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THE GEOLOGY OF ELEUTHERA ISLAND, BAHAMAS: A ROSETTA STONE OF QUATERNARY STRATIGRAPHY AND SEA-LEVEL HISTORY

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Abstract—A 5-km stretch of coastline in north Eleuthera reveals a long and detailed stratigraphy that includes all known surficial limestone units in the Bahamas, and supplements the record with several previously unrecognized ones. Eight paleosol-bounded limestone parasequences comprise at least six interglacial periods. The lithostratigraphy demonstrates cyclicity at several frequencies (10^5, 10^4 (20–40 ka), and 10^3 years) and displays a variety of distal to proximal shoreline facies indicative of shifting depocenters associated with changing sea-levels. Stratigraphy, petrology, pedology and whole-rock aminostratigraphy are used to correlate units and subunits among the 12 described sections. Amino acid ratios are also converted to absolute age estimates which support the lithostratigraphy. The parasequences are correlated with marine Oxygen Isotope Stages 1 to 13 or older. Evidence of middle Pleistocene highstands are abundant in the Eleutheran stratigraphy, including paleo-sea-levels of decreasing age at + 2 m, + 7 m, + 20 m associated with Stages 11 and/or 9, and two near-present highstands during Stage 7. A complex sea-level history is associated with Substage 5e, while Substage 5a is represented by near shore aggradation of coastal dune complexes in Eleuthera and throughout the Bahamas. Concordance of sea-level deposits between Bermuda and the Bahamas reinforce their tectonic stability, while the abundance of highstand evidence during the middle Pleistocene contradicts suggestions that platform subsidence has obscured all evidence of these events below present sea-level.

The high-resolution late Quaternary stratigraphy of Eleuthera is unrivaled among geologic records from stable carbonate coastlines, and thereby offers a 'Rosetta Stone' for interpretation of the Quaternary evolution of the Bahamas and sea-level history over the past 500 ka.

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INTRODUCTION

The building of the Bahama Banks and the islands upon them is in direct response to eustatic fluctuations during the Quaternary. The geologic/oceanographic system is particularly sensitive during highstand phases wherein superimposed short-term oscillations leave their mark as facies changes and/or geomorphic features. Low-stands during full glacials and prolonged periods of bank top emergence are recorded by *terra rossa* paleosols developed on interglacial limestone deposits. North Eleuthera provides an ideal area for reconstructing the Quaternary stratigraphic history of the Bahamas because of the extent of stacked sequences exposed in cliff walls and roadcuts.

Of the 700 islands and cays of the Bahamas, only a few have received any detailed scientific attention. A basic view of the surficial geology of some Bahamian Islands has emerged from studies in New Providence (Garrett and Gould, 1984; Hearty and Kindler, 1997a), San Salvador (Carew and Mylroie, 1985; Hearty and Kindler, 1993a), Lee Stocking Island (Kindler, 1995), and the Caicos Islands (Wanless and Dravis, 1989). A collection of papers relevant to this study is available in Curran and White (1995).

Many of the previously studied islands differ in geologic architecture from the large, narrow, windward, Atlantic-bank margin buildups that characterize the major Bahamian islands (Abaco, Eleuthera, Cat, Long, Crooked, Acklins, Inagua, and Turks and Caicos). The windward islands, due to vertical stacking of deposits on the steep, exposed, high energy coasts facing the open Atlantic Ocean, present a longer and more detailed stratigraphic record of the Quaternary than those from interior protected islands (Kindler and Hearty, 1996; 1997).

An extended sea-level highstand chronology from stable carbonate coastlines has only recently become available (Hearty and Vacher, 1994; Hearty and Kindler, 1995), and constitutes the depositional framework for this investigation. In an archipelago-wide study, Hearty and Kindler (1993b) illustrated similar first-order lithologic sequences among several islands, while Kindler and Hearty (1996) reinforced this regional correlation on the basis of the similarity of petrostratigraphic sequences from several of these islands. In general, higher-than-present sea-levels favor the formation of oolitic and peloidal grains, while equal, or lower-than-present sea-level highstands favor the production of bioclasts. Underlying this fundamental observation of carbonate island geology is the shift of the depocenter from the shelf margin during lower interglacial sea-levels, to bankwide circulation during higher-than-present sea-levels generating tidal channels and energetic platform environments.

Secular changes in sea-level are predicted by Milankovitchian orbital cycles with periods of approximately 100 000, 41 000, and 23 000 years — periodicities which are confirmed in deep-sea oxygen isotope records (Imbrie *et al.*, 1984) and U-series ages of coral reef tracts on uplifted coastlines (Bloom *et al.*, 1974; Bender *et al.*, 1979; Chappell, 1983; Radtke *et al.*, 1988). The platform sediments are an extremely sensitive medium in their response to sea-level changes. They are rapidly molded by wave and wind activity, lithify quickly upon subaerial exposure, and thus uniquely preserve a high-resolution stratigraphy. A record of sea-level maxima from stable carbonate platforms allows more precise calculation of ice volume changes than afforded by stable isotopes in deep-sea cores, and provides new data from which uplift rates on tectonic coastlines can be evaluated. The main objective of this study is to demonstrate the rich and unique character of the stratigraphy of Eleuthera, and from this, extract a better understanding of the dynamic aspects of Quaternary climate and sea-level changes that shaped the Bahamian landscape over the past half-million years.

STUDY AREA

Eleuthera lies on the northeastern margin of the Great Bahama Bank (Fig. 1), fully exposed to the enormous potential energy of the Atlantic Ocean. The northern part of the island is rocky, narrow (0.25–2 km), and high (often over 40 m). The geomorphology of north Eleuthera is characterized by old limestone cliffs (Fig. 2) on both margins, washover lobes, and younger high ridges. Foresets of older beds generally dip toward the platform, demonstrating an easterly source-to-sink depositional vector, which is aligned with prevailing trade winds, energetic seas, and hurricane tracks. Since the limestones on Eleuthera accumulated almost exclusively from the Atlantic margin, it follows that older rocks should lie nearer the interior lagoon side, while progressively younger ones accreted toward the Atlantic coast. Where exposed on the leeward margin, middle Pleistocene rocks are being deeply notched and cliffed by biological and physical processes. During the late Pleistocene and Holocene, pocket beaches formed between middle Pleistocene highs on the leeward margin. Because of the high-energy conditions along the Atlantic coastline, coarse

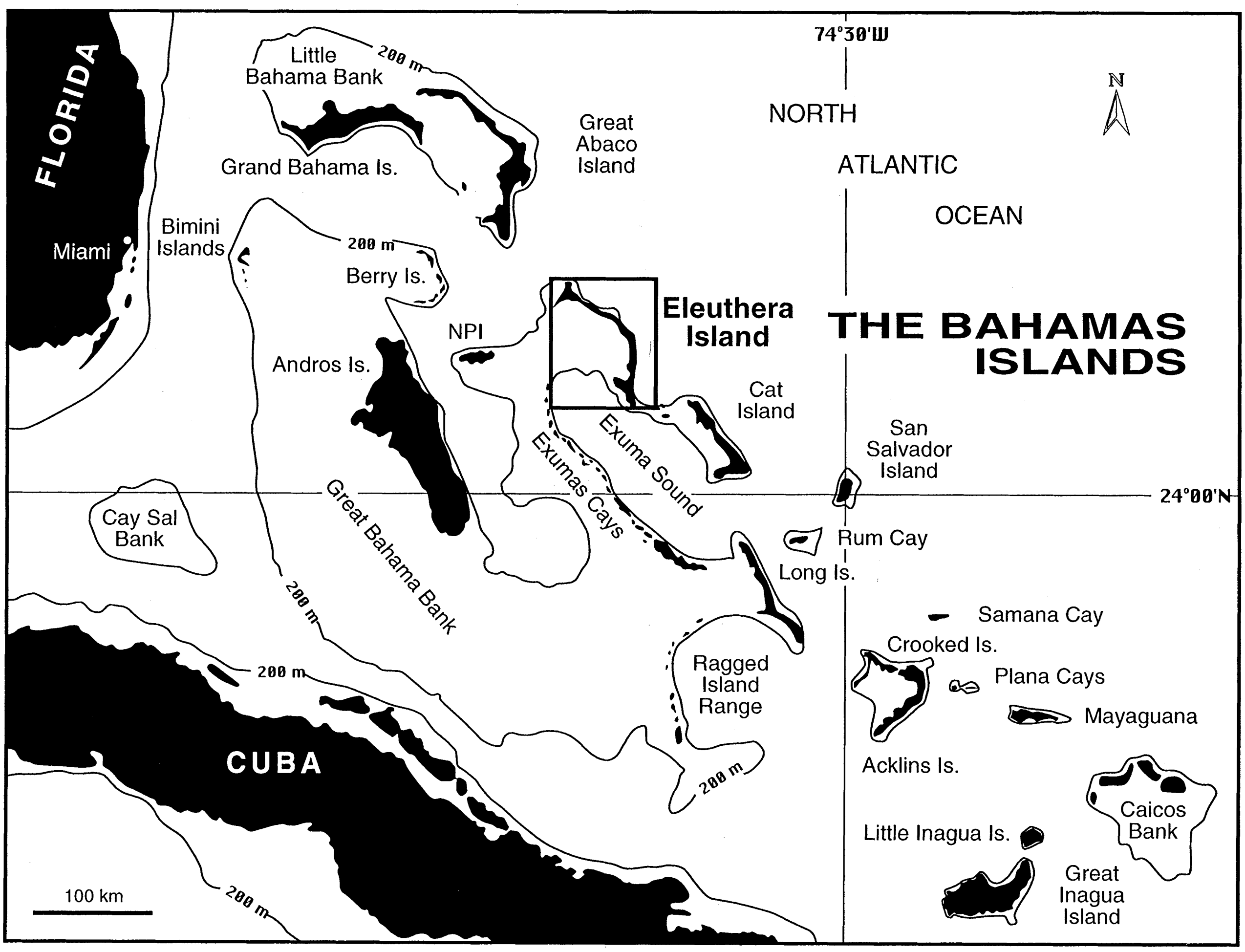


FIG. 1. Regional map of the Bahamas showing the island of Eleuthera on the eastern margin of the Great Bahama Bank (modified from Kindler and Hearty, 1997).

FIG. 2. View north from Cotton Hole of the cliffs of north Eleuthera. Whale Point and Harbour Island are seen in the far right of the photo. The photo shows the truncated coastal ridges of middle Pleistocene age.

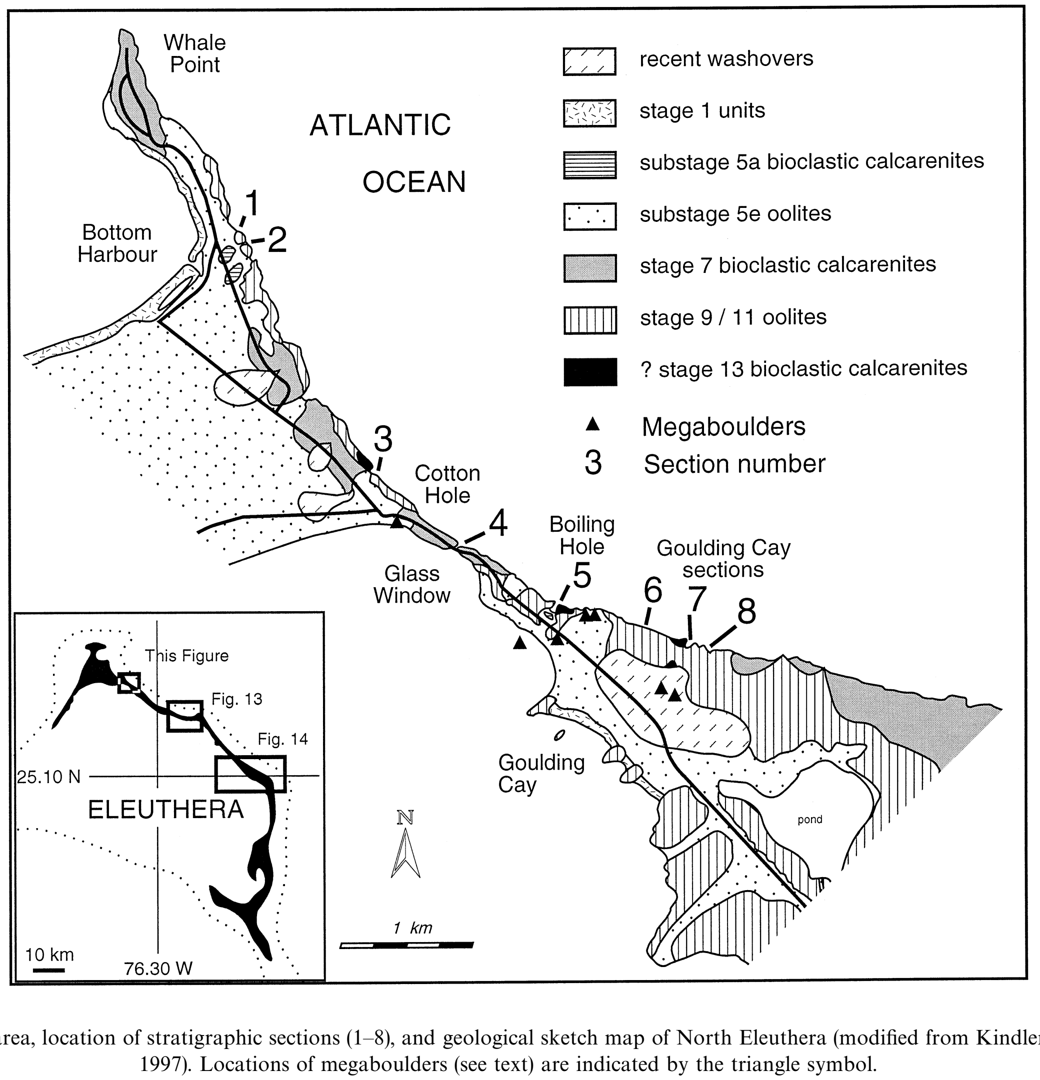


FIG. 3. Study area, location of stratigraphic sections (1–8), and geological sketch map of North Eleuthera (modified from Kindler and Hearty, 1997). Locations of megaboulders (see text) are indicated by the triangle symbol.

sediments frequently are washed through topographic lows between older ridges, and accumulate as wash-over fans, lobes, and basin fills bankward of the cliffs.

This study of the Quaternary stratigraphy of the Bahamas focuses on several informative sections located between Whale Point and Goulding Cay Quarry in north Eleuthera (Fig. 3). Additional sites from central Eleuthera are used to demonstrate high-resolution, stage and intra-substage stratigraphy. Site names are taken from the Bahamas DOS 1:25 000 topographic sheets.

The northern study sites are situated on a very narrow part of the island centered near Glass Window Bridge. Large fractures along the cliffs suggest that from time to time, perhaps mainly during glacial low-stands as suggested by Aby (1994), the bank margin retreats by spalling enormous blocks of limestone (Freeman-Lynde and Ryan, 1985; Mullins and Hine, 1989). At present, the shelf is narrow and deep, prohibiting significant accumulation of sediment except as wash-over deposits. Evidence from a sequence of truncated middle and late Pleistocene coastal ridges, as depicted in Fig. 2, suggests that significant cliff retreat occurred after the emplacement of the last interglacial sequence.

METHODS

Recognizing that single methodological approaches are inadequate to resolve stratigraphic problems on Quaternary carbonate platforms, the objective of this study was to 'characterize' limestone units of various ages with several independent methods (Hearty and Kindler, 1993a; Vacher *et al*., 1995). Stratigraphic superposition and geomorphic juxtaposition (Garrett and Gould, 1984) explain relationships among the main units, while limestone petrology (Kindler and Hearty, 1996), whole-rock aminostratigraphy (Hearty *et al*., 1992), and development of capping soils and calcretes were used to further characterize each unit.

Petrological results from Eleuthera are presented in a regional perspective in (Kindler and Hearty, 1995; Kindler and Hearty, 1996; Kindler and Hearty, 1997) and readers should refer to those studies for methods and thin-section summaries of major units. Soil colour analysis (Munsell (1994) wet colours reported in discussion below) reveals a positive correlation with stratigraphic age, while analyses of clay mineralogy, elemental composition, and soil fabric are under way to quantify these correlations. The underlying theory is that with greater age, soils will become progressively redder as ferromagnesian minerals evolve, and light-coloured carbonate is leached from the matrix. The soils also increase in finer textures as a function of weathering of parent materials and dissolution of coarser carbonate grains with time. To standardize the soil collections, samples were generally taken from the crests of ridges, karstic pits, or near-horizontal exposures in cliffs and roadcuts.

Whole-rock aminostratigraphy on limestones has previously shown its usefulness in establishing correlation and estimating ages of units. The AAR method is based on the racemization of amino acids preserved in biominerals. Through time, L-amino acids racemize (or, more specifically in the case of the amino acid isoleucine, epimerize) to their D-isomer form. The ratio of D/L (or isoleucine to alloisoleucine, A/I) amino acids measures the extent of racemization. In the A/I epimerization reaction, the ratio is initially zero and

TABLE 1 Stratigraphic nomenclature and correlation table of major units recognized in the Bahamas. Type sections representative of each of the units are provided for this study in Eleuthera

	San Salvador; Carew and Mylroie (1985)	San Salvador; Hearty and Kindler (1993a)	The Bahamas; Kindler and Hearty (1996)	Eleuthera Island; This study (type section #)	Inferred Isotope Stage
Holocene	Hanna Bay Mb, Rice Bay Fm	Hanna Bay Mb, Rice Bay Fm	Unit VIII	Singing Sands (12)	late 1
	North Point Mb, Rice Bay Fm	North Point Mb, Rice Bay Fm	Unit VII	Windermeer Island (12)	mid 1
Late Pleistocene	Unrecognized	Almgreen Cay Formation	Unit VI	Whale Point (2); Rainbow Cay (10)	5a
	Unrecognized	Fernandez Bay Mb, Grotto Beach Fm	Unit V	Whale Point (1)	late 5e
	Cockburn Town Mb, Grotto Beach Fm	Cockburn Town Mb, Grotto Beach Fm	Unit IV	Whale Point (1)	5e
	French Bay Mb, Grotto Beach Fm	French Bay Mb, Grotto Beach Fm	Unit IV	Boiling Hole (5); Savannah Sound (11)	5e
Middle Pleistocene	Unrecognized	Fortune Hill Formation	Unit III	Glass Window (4); The Cliffs (9)	late 7
	Owl's Hole Formation	Owl's Hole Formation	Unit II	The Cliffs (9)	early 7
	Unrecognized	Unrecognized	Unit I	Goulding Cay Q. (7, 8)	9/11
	Unrecognized	Unrecognized	Unrecognized	Goulding Cay Q. (8)	9/11
	Unrecognized	Unrecognized	Unrecognized	Goulding Cay Q. (6)	≥ 13?

increases to an equilibrium ratio of about A/I = 1.3 for isoleucine with time after death of an organism and removal of biological constraints. Like other chemical reactions, the rate of racemization/epimerization depends on the ambient temperature of the reaction medium within the rock units. In Bermuda, A/I ratios on marine shells (*Glycymeris* sp.), land snails (*Poecilozonites* sp.), and whole-rock bioclastic limestones, effectively resolved Holocene, numerous late and middle Pleistocene, and early Pleistocene interglacial deposits in 97% of 257 stratigraphically positioned samples (Vacher *et al.*, 1989, 1995; Hearty *et al.*, 1992). The integrity and concordance of whole-rock aminostratigraphy in bioclastic and oolitic limestones has been empirically demonstrated and discussed in studies from Bermuda (Hearty *et al.*, 1992), San Salvador (Hearty and Kindler, 1993a, 1994), and New Providence Islands, Bahamas (Hearty and Kindler, 1997a).

Whole-rock samples were gently disaggregated with a mortar and pestle and repeatedly sieved to exclude finer grains and cements, and separate the 250–850 μm grains for analysis. Once microscopic examination verified that mainly carbonate grains were isolated, samples were sent to the Amino Acid Laboratory at Utah State University for analysis. There samples were washed repeatedly with ultra pure H_2O and leached of the outer 30% of the grains with 2 M HCl and ana lyzed according to the procedures outlined in Miller and Brigham-Grette (1989). All A/I measurements used in this study are peak height hydrolysate ratios.

To facilitate identification of units and minimize the introduction of new terms to an already burdensome nomenclature in the Bahamas, a correlation with isotope stages and substages is inferred, and then demonstrated through identification of stratigraphic sequences and aminostratigraphy. Existing nomenclature in the Bahamas, and units keyed to isotopic stages are offered in Table 1.

STRATIGRAPHIC SECTIONS

The stratigraphy of north Eleuthera is summarized in eight sections (Fig. 4) located along a 5-km stretch of coastline. In many cases, units are physically traceable in outcrop from site to site, while in others, correlation is achieved by comparison of parasequences, petrology, pedology (Table 2) and aminostratigraphy (Table 3). The eight stratigraphic sections, arranged in Fig. 4 from NW to SE, concentrate on the three areas of Whale Point, Glass Window Bridge, and Goulding Cay. Four other sections further south are offered to show the intra-substage stratigraphic detail. In the interest of brevity and to minimize repetition, the following description of the stratigraphic sections highlights only the key features of each section. Soil colour and textures are reported in Table 2.

Whale point area

Section 1 (EWP3; Figs. 4 and 5)

The Whale Point Section 1 exposes poorly-preserved coral reef facies anchored on older oolitic/peloidal eolianites, both correlated to Stages 9/11. The reef facies is capped by an algal limestone and deep red (2.5YR 4/8) clayey paleosols (Fig. 5). Subsequent inundation, reef development, and marine erosion

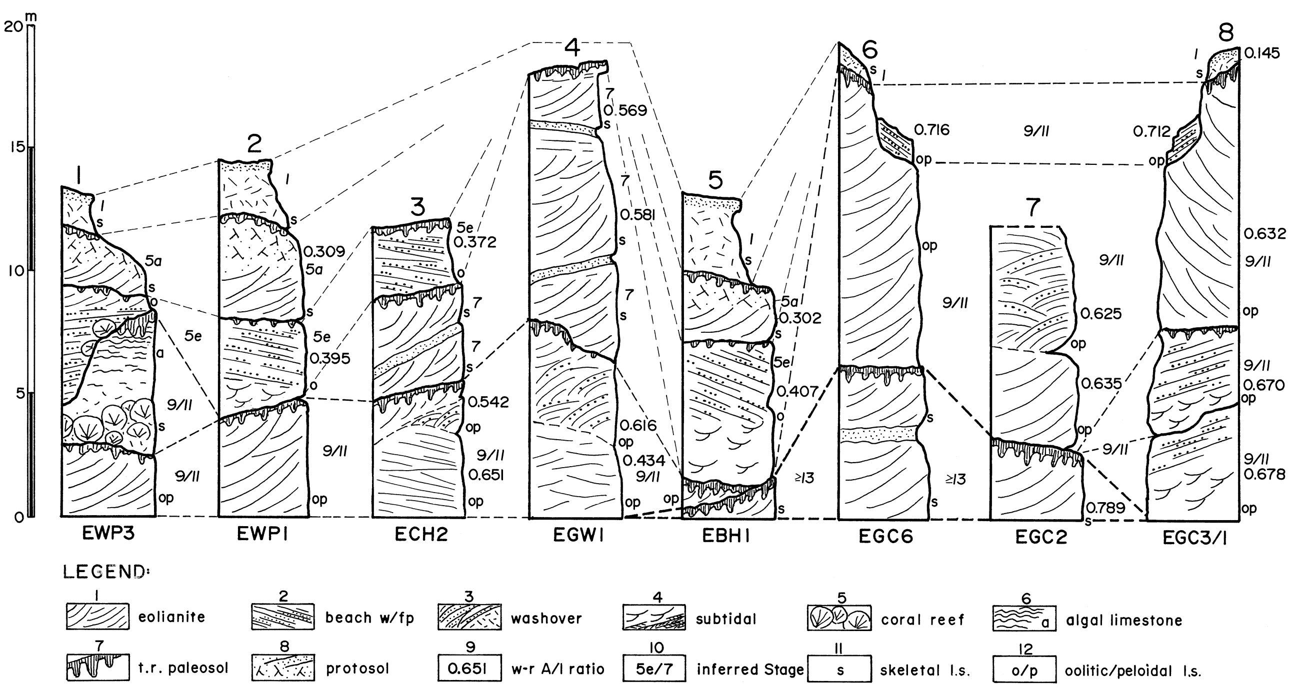


FIG. 4. Stratigraphy and correlation of eight sections in north Eleuthera. Whole-rock A/I ratios, limestone composition (skeletal, oolitic, peloidal, and algal), and inferred correlation with isotope stages are provided for the sections.

TABLE 2 Munsell (1994) wet colour and qualitative texture of soil samples from Eleuthera. Soil data are arranged in stratigraphic order based on lithostratigraphic position and other information

Field Number	Collection date	Munsell (1994) color (wet)	Texture	Post Stage?
EHS1b	19.2.94	10YR 7/4	Sandy	late 1
ETR1b	2.7.94	2.5Y 6/2	Sandy	late 1
ESS1b (2)	5.6.93	2.5Y 8.3	Sandy	mid 1
ESV2b	21.2.94	2.5Y 7/3	Silty	mid 5e
EBH2f	12.5.93	10YR 7/3	Silty	5e/5a
EWP2d	22.5.94	10YR 7/4	Sandy	5e/5a
EBH1f	2.4.95	10YR 7/4	Sandy	5e/5a
ERC3b	7.6.93	10YR 8/4	Sandy	5e/5a
ERC2b (3)	7.6.93	7.5YR 7/8	Sandy	5e/5a
ERC2b (1)	7.6.93	10YR 7/4	Sandy	5e/5a
ERC2b (2)	11.5.93	10YR 7/4	Sandy	5e/5a
EWP1h	22.5.94	10YR 4/3	Clayey silt	5a
ESB1b	1.7.94	5YR 4/6	Clayey silt	5a
EAB3b	16.4.94	5YR 4/4	Clayey	5e
ESV2d	3.8.93	7.5YR 4/3	Mottled silt	5e
EBH1e	2.4.95	7.5YR 5/8	Stony silt	5e
ELB2b	12.5.93	5YR 3/3	Stony clay	5e
ELP2b	30.6.94	5YR 4/6	Clayey	5e
ENP2	7.6.93	7.5YR 4/4	Sandy silt	5e
EHA1b	2.7.94	5YR 4/4	Clayey	5e
ERC5b	7.6.93	2.5YR 3/4	Clayey	5e
EHA1b	20.2.94	5YR 4/6	Clayey	5e
EGC1s	2.4.95	5YR 4/6	Dense clay	5e inherited 9/11
EGW1e	25.5.94	7.5YR 8/3	Sandy	mid 7
ETC1d	12.5.93	5YR 5/6	Stony sand	mid 7
ETC1d/e	12.5.93	5YR 5/6	Stony sand	mid 7
EGW1g	25.5.94	7.5YR 7/6	Sandy	mid 7
ECH2h	2.4.95	7.5YR 5/8	Sandy silt	7
ETC1g	12.5.93	5YR 4/4	Clayey	7
ESE1d	6.6.93	10YR 8/2	Stony sand	mid 9?
EAF1b	9.5.93	2.5YR 3/4	Clayey	9/11
EGC1e (1)	3.7.94	2.5YR 3/6	Clayey	9/11
EGC1e (2)	3.7.94	2.5YR 3/6	Clayey	9/11
EBH1b	2.4.95	2.5YR 4/6	Stony clay	9/11
EGC1e	24.5.94	2.5YR 2.5/4	Clayey	9/11
EWP3d	19.7.96	2.5YR 4/8	Sandy clay	9/11
ECH1d	31.3.95	5YR 3/4	Clayey	9/11
EOP1b	7.6.93	2.5YR 4/6	Stony clay	9/11
EOD1b	14.5.93	2.5YR 2.5/4	Clayey	9/11
EGT1e	4.8.93	2.5YR 3/4	Clayey	9/11
EWY2b	2.7.94	2.5YR 3/3	Silty clay	$\geqslant 11$
EWW1b (1)	31.7.93	2.5YR 3/3	Silty clay	$\geqslant 11$
ESE1b	6.6.93	5YR 4/4	Stony clay	$\geqslant 11$
EGC2b	3.7.94	5YR 5/8	Stony clay	$\geqslant 13$

associated with Substage 5e created spur and groove topography upon the paleosol-capped, middle Pleistocene reef. Sparsely distributed coral heads and regressive oolitic 5e beach deposits infill the grooves. Geochronological studies are under way to establish if radiometric and ESR dating methods can determine the age of the poorly-preserved middle Pleistocene corals from Whale Point. Substage 5a skeletal eolianites rest directly upon post-5e paleosols (10YR 7/4) and older 5e beach deposits (Fig. 6). At Whale Point these deposits consist of lobes of low-angle bedding that extend landward in topographic depressions in the older rocks. *Terra rossa* soils and Holocene dune and washover deposits complete the sequence.

Section 2 (EWP1, Whale Point; Fig. 4)

Section 2 is based in the same Stage 9/11 eolianite as Section 1, but lacks the older coral reef facies. Higher in the section, oolitic 5e beach and subtidal facies are overlain by sandy, reddish, brecciated paleosols (10YR 7/4) and skeletal 5a eolianites (Fig. 6). A/I ratios (5e = 0.395/5a = 0.309) (Table 3) confirm the passage of several tens of thousands of years between substage

TABLE 3 Whole-rock amino acid ratios (A/I) from major units in Eleuthera. Samples were prepared by the author, and analyzed by Dr Darrell Kaufman (Utah State University Amino Acid Laboratory)

Stage	Lab #	Field #	Mean (± 1σ)	Facies
1	1465A	ESS1a	0.086 ± 0.003	beach/eolian
	1463A	EWI1ab	0.100 ± 0.001	eolian
	1678A	EGC3z	0.145 ± 0.005	washover
				Mean: 0.110 ± 0.031 (*n* = 3)
Major paleosol				
5a	1464A	EFI1e	0.299 ± 0.002	eolian
	1466A	ESK1a	0.300 ± 0.001	eolian
	1467B	ERC2c*	0.248 ± 0.003	eolian
	1562A	EBH1g*	0.302 ± 0.003	eolian
	1573A	EWP2k*	0.309 ± 0.001	eolian
				Mean: 0.292 ± 0.025 (*n* = 5)
Minor paleosol				
5e	1094D	ESV1c	0.345 ± 0.005	eolian
	1094B/1104C	ETP1c	0.363 ± 0.010	eolian
	1104B/1094A	ETP1a	0.320 ± 0.026 (lc)?	eolian
	1094C	ESV1a	0.403 ± 0.004	eolian
	1275A	EHA1a	0.406 ± 0.007	beach
	1275B	EHA1a	0.388 ± 0.008	beach
	1564A	ECH2i	0.372 ± 0.010	beach
	1467A	ERC2a*	0.369 ± 0.006	eolian
	1563A	EBH1d*	0.407 ± 0.003	beach
	1567A	EWP2i*	0.395 ± 0.002	beach
	1812A	EMB4e	0.385 ± 0.004	beach
	1814A	EMB2o	0.400 ± 0.003	eolian
				Mean: 0.379 ± 0.027 (*n* = 12)
Major paleosol 7				
	1101B	ETC2c	0.352 ± 0.004 (lc,ni)	eolian
	1568A	ETC1e	0.382 ± 0.013 (lc,ni)	eolian
	1388D	EGW1h	0.569 ± 0.022 (lc)	eolian
Minor paleosol 7				
	1388C	EGW1f	0.581 ± 0.023 (lc)	eolian
	1101A	ETC2a	0.576 ± 0.008 (lc)	eolian/washover
				Stage 7 *Mean*: 0.575 ± 0.006 (*n* = 3)
Major paleosol 9/11				
	1389A/1561A	EGC3f	0.709 ± 0.181 (h)	beach (+ 13–20 m)
	1682A	EGC6f	0.716 ± 0.023 (h)	beach (+ 13–20 m)
				Mean: 0.712 ± 0.102 (*n* = 2)
Unconformity 9/11				
	1565A	ECH1c	0.542 ± 0.009 (lc,ni)	beach/washover?
	1676A	EGC2d	0.625 ± 0.010	washover
	1392A/1675A	EGC2c	0.635 ± 0.104 (lc)	eolian
	1387A	EGC1d	0.632 ± 0.013	beach (+ 5 m)
	1679A	EGC5e	0.631 ± 0.007	eolian
	1388B	EGW1d	0.616 ± 0.021	eolian
				Mean: 0.628 ± 0.007 (*n* = 5)
Numerous contacts and minor paleosols throughout 9/11				
	1388A	EGW1c	0.434 ± 0.013 (~ , ni)	eolian
	1677A	EGC3d	0.670 ± 0.005	beach (+ 7 m)
	1387A	EGC1c	0.678 ± 0.024	beach
	1566A	ECH1a	0.651 ± 0.019	beach (+ 2 m)
	1816A	ECC1a	0.699 ± 0.001	eolian
				Mean: 0.675 ± 0.020 (*n* = 4)
Megaboulders				
	1809A	EMB2g	0.734 ± 0.019	displaced boulder
	1810A	EMB4g	0.737 ± 0.025	displaced boulder
	1811A	EMB3	0.667 ± 0.016	displaced boulder
	1813A	EMB5	0.619 ± 0.013	displaced boulder
	1815A	EMB1	0.604 ± 0.008	displaced boulder
				Mean: 0.671 ± 0.063 (*n* = 5)
			Overall 9/11 complex	Mean: 0.671 ± 0.050 (*n* = 16)
Major paleosol ⩾ 13				
	1392B	EGC2a	0.789 ± 0.036 (lc)	eolian
	1681A	EGC6a	Trace	eolian
	1680A	EGC6c	Trace	eolian
	1673A	EBH3aa	Trace	eolian
	1674A	EGC2aa	Trace	eolian

(lc) = low concentrations of amino acids; (ni) = ratios excluded from mean. (h) = Surface heating probable based on field observations; *5e/5a pairs (same field number prefix) in superposition, separated by a well-developed red soil. ~ = petrographic analysis of sample EGW1c shows two generations of cements: the older precipitated in a freshwater vadose environment, the latter was formed in a marine phreatic environment. The younger generation of cements may be responsible for the discordant ratio. Trace = insufficient concentation of amino acids to make accurate measurement.

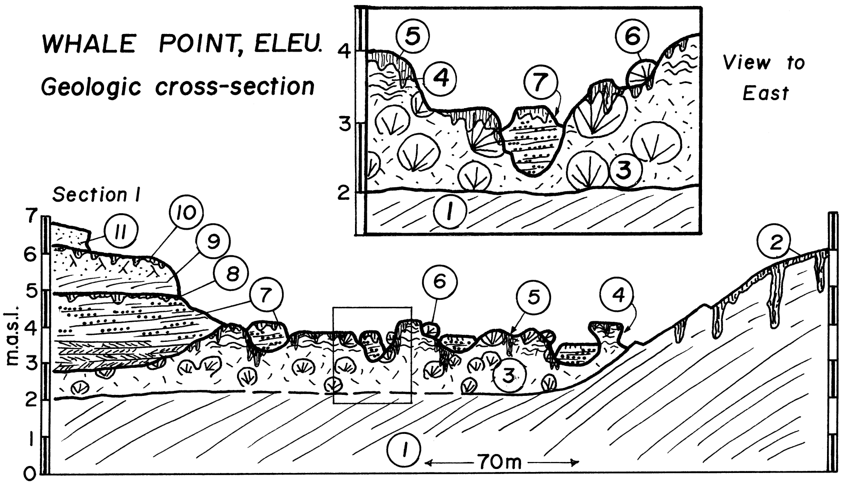


FIG. 5. Detailed stratigraphic section of the Whale Point coral reef area. (1) Stage 9/11 oolitic/peloidal eolianite; (2) deep red paleosol; (3) coral reef of middle Pleistocene age; (4) algal limestone capping reef facies; (5) dark red paleosol (2.5YR 4/8) capping reef and algal facies; (6) Substage 5e coral heads; (7) Substage 5e regressive beach deposits; (8) rocky, reddish brown, (10YR 7/4) 5e/5a paleosol; (9) Substage 5a skeletal eolianite; (10) post-5a paleosol; and (11) Holocene skeletal washover deposits.

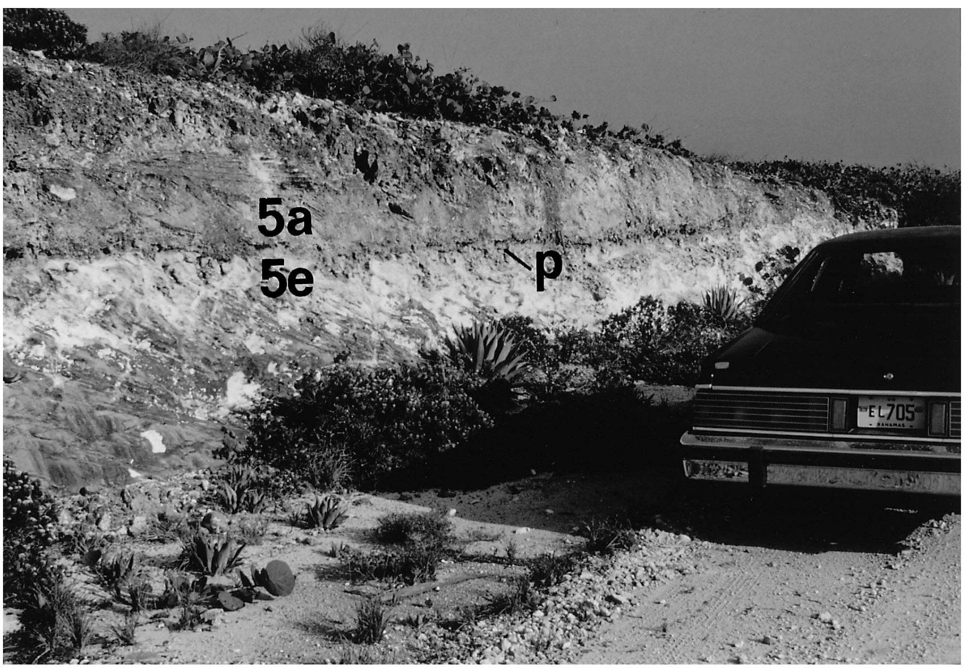


FIG. 6. Photo of paleosol at 5e/5a contact in a roadcut at Whale Point Section 2. The age difference between the two Stage 5 limestone units, indicated by the reddish paleosol ('p') and karstified surface, is supported by whole-rock A/I ratios of 0.395 (5e) and 0.309 (5a). Several other sections (1, 5, and 10) yield similar stratigraphy, petrology, and/or A/I ratios.

events, also indicated by the development of the karstified surface on 5e oolite and red paleosol separating these two units.

Glass Window area

Section 3 (ECH2, Cotton Hole; Fig. 4)

Three or four interglacials are represented in the area of Section 3 north of Cotton Hole. Like Whale Point, the section is based in oolitic/peloidal beach, washover, and eolian facies correlated to Stages 9/11. Thin, ferruginous, skeletal deposits with *Cerion* land-snails and rhizomorphs represent a distal backbeach facies equated with Stage 7. Terrestrial bioturbation during periods of vegetative growth has obscured all evidence of bedding in this unit. Oolitic washover and beach deposits of from Substage 5e rise to +10 to +12 m a.s.l., while Holocene skeletal washover sediments fill low areas landward of the section. A/I ratios associated with the units are Stages 9/11 = 0.651; 9/11 or 7? = 0.542; and 5e = 0.372.

Section 4 (EGW1; Glass Window; Figs. 4 and 7)

Section 4 at Glass Window contains two fairly complete, stacked sequences (9/11 and 7, Fig. 7) of middle

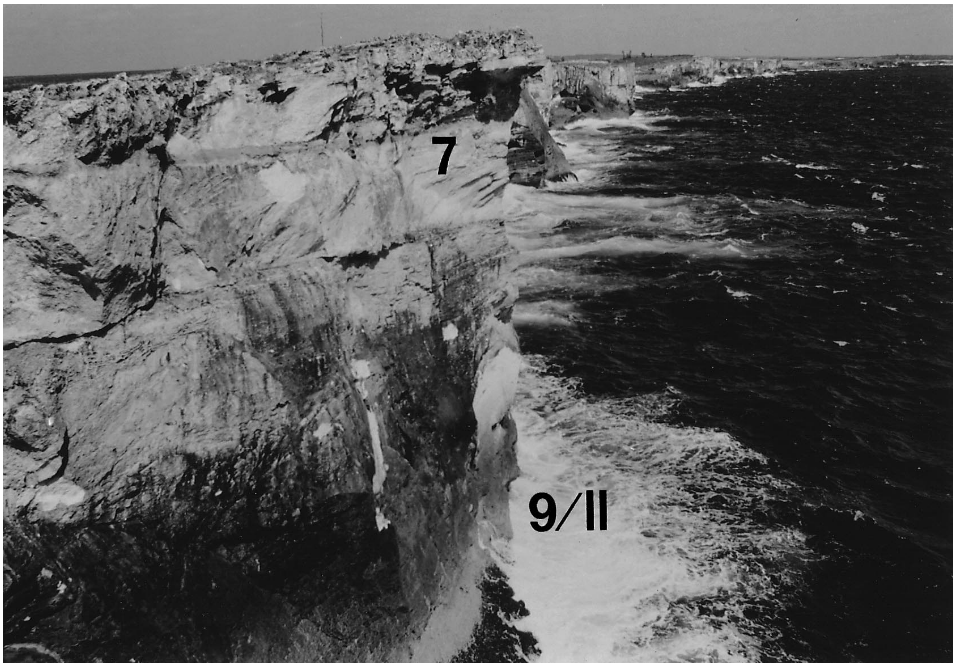


FIG. 7. Photograph of the Glass Window Section 4 representing Stages 7 through 9/11.

Pleistocene age. The lower is oolitic/peloidal eolianite and washover facies (A/I = 0.616) capped by a thick calcrete, while the upper sequence consists of skeletal eolianites and protosols. Close agreement with A/I ratios in Stage 7 sequence (0.581/0.569) suggests that each of these deposits were probably derived from the same offshore sediment pool. Interbedded eolianites and reddish-yellow protosols (7.5YR 7/6–8/3) imply a distal shoreline environment that was alternately blanketed by fresh bioclastic sediments, probably deposited mostly during major storms, and subsequently vegetated during periods of either ecological stability, minor negative sea-level oscillations, or both during Stage 7.

Section 5 (EBH1; Boiling Hole; Fig. 4)

Petrography and sedimentary facies of the Boiling Hole Section 5 are reported in Kindler and Hearty (1995). To add to these findings are (1) a more complex middle Pleistocene stratigraphy; (2) confirmation by A/I ratios of the suggested 5e and 5a ages of the upper units; and (3) mention of the Holocene, skeletal washover trough lying to the SW of the main section. Studies subsequent to Kindler and Hearty (1995) revealed that both oolitic/peloidal deposits (9/11) and older skeletal eolianites (Stage $> 13?$) capped by dark red paleosols (2.5YR 4/6) are present at the base of the section. AAR analyses of the oldest stratigraphic ($\geq$ Stage 13) unit provided unmeasurable trace levels of amino acids, while those from 'middle' and 'upper' units produced typical 5e and 5a A/I ratios of 0.407 and 0.302, which are concordant with Section 2 (0.395/0.307). The A/I ratios and intermediate reddish paleosol (10YR 7/4) confirm the age difference of several tens of thousands of years between early and late Stage 5 units. Where not overlain by skeletal eolianites, 5e oolites are capped by reddish paleosol (7.5YR 5/8) formed during the last glacial period.

Goulding Cay Quarry area

Section 6 (EGC6; midway between Boiling Hole and Goulding Cay; Figs. 4 and 8a,b)

The base of this section exposes a complex history of skeletal eolianites and paleosols belonging to the oldest surficial units recognized in the Bahamas ($\geqslant$ Stage 13). This lowest interglacial unit is overlain by a red paleosol, and further by a thick oolitic/peloidal eolianite correlated to Stages 9/11. Fenestrae-rich, horizontally-bedded intertidal facies (Fig. 8B) lie upon a narrow bench at + 15 and + 20 m, truncating an older steeply-dipping eolianite (Fig. 8A). A slightly elevated A/I ratio of 0.716 from these thin and exposed oolitic/peloidal deposits confirms a Stage 9/11 correlation of these deposits.

Section 7 (EGC2; Goulding Cay Quarry, north; Figs. 4 and 9)

A shore-parallel geologic cross-section in Fig. 9 summarizes the stratigraphy in the area of the Goulding Cay Quarry including both Sections 7 and 8. Section 7 contains a thick, eolian and washover sequence of oolitic/peloidal composition overlying Stage $> 13?$ eolianites and a yellowish red (5YR 4/8), partially-leached, stony-clay paleosol. The lower eolianite preserves standing palmetto casts, while the upper unit contains washover deposits and fenestrae between + 8 and + 20 m. These high-energy washover deposits appear to infill topographic lows among older beds, and

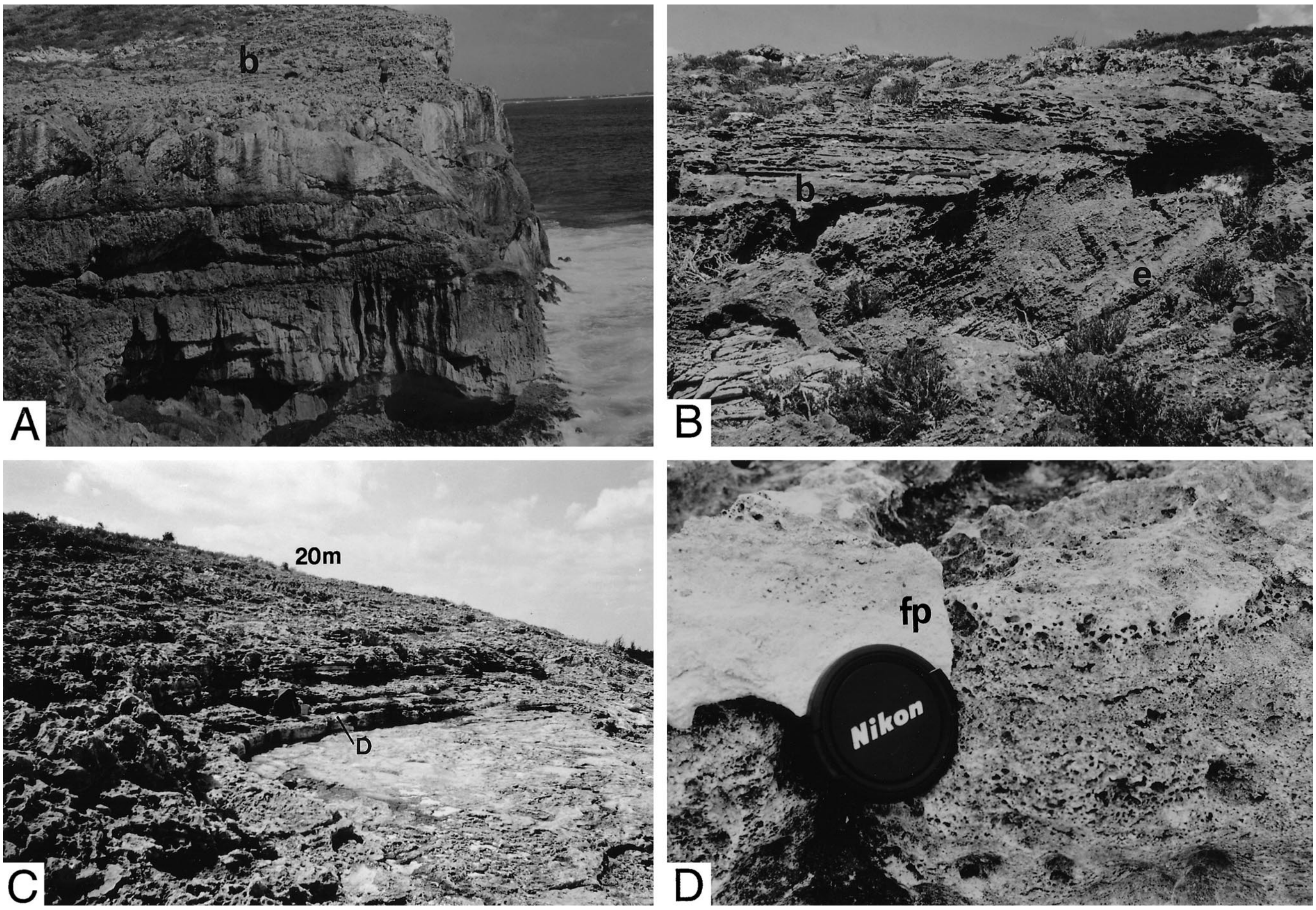


FIG. 8. (A) Setting of + 20 m beach deposits ('b') at Section 6 between Boiling Hole and Goulding Cay Quarry above a Stage 9/11/13 sequence. (B) Fenestrae-rich, horizontally-bedded beach deposits in the upper unit at Section 6, truncating older cross-bedded eolianitese of similar composition. (C) Fenestrae-rich, horizontally-bedded beach deposits on a narrow platform from + 13 to + 20 m at Section 8 ('D' indicates location of fenestrae in photo D). (D) Detail of beach fenestrae ('fp') in beach deposits at Section 8.

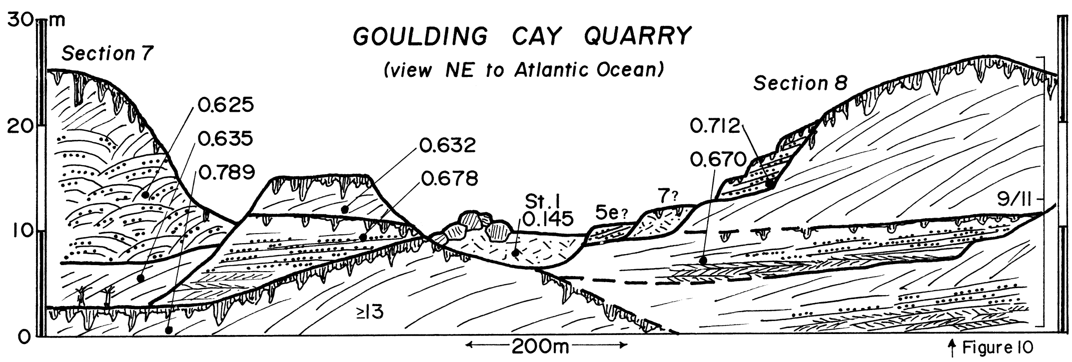


FIG. 9. Schematic cross-section of the Goulding Cay Quarry. With the exception of patchy deposits of Stage 1 and 5e, the entire section is of middle Pleistocene age.

are perhaps related (although it is not stratigraphically clear) to the sea-level regression from the + 20 m sea-level maximum.

Section 8 (EGC1/3; Figs. 4, 9 and 10; Goulding Cay Quarry, south)

Four distinct units of middle Pleistocene age comprise Section 8. The lowest of these oolitic/peloidal units exposes intertidal and subtidal facies, indicating a sea-level at around + 2 m. A subsequent highstand eroded a greater than 50-m-wide terrace at + 7 m into the lower unit (Fig. 10A). Subtidal, beach and eolian facies are present on the + 7 m terrace (Fig. 10B), suggesting a stable, prolonged sea-level during 9/11. The + 7 m beach is succeeded by a thin (inaccessible) paleosol or protosol and a massive eolianite rising to + 30 m. Into this eolianite, a horizontally-bedded, regressive beach sequence with fenestrae is deposited on a narrow bench at + 13 m (Fig. 8C,D). At Section 8, a cairn marks the highest elevation of beach fenestrae at + 20 m. Physical characteristics, stratigraphic position, and an A/I value of 0.712 establish a correlation of the + 20 m beach at Section 8 with a similar sequence at Section 6 (0.716) (Fig. 4). A/I ratios are statistically similar, but slightly elevated relative to adjacent beds, probably as a result of surface heating effects in the thin (< 1.5 m) beds. Above + 20 m, dark

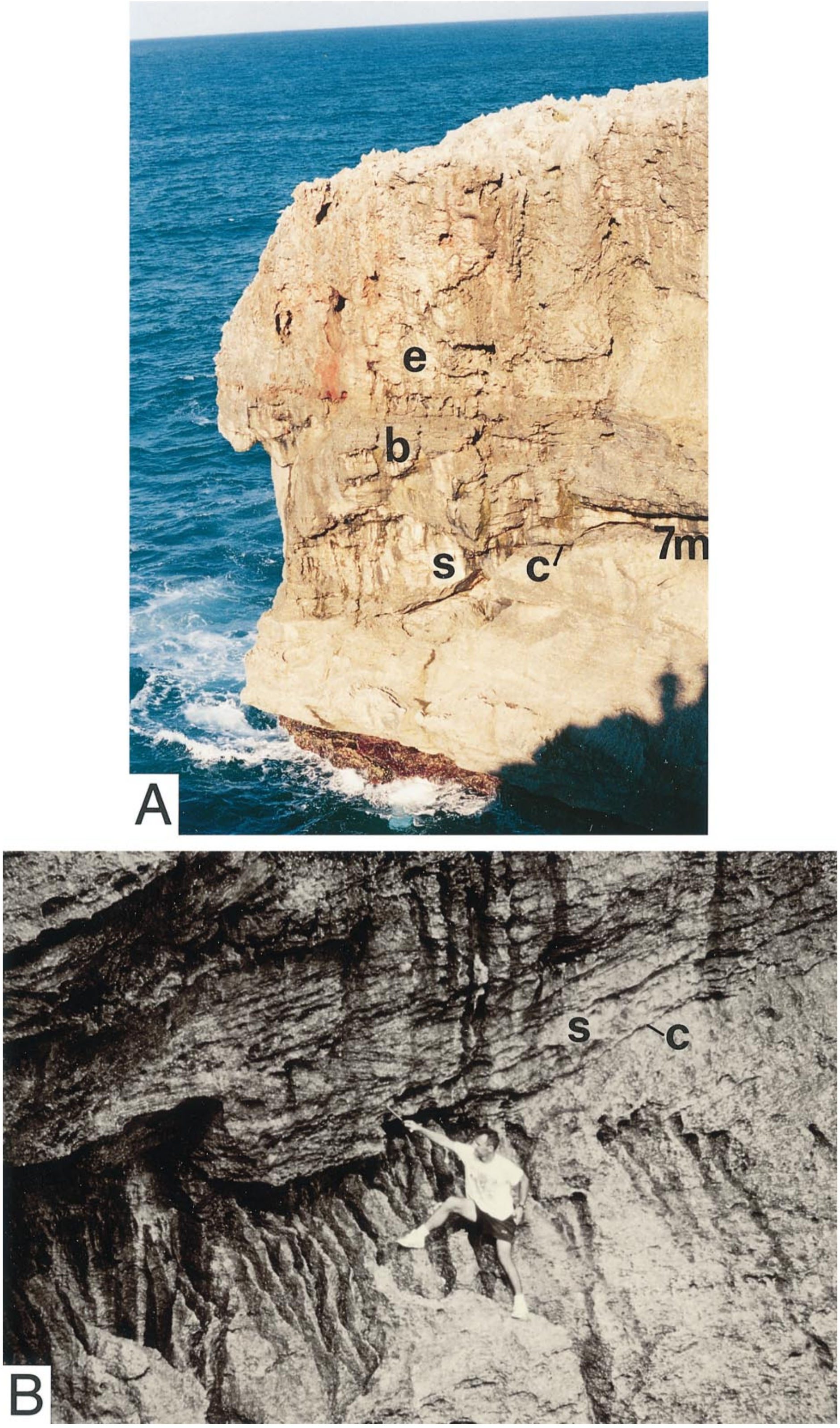


FIG. 10. Photos of the + 7 m platform at Goulding Cay Section 8 showing erosional terrace (photo A) mantled with subtidal ('s'), beach ('b'), and eolian ('e') deposits. Detail of basal contact ('c') and subtidal facies ('s') at + 7 m are pointed out in Photo B by P. Kindler.

red (2.5YR 3/6) clayey paleosols fill pits of deeply (1–3 m) karstified Stage 9/11 limestone. Numerous patches of younger washover deposits are distributed throughout the trough (labeled '7?' and '5e?' in Fig. 9). Westward or landward of the cliffs at Section 8, Holocene skeletal washover deposits (A/I = 0.145) over 8 m thick fill at 1 km^2 basin.

Section 8 at Goulding Cay Quarry reveals the complexity of the Stage 9/11 sequence in Eleuthera by exposing deposits of at least three important highstand events, with associated foreshore facies, eolianites, and capping dark red, clayey paleosols. The lower two units contain beach and subtidal bedding (Figs. 9 and 10), probably correlated to Stage 11. A/I ratios from the four units (0.678; 0.670; 0.632; 0.712) confirm the association of these deposits with a pre-Stage 7, middle Pleistocene time interval, however unfortunately, at this time cannot precisely establish which, if any of the several discontinuities (contacts and soils) mark the Stage 9/11 boundary. Independent methods will perhaps resolve this critical point in the future.

Megaboulder deposits

In the Glass Window area, very large boulders, the largest measuring 14 m in length and weighing over 2000 tonnes (Fig. 11), are testimony to the powerful waves that have struck the north Eleuthera coastline in the past. The location of these boulders are identified in Fig. 3 by the triangle symbol. Disorientation of bedding planes, sub-boulder stratigraphy, petrological analysis, and amino acid ratios confirm that the boulders are middle Pleistocene age, and that they were deposited by waves late in Substage 5e (Hearty, 1997). A/I ratios from five of the boulders (0.604, 0.734, 0.660, 0.737, and 0.619; mean = 0.671 $\pm$ 0.063) are consistent with mean ratios from the *in situ* Stage 9/11 oolitic/peloidal unit (mean = 0.660 $\pm$ 0.040; Table 3) situated near the base of the cliff sections. Some of the boulders rest upon 5e marine and eolian oolites yielding ratios averaging 0.393 $\pm$ 0.011 (2), indicating stratigraphic inversion. This mean agrees with the Eleuthera mean (0.379 $\pm$ 0.027 ($n = 12$)) for Substage 5e. Hypotheses on the possible genesis of the large waves are discussed elsewhere (Hearty, 1997).

Other sections

We present the following four sections in Fig. 12 from central Eleuthera (located on schematic geologic maps in Fig. 13 and Fig. 14) to further illustrate the detail and completeness of the Pleistocene and Holocene sections. The sections in Fig. 12 show multiple sea-level oscillations and depositional events at substage and intra-substage scale. The stratigraphy, petrology, and A/I ratios are concordant with north Eleuthera sections.

Section 9 (ETC1/2; The Cliffs; Figs. 12 and 13)

Section 9 at 'The Cliffs' is the most complete of the Stage 7 sequences in Eleuthera containing four eolian

FIG. 11. Largest of several megaboulders at the crest of a 15-m ridge in north Eleuthera near Section 5. This example measures 13 × 11.5 × 6.5 m, and weighs over 2000 tonnes. Whole-rock A/I ratios and boulder petrology yield a middle Pleistocene age, while underlying deposits are correlated to Substage 5e. The megaboulder setting and stratigraphy indicate that they were deposited by very large waves at the end of Substage 5e (Hearty, 1997).

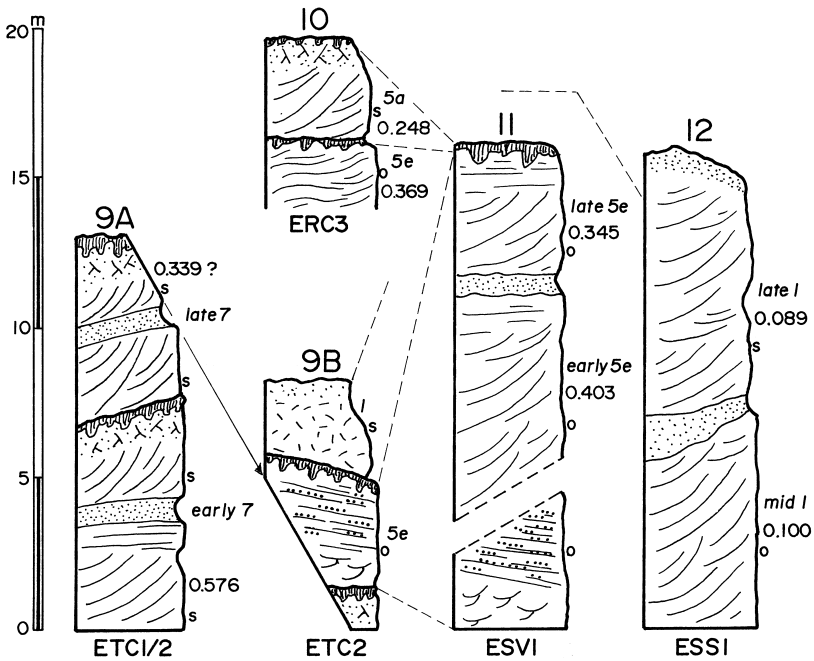


FIG. 12. Four stratigraphic sections from central Eleuthera highlighting intra-stage and substage stratigraphy. The legend is the same as Fig. 4, and the sections are located on Fig. 13 and Fig. 14.

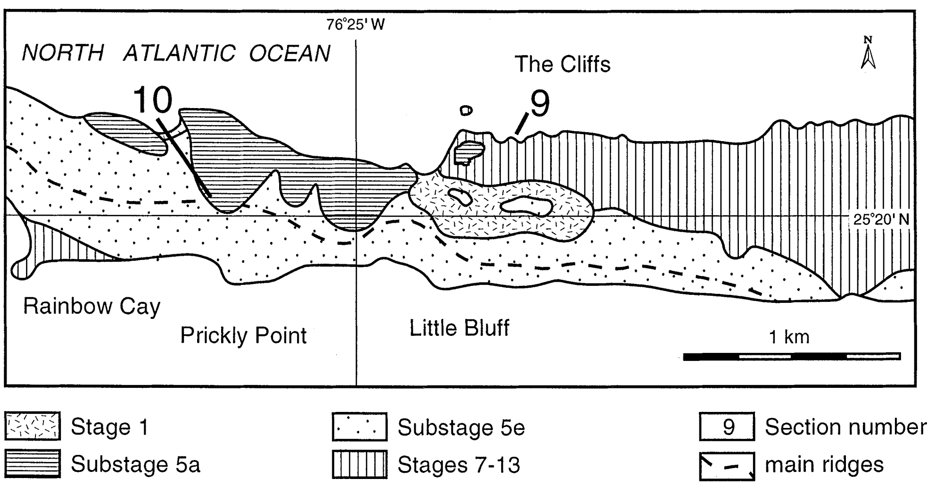


FIG. 13. Schematic geologic map of the area of The Cliffs (Section 9) and Rainbow Cay (Section 10).

units separated by protosols and midway by a well-developed *terra rossa* (5YR 5/6) paleosol. The stratigraphy and petrology of this section were examined in detail by Kindler and Hearty (1995), at which time the skeletal eolianite sequence was correlated with Stages 7 and 9. The author's view is that the entire span of Stage 7 from 240 to 190 ka comprises the older portion of Section 9. The important stony/sandy paleosol separating lower and upper eolianite pairs probably developed during a prolonged emergence (30–40 ka) *within* Stage 7. An A/I ratio on the lowest unit (0.576) corresponds to Section 4 at Glass Window (0.581) and supports the younger Stage 7 interpretation of the sequence. Landward of, and onlapping the older Cliffs section is an intertidal oolite correlated to 5e. These ooid shoal deposits demonstrate active tidal circulation around the middle Pleistocene islets. A landward basin is filled with thick, skeletal, Holocene washover deposits (Fig. 13).

Section 10 (ERC3: Rainbow Cay; Figs. 12 and 13)

The stratigraphy of Section 10 in a highway roadcut near Rainbow Cay illustrates most clearly the age separation between oolitic eolianites of 5e age, and skeletal eolianites deposited late in Stage 5. A brecciated red paleosol (7.5YR 7/8–10YR 8/4) and centimeter-thick calcrete separate the two Stage 5 units (Fig. 12; Hearty and Kindler, 1993b; Kindler and Hearty, 1996). A/I ratios from lower (0.369) and upper eolianites (0.248) support a 30–50 ka age difference, and correlate the units with other

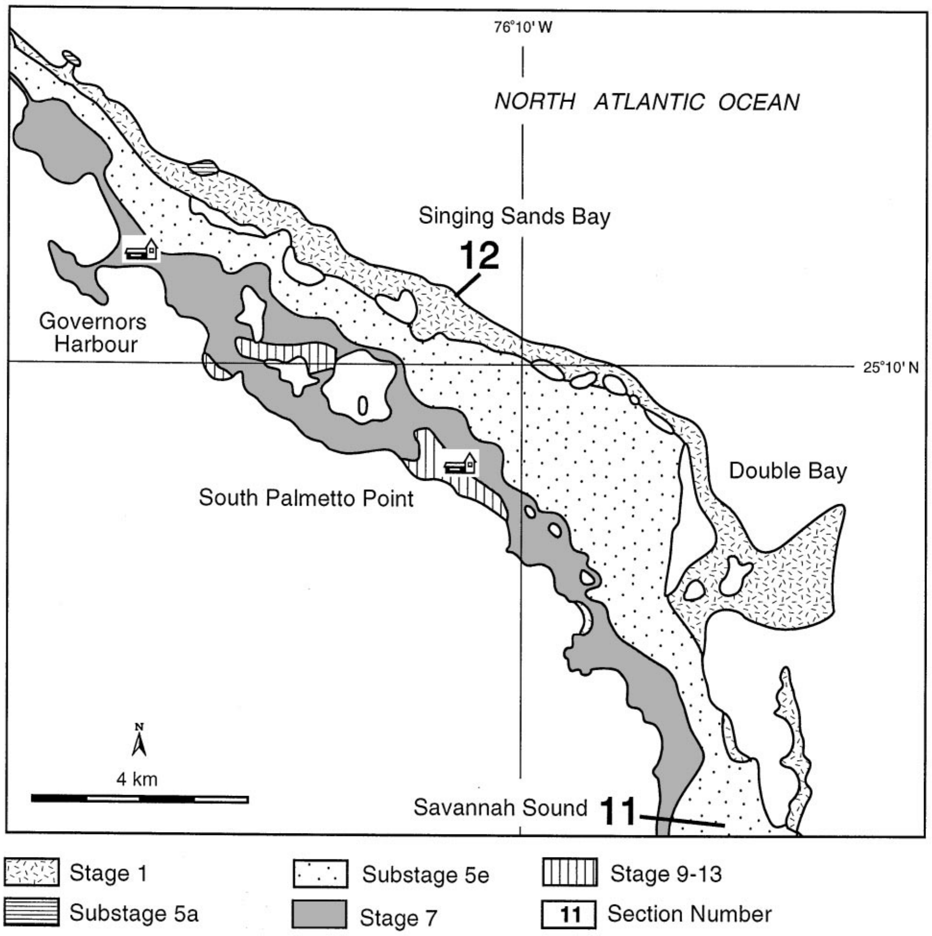


FIG. 14. Schematic geologic map of the area around Governor's Harbour including sites at Savannah Sound (Section 11) and Singing Sands (Section 12) (modified from Kindler and Hearty, 1996).

5e/5a sequences in north Eleuthera at Sections 1, 2 and 5.

Section 11 (ESV1; Savannah Sound; Figs. 12 and 14)

The stratigraphy at Section 11 from Savannah Sound demonstrates a double-5e highstand. As with 5e sections elsewhere in the Bahamas (Muhs *et al*., 1990; Hearty and Kindler, 1997a (New Providence); Chen *et al*., 1991 (Inagua); Hearty and Kindler, 1995; Neumann and Hearty, 1996), two depositional phases are recognized between 132 and 118 ka (Chen *et al*., 1991), with a regression indicated at around 124 ka. Section 11 shows mainly the early and late oolitic eolian facies, separated by a pale yellow (2.5Y 7/3) protosol with abundant *Cerion* landsnails and rhizomorphs. Late in the 5e, rapid mobilization of lagoon oolites by wind buried living trees and palmettos. Evidence of rapid fluctuations of sea-level late in 5e was presented by Neumann and Hearty (1996). Among the many features supporting this unsettled climatic interval are chevron ridges, runup deposits, and the transport of megaboulders (Hearty *et al*., in review; Hearty, 1997). A/I ratios show some age separation between lower (0.403) and upper (0.345) eolianites at Section 11, while mean ratios correlate these deposits with other 5e sections in Eleuthera and elsewhere in the Bahamas (Kindler and Hearty, 1996; Hearty *et al*., in review). Section 11 is capped by a mottled, silty, brown (7.5YR 4/3) paleosol.

Section 12 (ESS1; Singing Sands; Figs. 12 and 14)

The extent of the Holocene depositional sequence is revealed in beach exposures and an extensive dune field at Singing Sands near Governors Harbour. A mid Stage 1 oolitic eolianite formed when sea-level was lower than present, and was subsequently partially buried by younger skeletal beach and eolian deposits. A pale yellow (2.5Y 8/3) sandy protosol sometimes separates the two units. A/I ratios from an equivalent mid Holocene oolitic eolianite on Windermeer Island yields an A/I ratio of 0.100, while that from the skeletal unit from Singing Sands is 0.089.

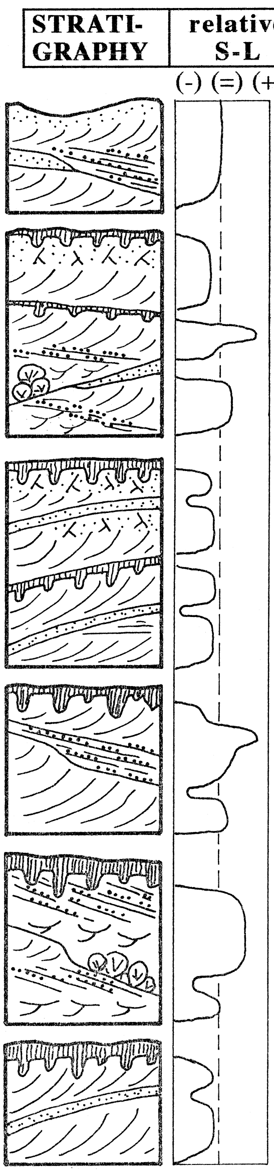
COMPOSITE SECTION

Physical stratigraphy and petrology

A stratigraphic mosaic (Fig. 15) is constructed from the most complete and exemplary of the 12 sections illustrated and discussed above. This composite is a summary of the major units identified on the basis of stratigraphic and geomorphic position, limestone petrology and diagenesis (Kindler and Hearty, 1995, 1996), sedimentary structures, pedogenesis, and amino acid geochemistry. This composite comprises at least six interglacial complexes. Within those, eight parasequences can be defined on the basis of *terra rossa* paleosol-bounded limestone units. The Holocene is counted among those, but of course, is lacking a *terra rossa* paleosol at its upper contact.

Pedostratigraphy

The results of this study indicate that soil colour and texture are good qualitative indicators of relative age of stratigraphic units. In general, soils become redder with greater age, a relationship graphically illustrated in a plot of Munsell (1994) soil colour vs. stratigraphic age (Fig. 16). In 44 sample cases, soil colour is used to distinguish three groups of deposits. The youngest, centered on 10YR 7/4, includes Holocene and mid-interglacial soil samples. The next older group comprises both post-Stage 5 and 7 soils, but cannot distinguish between them. This group is centered on 5YR 4/4 with some yellower outliers of post-5e age. The oldest group of paleosols are those capping Stage 9 and 11 limestone. With only two exceptions, the group is centered on 2.5YR 3/4. From this preliminary and cursory study, it is clear that soil characteristics can be used to distinguish broad classes of ages in a majority (> 80%) of cases. These findings disagree with those of Boardman *et al.* (1995) who concluded on the basis of soil type and clay mineralogy that soils were not a useful stratigraphic tool in the Bahamas. Neither soil colour nor samples representing multiple stratigraphic horizons were examined in their study.



STAGE	PETRO-LOGY	A/I RATIO	SEDIMENTARY FACIES
late 1	skeletal	0.089	Intertidal, supratidal, and eolian
mid 1	oolitic	0.100	Predominantly eolian foresets
paleosol	*5YR 4/4*	*post-5*	
5a	skeletal	0.292	Predominantly eolian foresets
paleosol	*10YR 7/4*	*mid-5*	
late 5e	oolitic	0.345	Subtidal, reef, intertidal, and eolian
early 5e	oolitic	0.405	Subtidal, reef, intertidal, and eolian
paleosol	*5YR 4/4*	*post 7*	
late 7	skeletal	0.569	Eolian
early 7	skeletal	0.576 0.581	Eolian and washover?
paleosol	*2.5YR 3/4*	*post 9/11*	
9/11?	oolitic/ peloidal	0.714	Beach and washover
9/11?	oolitic/ peloidal	0.628	Eolian
paleosol	*2.5YR 3/4*	*post 9/11*	
11?	oolitic/ peloidal	0.670	Subtidal, reef, and intertidal
11?	oolitic/ peloidal	0.687	Subtidal, reef, and intertidal
paleosol	*5YR 5/8*	*post-13/15*	
13 or 15?	skeletal	0.789	Eolian
13 or 15?	skeletal		Eolian

FIG. 15. A composite geology from Eleuthera Island showing physical stratigraphy, relative sea-level, petrographic composition of units, mean A/I ratios (from Table 3), soil colour, and dominant sedimentary facies.

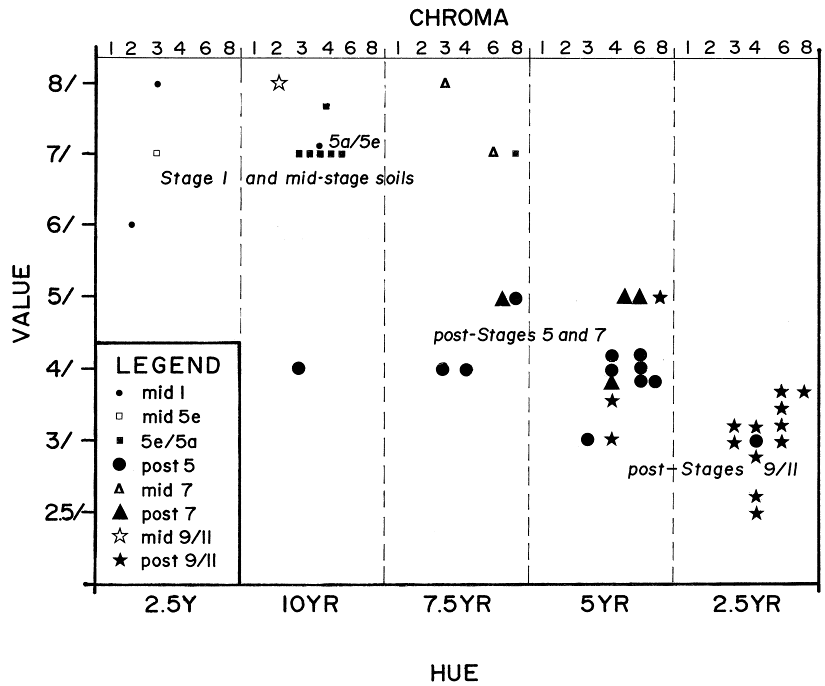


FIG. 16. Munsell plot of soil colour vs geologic age of 44 soil samples from Eleuthera. Three groups are defined based on colour: (1) the youngest (Stage 1) and mid-interglacial (e.g. 5e/5a) soils; (2) a middle group including soils capping Stage 5 and Stage 7 deposits; and (3) an oldest group of soils capping Stage 9 or older deposits.

Red paleosols are generally associated with glacial lowstands; however, it is clear from several examples that they may also form during periods of prolonged emergence *within* interglacials (Hearty and Vacher, 1994), and thus cannot be used exclusively as a criterion for defining only full glacial cycles. Major interglacial *terra rossa* soils (formed on a 10^5 year scale) are generally deep red (5YR 4/4 to 2.5YR 3/6), more clayey, and situated on a moderately to deeply karstified surface (> 1 m). Minor mid-interglacial soils (formed on a 10^4 year scale) are generally yellowish brown or reddish yellow (10YR 7/4 to 5YR 5/6) and contain more silt and sand. The karstification of the underlying limestone surface is moderate, extending downward some decimeters. The best examples of intra-stage reddish paleosols (tightly centered on 10YR 7/4) are the soils that formed between 5e and 5a (Sections 1, 2, 5, and 10; Fig. 6), each apparently requiring around 30 to 50 ka to develop. Protosols, which are sandy and buff colour (2.5Y 7/3), reflect brief periods (formed over a 10^3 year scale) of reduced carbonate sand deposition as a function of ecological stability, minor sea-level regression, or both. There is no significant karstification of the limestones underlying protosols, however, thin (2–3 mm) calcrete may be present on the limestone surface beneath the soil. With a reduced input of sediment to land, vegetation thrives on dunes and beach deposits, ultimately preserving root casts, land animals, and other organic traces common in protosols. Protosols are used to identify breaks in sedimentation *within* substage events, and thus, their formation is constrained to a few hundred to a few thousand years.

Aminostratigraphic correlation

The whole-rock A/I ratios presented in the stratigraphic sections are used as a geochemical signature with which lithostratigraphic correlations can be verified. In general, stratigraphic units keyed to isotopic stages and substages have mean ratios of: Stage $> 13? = 0.79$; Stage $9/11 = 0.67 \pm 0.05$; Stage $7 = 0.58 \pm 0.01$; Substage $5e = 0.38 \pm 0.02$; Substage $5a = 0.29 \pm 0.03$; and Stage $1 = 0.09 \pm 0.01$.

Stratigraphic order of the A/I ratios is maintained in over 90% of cases. Some of those in stratigraphic order appear to disagree with the lithostratigraphic sequence, indicating one or two interglacials younger than indicated by the geology. These 'younger' ratios may be either the result of slight leaching of the samples, or may indeed represent younger ages of the deposits. The samples and sites in question will be subject to additional tests in the future. Most samples from the oldest unit (Stage > 13) have amino acid concentrations too low to be accurately measured. Perhaps repeated subsequent inundation by marine and fresh waters have leached the bulk of amino acids. However, the near absence of amino acids is, in itself, an indication of the great age of this stratigraphic unit. Only those late Pleistocene samples closely associated with soils are ever found to be significantly leached. Thus, loss or alteration of amino acid composition most commonly occurs in samples that are completely recrystallized, shallowly-buried samples that have experienced significant surface leaching (generally associated with soils), or those that have experienced repeated submergence.

The thin deposits associated with the + 20 m beach in Section 8 have produced samples with a whole-rock mean A/I of 0.71, and normal levels of amino acids. This combination of characteristics appears to be a function of surface heating, rather than alteration of amino acids concentrations through selective leaching which generally lowers A/I ratios. Even with such minor thermal effects, the A/I mean of the + 20 m beach statistically agrees with ratios from adjacent beds, and confirms a middle Pleistocene correlation. Younger oolites differ significantly from the + 20 m oolitic beach deposits by producing consistently lower A/I ratios and a lower grade of diagenesis. A/I ratios from younger oolites (Stages 5a and 1) are concordant throughout the study area (Table 3) and the Bahamas (Kindler and Hearty, 1996). In summary, regardless of whether discordant A/I data are included or excluded from the mean aminozone values, comparable and compatible sequences are defined by both the litho- and aminostratigraphic methods (Fig. 15).

Ages of aminozones and interglacial deposits

Age estimates for aminozones can be derived from mean whole-rock A/I ratios for each unit (Table 3; Fig. 15) by the apparent parabolic kinetics method (or APK, Mitterer and Kriausakul, 1989). This dating approach uses a parabolic kinetic pathway to approximate the epimerization reaction as it proceeds from younger to older samples. In a previous study, Hearty and Dai Pra (1992) confirmed an imperfect parabolic configuration of the curve with empirical data, and identified three interim phases (I to III) of exponentially decreasing rates.

Target isotopic age 'windows' for the middle and late Pleistocene interglacials are: Stage 15 = 617–565 ka; Stage 13 = 513–478 ka; Stage 11 = 420–362 ka; Stage 9 = 331–303 ka; Stage 7 = 238–194 ka; Substage 5e = 128–122 ka; Substage 5a = 87–71 ka; Stage 1 = 12–0 ka (Imbrie *et al*., 1984). The first-order age estimates from the APK method, summarized in Table 4, compare favorably with the target interglacial ages identified through proxy methods.

APK age estimates are based on a Substage 5e calibration at 123 ka, which equates with a mean A/I of 0.38 ± 0.03 ($n = 12$). A single A/I ratio from the oldest Stage > 13? unit predicts an age of 533 ± 41 ka (Stage 15 or 13). Although it is well recognized that a single ratio is inadequate to establish sound conclusions regarding age, this age estimate agrees with its lithostratigraphic age of ≥ Stage 13. The Stage 9/11 mean ratio of 0.67 ± 0.05 ($n = 16$) yields an APK age estimate of 385 ± 59 ka (444 to 326 ka), encompassing depositional events during both Stages 11 and 9 — a complexity and duration that is evident in the Goulding Cay Quarry sections. The succeeding skeletal eolianites yield an APK age estimate of 283 ± 23 ka determined from an A/I mean of 0.58 ± 0.01 ($n = 3$). This age estimate is possibly concordant with an early Stage 7 cave-flooding event in the Bahamas TIMS dated at 233 ka by Lundberg and Ford (1994). Stage 7 samples may be particularly sensitive to accelerated rates during the warmth of Stage 5 during their earliest, fastest and most sensitive reaction phase (A/I 0.1–0.4) during their first 100 ka diagenesis of the samples. Data from this interval indicate that the epimerization reaction responds to warmer interglacial temperatures with faster rates (Hearty and Dai Pra, 1992), departing somewhat from the idealized APK model of Mitterer and Kriausakul (1989).

From a mean ratio of 0.29 ± 0.02 ($n = 5$), an age of 73 ± 6 ka is calculated for the post-5e Pleistocene deposits at several sections, and thus a correlation with the Southampton Fm in Bermuda (Vacher *et al*., 1989).

TABLE 4 Estimated ages of stratigraphic units by apparent parabolic kinetics (Mitterer and Kriausakul, 1989) using whole-rock amino acids ratios

Stratigraphic correlation stage	A/I mean $\pm 1\sigma$ (number of samples)	APK age estimate (years) ($\pm$ error from key + error from aminozone)
Stage 1	0.110 ± 0.031 ($n = 3$)	$10\,350 \pm 3600$
Red paleosol		
Stage 5a	0.292 ± 0.025 ($n = 5$)	$73\,000 \pm 6000$
Reddish paleosol		
Stage 5e	KEY 0.379 ± 0.029 ($n = 12$)	$123\,000 \pm 7700$
Red paleosol		
Stage 7	0.575 ± 0.006 ($n = 3$)	$283\,000 \pm 23\,000$*
Red paleosol		
+ 20 m 9/11 beach	0.712 ± 0.102 ($n = 3$)	$434\,000 \pm 95\,000$
Minor unconformity		
Stage 9/11	0.628 ± 0.007 ($n = 5$)	$338\,000 \pm 30\,600$
Minor unconformity		
Stage 9/11	0.675 ± 0.020 ($n = 3$)	$390\,000 \pm 38\,000$
Megaboulders	0.671 ± 0.063 ($n = 5$)	$385\,000 \pm 67\,000$
9/11 mean	0.671 ± 0.050 ($n = 16$)	$385\,000 \pm 59\,000$
Major complex paleosol		
Stage > 13	0.789 ± 0.000 ($n = 1$)	$533\,000 \pm 41\,000$

Error of age estimates is calculated by adding the error of the key (7.7%) plus error of mean values of each aminozone.
*Stage 7 age probably an overestimate due to significant heating of samples during Substage 5e at early phase of epimerization reaction (see text).

Given a correction for cooler temperature history, equivalent Bermuda units (both of bioclastic composition) yield parallel whole-rock ratios indicative of a 5e/5a relationship. This relationship was confirmed by U-series ages (Harmon *et al*., 1983) and epimerization models (Hearty *et al*., 1992). APK predicts an age difference between early last interglacial oolites (Substage 5e) and late interglacial skeletal eolianites (Substage 5a) of 40–50 ka, again supporting the inferred 80 ka, Substage 5a correlation of the younger deposits, rather than 5c. This age difference is most evident in the well developed red paleosol and karst surface separating the two units at Sections 1, 2 (Fig. 6), 5, and 10. Ludwig *et al*. (1996) recently reconfirmed the age of the Southampton Fm at 80 ka with TIMS U-series dates on corals, and endorsed the geological and aminostratigraphic findings of Vacher and Hearty (1989) of an 80 ka highstand at 0 to +1 m. Parabolic kinetics characteristically yield an obvious over estimate of 10.5 ka for Stage 1 deposits when compared to ^{14}C calibration of <5000 years BP (Carew and Mylroie, 1987).

Summary of composite stratigraphy

The Quaternary geology of Eleuthera provides a relatively complete, high-resolution stratigraphic record of at least six broad interglacial sea-level cycles (10^5 year cycles), comprising several intervals of prolonged platform emergence (10^4 (20–40 ka) year cycles), and minor ecological or eustatic oscillations (10^3 year cycles) (Fig. 15) indicated by protosols. The inferred correlation with isotopic stages is based primarily on the stacked stratigraphic sequences and major bounding deep red paleosols (Figs. 4 and 12). This correlation requires that the age of the oldest skeletal unit at the base of Sections 5, 6, and 7 is $\geqslant$Stage 13. Both Stages 11 and 9 may be represented in the complex stratigraphy (four or five units/numerous oolitic/peloidal facies) of Sections 1, 6, 7 and 8; however, our data relevant to this point are not yet conclusive. The Stage 7 skeletal eolianite complex appears to span the full interglacial with a prolonged period of emergence of the platform midway through the interglacial.

As shown in previous studies (Garrett and Gould, 1984; Hearty and Kindler, 1995, 1997a,b; Neumann and Hearty, 1996), Stage 5 is indeed complex. Three major depositional phases are recognized: two oolitic complexes associated with significant sea-level oscillations within Substage 5e (Aharon *et al*., 1980; Hollin and Hearty, 1990; Hearty and Kindler, 1995), and a final Substage 5a event, separated from 5e by a reddish paleosol. Extensive skeletal eolianite ridges were deposited throughout the windward Bahama Islands (Hearty and Kindler, 1993a; Kindler and Hearty, 1996) and Bermuda (Vacher and Hearty, 1989; Ludwig *et al*., 1996) during this interval. Remnants of a firmly-cemented, oolitic eolianite ridge from mid Stage 1 exists only on exposed, high-energy coastlines, while a lightly-indurated, skeletal sand late Stage 1 shoreline complex (beach, eolian, and protosol facies) is found on most islands of the Bahamas.

REGIONAL CORRELATION

The geology of north Eleuthera offers the most complete and complex stratigraphic record known from the Bahamas. Kindler and Hearty (1996) summarized the petrostratigraphy of 61 sites from seven island groups. Their study, like Hearty and Kindler (1993b), noted the similarities of stratigraphic columns from these and other islands, and established

TABLE 5 Correlation based on litho- and aminostratigraphy between Bermuda, New Providence, and Eleuthera Islands. Because of a cooler temperature history, the mean aminozone A/I ratios from Bermuda are lower than those from the Bahama Islands

Isotope stage [aminozone]	Bermuda; Hearty et al. (1992); Hearty and Vacher (1994)		New Providence Island, Bahamas; Hearty and Kindler (1997a)		Eleuthera Island, Bahamas (this study)	
	Site/Fm.	W-R A/I ratio	Site	W-R A/I ratio	Site	W-R A/I ratio
1 [A]	Recent	0.12 ± 0.01 (2)	Xanadu Beach	0.09 ± 0.01 (1)	Singing Sands; Windermeer I.	0.11 ± 0.03 (2)
5a [C]	Southampton	0.23 ± 0.03 (3)*	Green Cay	0.28 ± 0.01 (2)	Whale Point; Rainbow Cay	0.29 ± 0.03 (5)
5e [E]	Rocky Bay	0.29 ± 0.03 (12)*	Lyford Cay	0.36 ± 0.03 (4)*	Boiling Hole; Savannah Sound	0.38 ± 0.03 (12)
7 [F]	Belmont	0.49 ± 0.04 (11)*	Skyline Estates	0.56 ± 0.02 (3)	Glass Window; The Cliffs	0.58 ± 0.01 (3)
9 [G]	Upper Town Hill	0.56 ± 0.02 (11)	Blue Hill Ridge	0.67 ± 0.01 (2)*	Goulding Cay Quarry; Glass Window	
11 [H]	Lower Town Hill	0.69 ± 0.01 (6)	Hunt's Cave Quarry	0.71 ± 0.03 (2)	Goulding Cay Quarry	0.67 ± 0.05 (16)
$\geqslant 13$ [I]					Goulding Cay Quarry	0.78 (1)

*Correlation verified by uranium-series ages from coeval deposits.

the relationship between limestone composition (ooids, peloids and bioclasts) and the magnitude of interglacial sea-level highstands. This study expands on the findings of Kindler and Hearty (1996) with the further revelations on the complexity of the Stage 9/11 interval, and recognition of an older unit exceeding Stage 13? in age (Table 1). The morpho-, litho-, pedo, and aminostratigraphy of New Providence Island (Hearty and Kindler, 1997a) compares favorably with Eleuthera back to Stage 11 (Table 5).

With the exception of early Pleistocene deposits, the Eleuthera stratigraphy compares well with that of Bermuda (Vacher *et al.*, 1989) in duration (Hearty *et al.*, 1992), and rivals it in terms of detail and resolution. Given a correction for a cooler temperature history in Bermuda, the aminostratigraphies from Bermuda, New Providence, and Eleuthera Islands show equivalent aminozones (Table 5) between Stage 1 and 13. Noteworthy among both island groups is the rapid and voluminous sediment accumulations during Stages 9/11 and 5e, resulting in significant enlargement of the islands during those times. The pre-Stage 7 record of San Salvador Island (Hearty and Kindler, 1993a) is more obscure due to limited exposures of the older record.

SEA-LEVEL HISTORY

The Bahama Islands are the product of sea-level changes in the late Quaternary. Carbonate sediment production is greatly accelerated when sea-level rises above the shelf margin, while carbonate grains are either bioclastic, oolitic, or peloidal, dictated by the degree of platform flooding (Kindler and Hearty, 1996) and the energy setting on the platform. The overall volume of limestone deposited on islands appears to be a function of the duration and amplitude of the shelf-flooding events. Regressional intervals from interglacial highstands is an important period for island growth. Sediments accumulated on the shelf during the highstands are remobilized by water and wind, and transported to the island margins resulting in island growth. Furthermore, under high-energy conditions like those in Eleuthera, sediments are transported to higher ground during more numerous storm events, and have a greater potential for preservation at these elevations. Interglacial limestone deposits are bounded by *terra rossa* soils reflecting glacial lowstands or protracted intra-stage regressions, while reduced carbonate delivery to the shoreline during minor mid-substage regressions allows for extensive vegetative growth and ecological stability, resulting in the formation of protosols.

Parasequences from Eleuthera yield evidence of several important high sea-level events (Fig. 17A), and agree well with other curves constructed from the geology of Bermuda and the Bahamas (Hearty and Vacher, 1994; Hearty and Kindler, 1995), with some notable differences. The oldest part of the Bermuda record includes one or two early Pleistocene, and older middle Pleistocene parasequences, all of which have yet to be identified in the Bahamas. The earliest evidence (Stage >13?) of island building in the Bahamas occurs during the middle Pleistocene, identified by skeletal eolianites at the base of the Goulding Cay Quarry sections (Figs. 4 and 9). Sedimentary structures in cliff exposures in Sections 6, 7 and 8 reveal important highstands at $+2$ m and $+7$ m, correlated to Stages 9/11, with preference to the older interglacial (Burckle, 1993). As part of the Stage 9/11 complex, an extensive mid Pleistocene barrier reef (Section 1) developed under apparently stable sea-level conditions, with head corals rising to over $+3$ m.

A subsequent sea-level excursion during the Stage 9/11 interval left beach deposits perched between $+13$ and $+20$ m at Sections 6 and 8 in North Eleuthera. In Bermuda, thin, coarse beach deposits, originally described by Land *et al.* (1967) at Government Quarry, were situated on a narrow platform at $+22$ m, incised into the early Pleistocene Walsingham Formation. The site was subsequently destroyed by quarry expansion; however, in 1997, beach sediments were again discovered by the author at $+22$ m in a small cave not far from the original site in the quarry (Hearty and Kindler, 1997b). The $+22$ m beach deposits in Bermuda show many similarities to the two sites in Eleuthera including height above sea-level, narrowness of the terrace, and thinness of the beach deposits. These three localities from stable carbonate platforms support a rise of sea-level to over $+20$ m and provide new evidence of a high and rapid transgression during the middle Pleistocene.

Assuming that northern hemisphere ice was at its interglacial minimum at that time (no ice except possibly in Greenland), and that Eleuthera is tectonically stable (Carew and Mylroie, 1995), melting of Antarctic ice is necessary to account for an additional 10–15 m of global sea-level. Burckle (1993) summarized oceanographic and continental evidence indicating that Stage 11 was the warmest interglacial in the last 500 ka. Our data from Eleuthera provide strong evidence of a West Antarctic ice collapse during the Stage 9/11 interval. Interestingly, Haddad's (Haddad, 1994) reconstruction of a proxy glacio-eustatic sea-level curve (Fig. 17B) from a $\delta^{18}O$ record from Site 607 (Raymo *et al.*, 1990) suggests higher-than-present paleo-sea-levels during Stages 11 and 9, the older rising to near $+20$ m. The presence of these high deposits on the tectonically stable coastlines of the Bahamas may provide additional evidence that Antarctic ice may have collapsed more than once during warm interglacials of the Quaternary (Hearty and Kindler, 1997b).

Sea-level during Stage 7 rose at least twice to near the present datum. These transgressions were separated by a significant period during which reddish brown, stony paleosols developed. Hearty and Kindler (1997a) found beach fenestrae at 0 to $+2$ m in coeval Stage 7 deposits (Table 5) on New

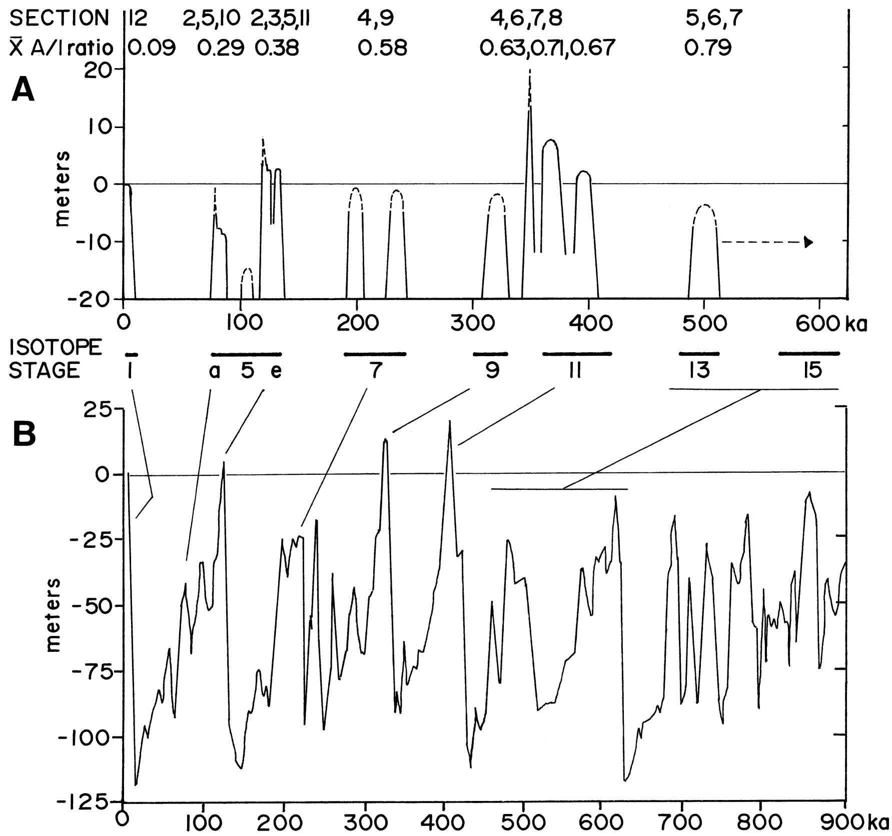


FIG. 17. (A) Sea-level highstands over the past > 500 ka as interpreted from geology and dating of deposits in north Eleuthera. (B) Haddad's (Haddad, 1994) conversion of Raymo et al. (1990) $\delta^{18}O$ record from ODP core 607 to sea-level. Note the similarities between evidence provided by direct (A) and interpreted (B) sea-level data.

Providence Island, indicating a rise of sea-level to near the present datum.

Substage 5e is represented by sub-, inter-, and supratidal marine deposits throughout Eleuthera and the Bahama Islands. Because of the immediate response time to sea-level changes in the sedimentary environment, evidence of 5e sea-level exists to over +8 m, while the slower-responding coral reefs only rise to a maximum of +2 m. A rapid, late Substage 5e sea-level rise and fall appears to have been responsible for bioerosional notches at +6 m, extensive parabolic beach/dune ridges ('chevron ridges'; Hearty *et al.*, in review) across the exposed bank margins, and massive eolian activity which built large dunes and buried standing forests (Neumann and Hearty, 1996). As envisioned by Hollin (1965), collapse of the West Antarctic ice sheet probably underlies the rapid rise of sea-level late in 5e. After a prolonged period of platform emergence and the development of paleosols on 5e oolites, large skeletal dune ridges were deposited on the Atlantic margin during Substage 5a. Vacher and Hearty (1989) defended a late Substage 5a sea-level rise to 0 to +1 m at 80 ka in Bermuda. Similarly in the Bahamas, the extensive 5a skeletal eolianite buildup positioned on island margins supports a 5a highstand very near the ordnance datum. The Holocene is marked by several episodes of ridge formation, with only the youngest periods associated with present sea-level values.

Tectonic stability of the Bahama platform

Tectonic uplift of middle Pleistocene shoreline deposits in Eleuthera can be largely ruled out because of (1) the concordance of numerous interglacial high sea-level maxima between Bermuda and the Bahamas (Hearty and Kindler, 1995); (2) the constant elevation of 5e reef crests and flank marginal caves at around + 2 to + 3 m throughout the Bahamas (Carew and Mylroie, 1995); and (3) the absence of historical earthquake activity in the Bahamas.

Tectonic stability without significant subsidence is also supported by the extensive record of middle Pleistocene highstand deposits in Eleuthera. These findings contradict the opinion that subsidence of the platform has obscured all evidence of pre-Substage 5e sea-level as maintained by Carew and Mylroie (1995).

Subsidence rates of the Banks are interpolated from deep core data over the past 100 Ma (Lynts, 1970; Mullins and Lynts, 1977; Freeman-Lynde and Ryan, 1985), from which an average 1–2 m/100 ka was estimated for the past 30 Ma. These rates are *assumed* to continue through the Quaternary; however, there is no dataset that can either prove or disprove the rate of subsidence of the Banks over the past 125 ka, which comprises only 0.1% of the subsidence record. Thus, any conclusions based on the *assumption of subsidence* are tenuous at best. It is possible, however, to *infer stability* by comparison of sea-level data with other global locations that are tectonically quiescent, as in our comparisons with Bermuda (cf Hearty and Kindler, 1995).

CONCLUSIONS

(1) Based on the correlation of 12 key sections in Eleuthera, eight soil-bounded limestone parasequences have been defined. These eight sequences represent at least six full interglacial periods encompassing the period from the Holocene to at least Stage 13. Each of the units have been stratigraphically ranked and characterized by a unique combination of sedimentary structures, petrographic composition, soil colour, and amino acid geochemistry (Fig. 15).

(2) Whole-rock aminostratigraphy demonstrates its utility by supplementing lithostratigraphic correlation, and providing a means to *estimate* unit ages. Straightforward, unambiguous correlations and concordance with the rock stratigraphy are achieved in over 90% of cases. Radiometric dating of corals is only rarely applicable to the largely non-coraliferous sedimentary deposits of the Bahamas thus making aminostratigraphy a valuable dating and correlation tool.

(3) Sedimentary evidence of paleo-sea-levels support higher-than, or near-present highstands throughout the past 500 ka. Eleuthera's geologically-derived sea-level record is of much greater resolution than proxy records, revealing multiple long-term stable sea-levels and punctuated high-level excursions during Stages 5e, 9 and 11. In addition, minor sea-level and ecological changes are discernible within stage and substage levels.

(4) A half-million year history of glacial and interglacial cycles is revealed in the stratigraphy of Eleuthera. This stratigraphy demonstrates several orders of cyclicity governed by orbital forcing including: a 400 ka cycle encompassing the entire Eleuthera sequence, 100 ka full glacial–interglacial cycles, 20–40 ka frequencies within interglacials, and numerous 1–4 ka cycles revealed in protosols. Shoreline facies of all types indicate a range of depositional intervals from prolonged highstands forming broad terraces to individual storm events revealed in washover deposits.

(5) The sedimentary system of the Bahama Banks is particularly sensitive to both minor and major oscillations of sea-level. The response time of the blanket of banktop sediments is immediate, and preservation potential of the sedimentary record in this geologic environment is high. Although coral reefs avail themselves to radiometric dating, their response-time to sea-level shifts is obscured, muted and delayed, recording mainly the prolonged highstand events. The slower response time of reefs is best demonstrated by the inability of the 5e reef to 'catch up' to the brief, + 6 m highstand (Neumann and Hearty, 1996) late in the period.

(6) Assumptions of constant uplift on tectonic coastlines are insufficiently tested, relying mainly on the Substage 5e 'golden spike' at + 6 m/125 ka, which is of dubious validity. A + 2 m, 128 ka calibration point based on maximum height of U-series dated reefs (Chen *et al*., 1991) would be more appropriate. Furthermore, the deep-sea oxygen isotope record is insensitive to minor eustatic changes, suffering the effects of bioturbation, diagenetic changes, biological variations in organisms, redistribution of foraminiferal tests, and numerous other assumptions concerning ocean salinity, paleotemperatures, and calculated ice volume. These proxy studies would benefit from the direct sea-level data provided by the long-term, high-resolution, geological record from the Bahamas.

(7) At present, the stratigraphy of Eleuthera is among the most complete and detailed known from the Bahamas. It records several scales of eustatic oscillations, as well as evidence for environmental, petrographic, pedogenic, and diagenetic changes over the past 500 ka.

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