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Carbonate petrography as an indicator of climate and sea-level changes: new data from Bahamian Quaternary units

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ABSTRACT

Coeval stratigraphic units of similar petrology occur throughout the northern Bahamas islands. The petrographic composition of these limestones provides clues about regional sea level and climate changes during the late Quaternary. At least eight fossil shoreline units, which are linked to transgressive episodes between the middle Pleistocene and the late Holocene, are recognized in the Bahamas. The petrographic composition of these units is either dominated by ooids and peloids or by bioclasts. Sedimentological observations demonstrate that oolitic–peloidal units were formed when sea level was higher than today, whereas skeletal units were deposited at or below modern ordnance datum. Skeletal units may reflect times of partial, or modest platform flooding, when the bulk of sediments brought to islands originates from bank-margin reefs. In contrast, oolitic–peloidal units correspond to major flooding events and active water circulation on the bank top. Cement fabrics further show that the early diagenesis of oolitic units took place during warm and humid climatic conditions, whereas skeletal rock bodies underwent subaerial diagenesis during drier climatic conditions characterized by marked seasonal changes. This example from the Bahamas suggests that compositional analysis of limestone from fossil carbonate platforms could be used for resolving ancient climate and sea-level changes.

INTRODUCTION

Geological research in the Bahamas archipelago traditionally focused on modern sediments and sedimentation processes (e.g. Illing, 1954; Purdy, 1963; Ball, 1967; Hine, 1977; Hine *et al.*, 1981) and platform architecture (e.g. Eberli & Ginsburg, 1989). Only recently have geologists begun to resolve the stratigraphy of individual islands (Garrett & Gould, 1984; Carew & Mylroie, 1985; Hearty & Kindler, 1993a; Kindler, 1995; Kindler & Hearty, 1995). Petrographic studies of Bahamian limestones are still sparse and, in most cases, report on diagenetic textures and processes (Friedman, 1964; Robinson, 1967; Harris, 1979; Gardner & McLaren, 1993; McLaren, 1993). Many of these studies (e.g. Garrett & Gould, 1984; Hutto & Carew, 1984) concluded that limestone composition only reflects local morphological controls and cannot be used as a tool for correlating stratigraphic units within and between islands.

Contrasting with previous studies, this paper shows that coeval stratigraphic units of similar petrology occur throughout the northern Bahamas islands. The petrographic composition of these limestones, which may be dominated either by ooids or by bioclasts, further provides important information about regional sea-level and climate changes during the late Quaternary.

GEOLOGICAL SETTING

The Bahamas islands (Fig. 1) represent the emerged portion of a series of isolated flat-topped carbonate platforms located to the east of Florida and to the north of Cuba, extending for more than 1200 km in a N–S direction and 500 km in an

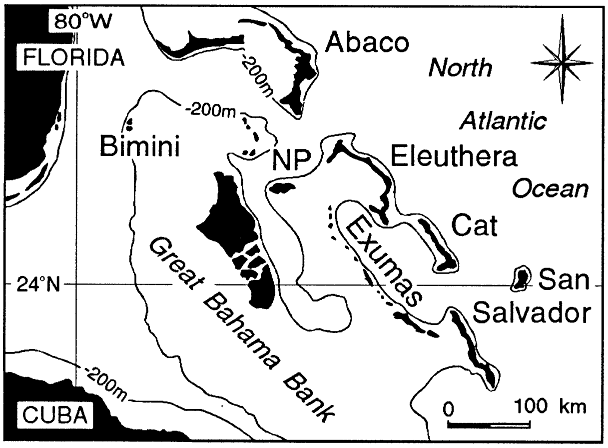


Fig. 1. Location map of the study area.

E–W direction. We focused our research on the north-western Bahamas (the islands of Abaco, Bimini, New Providence, Eleuthera, Cat, San Salvador and the Exuma chain), which are considered to be tectonically stable or undergoing slight subsidence (1·6 cm 10^3 yr^{-1} according to Lynts, 1970, and Mullins & Lynts, 1977).

According to many previous authors (e.g. Newell & Rigby, 1957; Bathurst, 1975; Beach & Ginsburg, 1980), the Bahamas islands mainly consist of oolitic limestone formed during the last interglacial period (Sangamonian). Only recently did Garrett & Gould (1984) recognize several distinct depositional phases on New Providence Island, including three subphases pre-dating the Sangamonian. On the basis of earlier work on San Salvador (Carew & Mylroie, 1985, 1987; Stowers *et al.*, 1989), Carew & Mylroie (1991) proposed a tripartite stratigraphy for the Bahamas comprising a Holocene unit (Rice Bay Formation), a Sangamonian unit (Grotto Beach Formation) and a pre-Sangamonian unit (Owl's Hole Formation).

This stratigraphic succession was thoroughly revised and completed by Hearty & Kindler (1993a,b, 1994). It now includes eight lithostratigraphic units extending from the middle Pleistocene to the late Holocene (Table 1). These units were formed in terrestrial and marine environments and are bounded by palaeosols that are not considered in this study.

METHODS

This study relied on a multi-method approach combining morphostratigraphy, geomorphology, sedimentology, petrography, and radiometric and amino-acid racemization dating. This approach is detailed in previous papers (Hearty & Kindler, 1993a, 1994; Kindler, 1995) and will only be briefly summarized below.

We first evaluated the morphostratigraphy with topographic maps and air photographs applying the principles of lateral accretion (Itzhaki, 1961; Vacher, 1973) and catenary growth (Garrett & Gould, 1984). The former states that, on a prograding shoreline, deposits become younger seaward. In contrast, the latter principle asserts that catenary ridges are younger than their anchoring headlands (Fig. 2). Measured sections were established at 61 critical sites (Fig. 3). Physical and biogenic sedimentary structures were examined in the field to obtain information about depositional settings and sea-level elevation during formation of the different rock units. Following petrographic examination in the field, over 500 samples were collected from the measured sections and from some 150 additional locations. Two hundred and fifty selected samples were impregnated with blue epoxy resin, thin-sectioned and examined under a polarizing

Table 1. Nomenclature of Bahamian stratigraphic units.

Epoch	Isotope stage	San Salvador Carew & Mylroie (1985)	San Salvador Hearty & Kindler (1993a)	The Bahamas Hearty & Kindler (1993b)	This study
Holocene	1	Hanna Bay Member	Hanna Bay Member	complex VIIb	unit VIII
	1	North Point Member	North Point Member	complex VIIa	unit VII
Late Pleistocene	5a	unrecognized	Almgreen Cay Formation	complex VIc	unit VI
	5e	unrecognized	Fernandez Bay Member	complex VIb	unit V
	5e	Cockburn Town Member	Cockburn Town Member		
	5e	French Bay Member	French Bay Member	complex VIa	unit IV
Middle Pleistocene	7	unrecognized	Fortune Hill Formation	complex Vb	unit III
	7	Owl's Hole Formation	Owl's Hole Formation	complex Va	unit II
	? 9	unrecognized	unrecognized	complex IV	unit I

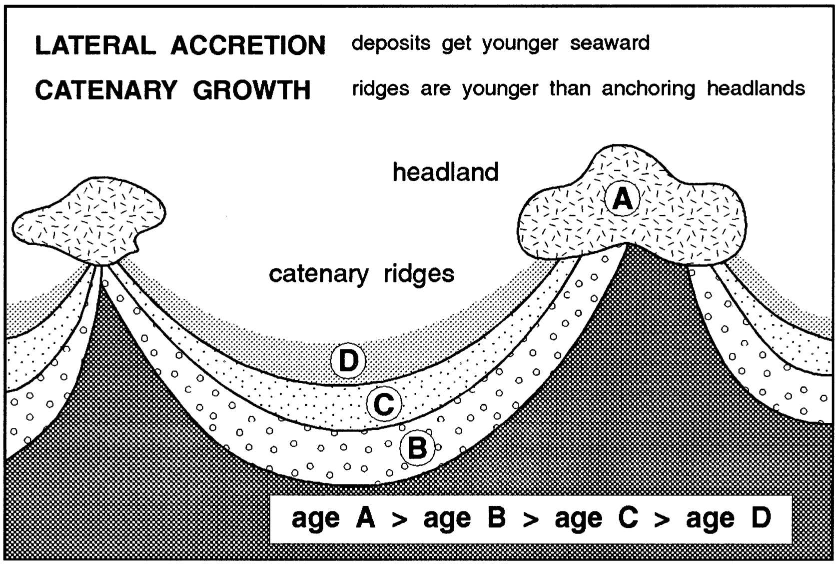


Fig. 2. Sketch illustrating the basic principles of morphostratigraphy used in this study.

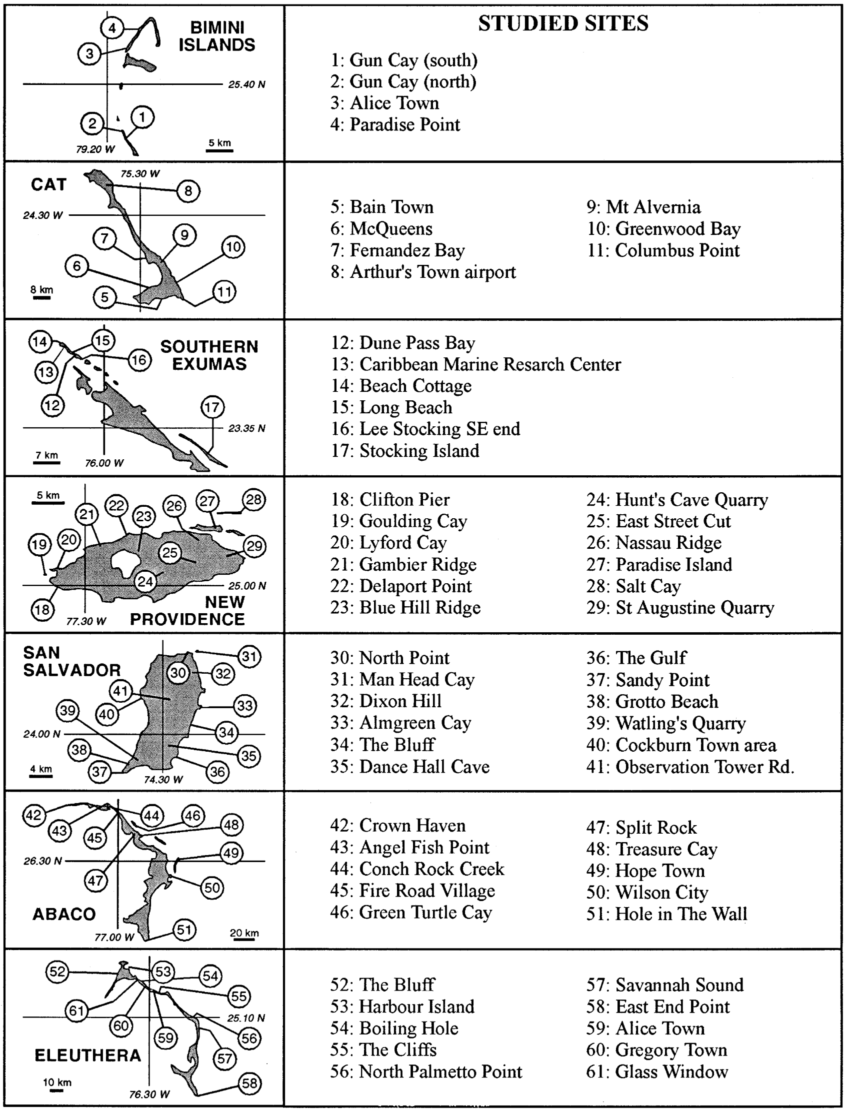
microscope. Carbonate minerals were identified by staining techniques (Friedman, 1959; Miller, 1988). Quantitative analysis was made with a SWIFT automatic point-counter (model F), according to the method developed by Chayes (1956) and later revised by Halley (1978), Harrel (1981) and Flügel (1982). A minimum of two 250-point counts were performed on separate portions of each thin-section to reduce errors linked to rock heterogeneity. We first calculated the percentages of grains, cement and primary porosity. Among the grains, we tabulated peloids, normal and superficial ooids, lithoclasts, aggregates and several types of bioclasts (algae, coral and mollusc fragments, benthonic foraminifers). Peloids include faecal pellets and rounded, structureless micritic grains. Micritized bioclastic particles, identified by distinctive shape or partly preserved texture, were counted as bioclasts. Standard deviation varies between 1 and 5% depending on particle frequency. For comparative purposes, we established a 'skeletal ratio' for each sample by dividing the percentage of bioclasts by the total percentage of ooids, peloids and bioclasts. Tables 3–9 provide a synthesis of our results for each rock unit; more details of the grain counts are available upon request.

Whole-rock ^{14}C-dating analyses were performed on a few Holocene samples, whereas uranium-series dating of unaltered corals carried out by other authors (e.g. Chen *et al.*, 1991) provided 'golden spikes' in the Pleistocene. Amino-acid racemization (AAR) dating was used on whole-rock samples for correlating units within and between islands, and determining their relative ages. The method relies on the slow interconversion (racemization) of L-amino acids, within indigenous proteins preserved in the sample, to increasing proportions of their respective D-configurations until an equilibrium mixture of D- and L-amino acids is attained. This study utilized the ratio of stereoisomers of isoleucine (D-alloisoleucine/L-isoleucine or A/I ratio). A/I ratio is zero in most living tissues (D-alloisoleucine is not present), and approaches an equilibrium ratio of 1·3 at an exponentially decreasing rate with increasing time since death of the organism. In numerous previous studies (e.g. Wehmiller, 1983; Hearty *et al.*, 1986; Miller & Brigham-Grette, 1989), A/I ratios are measured from commonly occurring terrestrial and marine mollusc shells, but the method has also been successfully applied to whole-rock limestone samples (Hearty *et al.*, 1992; Hearty & Kindler, 1993a, 1994). The AAR results are summarized in Table 2; however, because this study focuses on petrography, the AAR data will be reported in greater detail in a subsequent paper.

STRATIGRAPHY OF THE BAHAMIAN ISLANDS

Unit I – middle Pleistocene oolites (? isotope stage 9)

Friedman (1964) had previously noticed 'tracts of altered oolitic limestone' in the central part of New Providence, contrasting with better-preserved Pleistocene oolite elsewhere on the



STUDIED SITES

1: Gun Cay (south)
2: Gun Cay (north)
3: Alice Town
4: Paradise Point

5: Bain Town
6: McQueens
7: Fernandez Bay
8: Arthur's Town airport
9: Mt Alvernia
10: Greenwood Bay
11: Columbus Point

12: Dune Pass Bay
13: Caribbean Marine Resarch Center
14: Beach Cottage
15: Long Beach
16: Lee Stocking SE end
17: Stocking Island

18: Clifton Pier
19: Goulding Cay
20: Lyford Cay
21: Gambier Ridge
22: Delaport Point
23: Blue Hill Ridge
24: Hunt's Cave Quarry
25: East Street Cut
26: Nassau Ridge
27: Paradise Island
28: Salt Cay
29: St Augustine Quarry

30: North Point
31: Man Head Cay
32: Dixon Hill
33: Almgreen Cay
34: The Bluff
35: Dance Hall Cave
36: The Gulf
37: Sandy Point
38: Grotto Beach
39: Watling's Quarry
40: Cockburn Town area
41: Observation Tower Rd.

42: Crown Haven
43: Angel Fish Point
44: Conch Rock Creek
45: Fire Road Village
46: Green Turtle Cay
47: Split Rock
48: Treasure Cay
49: Hope Town
50: Wilson City
51: Hole in The Wall

52: The Bluff
53: Harbour Island
54: Boiling Hole
55: The Cliffs
56: North Palmetto Point
57: Savannah Sound
58: East End Point
59: Alice Town
60: Gregory Town
61: Glass Window

Fig. 3. Index maps of studied sites.

island. However, he did not recognize these 'tracts' as a separate stratigraphic unit. Unit I usually occurs in the interior of islands and at the base of rapidly eroding cliffs along the Atlantic shorelines. Apart from New Providence, we have recognized this unit on cliff exposures in Abaco, Cat and Eleuthera, and in the centre of San Salvador (Sites 6, 35, 41, 47, 50, 51, 54, 61, Fig. 3).

Sedimentary structures commonly observed within Unit I are steep (>30°), landward-dipping foresets indicative of an aeolian setting and fenestrae-rich planar cross-beds typical of foreshore sedimentation. At Hunt's Cave Quarry (Site 24, Figs 3 and 4), low-angle cross-bedding, shell hash and fenestrae occur at an elevation of +7 m, suggesting that sea level was higher than present (about +6 m) during deposition. Ooids and peloids make up over 70% of the constituent grains of this unit (Table 3). Ooids, which usually outnumber peloids, display rather thick cortices that may still retain their original aragonite mineralogy and tangential microstructure. However, in many cases, leaching and calcitization of cortices resulted in the formation of oomoulds, fallen nuclei and '*in-situ* calcitized ooids' (Richter, 1983; Fig. 5), the latter being less common within Sangamonian and Holocene oolites. The high proportion of peloids in most samples collected from Eleuthera (Table 3) suggests some local morphological control on petrographic composition or a slightly different age for these samples. Bioclasts are represented by mollusc, algal and coral fragments which seldom exceed 20% of the constituent grains. Unit I is further characterized by a large proportion (over 25%, Table 3) of low-magnesium calcite (LMC) cement

Table 2. Mean whole-rock A/I ratios and number of analysed samples (in parentheses) from the islands of Abaco (ABI), New Providence (NPI), Eleuthera (ELU), Cat (CAT), San Salvador (SSI) and the Exuma chain (EXU). Unit designations correspond with those used in Table 1. All data reported in this table were obtained from Dr Darrell Kaufmann (Utah State University). Statistical data are available upon request from Dr P. J. Hearty.

Unit	Stage	ABI	NPI	ELU	CAT	SSI	EXU
VIII	1		0·089 (1)	0·086 (1)		0·090 (1)	
VII	1			0·100 (1)			0·103 (2)
VI	5a			0·292 (5)		0·312 (5)	
V	5e	0·347 (1)	0·352 (4)	0·368 (3)		0·419 (4)	0·411 (2)
IV	5e			0·391 (7)	0·410 (1)	0·431 (2)	0·423 (6)
III	7	0·530 (2)		0·569 (1)			0·547 (1)
II	7			0·579 (2)			
I	? 9		0·681 (4)	0·640 (5)		0·680 (1)	

Table 3. Petrographic characteristics of Unit I (? isotope stage 9 oolite). This unit was found on the islands of Abaco (ABI), New Providence (NPI), Eleuthera (ELU), Cat (CAT) and San Salvador (SSI). It has so far not been identified in the Bimini islands or in the Exuma chain. In parentheses, the number of analysed samples per island. Skeletal ratio (*S ratio*) is obtained by dividing the percentage of bioclasts by the total percentage of bioclasts, peloids and ooids.

%	ABI *(5)*	NPI *(7)*	ELU *(11)*	CAT *(1)*	SSI *(2)*
Grains	59·4	61·4	57·1	58·0	62·8
Pores	15·3	12·7	12·0	8·6	9·5
Cement	25·3	25·9	30·9	33·4	27·9
Biocl.	13·9	6·3	16·0	5·5	7·7
Ooids	45·6	64·6	13·9	74·2	70·4
Peloids	35·5	14·4	61·8	16·2	16·0
Misc.	5·0	14·7	8·2	4·1	6·0
S ratio	0·147	0·074	0·175	0·057	0·082

typical of the meteoric environment (Longman, 1980). Cement textures include isopachous rims of anhedral crystals, menisci, blocky fillings and large (>1 mm) subhedral crystals enclosing adjacent grains. One sample collected at +5 m in northern Eleuthera (Site 61, Fig. 3) clearly shows two generations of cement (Fig. 6): (1) early LMC equant spar occurring at grain contacts and locally infilling pore spaces, and (2) late isopachous rims of fibrous aragonite. The former cement precipitated in a freshwater, possibly vadose setting, whereas the latter was formed in a marine phreatic environment (Longman, 1980).

The age of Unit I is demonstrated by (1) its stratigraphic position in the central part of islands or at the base of vertical successions; (2) its occurrence below deep-red, mature palaeosols and thick calcrete crusts; (3) a substantial degree of diagenetic alteration; (4) the local occurrence of a second generation of marine cement indicating submergence by a younger, possibly Sangamonian (Hearty & Kindler, 1995) flooding event that reached higher than modern sea level; and (5) elevated A/I ratios (Table 2). The high (+6 m) palaeo sea-level datum inferred from these limestones suggests that the oxygen isotope composition of coeval oceanic waters was close to Sangamonian values. Comparison with the isotopic record from deep-sea sediments indicates that deposition of this unit could have occurred during isotope stage 9 (see Fig. 20).

Units II and III – middle Pleistocene bioclastic calcarenites (isotope stage 7)

Garrett & Gould (1984) and Carew & Mylroie (1985) mentioned earlier pre-Sangamonian bioclastic calcarenites on New Providence and San Salvador, respectively. Recently, Hearty & Kindler (1993a) and Kindler & Hearty (1995) showed that these deposits are far more extensive than previously thought. In particular, they form

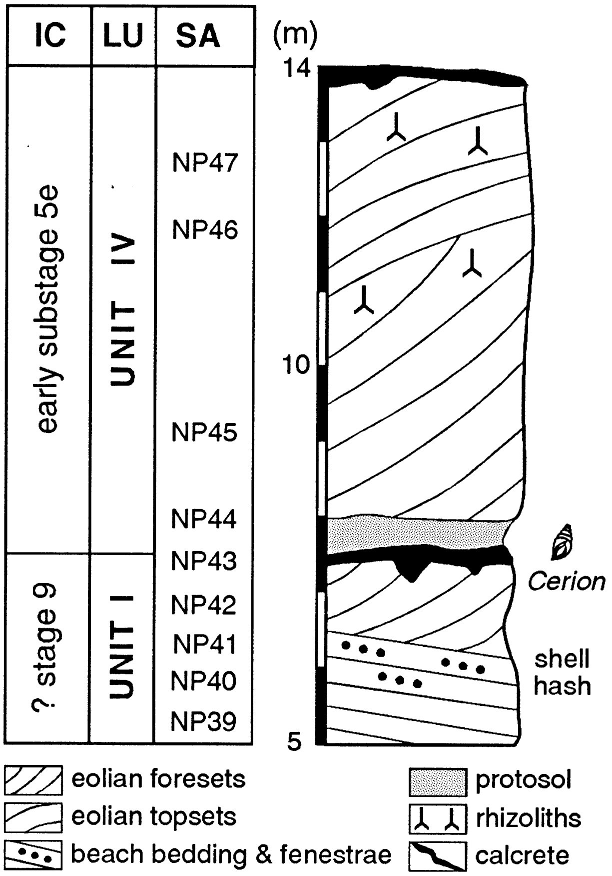


Fig. 4. Hunt's Cave Quarry section (New Providence Island, Site 24, Fig. 3) showing the superposition of Units I and IV. IC=isotope chronology; LU=lithostratigraphic unit; SA=sample number.

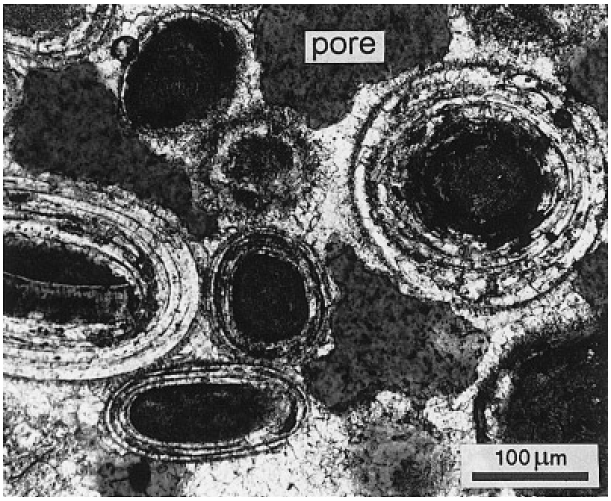


Fig. 5. Sample NP 41, Unit I, Hunt's Cave Quarry, New Providence. *In situ* calcitized ooids. Ooid cortices have been calcitized, but peloidal nuclei still retain their aragonitic mineralogy and have stained black when covered with Fiegl's solution. *In situ* calcitized ooids frequently occur in Unit I deposits, but are less common in younger oolites.

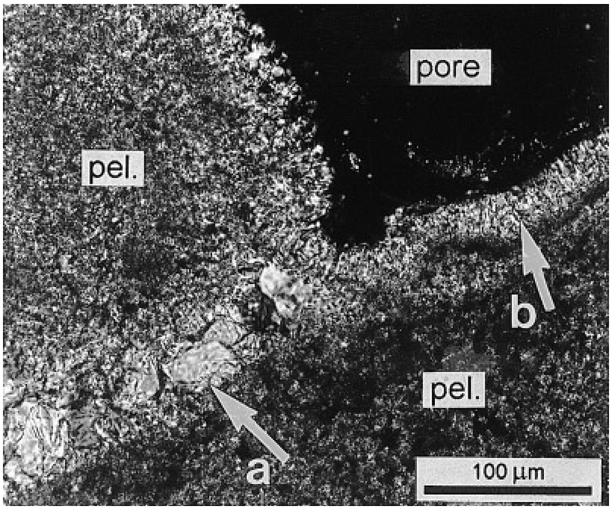


Fig. 6. Sample EL 92, Unit I, Glass Window (Eleuthera, Site 61, Fig. 3). A second generation of fibrous aragonite cement (arrow b) overlies an early low-Mg calcite cement (arrow a) linking two peloids (pel.). The former calcitic cement precipitated in a freshwater vadose setting, whereas the latter aragonitic fibres formed in a marine phreatic setting during a younger phase of platform flooding.

impressive sea cliffs along the ocean-facing shoreline of Abaco, Eleuthera and Cat (Sites 5, 11, 43, 51, 54, 55, 61, Fig. 3), and probably occur also in the Exumas (Site 12, Fig. 3; Kindler, 1995). Two stratigraphic units of similar petrographic composition can be recognized among these deposits. In San Salvador, the Fortune Hill Formation (Hearty & Kindler, 1993a; Unit III) includes the rocks of Dixon and Fortune Hills (Site 32, Fig. 3), whereas the Owl's Hole Formation (Carew & Mylroie, 1985; Unit II) is exposed at Grotto Beach and in Watling's Quarry (Sites 38, 39, Fig. 3). In Cat and Eleuthera (Sites 11, 55, 61, Figs 3 and 7), both units appear in vertical succession and are separated by a brecciated red palaeosol containing black pebbles and calcrete horizons. On New Providence (Site 23, Fig. 3), two pre-Sangamonian units clearly occur in distinct morphostratigraphic positions (fig. 5 in Garrett & Gould, 1984).

Units II and III were deposited in a subaerial environment as shown by steep aeolian foresets (Fig. 7) and low-amplitude wind-ripples (fig. 8b in Kindler & Hearty, 1995). Occurrence of these sedimentary structures below modern ordnance datum indicates that deposition took place when sea level was lower than today. Bioclasts, which can either be leached or wholly micritized (Fig. 8), usually represent over 60% of the constituent grains (Table 4). They essentially derive from the breaking of marine organisms typically found in

Fig. 7. The Cliffs section (Eleuthera, Site 55, Fig. 3). Cliff section showing the vertical succession of Units II and III. Both units consist of bioclastic aeolianites pre-dating the Sangamonian interglacial period (Kindler & Hearty, 1995). A palaeosol including breccia pockets and calcrete horizons separates both units. Large arrow points to steep aeolian foresets dipping below sea level at the base of Unit II. Cliff height is 15 m.

reefs and windward lagoons in the Bahamas (coral and red algae debris, benthic foraminifers; Newell & Rigby, 1957). Ooid content averages around 4% (Table 4). Grains are usually cemented by finely crystallized LMC spar that either concentrates at grain contacts or forms non-isopachous rims ('grain-skin' cement; Land *et al.*, 1967; Ward, 1975; Fig. 9). Syntaxial cement overgrowth also occurs around echinoid fragments. These cementation fabrics indicate a freshwater vadose diagenetic environment (Longman, 1980; McLaren, 1993). A second generation of marine vadose cement has been observed within one sample collected at 11 m above mean sea level from a coastal cliff in Eleuthera. The patchy distribution of this cement and the elevation at which it occurs suggest that it could be related to modern sea spray.

The ages of Units II and III have been locally estimated at about 200–300 ka on the basis of high A/I ratios (Table 2; Hearty & Kindler, 1993a). These ages are supported by the morphostratigraphic and stratigraphic position of the units between middle Pleistocene and Sangamonian oolites (Fig. 10), and possibly by their advanced stage of diagenetic alteration at all scales. Recognition of a lower than present sea level during formation of these calcarenites and comparison with the oxygen-isotope record from deep-sea sediments suggest that they could represent separate depositional events during isotope stage

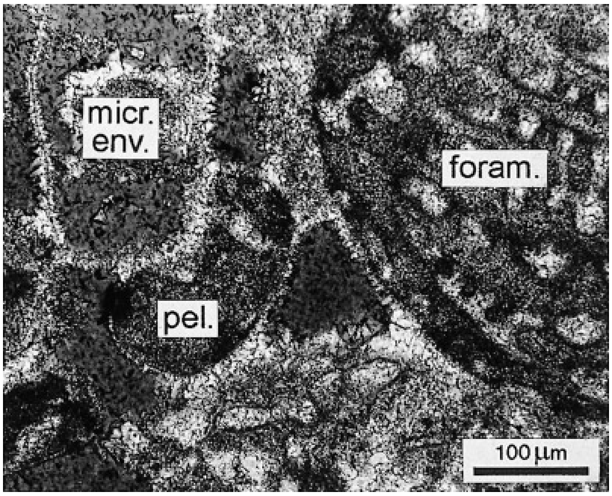


Fig. 8. Sample EL 76, Unit II, The Cliffs, Eleuthera. Microfacies of middle Pleistocene bioclastic calcarenites; note recrystallized foraminifer fragment (foram.) and empty micrite envelope (micr. env.); pel. = peloid. Leaching and recrystallization of particles characterize Units II and III, but are less common in younger bioclastic limestones (Units VI and VIII).

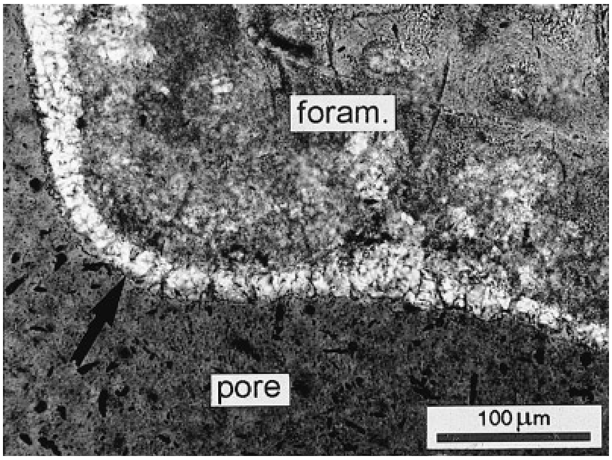


Fig. 9. Sample EL 76, Unit II, The Cliffs, Eleuthera. 'Grain-skin' cement (arrow) rimming foraminifer fragment (foram.). Note small crystal size.

Table 4. Petrographic characteristics of Units II and III (isotope stage 7 bioclastic calcarenites). Abbreviations are the same as for Table 3. Note the high percentages of cement compared to younger bioclastic units (Tables 7 and 9).

%	ABI *(5)*	NPI *(8)*	ELU *(15)*	CAT *(3)*	SSI *(13)*	EXU *(2)*
Grains	57·9	59·6	58·0	61·9	58·5	56·5
Pores	24·2	22·4	29·5	29·1	30·1	40·6
Cement	17·9	18·0	12·5	9·0	11·4	2·9
Biocl.	75·5	59·4	86·6	84·7	75·6	88·4
Ooids	5·6	9·0	2·8	1·2	0·7	2·7
Peloids	15·0	22·5	7·0	11·8	18·9	7·1
Misc.	4·0	9·1	3·6	2·4	4·7	1·7
S ratio	0·786	0·654	0·898	0·867	0·794	0·901

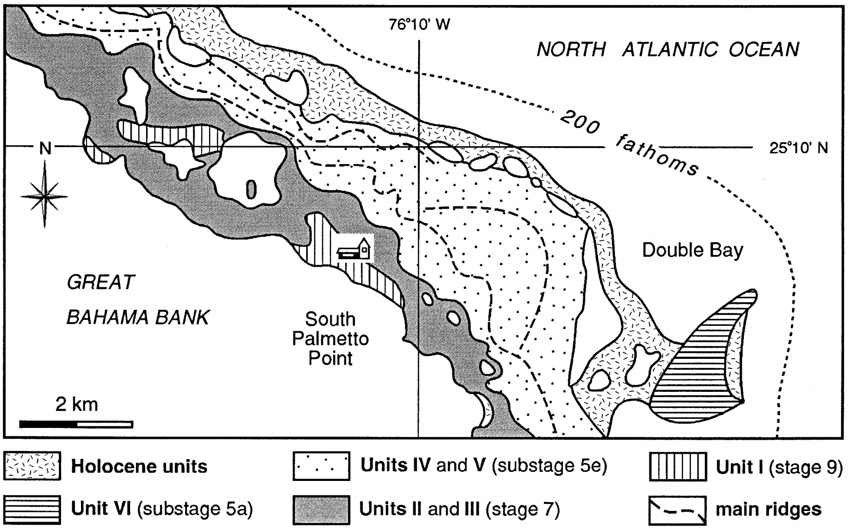


Fig. 10. Geological map of the Palmetto Point area in central Eleuthera. Stage 7 bioclastic calcarenites (including Units II and III) occur between stage 9 (Unit I) and substage 5e (Units IV and V) oolites. Note that Pleistocene units become younger seaward.

7 (see Fig. 20). Pre-Sangamonian bioclastic calcarenites can be distinguished from younger skeletal counterparts (Units VI and VIII) by the frequent occurrence of grain recrystallization and leaching, and a higher percentage of cement.

Unit IV and V – early Sangamonian oolites (isotope substage 5e)

On San Salvador Island, early Sangamonian (substage 5e) deposits comprise the Grotto Beach Formation (Carew & Mylroie, 1985; Hearty & Kindler, 1993a) and include three distinctive lithostratigraphic units: (1) the French Bay Member (Carew & Mylroie, 1985), (2) the Cockburn Town Member (Carew & Mylroie, 1985) and (3) the Fernandez Bay Member (Hearty & Kindler, 1993a). The French Bay and the Fernandez Bay Members are former oolitic coastal deposits, whereas the Cockburn Town Member represents a reef facies that has been precisely dated at 131–119 ka (Chen *et al.*, 1991). Substage 5e oolites occur throughout the Bahamas. They form the highest elevation of the archipelago (63 m, Mt Alvernia on Cat, Site 9, Fig. 3) and virtually blanket Grand Bahama (Gerhardt, 1983), San Salvador and Abaco Islands. The conspicuous nature of these units perhaps led to the common misconception that rock exposures in the Bahamas only consist of late Pleistocene oolite (e.g. Newell & Rigby, 1957; Bathurst, 1975; Beach & Ginsburg, 1980).

The early Sangamonian oolites display shallowing-upward sequences from subtidal to aeolian facies. Shoreface and beach deposits can be observed up to an elevation of 7 m. Elevated subtidal deposits, showing small-scale trough cross-stratification, herring-bone structures and callianassid burrows, are best exposed at Clifton Pier (New Providence, Site 18, Fig. 3; fig. 7 in Aurell *et al.*, 1995), Sandy Point (San Salvador, Site 37, Fig. 3) and Boiling Hole (Eleuthera, Site 54, Fig. 3; Kindler & Hearty, 1995). In addition to steep foresets and rhizoliths, aeolian deposits

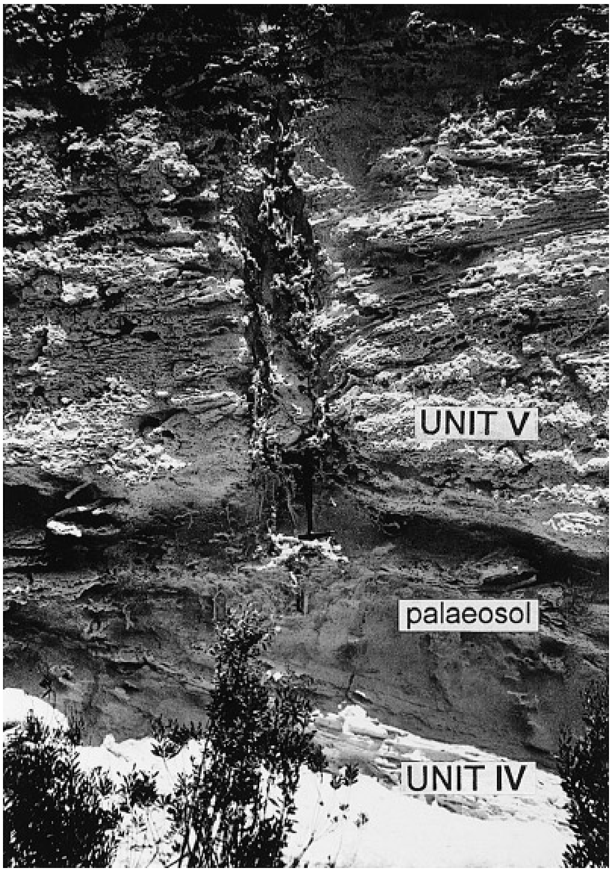


Fig. 11. Two Pines section (Eleuthera). A thick sandy palaeosol supporting a fossil trunk separates the early (Unit IV) and late (Unit V) substage 5e oolites. Scale is given by the hammer at the base of fossil tree. Entombing of standing trees and leafy vegetation suggests a rapid rate of deposition for Unit V.

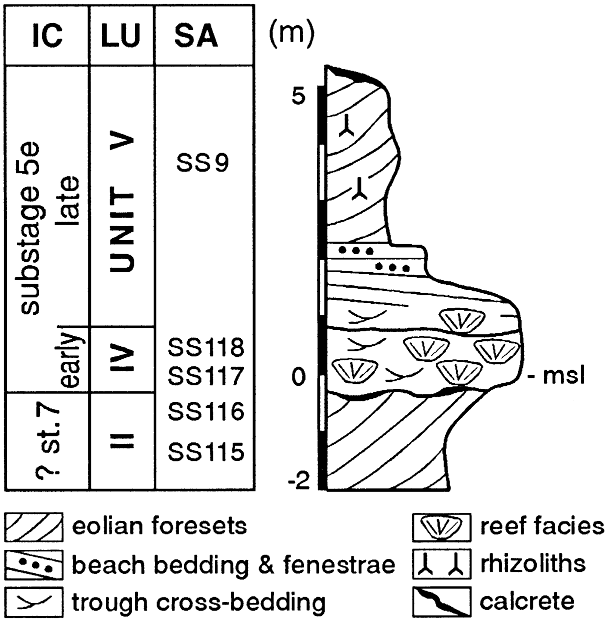


Fig. 12. Grotto Beach section (San Salvador, Site 38, Fig. 3). IC=isotope chronology; LU=lithostratigraphic unit; SA=sample number. Pre-Sangamonian aeolianites (Unit II) are overlain by early Sangamonian deposits. A discontinuity within the fossil reef shows that Unit IV (reef facies) and Unit V (shallowing-upward sequence from reef to aeolian facies) are represented at this location.

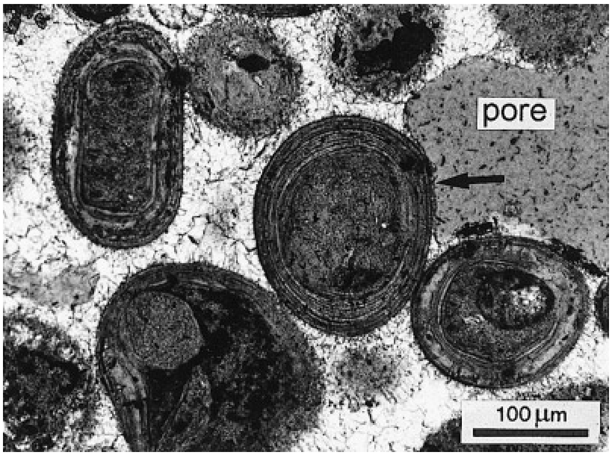


Fig. 13. Sample EL 83, Unit IV, The Cliffs, Eleuthera. Microfacies of the early substage 5e oolite. Note thickly coated ooids (arrow) and coarse sparry cement.

include fenestral voids possibly caused by heavy rainfall (Bain & Kindler, 1994) that must not be confused with swash-induced fenestrae.

Substage 5e oolites differ in their stratigraphic and morphostratigraphic position, petrological composition and amino-acid content (Table 2; Hearty & Kindler, 1993a, 1994). Unit IV is found at the base of the last interglacial stratigraphic sections (Sites 26 and 57, Fig. 3) and in a more landward position than Unit V. In vertical successions, a thick sandy palaeosol commonly separates the aeolian facies of these deposits (Fig. 11). Field evidence also shows that Unit IV pre-dates or is coeval with early Sangamonian reefs, whereas Unit V clearly post-dates them (Fig. 12). Both units are oolites, but the younger one usually contains a higher proportion of bioclasts and aggregates (Table 6, Fig. 14) than the older one (Table 5, Fig. 13). The most common constituent grains are tangential-aragonitic ooids and peloids that still preserve their original mineralogy. Ooids typically show thick cortices (up to 100 µm, Fig. 13) and small peloidal nuclei. Superficial ooids (Illing, 1954) also occur, but are less abundant than in middle Holocene oolites. Peculiar radial ooids have also been observed in several samples collected from Eleuthera (Kindler & Hearty, 1995, fig. 4e). In both units, allochems are bound by

Table 5. Petrographic characteristics of Unit IV (early substage 5e oolite). Abbreviations are the same as for Table 3. Very low skeletal ratios indicate the predominance of ooids and peloids over bioclasts.

%	ABI *(4)*	BIM *(1)*	NPI *(11)*	ELU *(13)*	CAT *(3)*	SSI *(12)*	EXU *(5)*
Grains	60·7	53·8	61·1	62·5	63·5	65·8	65·8
Pores	9·4	28·8	16·1	10·2	13·8	12·2	13·0
Cement	30·0	17·4	22·7	27·3	22·7	22·0	21·2
Biocl.	2·2	3·4	2·6	2·9	5·7	4·7	5·0
Ooids	73·2	63·1	73·6	61·8	56·7	70·8	55·3
Peloids	21·9	20·5	18·5	25·1	33·3	20·1	26·6
Misc.	2·8	13·0	5·3	10·2	4·4	4·5	13·0
S ratio	0·022	0·039	0·028	0·032	0·060	0·049	0·058

Table 6. Petrographic characteristics of Unit V (late substage 5e oolite). Abbreviations are the same as for Table 3. Bioclasts are more abundant than in slightly older Unit IV (Table 5).

%	ABI *(3)*	BIM *(3)*	NPI *(8)*	ELU *(3)*	SSI *(15)*	EXU *(1)*
Grains	62·8	65·7	65·2	62·3	63·6	69·6
Pores	12·5	14·7	18·9	17·9	26·8	19·6
Cement	24·7	19·5	16·0	19·8	9·7	10·8
Biocl.	12·3	20·8	9·6	26·6	19·0	13·1
Ooids	52·9	50·8	43·0	38·0	40·6	42·9
Peloids	30·9	16·3	21·5	28·3	28·8	26·1
Misc.	3·9	12·0	25·9	7·2	11·3	17·9
S ratio	0·128	0·237	0·130	0·286	0·215	0·160

coarse LMC equant spar which either occurs at grain contacts or totally fills pore spaces. Cement may represent up to 30% of the rock volume in Unit IV and around 15% in Unit V (Tables 5 and 6). For both units, the degree of cementation seems to correlate with sample location. Cement percentages tend to be higher in samples collected from the northern islands (e.g. Abaco) than in those gathered from southern locations (e.g. Cat, San Salvador). This cementation trend mirrors the northward increase in the amount of annual rainfall and associated leaching in this region (Pierson & Shinn, 1985).

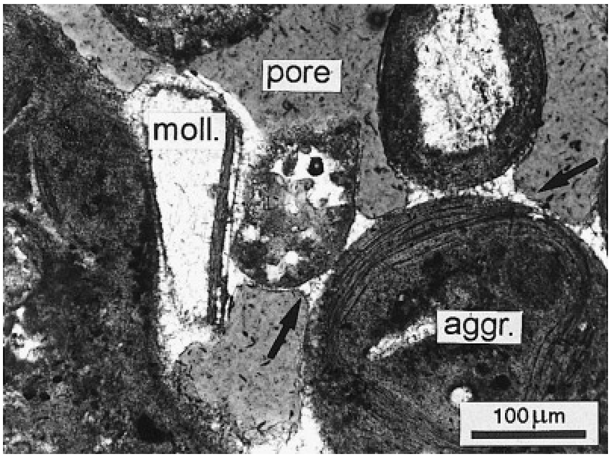


Fig. 14. Sample SS 9, Unit V, Grotto Beach, San Salvador. Microfacies of the late substage 5e oolite; (aggr.) = aggregate grain; (moll.) = mollusc fragment. Menisci (arrows) at grain contacts indicate that early diagenesis took place in a freshwater vadose environment.

The ages of the early Sangamonian oolites are estimated at *c.* 135 000 and 120 000 yr BP (see Fig. 20), respectively, based on their relative position with respect to well-dated substage 5e reefs and AAR analyses (Table 2; Hearty & Kindler, 1993a). These units differ petrographically from middle Pleistocene oolites by a lesser degree of diagenetic alteration and from Holocene oolites by the abundance of thickly coated ooids.

Unit VI – late Sangamonian bioclastic calcarenites (isotope stage 5a)

Late stage 5 deposits were recently defined on the eastern shoreline of San Salvador by Hearty & Kindler (1993a, 1994) and correlated with the Southampton Formation in Bermuda (Vacher & Hearty, 1989). Similar deposits have since been identified in Abaco (Sites 46 and 49, Fig. 3), Bimini (Site 2, Fig. 3), Eleuthera (Site 54, Fig. 3) and New Providence (Site 19, Fig. 3), where they form coastal bluffs and promontories that are

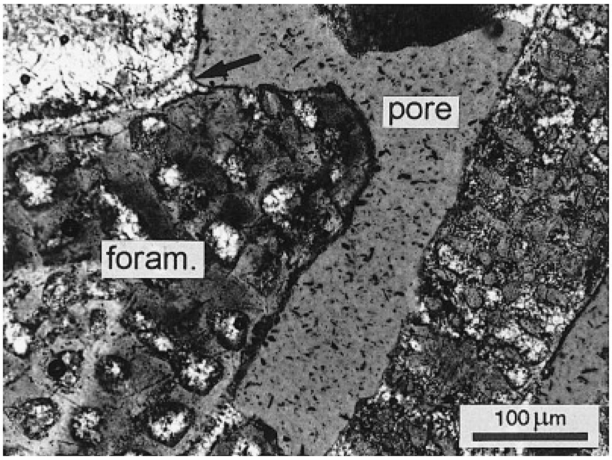


Fig. 15. Sample SS 69, Unit VI, Almgreen Cay (San Salvador, Site 33, Fig. 3). Microfacies of substage 5a bioclastic calcarenite. Note high primary porosity and sparse 'grain-skin' cement (arrow) at grain contacts; (foram.)=foraminifer fragment.

always situated close to the platform margin. These landforms commonly display abundant rhizoliths and large (>5 m), steep foresets that systematically dip below modern sea level. Unit VI can thus be interpreted as partly eroded aeolian dunes deposited when sea level was lower than today. Except for a few basal samples that contain ooids, probably reworked from early Sangamonian deposits, Unit VI calcarenites principally consist of bioclastic fragments characteristic of a high-energy marine setting, such as coral and red algae debris (Fig. 15, Table 7). These allochems are loosely bound by sparse (average 3%, Table 7), finely crystallized sparry cement, mostly found at grain contacts. Diagenetic features, such as empty micrite envelopes or recrystallized grains, are virtually absent from the studied samples, which may still contain traces of high-Mg calcite (HMC).

A substage 5a (*c*. 80 ka BP, see Fig. 20) age can be attributed to Unit VI on the basis of: (1) its stratigraphic position between two palaeosols, a lower one overlying substage 5e oolites (Fig. 16) and an upper one underlying Holocene units; (2) its location close to the bank edges indicating deposition during a modest transgressive event; (3) the small amount of diagenetic alteration of samples; and (4) low A/I ratios (Table 2; Hearty & Kindler, 1993a, 1994). These deposits can be recognized from middle Pleistocene bioclastic calcarenites (Units II and III) by a lesser degree of diagenetic alteration and from late Holocene skeletal limestones (Unit VIII) by the absence of associated beach facies.

Units VII and VIII – Holocene oolites and bioclastic calcarenites (isotope stage 1)

Unit VII is a volumetrically small rock body that was first identified on San Salvador (North Point Member, Carew & Mylroie, 1985; Hearty & Kindler, 1993a; Site 30, Fig. 3). It also occurs on Little San Salvador and West Plana Cay (Wilber, 1987) and, more recently, it was studied on Lee Stocking Island (Exuma Chain; Dune Pass Bay oolite, Kindler, 1995; Sites 12 and 16, Fig. 3) and Cat (Kindler, 1992; Site 7, Fig. 3). We have further recognized comparable deposits on Abaco (Site 48, Fig. 3), New Providence and Eleuthera (Site 58, Fig. 3). Unit VII consists of oolitic–peloidal limestones, which usually form 4–8-m-high 'haystack' dunes. These limestones show pristine small-scale aeolian structures, such as sandflow cross-strata, wind-ripple and grainfall strata (White & Curran, 1988; Caputo, 1993). Systematic occurrence of these wind-induced sedimentary structures in the modern subtidal zone clearly indicates that Unit VII was deposited when sea level was lower than today (see Fig. 20). This assumption is consistent with the *c*. 5-ka radiometric age obtained from these oolites (Carew & Mylroie, 1987; Kindler, 1992). Despite its young age, Unit VII is fairly well lithified. Sparry cement

Table 7. Petrographic characteristics of Unit VI (substage 5a bioclastic calcarenites). Abbreviations are the same as for Table 3. Note the small percentages of cement.

%	ABI *(1)*	BIM *(1)*	NPI *(3)*	ELU *(7)*	SSI *(8)*
Grains	53·3	54·7	60·7	61·1	61·0
Pores	42·8	43·9	35·7	34·7	37·6
Cement	3·9	1·4	3·6	4·2	1·5
Biocl.	88·8	74·4	65·5	86·7	78·8
Ooids	0·0	0·5	2·6	0·7	3·8
Peloids	10·1	18·6	10·3	7·3	10·3
Misc.	1·1	6·5	21·6	5·3	7·2
S ratio	0·898	0·796	0·835	0·915	0·848

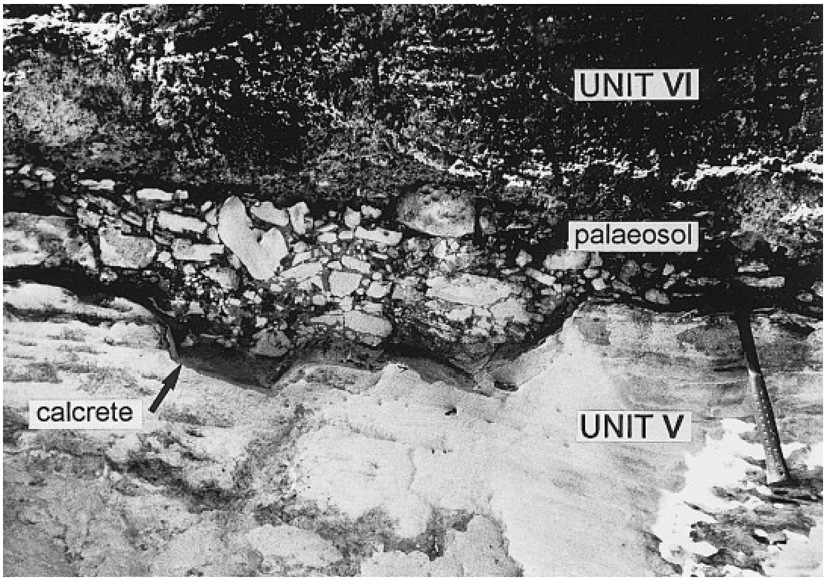


Fig. 16. Roadcut near The Cliffs section, Eleuthera, showing the vertical succession of Units V (late substage 5e oolite) and VI (substage 5a bioclastic calcarenite). The red brecciated palaeosol, 0·5-cm-thick calcrete and karstified surface on the top of Unit V show that a considerable amount of time elapsed before deposition of Unit VI.

Table 8. Petrographic characteristics of Unit VII (middle Holocene oolite). Abbreviations are the same as for Table 3.

%	ABI *(3)*	NPI *(2)*	ELU *(3)*	CAT *(2)*	SSI *(7)*	EXU *(14)*
Grains	62·3	57·6	62·7	66·3	63·9	65·4
Pores	24·1	22·3	17·7	14·7	23·4	19·0
Cement	13·6	20·2	19·6	19·0	12·8	15·6
Biocl.	5·9	11·2	13·7	1·5	8·0	9·9
Ooids	77·6	52·3	47·3	74·6	53·7	68·3
Peloids	14·1	21·0	33·8	17·8	30·9	14·5
Misc.	2·5	15·5	5·1	6·2	7·4	7·3
S ratio	0·060	0·133	0·145	0·016	0·087	0·106

may represent up to 20% of the rock volume (Table 8). Complete or partial leaching of ooid cortices also occurs, which is unusual for Holocene carbonates (Gavish & Friedman, 1969). These limestones differ petrographically from older oolites (Units I, IV and V) by the predominance of superficial ooids consisting of large, usually peloidal, nuclei and thin cortices (Fig. 17).

Late Holocene skeletal calcarenites occur extensively on the Bahamas islands. Initially defined on San Salvador (Hanna Bay Member, Carew & Mylroie, 1985), they have also been reported from the Exuma Chain (Perry Peak limestone, Kindler, 1995; Sites 14, 15, 17, Fig. 3), Cat (Kindler, 1992; Site 10, Fig. 3) and Bimini (Strasser & Davaud, 1986; Site 4, Fig. 3). In addition, we have recently examined similar deposits on Abaco, Eleuthera and New Providence (Sites 28, 46, 53, 56, 59, Fig. 3). Biogenic and primary sedimentary structures show that Unit VIII was formed in shallow-

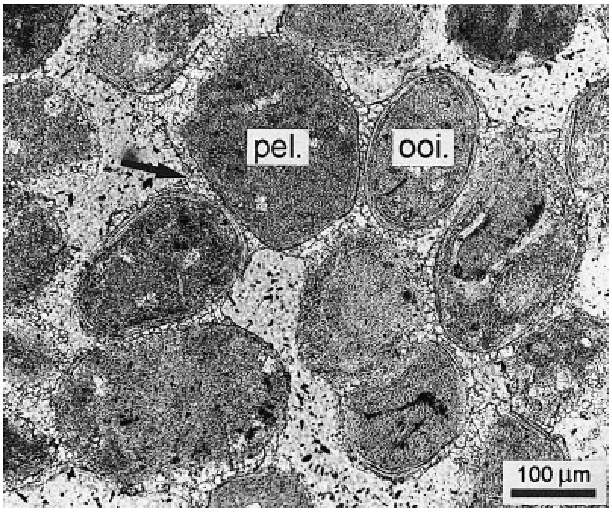


Fig. 17. Sample LSI 1, Unit VII, Dune Pass Bay, Lee Stocking Island (Exumas, Site 12, Fig. 3). Microfacies of the middle Holocene oolite. Note superficial ooids (ooi.), peloids (pel.) and patchy coarse spar cement forming menisci at grain contacts (arrow).

Fig. 18. Paradise Point, North Bimini (Site 4, Fig. 3). Shallowing-upward sequence in Unit VIII from foreshore to aeolian deposits. Note that the fossil (exhumed) beach is congruent with modern sea-level stand. Person is 1·65 m tall.

marine, beach and aeolian environments when sea level was close to its present elevation (see Fig. 20). Indeed, exhumed or 're-exposed' beaches (Strasser & Davaud, 1986) consisting of well-cemented bioclastic calcarenite frequently occur in the modern intertidal zone (Fig. 18). This unit is composed of friable to well-lithified, yellowish bioclastic limestones containing coral, algal and mollusc debris (Fig. 19), as well as abundant fragments of the pink foraminifer *Homotrema rubrum*. Relative abundance of bioclasts is usually lower than for Pleistocene skeletal eolianites (Table 9) because of frequent reworking of ooids and peloids from middle Holocene deposits. Late Holocene bioclastic calcarenites have been cemented by freshwater LMC cements following phases of shoreline progradation (Strasser & Davaud, 1986). Cement may reach 10% of the rock volume in the beach facies, but seldom more than 5% in the associated aeolianites. A second generation of recent marine cement commonly occurs within Unit VIII rocks now exposed in the intertidal zone (Kindler & Bain, 1993). In San Salvador, whole-rock ^{14}C analyses on the Hanna Bay Member yielded ages between 3200 and 420 yr BP (Carew & Mylroie, 1987; Kindler & Bain, 1993). Likewise, Gifford (1973) reported ages of 2300 yr BP from similar deposits in Bimini. However, an age of 5070 ± 70 yr BP was measured from one sample collected from the cliffs situated to north of Dune Pass on Lee Stocking Island (Site 15, Fig. 3). We speculate that this apparently anomalous age could be in part related to the high percentage of reworked ooids (26·5%) and peloids (46·9%) within this particular sample. The aeolian facies of Unit VIII differs from its Pleistocene counterparts (Units II, III and VI) by the occurrence of associated marine facies and a lesser stage of diagenetic alteration.

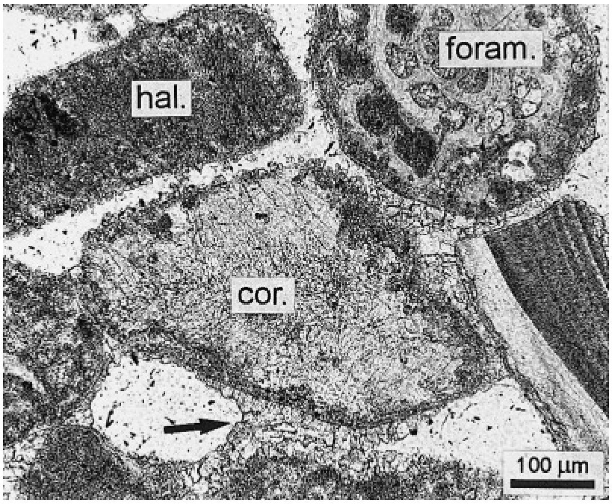


Fig. 19. Sample LSI 2, Unit VIII, Beach Cottage, Lee Stocking Island (Exumas, Site 14, Fig. 3). Microfacies of the late Holocene bioclastic calcarenites. Note coral (cor.), foraminifer (foram.) and micritized *Halimeda* (hal.) fragments. Arrow points to patchy sparry cement.

DISCUSSION

Petrography of Bahamian stratigraphic units

Two major points emerge from the petrographic data presented earlier, summarized in Table 10.

Table 9. Petrographic characteristics of Unit VIII (late Holocene bioclastic calcarenite). Abbreviations are the same as for Table 3. Relative percentages of bioclasts tend to be lower than for Pleistocene skeletal calcarenites due to the common reworking of ooids and peloids from Unit VII.

	ABI	BIM	NPI	ELU	CAT	SSI	EXU
%	*(1)*	*(3)*	*(3)*	*(5)*	*(2)*	*(11)*	*(19)*
Grains	64·0	63·3	67·8	60·5	66·0	62·2	63·8
Pores	31·0	30·1	24·5	34·5	27·2	28·7	31·1
Cement	5·0	6·7	7·7	5·0	6·9	9·2	5·1
Biocl.	43·3	64·9	84·2	74·2	60·1	50·9	59·8
Ooids	24·2	1·9	2·0	11·2	16·0	24·1	13·4
Peloids	18·5	14·8	8·1	11·5	19·7	17·2	16·3
Misc.	14·0	18·4	5·8	3·1	4·2	7·9	10·6
S ratio	0·531	0·762	0·916	0·766	0·748	0·615	0·714

Table 10. Comparative petrography of Bahamian Quaternary units. Skeletal ratios obtained in Tables 3–9 are placed in cells defined by islands (columns: ABI=Abaco; BIM=Bimini; NPI=New Providence; ELU=Eleuthera; CAT=Cat; SSI=San Salvador; EXU=Exumas) and stratigraphic units (rows: I–VIII, as in Table I). Coeval units have a similar petrographic composition on each of the studied islands, e.g. values of skeletal ratios (obtained by dividing the percentage of bioclasts by the total percentage of bioclasts, peloids and ooids) for Unit I vary between 0·057 (CAT) and 0·175 (ELU). Two groups of contrasting lithologies can be defined. The first group (Units II, III, VI and VIII) is dominated by skeletal fragments (ratios greater than 0·50). The other one (Units I, IV, V and VII) is characterized by the predominance of ooids and peloids (ratios smaller than 0·25).

Unit	ABI	BIM	NPI	ELU	CAT	SSI	EXU
VIII	0·531	0·762	0·916	0·766	0·748	0·615	0·714
VII	0·060		0·133	0·145	0·016	0·087	0·106
VI	0·898	0·796	0·835	0·915		0·848	
V	0·128	0·237	0·130	0·286		0·215	0·160
IV	0·022	0·039	0·028	0·032	0·060	0·049	0·058
II/III	0·786		0·654	0·898	0·867	0·794	0·901
I	0·147		0·074	0·175	0·057	0·082	

First, as shown by the values of skeletal ratios, coeval stratigraphic units have a comparable petrographic composition throughout the study area. In other words, the studied limestone units form a similar lithostratigraphic sequence on each of these widely spaced islands. When complete, this sequence includes at least one middle Pleistocene oolite, two skeletal units of stage 7 age, two early Sangamonian oolites, one substage 5a bioclastic calcarenite, and two Holocene units. Further analysis of Table 10 shows that the lithostratigraphic units exposed on the Bahamas islands can be separated into two groups presenting contrasting lithologies. The first group (Units II, III, VI and VIII) is dominated by bioclasts (skeletal ratios greater than 0·50). The other group (Units I, IV, V and VII) is characterized by the predominance of tangential-aragonitic ooids and peloids (skeletal ratios smaller than 0·25). Before further discussion, the factors controlling the formation of ooids and bioclasts must be clear.

Most authors (e.g. Newell *et al.*, 1960; Simone, 1981; Richter, 1983) agree that conditions required for optimal production of tangential-aragonitic ooids are: (1) a flat topography where particles can remain in their formation locus; (2) a very shallow and potentially turbulent environment; (3) a mixture of cool, CO_2-rich, oceanic water and warm bank-water supersaturated with respect to aragonite. Factors favouring reef growth, and thus indirectly bioclast production, are: (1) a hard substrate, (2) a high-energy setting, (3) shallow to moderate depths (up to 20 m), (4) normal-salinity, low-turbidity waters and (5) water temperatures between 20 and 30 °C (Newell & Rigby, 1957; Voss, 1988). Both grain types thus form close to the platform margins (Hine, 1977; Demicco & Hardie, 1994); however, ooid

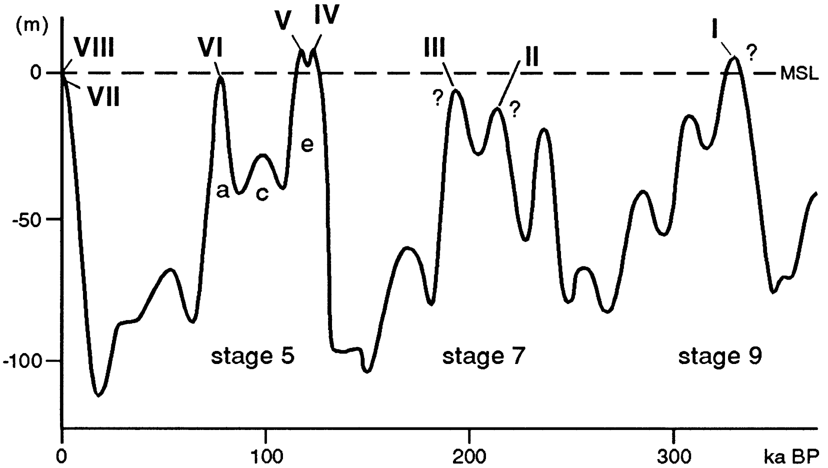


Fig. 20. Location of the studied units on a late Quaternary sea-level curve modified from Imbrie *et al.* (1984). Units I, II and III pre-date the Sangamonian period. Unit I was formed when sea level was higher than present, probably during isotopic stage 9. Units II and III were deposited during lower sea-level stands that could correspond to distinct transgressive phases during isotope stage 7. The Sangamonian record includes Units IV (early substage 5e), V (late 5e) and VI (substage 5a). As shown in Bermuda (Vacher & Hearty, 1989), the 5a sea-level event reached higher than indicated by the isotopic record from deep-sea sediments. The Holocene record consists of Units VII and VIII deposited during the early transgression and stillstand, respectively.

formation requires flooding of the platform top, whereas marginal reefs anchored on the platform slopes may produce bioclasts during relative sea-level lowstands.

Petrography and sea level

The petrographic composition of the Bahamian stratigraphic units is related to past sea-level elevation (Fig. 20). Except for Unit VII, oolitic–peloidal deposits (Units I, IV and V) were formed when sea level was higher than today, as shown by the occurrence of perched beach and shoreface facies. In contrast, bioclastic formations (Units II, III, VI and VIII) accumulated when sea level was equivalent to, or lower than, modern ordnance datum (Fig. 7). Due to the wide extension of the described units (700 × 450 km), regional, if not global, factors must be invoked to explain this relationship. We think that the degree of platform flooding ultimately controlled the petrography of the limestones now exposed on the Bahamas islands. When the platform was only marginally flooded (Fig. 21a), conditions were unfavourable to ooid production because of the absence of an extensive layer of shallow water on the bank top. In contrast, reefs, which do not require a wide surface for growth, could thrive on the bank slopes just below the platform edges and produce bioclasts. These particles formed coastal deposits near the bank margins, which are partially submerged today. Such was the case for isotope stage 7 and substage 5a bioclastic calcarenites. During complete flooding (Fig. 21c), warm, saline and actively circulating bank waters were deleterious to reef growth, but stimulated ooid and peloid production on the platforms. These particles formed shallowing-upward sequences from subtidal to aeolian facies that are now found above modern ordnance datum. The middle Pleistocene and substage 5e oolites typically show such elevated sequences. Stage 1 conditions seem to be intermediate between the extreme cases described (Fig. 21b). Although the banks are flooded today, and although ooid production is locally significant (e.g. Joulters Cays, Harris, 1979), water circulation is somehow restricted and the bulk of sediments supplied to islands consists of bioclastic particles produced by marginal reefs. The middle Holocene oolite (Unit VII) corresponds to an early transgressive event (Kindler, 1992, 1995) that is presently being eroded and will probably not be preserved in the geological record. Similar events probably occurred during isotope stage 7 and substage 5a, but may just be recorded by a higher proportion of ooids in the lowermost beds of the bioclastic calcarenites deposited during those time periods. Skeletal limestones are thus truly representative of isotope stage 1 sedimentation.

Petrography and climate

Because of the quiescent tectonic setting in the Bahamas (Lynts, 1970; Mullins & Lynts, 1977),

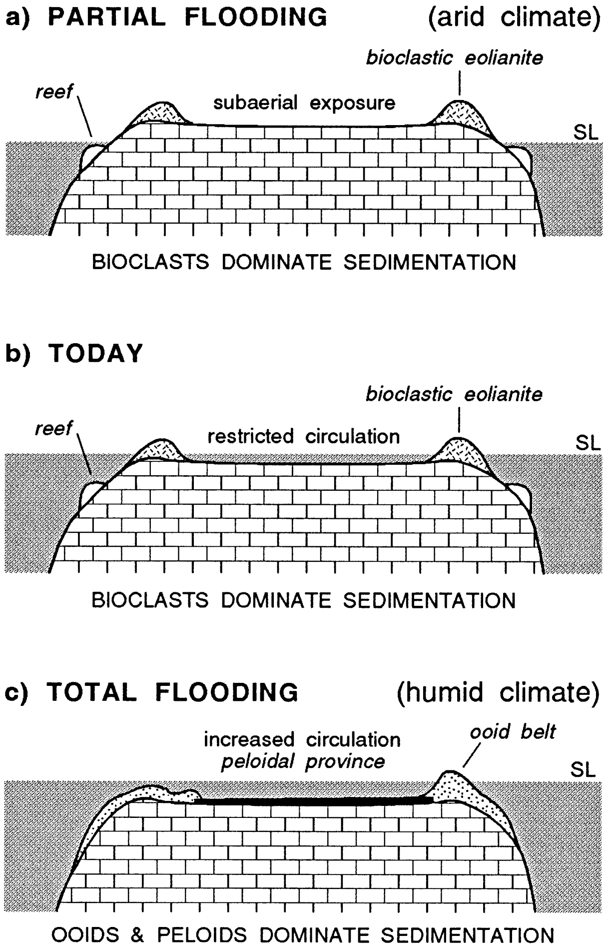


Fig. 21. Model showing the relationship between sea-level changes and the petrographic composition of the rock units exposed on the Bahamas islands. (a) Partial flooding, sea-level lower than present: production of bioclasts by bank-margin reefs, deposition of bioclastic rock-bodies (stage 7, substage 5a). (b) Moderate flooding, sea-level stand like present: ooids may be produced locally, but the bulk of material brought to islands is made of bioclastic fragments (stage 1). (c) Complete flooding, sea level higher than present: increased production of ooids due to active water circulation on the platform, deposition of oolitic–peloidal units (stage 9, substage 5e).

sea-level changes controlling the petrography of the stratigraphic units must have been induced by eustatic phenomena. The frequency of these fluctuations (10^4–10^5 yr) can logically be correlated with orbital cyclicities and hence with climate changes (e.g. Imbrie *et al.*, 1984). Preliminary study of cement textures further shows that climatic conditions during complete flooding of the banks may have been different from those existing during partial flooding. The common occurrence of coarse sparry cement within stage 9 and substage 5e oolites (Fig. 13) suggests a rather humid climate, characterized by small seasonal changes (Ward, 1973). In contrast, the finely crystallized cements (Fig. 9) frequently observed within stage 7 and substage 5a bioclastic calcarenites corresponds to a more arid and seasonal climate (Ward, 1973). However, these assumptions cannot be considered as facts until more is known about the relative importance of the primary mineralogy of constituent grains on cement textures.

Correlation with deep-water deposits

In their study of slope and trough sedimentation in the Bahamas, Haak & Schlager (1989) and Schlager *et al.* (1994) proposed a model similar to ours to explain the difference of petrographic composition between turbidites formed during glacial periods, which are dominated by skeletal components, and their interglacial counterparts, which are characterized by ooids and peloids. According to these authors, ooids and peloids are predominant in interglacial turbidites because flooding of the bank tops by a shallow (<10 m) layer of water is favourable to their production. In contrast, due to bank exposure, these particles rarely occur within turbidites formed during glacial periods, which essentially contain bioclasts produced by lowstand reefs anchored on the platform flanks. Our model is thus consistent with Haak & Schlager's (1989) and Schlager *et al.*'s (1994) observations. However, the shoreline deposits studied in this paper were all deposited during periods of relative sea-level highstand. Because of the steepness of the platform slopes, skeletal dunes could not accumulate on the bank margins during a full glacial period, when sea level was roughly 120 m below modern ordnance datum. Therefore, the observed petrographic variations only reflect small-scale (10–30 m) sea-level changes during an interglacial period and not the large-scale (100 m) glacial–interglacial fluctuations recorded by basinal turbidites. According to Schlager *et al.* (1994), such small sea-level variations are sufficient to shift the 'carbonate factory' on a rimmed platform from a highstand mode (ooid and peloid production) to a lowstand mode (bioclast production).

CONCLUSIONS

Our multi-method approach to Bahamian Quaternary geology now provides a refined stratigraphic record for this region based on observations from several islands. This record includes eight fossil shoreline units, two of Holocene age and six of Pleistocene age. Three units (I, IV and V) were formed when sea level was higher than today. They predominantly consist of ooids and peloids bound by coarse sparry cement. Four units (II, III, VI and VIII) were deposited at or below modern sea-level ordnance datum. These rock bodies essentially contain bioclastic particles and usually display finely crystallized spar cement. The middle Holocene oolite (VII) was also formed when sea level was lower than today, but it represents an early transgressive event which is not representative of stage 1 sedimentation.

We propose that climate and sea-level changes during the Quaternary directly controlled the petrographic composition of the stratigraphic units exposed on the Bahamas islands. During isotope stage 9 and substage 5e, complete flooding of the platform, possibly related to warm and humid climatic phases, resulted in increased production and accumulation of ooids and peloids; in contrast, during periods of partial or moderate platform flooding (stage 7, substage 5a and stage 1), which could correspond to dryer climatic phases, sedimentation was dominated by bioclastic components produced by marginal reefs.

Our study shows that petrographic analysis is a valuable complementary tool for correlating lithostratigraphic units within and between Bahamian islands. It further suggests that petrographic composition and cementation patterns from ancient coastal carbonates could also provide useful information on past climate and sea-level changes.

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