (Figure 5A) of SHACKLETON *et al.* (1988) are indicated. Two positive sea levels are recorded from Bermuda during the early Pleistocene (< +5 m and +22 m) and at least three highstands occurred during the middle Pleistocene (+4 m, +4 m, and +2.5 m). The early Sangamonian is characterized by two or three positive oscillations, and a brief rise to near present at the end of the interglacial (Substage 5a).

Table 2 similarly provides a summary of the important localities, estimated ages of highstands, approximate elevations, and proposed correlation with the oxygen isotopic record. Amplitudinal error is estimated at ±1 to 3 m. Ages are fairly secure back to Stage 9, while older events are increasingly uncertain, perhaps accurate within one interglacial period.

In available records from South Carolina (HOLLIN and HEARTY, 1990), the Mediterranean (HEARTY *et al.*, 1986), and Bermuda (HEARTY *et al.*, 1992), an early-middle Pleistocene hiatus of several hundred thousand years between 450 ka and 850 ka is evident. This prolonged period of lower-than-present highstands during the mid-middle Pleistocene was proposed for the southeast U.S. Coastal Plain by BLACKWELDER (1981).

The Last Interglacial

Sea level during the early Sangamonian is characterized by change, instability and at least two sea-level oscillations (HEARTY, 1986; HOLLIN and HEARTY, 1990; SHERMAN *et al.*, 1993). The early Sangamonian opens with a transgression (perhaps 135 to 128 ka) to approximately +4.5 m (Figure 6). This positive excursion was sufficiently long to build large, interior eolianite ridges on most islands. In Bermuda, this early skeletal eolianite ridge is larger than the type Pembroke to follow.

In the Bahamas, the interior ridge is oolitic in

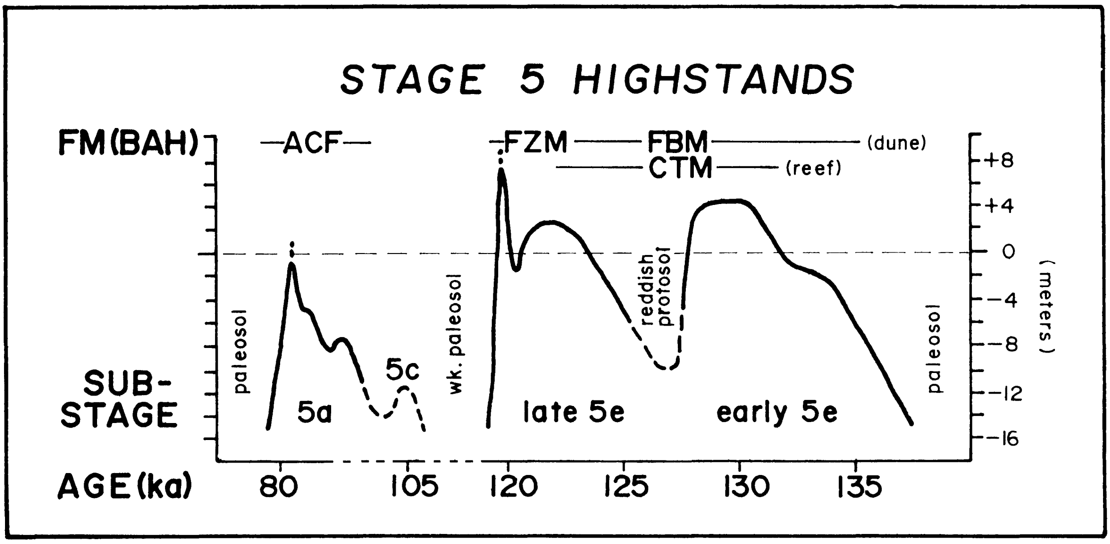


Figure 6. A detailed sea-level curve for the Sangamonian of Bermuda and the Bahamas. At least two major oscillations separated by weak soils are noted during Substage 5e. Sea level appears to have peaked both at the end of Substage 5e and 5a. There is sketchy evidence that sea level only reached between −10 and −15 m during Substage 5c.

composition and forms the axis of many islands (Hearty and Kindler, 1993b). Dune and reef formation commenced early on (Chen *et al.*, 1991) and continued throughout this first oscillation. The end of the first oscillation is marked by a rubified protosol corresponding to a sea-level regression of several thousand years (128–123 ka?). During a second oscillation, sea level rose to approximately +2 to +4 m for some duration, after which it rose quickly to at least +6 m (+9 m at Spencer's Point, Bermuda), perhaps prompted by an East Antarctic ice surge (Mercer, 1978; Hollin, 1980). Notches were left at +6m while marine deposition penetrated far inland on some islands, sometimes overtopping older 5e ridges (near St. Augustine Monastery, Nassau). After peaking, sea level fell rapidly exposing shelf sediment to landward transport and constructing large dunes that quickly buried standing vegetation and interior soils (Neumann and Hearty, 1993; *in review*). The GRIP (1993) ice core data from Greenland summit cores support similar climatic instability, timing and the catastrophic change of climate we observed in the rock record in the subtropics during the 5e/5d transition.

These apparently dramatic changes in climate during Stage 5e are not unique to the Atlantic. Woillard (1979) noted the speed with which the Eemian climate deteriorated during her Event 3 at the close of Substage 5e in northern France. The main shift from warmth-loving tree pollen to more boreal types took place in from two to a few decades. The exotic, tropical Senegalese fauna (Bonifay and Mars, 1959) was apparently exterminated in the Mediterranean by major climatic fluctuations over a very short period at the end of the Eutyrrhenian (Mediterranean equivalent of the Eemian and Sangamonian) (Hearty, 1986).

CONCLUSIONS

(1) Estimates of sea-level highstand positions from stable carbonate platforms are presented for the early, middle and late Pleistocene. Geological and morphostratigraphic evidence is consistent between both Bermuda and the Bahamas and is generally reinforced by independent methods.

(2) Deep-sea oxygen isotope records suggest that several interglacials during the Pleistocene exceeded the isotopic magnitude of the present interglacial. Higher-than-present Stages include 5e, 9, 25, and 37(?). Those interglacial stages having values similar to the present include 7, 11, 31, and 35. It appears there is a correspondence between the events of greatest isotopic value and

the volume of sediment deposited: in the case of Bermuda, the Rocky Bay Fm (Stage 5e), the Town Hill Fm (Stages 9 and 11) and the Walsingham Fm (Stage 37?). Sedimentary evidence of those equivalent to present is somewhat diminutive, the Belmont Fm (Stage 7) and the Southampton Fm (Stage 5a). Among all the proxy and geologic records, sea-level maxima for *ca.* 400 ka between 450 and 850 ka ago appear to have peaked below present sea level; these maxima left no significant evidence of their passing except deeply micritized and karstified surfaces and deep red paleosols.

(3) At least two major interglacial events are recorded during the early Pleistocene, one at around 1.1 my and the other at around 0.9 my. In Bermuda, the Walsingham Fm (Stage 37?) comprises a large eolianite ridge with basal marine deposits at $\leq +5$ m a.s.l., while a younger event (Stage 25?) is associated with a $+22$ m marine deposit cut into the Walsingham. Post-dating the half-million year hiatus in carbonate deposition, the mid- to late-middle Pleistocene (Stages 11 and 9) marks a return to island building with at least two important interglacial events (both *ca.* $+4$ m). The penultimate interglacial Stage 7, although somewhat diminutive in terms of volume and isotopic value, rose at least briefly to about $+2.3$ m. The last interglacial is characterized by two major and several minor oscillations. The major oscillations each peaked at between $+4$ m and $+8$ m (the latter the higher), separated by an unconformity and soil representing a regression of several thousand years. Toward the end of Stage 5, sea level was hovering well below present for some time (15 ka?) around -5 to -15 m during which the extensive dune ridges of the Southampton and Almgreen Cay Fms were deposited. Sea level then rose briefly at the close of Substage 5a to about present sea level at about 85 ka.

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