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Rapid sea level and climate change at the close of the Last Interglaciation (MIS 5e): evidence from the Bahama Islands

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Abstract

The geology of the Last Interglaciation (sensu stricto, marine isotope substage (MIS) 5e) in the Bahamas records the nature of sea level and climate change. After a period of quasi-stability for most of the interglaciation, during which reefs grew to +2.5 m, sea level rose rapidly at the end of the period, incising notches in older limestone. After brief stillstands at +6 and perhaps +8.5 m, sea level fell with apparent speed to the MIS 5d lowstand and much cooler climatic conditions. It was during this regression from the MIS 5e highstand that the North Atlantic suffered an oceanographic "reorganization" about 118 ± 3 ka ago. During this same interval, massive dune-building greatly enlarged the Bahama Islands. Giant waves reshaped exposed lowlands into chevron-shaped beach ridges, ran up on older coastal ridges, and also broke off and threw megaboulders onto and over 20 m-high cliffs. The oolitic rocks recording these features yield concordant whole-rock amino acid ratios across the archipelago. Whether or not the Last Interglaciation serves as an appropriate analog for our "greenhouse" world, it nonetheless reveals the intricate details of climatic transitions between warm interglaciations and near glacial conditions. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Records of interglacial climate change are amplified in detail and degree within the geology of subtropical islands on stable carbonate platforms such as the Bahamas. Short-term depositional and erosional features from rapid sea level changes and intense storms are superimposed upon island coastlines. Although these records may be fragmented, short-term episodes are often completely lost in more continuous, broad-band sequences, such as deep-sea cores or reef growth complexes.

During an interglacial episode, shallow shelves and lagoons are flooded and marine carbonate sediments are produced that blanket the platforms. Full platform flooding increases the depth of the water column, and thus increases exposure of the banks to waves and tidal currents, favoring the formation of oolitic sediments (Kindler and Hearty, 1996). Broad mobile sheets of ooids on the bank margins are redistributed into island beach and dune ridges as sea level falls. This must be a fast-acting process because shallow, sandy, carbonate sediments tend to cement rapidly to several decimeter depth if left immobile (e.g., Taft et al., 1968), even on an annual or decadal time scale (Dravis, 1979). Dune and island building can occur during early transgression (Carew and Mylroie, 1995a, b), but the features formed would be subject to later destruction by the same continued transgression, and are thus considered restricted as an eolianite source. By far the largest volume of eolianite is formed during, and emplaced after a prolonged highstand. As the cycle closes these sediments are swept bankward and remain preserved in situ at the island margin as sea level falls. Upon exposure, these sandy landforms at the top of the cycle sequence are rapidly stabilized by vadose cementation (Halley and Harris, 1979) which further increases their preservation potential.

The last major interglacial period (sensu stricto; MIS 5e; Sangamonian, Eemian, etc.) spans the interval from 132 to 118 ka, as determined from thermal ionization mass spectrometry U-series dates on in situ fossil reef corals by Chen et al. (1991). This period is well-recorded in the geomorphology, geochemistry, stratigraphy, paleontology, and sedimentary structures of the fossil

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reefs and sediments of the islands of the northern Bahamas. In this study existing data from several sites on Abaco, New Providence, Eleuthera, and the Exuma Islands are summarized (Fig. 1), and new observations are presented from the Bahamas that concern the history of sea level and climate change during the end of the Last Interglacial.

Recent evidence indicates that the close of MIS 5e was marked by sudden changes in sea level and climatic events of catastrophic proportions. These rapid sea level changes were accompanied by powerful waves that struck the eastern margin of the Bahama Banks, significantly reshaping the geomorphic face and facies of this critical interval (Hearty and Kindler, 1995; Neumann and Hearty, 1996; Hearty, 1997; Hearty et al., 1998; Tormey et al., 1999; Hearty and Kaufman, 2000). Further evidence of rapid sea level change is seen in the facies and morphology of dunes, stranded coastal sea cliffs, notches and ramps, and in the excellent preservation of reef-top corals (Neumann and Hearty, 1996). From these findings, it is reasonable to surmise that the close of the present interglacial may be marked by equally dramatic climatic changes.

1.1. Tectonic stability of the Bahama Platform

The sensitivity of the geologic record of reefs and sediments in the Bahamas, as well as the relative tectonic stability of the region, combine to provide a natural "tide gauge" (Land et al., 1967) for the Late Quaternary. Although sea level histories recorded on active, tectonic coastlines may be more complete, they are still limited by the assumption of constant uplift. 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, the Bahamas, and Australia (Hearty and Kindler, 1995; Stirling et al., 1998); (2) the constant elevation of 5e reef crests and flank marginal caves at around +2 to +3 m throughout the Bahamas (Carew and Mylroie, 1995a); and (3) the absence of historical earthquake activity in the Bahamas.

Quaternary subsidence rates of the Bahama Banks are grossly extrapolated from deep well data over the past 100 Ma (Lynts, 1970; Mullins and Lynts, 1977; Freeman-Lynde and Ryan, 1985). An average of 1–2 m/100 ka was estimated for the past 30 Ma. These average

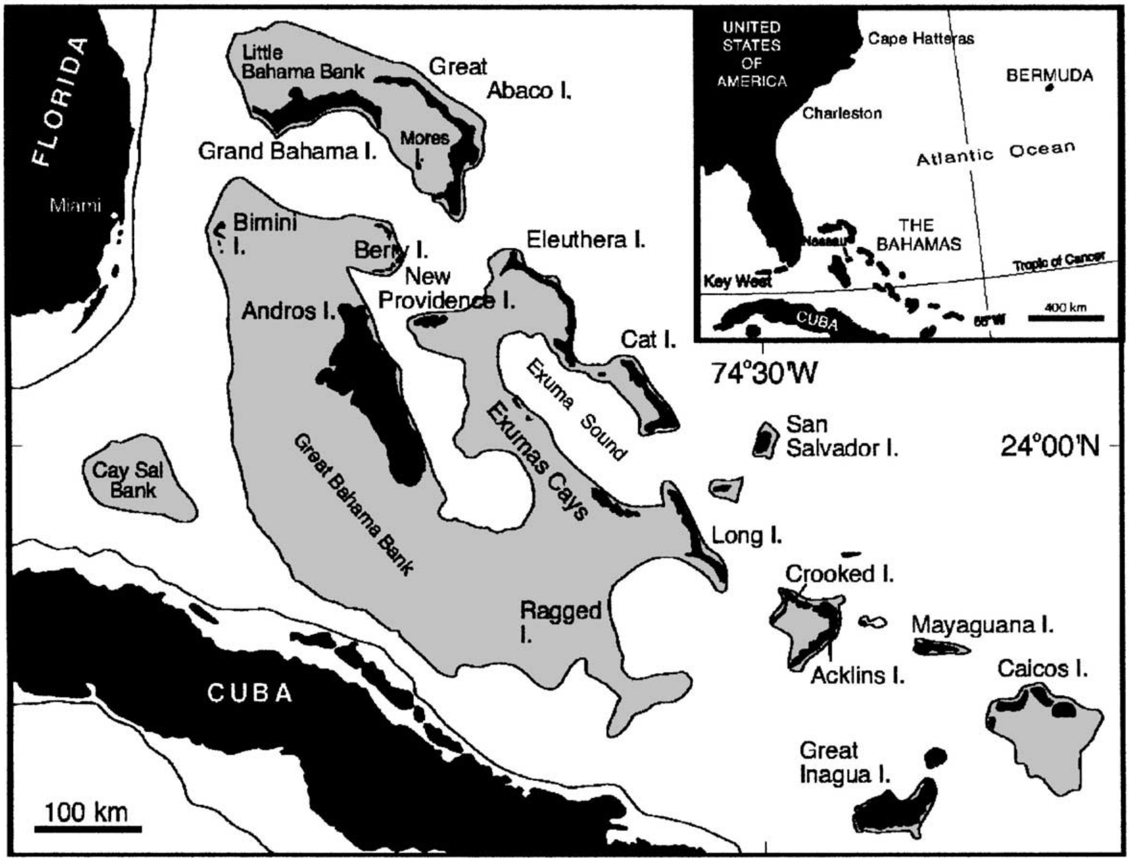

Fig. 1. Location map of the Bahamas. Key sites in this study are located in Abaco, New Providence, Eleuthera, and Exuma Islands.

rates are assumed to continue through the Quaternary, however, there are no data on the rate of subsidence of the Banks over the past 125 ka, which comprises only 0.1% of the well core subsidence record. Thus, any conclusions based on the assumption of recent subsidence rates are tenuous at best. It is possible, however, to infer stability by comparison of sea level data with similar locations that are also tectonically quiescent, such as Bermuda (cf. Hearty and Kindler, 1995) and western Australia (Murray-Wallace and Belperio, 1991; Stirling et al., 1998), or mildly uplifted, such as in Oahu, Hawaii (Hearty et al., 2000).

1.2. Identification of MIS 5e deposits

The deposits of MIS 5e are easily identified throughout the Bahamas. Typical characteristics include: (1) high and voluminous eolianite ridges of accretionary morphology; (2) emergent subtidal, reef, beach, and shoreline facies (Neumann and Moore, 1975; Chen et al., 1991; White et al., 1998); (3) tangential–aragonitic ooids with thick cortices cemented by coarse low-Mg equant spar at grain contacts or filling pore spaces (Kindler and Hearty, 1996); (4) interbeds of loose, buff-colored entisols ("protosols" of Vacher and Hearty, 1989) with *Cerion* land snails and rhizomorphs; (5) patchy, friable cementation in outcrop; (6) superposed Holocene or MIS 5a skeletal sands (misprinted as "stage 5e skeletal sands" in Neumann and Hearty, 1996, p. 776); (7) a base of older partially, or largely recrystallized Middle Pleistocene skeletal, or oolitic/peloidal limestone (Kindler and Hearty, 1996); and (8) caps of well-developed *terra rossa* soil (average Munsell, 1994, moist color of 7.5YR to 5YR 4/5) (Hearty and Kindler, 1997; Hearty, 1998).

Long-term changes are recorded in the Bahamas by radiometrically dated fossil reefs and speleothems that provide climatic data from stable isotope ratios. Radiometric ages and A/I (D-alloisoleucine/L-isoleucine) ratios are incorporated with morphostratigraphic position and degree of diagenesis in order to define the deposits of the Last Interglacial.

1.3. Aminostratigraphic background

Evidence of short-term, high-intensity depositional events in the Bahamas is preserved in the highly mobile and malleable littoral and eolian sands that blanket the platforms. Relative ages from whole-rock eolian and littoral sands have been obtained using the amino acid racemization (AAR) method (Hearty et al., 1992; Hearty and Kaufman, 2000). Numeric age estimates derived from A/I ratios can be achieved through calibration with independently dated sites (Hearty et al., 2000).

Detailed descriptions of the whole-rock amino acid racemization (AAR) method and related laboratory procedures are available in Hearty and Kaufman (2000). Previously published regional geochronological surveys of MIS 5e deposits have established that whole-rock A/I ratios are a reliable means for the correlation of MIS 5e deposits throughout the Bahamas (Fig. 2), from Abaco to the Great Inagua Islands (Hearty and Kaufman, 2000). Kindler and Hearty (1996) established that the petrographic composition of MIS 5e oolite shows little regional variation; thus, the potential effect of composition on A/I ratios is minimal. The concordance of mean A/I ratios from dunes, chevron ridges, runup and sub-boulder deposits on several islands documents the effectiveness of the whole-rock AAR method for regional correlation (Table 1).

1.4. Sea level curve for the Last Interglacial period

A sea level curve for the Last Interglacial period as it relates to the Bahamas has been constructed from the detail of sedimentary and reef outcrops in the Bahamas (Fig. 3) (Neumann and Hearty, 1996; Hearty and Kaufman, 2000). The Bahamas sea level curve compares well with MIS 5e sea level histories in Bermuda (Land et al., 1967), the Mediterranean (Hearty, 1987), the Southeast US Coastal Plain (Hollin and Hearty, 1990), and Hawaii (Hearty et al., 2000). Geological data and TIMS U-series dating obtained by Chen et al. (1991) and Stirling et al. (1998) provide constraints on the timing and magnitude of sea level changes during MIS 5e. Of particular geological relevance to the Bahamas curve is: (1) the maximum height and ages of in situ *Acropora palmata* reef crests in the Bahamas (Fig. 4) which never exceed +3 m elevation (Neumann and Hearty, 1996); (2) discontinuities within the reef-building and shoreline sequences (Hearty and Kindler, 1998); and (3) other evidence of sea levels determined from high notches, rubble benches, and sedimentary shoreline sequences.

The elevation relative to present sea level of in situ MIS 5e reef-crest corals (*A. palmata*) throughout the Bahamas has not been reported to be more than +2.5 m (Fig. 4). Since these reef-crest corals typically grow to the low-water mark today, and had 14 ka to do so between 132 and118 ka (Chen et al., 1991), we conclude that +2.5 m closely approximates the maximum elevation of sea level during most of 5e between 132 and 122 ka. White et al. (1998) maintain that sea level hovered around +6 m for the period between 124 and 119 ka. Had sea level remained at this +6 m level for 5000 to 6000 years, as they propose, there is no explanation why reefs grew no higher than +2.5 m anywhere in the Bahamas. Presumably ideal coral growth conditions would prevail if an additional +4 m

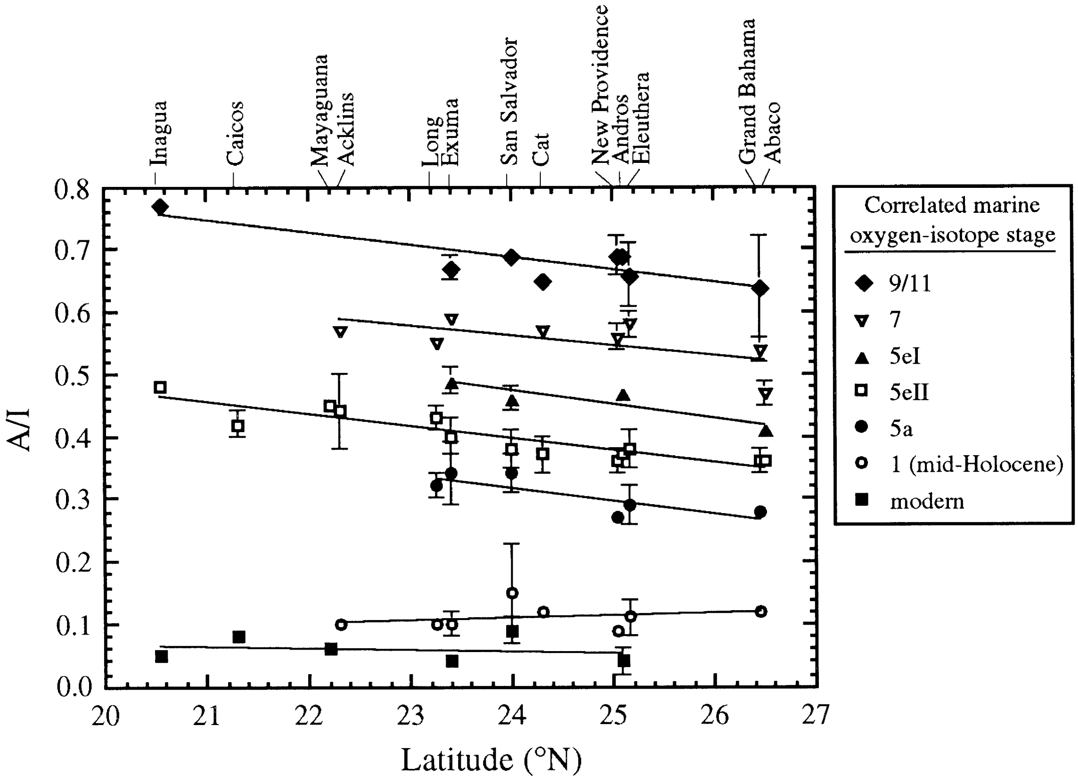

Fig. 2. Graph of island mean of A/I ratios from MIS 5e and other interglacial highstand events deposits from islands across the Bahama archipelago (900 km). After Hearty and Kaufman (2000).

of accommodation space were provided by a sustained +6 to +8.5 m highstand. Only a brief and rapid rise to and fall from the highest interglacial levels could account for the obvious age and maximum +2.5 m growth position of the fossil corals of 5e in the Bahamas.

Deep notches of flattened elliptical profile are formed largely by bioerosion in the lower intertidal on rocky carbonate coasts of low or moderate energy (Neumann, 1965). The same profile can be observed in emergent notches on cliffs at +6 m and higher cut into pre-5e rocks on several islands throughout the Bahamas (i.e., Little Sale Cay and Mores Island; Neumann and Moore, 1975; and Rocky Dundas, Low Cay, Square Rock, Pigeon Cay, and Exuma Cays). On the basis of rates determined during the Holocene, Neumann and Hearty (1996) estimated 5e-notch cutting at the +6 m level required no more than 600 years to form (Fig. 5A and B).

Bioerosional notches are excellent ancient sea level indicators and only in uncommon cases can they be confused with intersecting flank margin caves, as described by Mylroie and Carew (1988). Either way they are both sea level indicators—the former developed by bioerosion at sea level on open coasts; the latter by the fresh water phreatic lens which is ultimately dictated by sea level.

Both littoral and subtidal facies are also common in 5e sequences above present sea level on New Providence, Eleuthera and Caicos Islands. From the elevated nature of erosional and depositional features, it is apparent that sea level rose to well over +6 m at the end of 5e, but only for a short interval. Had the sea level been slow (i.e., over several thousand years) to rise to and fall from its highest levels, as often stated (Chen et al., 1991; Carew and Mylroie, 1995a; White et al., 1998) the corals would have kept up and grown to near these high levels up to and over +6 m, and the inter- and subtidal notching process over thousands of years would have produced erosional platforms at these high levels instead of perched notches on the faces of contemporary sea cliffs. Because reef-crest corals were delicately preserved and reef crests were not reduced to rubble, it is appropriate to deduce that sea level must have stayed only briefly and also fallen quickly from this maximum level (Neumann and Hearty, 1996; Hearty et al., 1998). Thus, we infer that it was during the brief interval of this rapid fall of sea level at these high levels at the end of MIS 5e to bank margin depths (−5 to −10 m) that intense storms generated during a period of climate

Table 1
Comparison of whole-rock A/I ratios (Hearty and Kaufman, 2000) from late MIS 5e eolianite, chevron ridges, runup, and sub-boulder deposits from study sites according to latitude included in this investigation

Lab# Field#	Locality	Mean $\pm 1\sigma(n =)$	Stratigraphic unit
Grand Bahama island			
1091B GNC1	Churchill Drive	0.363(1)	Late 5e beach
Andros			
1093A ONC1a	N. Andros Clinic	0.371(1)	Chevron
New providence			
1073A NLC3g	Lyford Cay	0.356 ± 0.001	Late 5e Eolianite; 117 ka[a]
1073B NLC-3cc	Lyford Cay	0.384 ± 0.015	Early 5e Eolianite; 128 ka[a]
1074A NHQ-1c-4a	Hunt's Cave Quarry	0.333 ± 0.000(2)	+6 m beach
Eleuthera			
1094B ETP1c	Two Pines	0.363 ± 0.001(2)	Runup
1814A EMB2o	Cow and Bull	0.400(1)	Sub-boulder eolianite
1812A EMB4e	Hole in Rock	0.385(1)	Sub-boulder late 5e marine
2533 EEB 1a	Eastern Bluff	0.387(1)	+30 m runup with fp
2534 ESP 2a	Sweeting's Pond Q.	0.381(1)	+20 m runup with fp
Exuma cays			
1688A XBI-3a	Bell Island	0.371(1)	Chevron
1391A XLS1a	Lee Stocking Island	0.408(1)	Chevron; Surface samp
1394ADXC1-0-1	LSI Core-top 7 m	0.428 ± 0.025(4)	Late 5e; sub-chevron
1394E XC1-07-6	LSI Core-mid	0.315(1)	Mid 5e soil @ −8 m; leached
1394FGXC1-11-7	LSI Core-basal 12–21 m	0.489 ± 0.018(2)	Early 5e marine/eolian
Great Exuma			
1390A XOL1c	Old Land Road	0.415(1)	Runup to +25 m
1390B XOL1a	Old Land Road	0.428(1)	Early 5e eolianite
2536 XMT 1a	Mt. Pleasant N.	0.424(1)	Chevron
2537 XBB 1a	Bahama Blvd.	0.462(1)	Chevron
2538 XFH 1a (2)	Farmer's Hill Q.	0.382(1)	Chevron
San Salvador island			
1096A SFB4a	French Bay	0.402 ± 0.004(2)	Late 5e eolianite
1096B SFB4c	French Bay	0.415(1)	Late 5e eolianite/runup
1096C SOT3b	Observation Tower Rd	0.370(1)	Latest 5e +6 m beach
1267A SOT1b	Observation Tower Rd	0.462 ± 0.020(2)	Early 5e eolianite
Long island			
1274A LSP1c	Salt Pond	0.423(1)	Late 5e eolianite
1273ABLMI1c	Miller's Sett.	0.454 ± 0.010(2)	Chevron
2539 LOG 1a	Old Gray's	0.415(1)	Chevron
2540 LMK 1a	McKinnon's Sett.	0.409(1)	Chevron
Mayaguana insland			
2135A MAW 1a	Abraham Bay	0.458(1)	Late 5e eolianite
2136A MNB 2a	Flamingo Hill	0.439(1)	Chevron
Inagua island			
1097ABIML1a	Matthew Town	0.480 ± 0.019(2)	Late 5e marine
1102A IMC2a	Maroon Hill	0.471(1)	Chevron?

[a] Dates from Muhs et al. (1990). "Sub-boulder" refers to sediments beneath the giant, wave-deposited boulders of north Eleuthera; fp = fenestral porosity or beach bubbles.

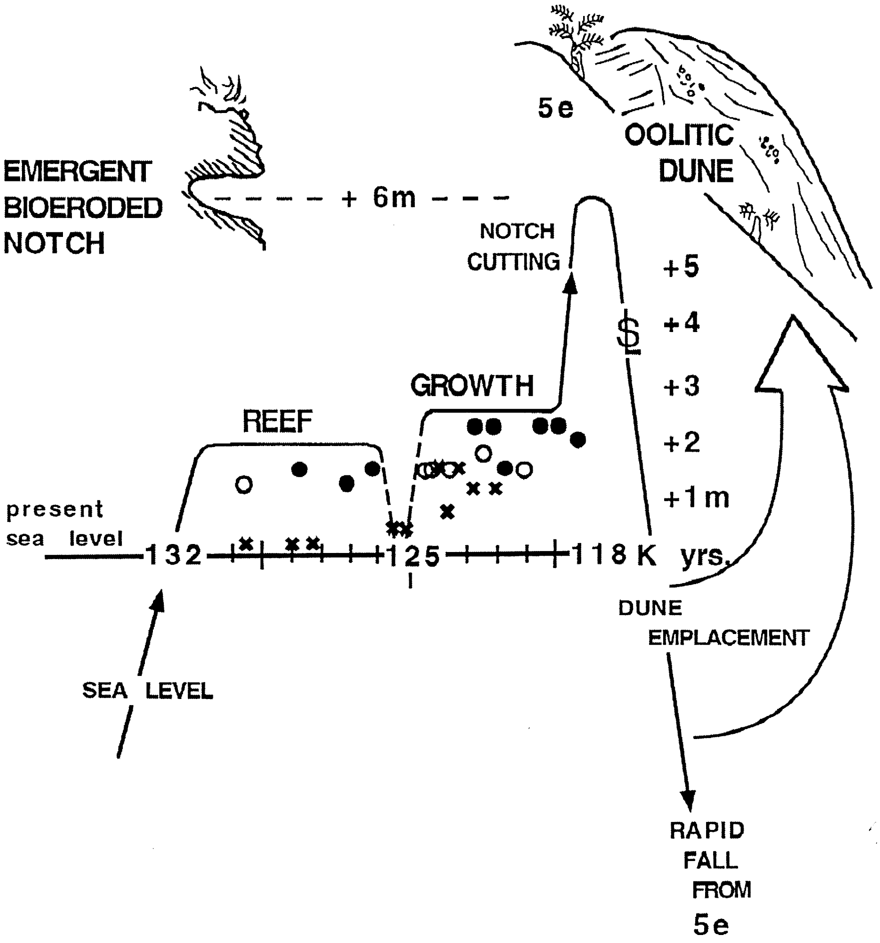

Fig. 3. Sea level curve during MIS 5e (after Hearty and Kindler, 1995; from Neumann and Hearty, 1996). This precision of the curve has been refined with TIMS ages of Chen et al. (1991) and from outcrop information in the Bahamas. Solid circles, in situ coral; open circles, coral rubble; small "x", in situ corals from Great Inagua.

change directly affected and significantly reshaped the present Bahama Islands.

2. "Catastrophic" events late in MIS 5e

2.1. *Late 5e dune build up*

Extensive 5e oolitic dune ridges often span the width and length of many islands, and often crest between 30 and 50 m above sea level along the windward eastern Bahamas. A build up of dunes of this magnitude requires that a large and constant supply of oolitic sediment was available for transport landward as sea level fell. This fact precludes abundant dune formation during transgressive intervals. In addition, the subtidal movement of these sediments to the shore requires a powerful and sustained landward energy source. The large volume of sediments stored or available in subtidal areas implies that a prolonged period of high sea level preceded the final transfer of sediments from subtidal to subaerial environments during a fall of sea level. Once built up at the shoreline, sustained prevailing winds were necessary to drive the sediments up and over the coastal ridge. Because of the eastward orientation of the windward Bahama Islands, persistent onshore winds from the northerly to easterly quadrant were required.

These large dune deposits occupy the youngest stratigraphic position in the MIS 5e succession. Regressive dune bedforms from these deposits often extend well below present sea level. Thus, we interpret these events to have occurred late in MIS 5e after the formation of multiple, smaller ridges which are observed in outcrop at numerous sites (Hearty and Kindler, 1997). That emplacement of these dunes was relatively rapid is inferred from the burial of large standing trees (Fig. 6) and palmetto leaves in living position (Neumann and Hearty, 1996).

2.2. *Chevron ridges*

In the Bahama Islands, common and extensive oolitic sand ridges with a distinctive landward-pointing

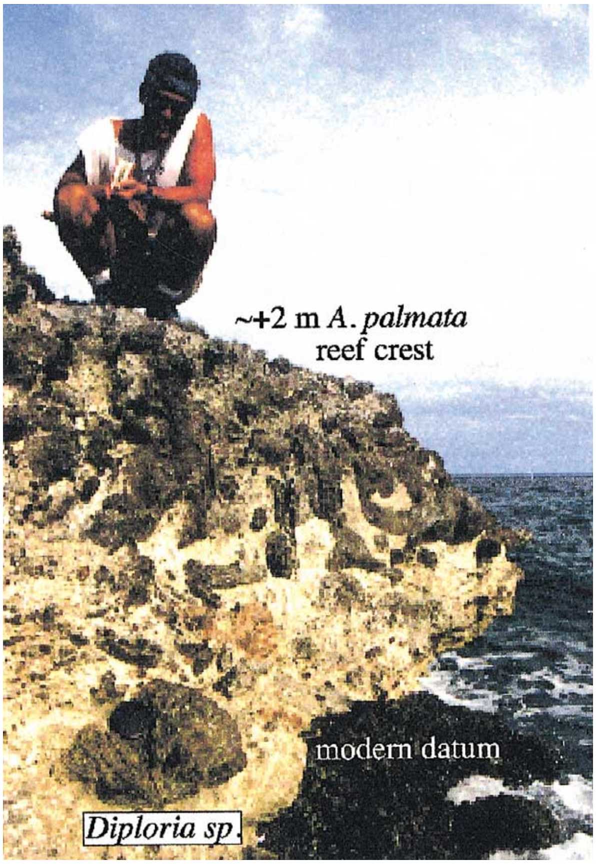

Fig. 4. Outcrop of in situ *Acropora palmata* up to +2 m at Hole in the Wall, Great Abaco Island, which reflects the average maximum elevation of *A. palmata* reef crests in the Bahamas. Had sea level remained at +6 m or higher for several thousand years, as suggested by many authors, there is no explanation why the fast growing reefs did not grow to near that level.

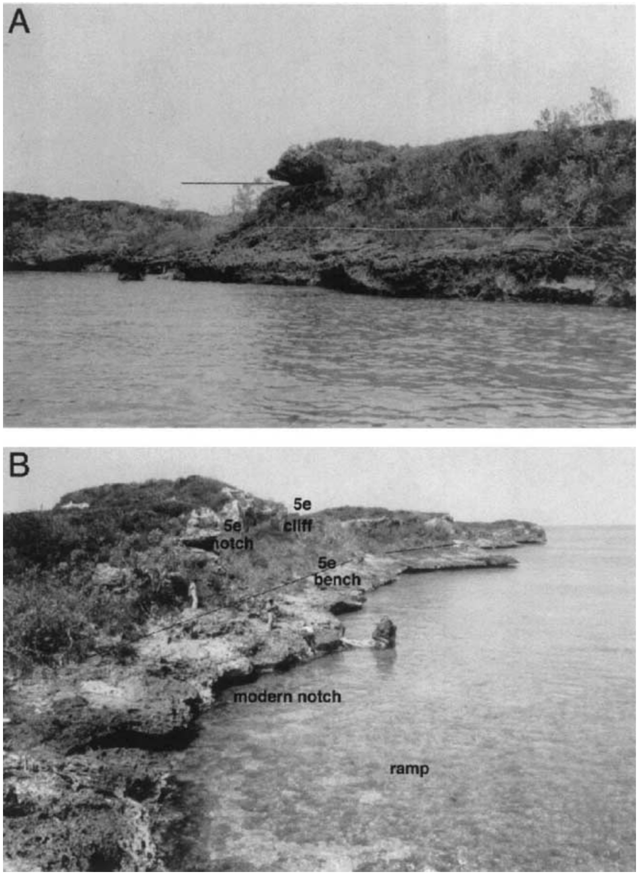

Fig. 5. (A and B) Detail of a 5e notch, cliff and ramp (bench) on Little Sale Cay, northern Little Bahama Bank. The notch level +6 m and the ramp–cliff contact at ~+2.5 m are noted. In order to preserve this morphology, a progression of events must have occurred: (1) formation of the +2–3 m ramp and platform on which the people are standing; (2) rapid sea level rise and notch incision at +6 m; (3) rapid retreat from the +6 m level preserving earlier morphology; and (4) Holocene coastal attack of antecedent morphology, and formation of new ramp and platform just below the present sea level datum.

V-shape form stand in relief across several kilometers of the emergent, low- lying, flat land adjacent to windward margins. Termed, "chevron ridges" from their characteristic shape, these beach ridges are found on broad, low-lying platforms or ramps throughout the Atlantic-facing, deep-water margins of the Bahamas ridges (Hearty et al., 1998). They are distinguished from typical coast-parallel ridges (strand or chenier plains) by their extended, V-shaped orientation oblique or perpendicular to the general shelf margin trend (Fig. 7A and B). Throughout the Bahamas, the limbs of chevrons converge southwestward at a common orientation of S65°W (±10°) to a bankward or landward apex. The chevron landforms average approximately 3–10 km long. The width generally measures about 25–40% of the length.

The ridges are composed of sub-parallel, aggrading beds with few interruptions or truncations. Internal sedimentary structures include predominantly thin, low-angle planar cross-beds rich in beach-like fenestral porosity (Fig. 9A), similar to that found in the intertidal zone of most modern beaches of the Bahamas (Bain and Kindler, 1994). Interbeds of fine, wind-ripple laminations are also common, and indicative of the windy conditions throughout the time of chevron formation.

As with all MIS 5e deposits in the Bahamas, the chevrons and their counterparts are predominantly aragonitic oolite, with minor percentages of skeletal grains, peloids, and aggregates (Kindler and Hearty, 1996). Their regionally consistent orientation implies a common and synchronous wave source from the northeast. These landforms are interpreted to have originated by the rapid remobilization and redeposition of bank margin ooid bodies, probably sediment concentrations around flood tidal ooid shoals such as those developing now bankward of channels between margin highs. Also,

Fig. 6. Cast of large standing tree 4 m high at the crest of Collins Avenue, Nassau, New Providence Island. The large tree was buried in living position as eolian sand vertically accumulated (note near horizontal bedding) on the island at the end of MIS 5e.

terrigenous lowland areas with established vegetation were also flooded during chevron formation. Palmetto leaf impressions, cast in place as intertidal, fenestrae-rich sediments were deposited during chevron beach ridge formation, are preserved in detail on Great Exuma Island (Fig. 8).

The possibility of an eolian origin of the chevron ridges and runup deposits as migrating parabolic dunes, has been discussed, confronted, and rejected (Hearty et al., 1998; Kindler and Strasser, 2000; Hearty et al., in press) on the basis of pervasive, water-formed structures (fenestral porosity, scour structures), and conspicuous absence of foreset bedding characteristic of migrating dunes in the chevron ridges. Further and most convincing is the presence of wave-deposited, 1000-ton boulders (below) within a few kilometers of the chevron ridges.

2.3. *Runup deposits*

Chevron ridges are not found behind older and higher coastal ridges of early MIS 5e or older stages. Instead, the youngest deposits on shore-parallel 5e ridges consist of thick (1–3 m) fenestrae-rich, seaward-dipping tabular beds. These beds rise up to +40 m, well above the sea level stand maxima of the Last Interglacial. Scour structures are evident, and lenses of pebbles, rhizocretions, and land snails are interbedded between fenestral beds which occur in numerous road cuttings. Fenestrae-rich planar beds result from air bubbles trapped by the sheet-like inundation of dry sand by waves on modern beaches. These beds dip seaward and pinch out against topographic irregularities in the older eolianite (Fig. 9A). Fenestrae-rich deposits in north Eleuthera at +25 m (Fig. 9B) are nearly identical to those on active Bahamian beaches and reflect the runup of large waves on contemporaneous dune ridges. Wanless and Dravis (1989) observed similar runup features far inland on Provodentiales, Turks and Caicos Islands, and concluded they could be the work of "catastrophic swells and waves [that swept] onto the platform unimpeded and [broke] as giant waves surging high up onto [the] ridges".

2.4. *Giant boulders*

Giant displaced Pleistocene boulders composed of Middle Pleistocene limestone, located at the ridge crest and far landward along the coast of north Eleuthera (Hearty, 1997), are the strongest evidence of the work of enormous waves. Fenestrae-rich washover beds of MIS 5e age are present throughout the area of the megaboulders, and within 10 m of one of them. The largest boulder measures nearly 1000 m^3, and is estimated to weigh over 2000 metric tons. They rest on MIS 5e protosol and beach deposits and are flanked by reddish paleosols (Fig. 10) that typically form during sea level lowstands (i.e., glacial periods). The *maximum* age of boulder emplacement is established from the younger MIS 5e deposits upon which the giant boulders came to rest. These deposits have been dated and correlated with MIS 5e on the basis of A/I ratios on both *Cerion* landsnails and whole-rock samples (Hearty, 1997). The *minimum* age is constrained by attached and overlying *terra rossa* paleosols (Bricker and Mackenzie, 1970) which presumably begin to form with cessation of coastal deposition (i.e., sea level regression). A seacliff at +2.5 m landward of Boulder 4 (Fig. 10), and the MIS 5e stratigraphy beneath the boulders indicates that they were deposited after sea level passed below the +2.5 m level at the end of the substage (Hearty, 1997).

Finally, it is reasonable to assume that the boulders were emplaced by waves at a time when sea level

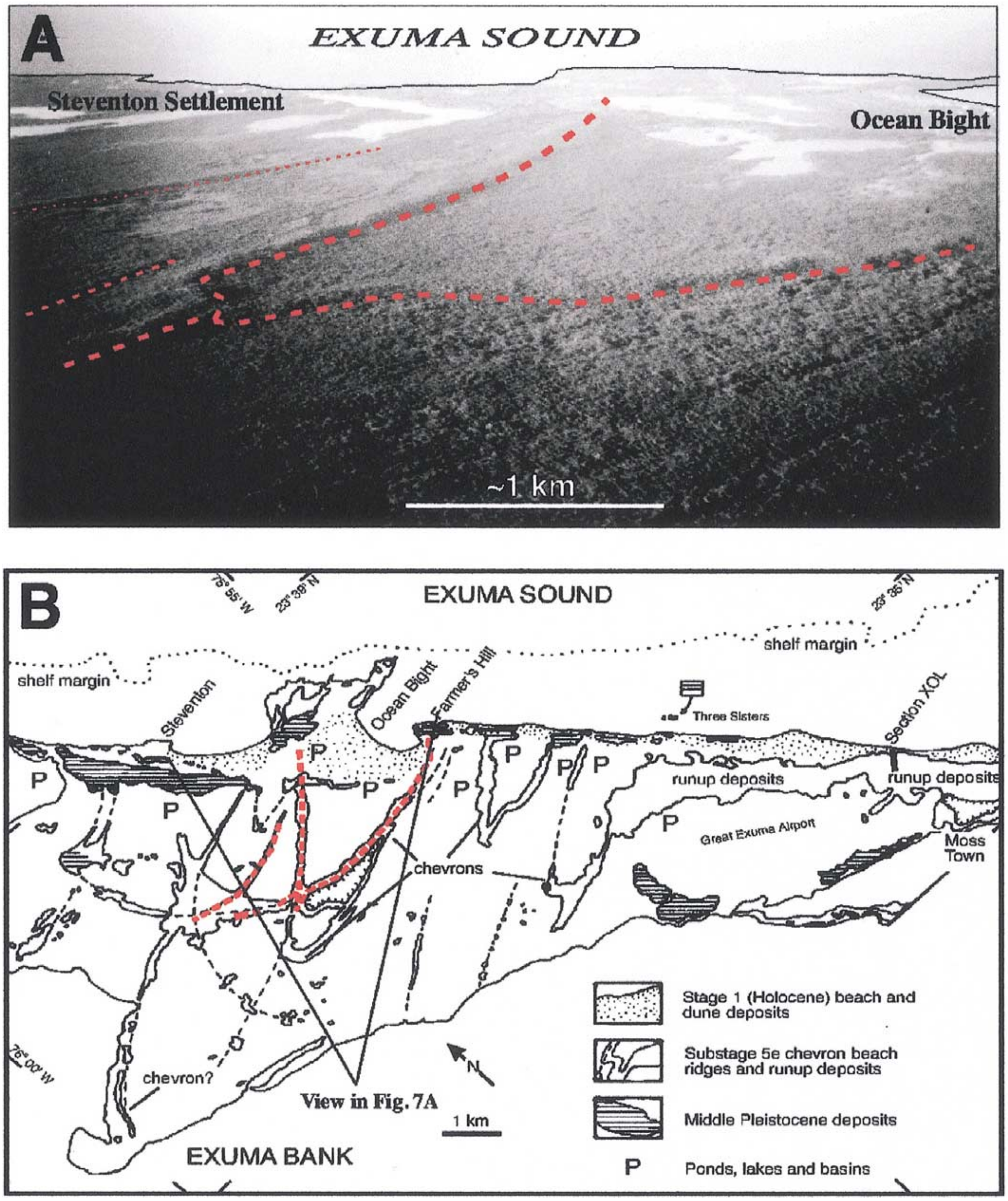

Fig. 7. (A) Oblique aerial photo of chevron beach ridges on northern Great Exuma Cay. The common orientation of the ridges (S65 ± 10°W) across the Atlantic-facing Bahama Banks suggest a common time and mechanism of formation; (B) Location of view in (A) showing the distribution and orientation of chevron beach ridges in Great Exuma (after Hearty et al., 1998).

remained relatively high during the regression from the MIS 5e high stand, since even larger waves would have been required during times of lower sea levels in order to lift the boulders over the 20-m cliffs and transport them beyond (Hearty, 1997). Because the boulders could only have been transported by giant waves, and given their similar age and proximity to chevron ridges and runup deposits, it is reasonable to conclude that either the same waves, or events of similar timing and magnitude were responsible for the formation of the chevron ridges and runup deposits. However, we cannot exclude the possibility of their formation by tsunamis generated by random tectonic or cosmic events.

2.5. *Mass wasting of the bank margin*

The sedimentary structures of the MIS 5e dunes along the seaward margin of the northern Bahamas all indicate a seaward, easterly source of the oolitic eolian material. With the exception of some nearshore production (Ward et al., 1985; Lloyd et al., 1987;), most ooid formation requires broad flat, tide-swept shelves (e.g. Hine, 1983). Today there are no broad shelves eastward of the eolian bodies in North Eleuthera, thus making the provenance of the ooids composing them a mystery. Seaward of the cliffed MIS 5e dune deposits is a boulder-strewn slope that falls abruptly to very deep

Fig. 8. Palmetto frond casts created as vegetated landscapes were inundated by seas and buried under chevron ridges. Fenestrae-rich bedding created the palemetto casts several meters above present sea level, and 2 km inland near Farmer's Hill, Great Exuma.

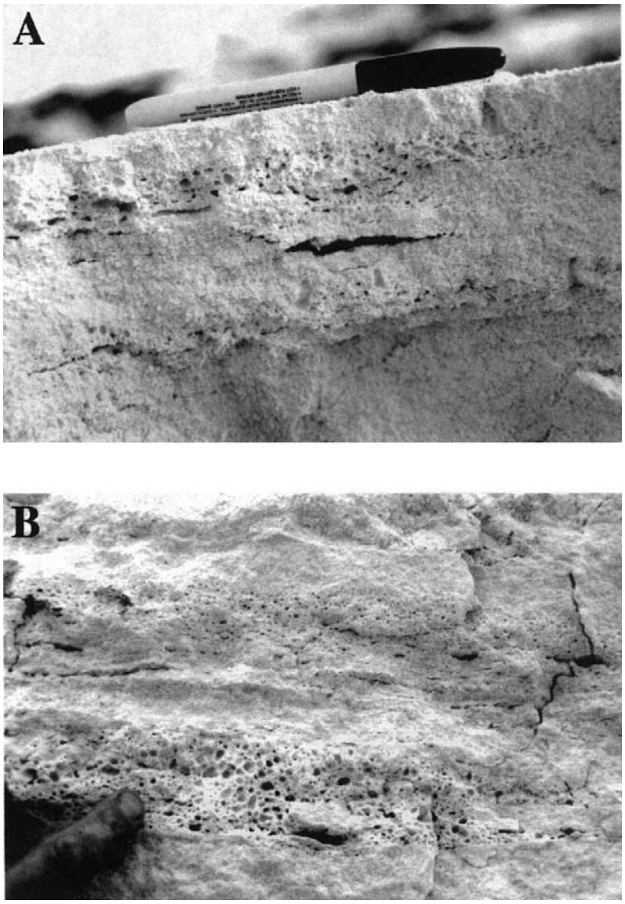

Fig. 9. (A). Fenestrae preserved in modern beach sands in Eleuthera as waves and the rising tide flood over dry sand. (B). Fenestrae preserved in oolite at +25 m at Licrish Hill, located 8 km inland from the coastline in North Eleuthera. These features show remarkable similarity to their modern counterpart formed by waves on the beach.

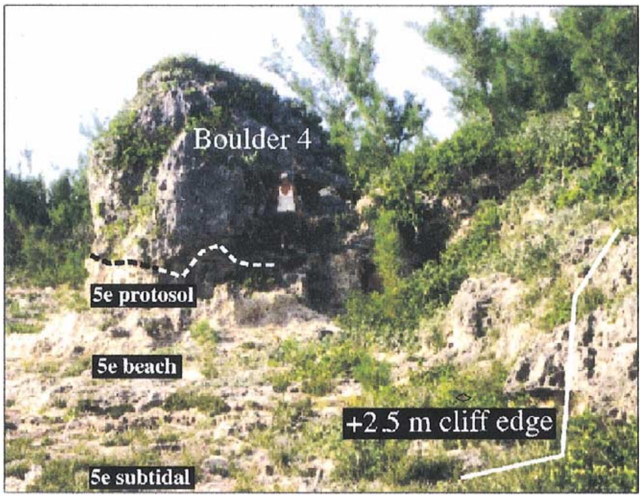

Fig. 10. Megaboulder 4 in North Eleuthera (Hearty, 1997) showing sea cliff at +2.5 m landward of the boulder. The boulder, composed of middle Pleistocene limestone (MIS 9/11?), was deposited by waves late in MIS 5e. It overlies regressive (shallowing upward) MIS 5e sequence of subtidal, intertidal (beach), and a terrigenous protosol with root casts and land snails. A reddish calcrete and soil (dashed line) encircle the boulder, but do not underlie it. This setting indicates that the maximum age of emplacement of the boulder occurred late in MIS 5e on a falling sea level, yet before the formation of the calcrete and soil during the subsequent lowstand.

waters a few hundred meters off the shore. This has led to the common and obvious conclusion that a broader shelf had existed (in order to generate the oolitic deposits) but has now disappeared. Being at the edge of a deep and steep drop off, it has been suggested by some that in places along the east-facing Bahamas that the margin has been eroded or collapsed, and along with it the ancestral source of the 5e oolitic sediment.

Mullins and Hine (1989) cite the morphological evidence of scalloped margins, and Freeman-Lynde and Ryan (1985) cite seismic data and submersible observations that indicate a Late Quaternary collapse of the bank margin along sections of the northeastern Bahamas. Even today, hints of the mass wasting potential of the margin exist in the form of extensive fracture systems along the cliffs (Fig. 11).

Reasoning that, (1) a broad, shallow seaward bank margin must have been present during most of MIS 5e in order to generate the substantial volume of 5e oolite; (2) these oolitic deposits are now truncated by vertical cliffs and a deep Atlantic margin; and (3) at the time of the giant boulder deposition, a cliffed margin, rather than a ramp, must have been exposed to powerful waves that transported the 1000-ton boulders, we conclude that the bank margin collapse must have occurred near the end of MIS 5e.

Backwash from waves (local tsunamis) generated by the collapse of the bank margin might have been responsible for deposition of the megaboulders in north

Fig. 11. Deep fracture along the cliffs of North Eleuthera. The presence of abundant MIS 5e sediments along the coast suggest that a shallow offshore platform existed during the Last Interglaciation, but has since collapsed, leaving cliffs, stranded dunes, and a deep ocean margin.

Eleuthera, however, this mechanism is inadequate to explain the formation of the NE–SW oriented chevron-shaped storm beach ridges and runup deposits across several hundred kilometers of the Atlantic margin of the Bahamas.

3. Discussion

3.1. Sea levels, giant waves, and climate change at the close of the Last Interglaciation

Excluding random or coincidental tsunami-generating events, the assembled observations appear to support a turbulent climatic transition from MIS 5e to 5d. After prolonged stability around +2.5 m (from perhaps 132–122 ka), sea level peaked briefly at levels of +6 and possibly +8.5 m at the close of MIS 5e, then fell quickly at the onset of MIS 5d (Neumann and Hearty, 1996). The stand at +2.5 m is documented throughout the Bahamas by the elevation of reef crests, notches, caves, ramps and sea cliffs of 5e age (Figs. 4,5 and 10). These 5e cliffs are cut into older material and are usually present on coastal outcrops on or facing the protected bank interior where Holocene erosion has spared them. The 5e cliffs at or near the ocean margin have either been eroded by the higher energy there, or have been covered by 5e or post 5e sands. In a few places a +6 m notch is still apparent in the fossil cliff face (Fig. 5). The only reasonable sequence that can explain this morphology is as follows: (1) Sea level rose to +2.5 m to cut a ramp and the sea cliff; (2) A rapid rise and temporary halt at +6 m cut the notch into the sea cliff. (Had the rise to +6 m occurred first, the ramp–cliff–notch sequence could not have been formed or been preserved (Fig. 5A and B)); (3) A rapid fall from the +6 m level was necessary to preserve the coral heads intact, and not reduce them to rubble; and (4) Holocene sea level has destroyed much of the ramp, and created its own ramp reflecting the present datum. Similarly, on New Providence Island, a series of coastal dunes was topped by rising sea level which cliffed an interior dune at St. Augustine Monastery (Hearty and Kindler, 1997).

It was also during the interval of 5e that the landscape of the Bahamas was dramatically reshaped by extensive sedimentation and the impact of giant waves from a northeastern source. The waves remobilized marginal oolitic sand bodies such as flood tidal deltas, plus littoral and nearshore sands. They were swept bankward and redeposited as chevron ridges. At the same time by the same waves, runup deposits and scour features were superimposed upon older dune ridges. The effect of inundation, as evidenced by beach fenestrae and hydraulic scour structures was extended to over +25 m (Hearty et al., 1998). All unprotected coastlines of the Bahamas exposed to the east and north appear to have been affected by these waves. All this strongly implies that large areas of shelf ooids were transported shoreward during falling wave base, rapidly exposed and subsequently transported by strong prevailing winds before cementation and a vegetative cover could anchor the carbonate sands. The apparently rapid shoreward transport and exposure of oolitic sediments draws the same conclusion as that from the stranding of the reef on other coastlines—sea level fell rapidly from its highstand maximum at the end of MIS 5e (Neumann and Hearty, 1996).

3.2. Global disruptions during late MIS 5e

The proposed unsettled and abrupt climatic transition apparent from the Bahamas at the termination of MIS 5e is replicated by evidence from elsewhere. Radical shifts in pollen records from France (Woillard, 1979) and Germany (Field et al., 1994) support this interpretation. The exotic, tropical "Senegalese Fauna" (Bonifay and Mars, 1959) appears to have been largely extirpated from the Mediterranean at the end of MIS 5e (Hearty, 1986). Warm interglacial benthic foraminifera from Denmark showed a 1000-year shift to a subarctic fauna late in 5e (Seidenkrantz and Knudsen, 1994). Lauritzen (1995) identified a major isotopic excursion in dated speleothem from Norway at around 115 ka ago, while Linsley (1996) identified a brief interval of higher δ^{18}O values in planktonic foraminifera at $\sim$122 ka ago from ODP Site 769 from the Sulu Sea. He interpreted this light excursion as an indication of climatic instability during MIS 5e in the western Pacific. Given all the dating uncertainties associated with these studies, their ages nonetheless converge on approximately 118 ± 3 ka, and mutually support a period of radical climate transition at that time.

3.3. Potential role of collapse of Antarctic ice in North Atlantic disruptions

Hearty et al. (1998) postulated that the waves were generated in the North Atlantic Ocean by massive northeast storms impacting tropical oceans as the climate cooled at the onset of MIS 5d and the belt of westerlies pushed southward to narrow and thus intensify the subtropical tradewind belt.

An abrupt rise of sea level of about 4–6 m can be most likely attributed to the collapse of the West Antarctic Ice Sheet (Hollin, 1965; Mercer, 1978; Oppenheimer, 1998). The abrupt fall of sea level at the close of MIS 5e reflects the rapid expansion of high latitude snow cover, albedo increase and the following rapid growth of the ice sheets. The inundation of the low lying coastal slopes of the Arctic may have been the source of moisture to the polar atmosphere that extended the snow perimeter of the northern hemisphere. A rapidly extended area of shallow turbulent water might have stayed open long enough to supply the moisture that produced the perennial ice expansion required to initiate the next glaciation (Andrews and Mahaffy, 1976; Neumann and Hearty, 1996). Furthermore, Adkins et al. (1997, p. 155) identified a "rapid shift in oceanic conditions in the western North Atlantic" about 118 ka ago on the basis of high-resolution ocean–sediment geochemical records from the Bermuda rise. They attribute the shift to an increase in southern source waters (i.e., Antarctic waters), a marked reorganization of the oceanic circulation patterns, and the initiation of a "climatic deterioration" over a $\sim$400-year period.

Although remote to the Bahamas, the possibility must be considered that the collapse of Antarctic ice may have been a driving force (Hearty, 1999) in the climate change that we observe in the North Atlantic and the Bahamas. The effect would follow a complex and poorly understood oceanic chain reaction on a global scale. Collapse of Antarctic ice would flood the world's oceans by several meters with fresh water supplied from melting fleets of icebergs discharged from the Antarctic continent. This cap of fresh water would lighten the mixed layer and would initiate changes in thermohaline circulation by slowing or stopping the sinking of dense seawater in the North Atlantic. Slowing sinking of cold surface waters would cause a slowing of the waters needed to replace them. Thus the conveyor belt would be slowed or halted. Indeed, at the end of MIS 5e, over a 400-year period, all of the deep ocean parameters changed, probably as a result of "a synchronous switch to bottom waters that have a higher proportion of southern source component" (Adkins et al., 1997, p. 156).

As pointed out by Broecker (1997), slowing of the circulation pattern, and that of the conveyor belt would have the dramatic effect of cooling of the North Atlantic Ocean. Yet, the same conveyor that warms the North Atlantic, does so by extracting heat from the tropical Atlantic. Presumably, if the conveyor belt to northern latitudes were quickly shut down or diminished, the antiphase effect would be *increased warming* of tropical oceans. Indeed, Cortijo et al. (1999, Fig. 3c) have demonstrated this effect. They showed that SST's at 33° north latitude were *warming significantly* toward the end of MIS 5e, while those SST's north of 52° were *decreasing dramatically*, up to 4–6°C cooler during the period between 120 and 115 ka.

If it could be demonstrated that the conveyor was shut down at the close of MIS 5e, as Broecker (1997) suggests, then it would be reasonable to assume that for at least a short period of time at the transition from MIS 5e to MIS 5d, that the contrast in ocean temperature and climate belts was at its greatest. Steeper pressure, temperature, and moisture gradients adjacent to warm tropical waters could presumably spawn larger and more frequent cyclonic storms in the North Atlantic than those seen today. It would be at this time of greatest temperature contrast between the temperate and tropical North Atlantic that fronts would spawn exceptionally large storms. During this interval, massive storms may have been generated that dispersed large, well-organized waves that struck the Bahamas and produced the features described herein. The concordance of the Bahamas record with these rapid climate shifts on a global basis show remarkable synchroneity around 118 ka. With such a preponderance of evidence of climate change at the end of MIS 5e, the generation of tsunamis by random tectonic or cosmic events at the same precise interval would be the ultimate case of serendipity.

If and when events of this nature and magnitude will reoccur at the close of our present interglacial is no more certain than just when that close will happen. However, there is no reason to believe that the action of the past, as played out in the 5e deposits of the Bahamas, does not imply the plot of the future. The behavior of Antarctic ice and the circulation of the North Atlantic should be respected bellweathers of things to come. We have the synoptic means to keep an eye on these climatically critical regions.

4. Conclusions

The geological units of MIS 5e are unique in their physical properties as well as by common whole-rock A/I ratios (Table 1; Fig. 2) that correlate over 75 sites including those associated with chevron ridges, runup deposits, giant boulders, and massive dune build ups across the Bahamas. It is in these sedimentary units that the record of climatic events during and at the close of the interval are revealed.

The geology of the Bahama Islands provides critical outcrop information from which sea level and climate history between 132 and 118 ka can be reconstructed. Within that period, three oscillations of sea level can be distinguished. Early in the period (132–125 ka) sea level appears to have maintained a level around +2.5 m as evidenced by reefs capped by *A. palmata* at that datum. A mid 5e regression around 124 ka is documented by a mid-5e unconformity and from numerous beach, reef, and dune sections (Chen et al., 1991; Hearty and Kindler, 1993, 1997, 1998; White et al., 1998). Sea level rose again to a slightly higher level than the previous one, which again initiated reef growth to a maximum elevation of less than +3 m. This near stillstand was short lived, however. At the end of the period, sea level rose to +6 to +8.5 m, flooding areas of the platform inland of the coastal ridge and cutting notches into sea cliffs of older material. A rapid fall followed which permitted the preservation of antecedent morphology, stranded storm beaches and local reef tops left in near pristine condition (Fig. 4).

The last recorded events at the close of MIS 5e are marked by a turbulent and unsettled interval of falling sea level during which giant waves impacted the coastline, displacing huge boulders, re-depositing chevron-shaped storm beach ridges, and running up and over older coastal ridges. The geomorphology and stratigraphy of the entire Bahamas was vastly remolded during this critical climate transition.

The end of MIS 5e was marked by abrupt shifts that appear to be coupled to widespread global oceanic and climate changes. A glacial collapse of sufficient magnitude to raise sea level 4–6 m could have affected the density of the mixed layer in the Atlantic to the extent that thermohaline circulation could have slowed to the point where the extremes of surface temperature between north and equatorial Atlantic would have maximized. This, plus the narrowing of the westerlies belt, would increase frontal gradients and produce far stronger and more widespread storms than are now observed.

The geology of MIS 5e in the Bahamas reveals a story of extreme events and conditions at the close of the Last Interglacial interval. The close of the Last Interglacial in the nearby latitude of the Bahamas suggests that we keep a weather eye on critical areas of ice and ocean behavior as our present interglacial interval progresses.

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References

Adkins, J.F., Boyle, E.A., Keigwin, L., Cortijo, E., 1997. Variability of the North Atlantic thermohaline circulation during the last interglacial period. Nature 390, 154–156.

Andrews, J.T., Mahaffy, M.A.W., 1976. Growth rate of the Laurentide Ice Sheet and sea level lowering (with emphasis on the 11,500 BP sea level low). Quaternary Research 6, 167–183.

Bain, R.J., Kindler, P., 1994. Irregular fenestrae in Bahamian eolianites: a rainstorm-induced origin. Journal of Sedimentary Petrology A64 (1), 140–146.

Bonifay, F., Mars, P., 1959. Le Tyrrhnien dans le cadre de la chronologie quaternaire Mediterrannne. Bulletin Sociologique Francaise 7 (1), 62–78.

Bricker, O.P., Mackenzie, F.T., 1970. Limestones and red soils of Bermuda, discussion. Bulletin of the Geological Society of America 81, 2523–2524.

Broecker, W.S., 1997. Thermohaline circulation, the Achilles Heel of our climate system: will man-made CO_2 upset the current balance? Science 278, 1582–1588.

Carew, J.L., Mylroie, J.E., 1995a. Quaternary tectonic stability of the Bahamian Archipelago: evidence from fossil coral reefs and flank margin caves. Quaternary Science Reviews 14, 145–153.

Carew, J.L., Mylroie, J.E., 1995b. Depositional model and stratigraphy for the Quaternary geology of the Bahama Islands. In: Curran, H.A., White, B. (Eds.), Terrestrial and Shallow Marine Geology of The Bahamas and Bermuda. Geological Society of America Special Paper, Vol. 300, pp. 5–32.

Chen, J.H., Curran, H.A., White, B., Wasserburg, G.J., 1991. Precise chronology of the last interglacial period: $^{234}U/^{230}Th$ data from fossil coral reefs in the Bahamas. Geological Society of America Bulletin 103, 82–97.

Cortijo, E., Lehman, S., Keigwin, L., Chapman, M., Paillard, D., Labeyrie, L., 1999. Changes in meridional temperature and salinity gradients in the North Atlantic Ocean (30°–72°N) during the last interglacial period. Paleoceanography 14 (1), 23–33.

Dravis, J., 1979. Rapid and widespread generation of Recent oolitic hardgrounds on a high energy Bahamian Platform, Eleuthera Bank, Bahamas. Journal of Sedimentary Petrology 49, 195–208.

Field, M.H., Huntley, B., Muller, H., 1994. Eemian climate fluctuations observed in a European pollen record. Nature 371, 779–783.

Freeman-Lynde, R.P., Ryan, W.B.F., 1985. Erosional modification of Bahamian escarpment. Geological Society of America Bulletin 95, 209–220.

Halley, R.B., Harris, P.M., 1979. Freshwater cementation of a 1000 year old oolite. Journal of Sedimentary Petrology 49, 969–988.

Hearty, P.J., 1986. An inventory of last interglacial (s.1) age deposits from the Mediterranean basin: a study of isoleucine epimerization and U-series dating. Zeithschrift für Geomorphologie 62 (Suppl.), 51–69.

Hearty, P.J., 1987. New data on the Pleistocene of Mallorca. Quaternary Science Reviews 6, 245–257.

Hearty, P.J., 1997. Boulder deposits from large waves during the last interglaciation on North Eleuthera, Bahamas. Quaternary Research 48, 326–338.

Hearty, P.J., 1998. The geology of Eleuthera Island, Bahamas: a Rosetta Stone of Quaternary stratigraphy and sea-level history. Quaternary Science Reviews 17, 333–355.

Hearty, P.J. (1999). Warm interglaciations, abrupt environmental change, and the Antarctic "wild card". In: Fletcher, C.H., III, Matthews, J.V. (Eds.), The Non-Steady State of the Inner Shelf and Shoreline: Coastal Change on the Time Scale of Decades to Millennia in the late Quaternary. Abstracts with Programs, Inagural Meeting of the IGCP Project #437 "Coastal Environmental Change During Sea Level Highstands", University Hawaii, Honolulu, USA, November 9–12, pp. 99–100.

Hearty, P.J., Kaufman, D.S., 2000. Whole-rock aminostratigraphy and Quaternary sea-level history of the Bahamas. Quaternary Research 54 (4), 163–173.

Hearty, P.J., Kaufman, D.S., Olson, S.L., James, H.F., 2000. Stratigraphy and whole-rock amino acid geochronology of key Holocene and last interglacial carbonate deposits in the Hawaiian Islands. Pacific Science 54 (4), 423–442.

Hearty, P.J., Kindler, P., 1993. New perspectives on Bahamian geology: San Salvador Island, Bahamas. Journal of Coastal Research 9 (2), 577–594.

Hearty, P.J., Kindler, P., 1995. Sea-level highstand chronology from stable carbonate platforms (Bermuda and the Bahamas). Journal of Coastal Research 11 (3), 675–689.

Hearty, P.J., Kindler, P., 1997. The stratigraphy and surficial geology of New Providence and surrounding islands, Bahamas. Journal of Coastal Research 13 (3), 798–812.

Hearty, P.J., Kindler, P., 1998. Comment on White et al. (1998). "Bahamian coral reefs yield evidence of a brief sea-level lowstand during the last interglacial". Carbonates and Evaporites 13 (2) 229–230.

Hearty, P.J., Neumann, A.C., Kaufman, D.S., 1998. Chevron ridges and runup deposits in the Bahamas from storms late in oxygen isotope substage 5e. Quaternary Research 50, 309–322.

Hearty, P.J., Tormey, B., Neumann, A.C., in press. Discussion: "Palaeoclimatic significance of co-occurring wind- and water-induced sedimentary structures in the last-interglacial coastal deposits from Bermuda and the Bahamas". Sedimentary Geology 131, 1–7.

Hearty, P.J., Vacher, H.L., Mitterer, R.M., 1992. Aminostratigraphy and ages of Pleistocene limestones of Bermuda. Geological Society of America Bulletin 104, 471–480.

Hine, A.C., 1983. Relict sand bodies and bedforms of the northern Bahamas: evidence of extensive early Holocene sand transport. In: Peryt, T.M. (Ed.), Coated Grains. Springer, Berlin, Heidelberg, pp. 116–131.

Hollin, J.T., 1965. Wilson's theory of ice ages. Nature 208, 12–16.

Hollin, J.T., Hearty, P.J., 1990. South Carolina interglacial sites and stage 5 sea levels. Quaternary Research 33, 1–17.

Kindler, P., Hearty, P.J., 1996. Carbonate petrology as an indicator of climate and sea-level changes: new data from Bahamian Quaternary units. Sedimentology 43 (2), 381–399.

Kindler, P., Strasser, A., 2000. Palaeoclimatic significance of co-occurring wind- and water- induced sedimentary structures in the last-interglacial coastal deposits from Bermuda and the Bahamas. Sedimentary Geology 131, 1–7.

Land, L.S., Mackenzie, F.T., Gould, S.J., 1967. The Pleistocene history of Bermuda. Geological Society of America Bulletin 78, 993–1006.

Lauritzen, S.E., 1995. High-resolution paleotemperature proxy record for the last interglaciation based on Norwegian speleothems. Quaternary Research 43, 133–146.

Linsley, B.K., 1996. Oxygen-isotope record of sea level and climate variations in the Sulu Sea over the past 150,000 years. Nature 380, 234–237.

Lloyd, R.M., Perkins, R.D., Kerr, S.D., 1987. Beach and shoreface ooid deposition on shallow interior banks, Turks and Caicos Islands, British west Indies. Journal of Sedimentary Petrology 57 (6), 976–982.

Lynts, G.W., 1970. Conceptual Model of the Bahamian Platform for the last 135 million years. Nature 225, 1226–1228.

Mercer, J.H., 1978. West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster. Nature 271, 321–325.

Muhs, D.H., Bush, C.A., Stewart, K.C., Rowland, T.R., Crittenden, R.C., 1990. Geochemical evidence of Saharan dust parent material for soils developed on Quaternary limestones of Caribbean and western Atlantic islands. Quaternary Research 33, 157–177.

Mullins, H.T., Hine, A.C., 1989. Scalloped bank margins: beginning of the end for carbonate platforms? Geology 17, 30–33.

Mullins, H.T., Lynts, G.W., 1977. Origin of the northwestern Bahama Platform: review and reinterpretation. Geological Society of America Bulletin 88, 1447–1461.

Munsell 1994. Soil Color Charts, 1994 (revised edition) Macbeth Division of Kollmorgan Instruments Corporation, New Windsor, NY.

Murray-Wallace, C.V., Belperio, A.P., 1991. The last interglacial shoreline in Australia—A review. Quaternary Science Reviews 10, 441–461.

Mylroie, J.E., Carew, J.L., 1988. Solution conduits as indicators of Late Quaternary sea level position. Quaternary Science Reviews 7, 55–64.

Neumann, A.C., 1965. Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge Cliona lampa. Limnology and Oceanography 11 (1), 92–108.

Neumann, A.C., Hearty, P.J., 1996. Rapid sea-level changes at the close of the last interglacial (stage 5e) recorded in Bahamian Island geology. Geology 24, 775–778.

Neumann, A.C., Moore, W.S., 1975. Sea level events and Pleistocene coral ages in the northern Bahamas. Quaternary Research 5, 215–224.

Oppenheimer, M., 1998. Global warming and the stability of the West Antarctic ice sheet. Nature 393, 325–332.

Seidenkrantz, M.-S., Knudsen, K.L., 1994. Foraminiferal evidence of a short term cold period during the last interglacial at Skagen, Denmark, AMQUA Abstracts: 157.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the last interglacial: evidence for a restricted interval of widespread coral reef growth. Earth and Planetary Science Letters 160, 745–762.

Taft, W.H., Arrington, F., Haimoritz, A., MacDonald, C., Woolheater, C., 1968. Lithification of modern carbonate sediments at Yellow Bank, Bahamas. Bulletin of Marine Sciences of the Gulf and Caribbean 18 (4), 762–828.

Tormey, B.R., Neumann, A.C., Hearty, P.J., 1999. Substage 5e carbonate eolianites of Eleuthera Isand, Bahamas: indicators of climate change during the last interglacial. Geological Society of America, 48th Annual Meeting., SE Section, Abstracts with Programs: A-72.

Vacher, H.L., Hearty, P.J., 1989. History of stage-5 sea level in Bermuda: with new evidence of a rise to present sea level during substage 5a. Quaternary Science Reviews, 159–168.

Wanless, H.R., Dravis, J.J., 1989. Carbonate environments and sequences of Caicos Platform. Field Trip Guidebook T374. 28th International Geological Congress, American Geophysical Union, 75 pp.

Ward, W.C., Weidie, A.E., Back, W., 1985. Geology and hydrogeology of the Yucatan and Quaternary geology of the northeastern Yucatan Peninsula: New Orleans, LA. New Orleans Geological Society Publications, New Orleans, 160 pp.

White, B., Curran, H.L., Wilson, M.A., 1998. Bahamian coral reefs yield evidence of a brief sea-level lowstand during the last interglacial. Carbonates and Evaporites 13 (1), 10–22.

Woillard, G., 1979. Abrupt end of the last interglacial s.s. in north-east France. Nature 281, 558–562.