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(Cover photo: Rice Bay Formation, looking southwest along Grotto Beach by Sandy Voegeli)

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ABSTRACT

Our review of the last interglacial (Marine Isotope Stage 5e) stratigraphic record from the Boiling Hole exposure in northern Eleuthera Island, Bahamas, revealed the occurrence of two vertically stacked shallowing-upward sequences of oolitic coastal deposits showing beach facies at about 3 and 6 m above mean sea level, respectively. These beach strata dip towards the bank interior and the upper one includes a paleosurface on top of an oolitic grainstone bed with a 2-m-long bird trackway. These fossil beaches correspond to two distinctive sea-level highstands during the last interglacial that could have possibly reached +5 and +8 m above modern datum, respectively, if estimates of regional subsidence are indeed correct. The bird footprints are the first reported occurrence of vertebrate trace fossils from the Bahama Archipelago. The track maker was probably an extant shorebird belonging to the Order Charadriiformes. Track preservation in an oolitic grainstone is remarkable and may be related to an early phase of halite cementation. Finally, the dip of the beach beds indicates that constituent grains were transported onto the island from the bank side by a westerly flux opposite to the modern sediment transport direction in the area.

INTRODUCTION

Northern Eleuthera has some of the most spectacular rock exposures in the Bahamas, owing to the presence of steep cliffs bordering the open North Atlantic Ocean. Moreover, these outcrops have only been studied in a preliminary way. Here, impressive 25 m-high sea cliffs displaying several stratigraphic units await further examination and promise to provide more information on past sea-level stands, ancient climates, and sedimentary processes that are no longer operational. This paper revisits one of the most prominent of these exposures, the Boiling Hole, in order to (1) complement the stratigraphic and sea-level records from the Bahamas for the early part of the last interglacial period (Marine Isotope Stage 5e); (2) describe the first fossil vertebrate tracks reported from the archipelago; and (3) present an example of a large amount of oolitic sediment that was transported from west to east, contrary to the present-day main sediment transport vector on Great Bahama Bank.

GEOLOGICAL SETTING

Eleuthera is a long and narrow carbonate island (140 x 2-5 km), located on the northeastern and windward margin of the Great Bahama Bank (GBB, Figure 1).

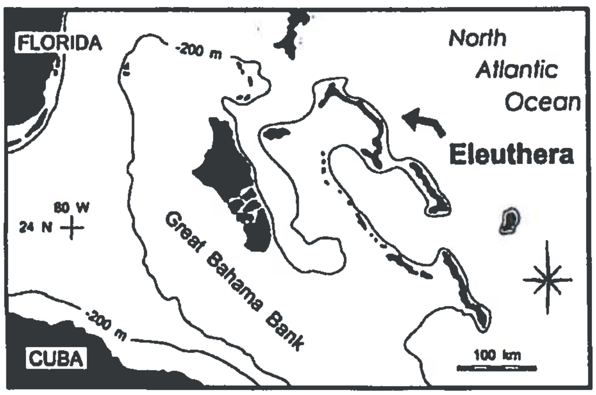

Figure 1. Location of the study area (modified from Kindler and Hearty, 1995).

This area belongs to the tectonically passive northwestern Bahamas (Sheridan et al., 1988) and is only affected by slow (1.6 cm/10^3 years; Lynts, 1970; Mullins and Lynts, 1977; Carew and Mylroie, 1995) subsidence mostly due to thermal decay and sedimentary loading (Pindell, 1985). The main physical parameters controlling sediment distribution on the GBB are wind, wind-induced waves and currents, and tidal currents. The long-term influence of tropical storms and hurricanes is less well constrained (Harris, 1979; Boss and Neumann, 1993). In the Bahamas, prevailing winds are from northeast to southeast during most of the year (Sealey, 1994), with strong northwesterly winds, related to cold fronts, further affecting the area in the winter. Wind further generates waves and currents that determine the subaqueous transport of sediment and the primary generation and distribution of sedimentary bedforms (Purdy, 1963; Swart et al., 2005). Predominant water movement and sediment transport on the GBB is thus towards the west, although some southward and eastward motion can occur during northwesterly gales in the winter (Bathurst, 1975).

The eastern coast of northern Eleuthera displays locally high (>20 m) cliffs, composed of vertically stacked carbonate units and paleosols, that commonly stand less than 1 km from the bank edge. Carbonate units accumulated during interglacial sea-level highstands, whereas the paleosols developed mostly during glacial lowstands (Carew and Mylroie, 2001). Details on the geology and stratigraphy of the area can be found in Kindler and Hearty (1995, 1997), Hearty (1997, 1998), Hearty and Kaufman (2000) and Panuska and others (2002). These carbonate units are dominantly composed of eolian sediments, but marine deposits recording ancient sea stands are present, with some reported to lie up to 18 m above modern sea level (Hearty et al., 1999; Kindler and Hearty, 2000). Eolianite foresets most commonly dip towards the interior of islands, emphasizing further that the source material for these dunes originated from the shore and that only onshore winds are effective in dune buildup (Mackenzie, 1964; Ball, 1967). The widespread occurrence of oolitic deposits in northern Eleuthera, as well as on other windward islands is problematic because no ooids have been reported as presently forming on the narrow outer platforms fronting these islands, which raises the question of the origin of these constituent grains.

The Boiling Hole (lat. 25°25'56"N, long. 76°35'54") is a 75 m-wide cove on the eastward, ocean-facing shoreline of northern Eleuthera, situated about 800 m to the southeast of the Glass Window bridge (Figure 2). The back end of the cove comprises a large sea cave that is only accessible during fair weather and at low tide. The outcrop includes three vertically stacked stratigraphic units (Figure 3) that were first identified by Kindler and Hearty (1995). Unit I forms a chain of deeply karstified eolian dunes of middle Pleistocene age that nonetheless exhibit original topography. The ancient dune crests may reach elevations of up to 25 m above sea level, whereas the interdune swales, such as the Boiling Hole cove, are partly submerged.

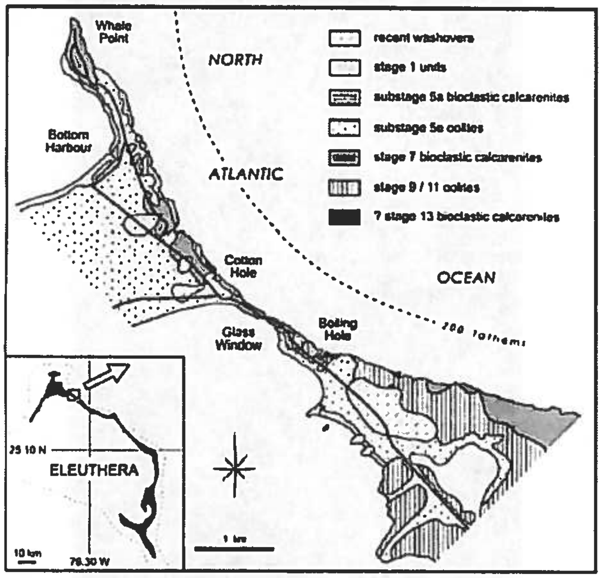

Figure 2. Geologic map of the Boiling Hole area (modified from Kindler and Hearty, 1997).

The northwestern and southeastern flanks of the cove consist of oolitic-peloidal and bioclastic eolianites, respectively (Figure 4) that may correspond to discrete depositional events during separate interglacials (possibly MIS 9/11 and 13, respectively; Hearty, 1998). The upper surface of these limestones is capped by a calcrete and breccia-rich paleosol that commonly has been stripped away by marine erosion particularly at low elevations. Unit II is composed of light-grey beds that partly fill the interdunal depression corresponding to the Boiling Hole cove. Its thickness varies from zero on the sides of the depression, to over six meters in the trough axis. These beds consist of well-cemented, oolitic-peloidal limestone including a small, but remarkable proportion of radial ooids (Kindler and Hearty, 1995; Figures 5a and b). According to previous authors (Kindler and Hearty, 1995; Hearty, 1998; Hearty and Kaufman, 2000), this unit corresponds to one shallowing-upward sequence from lower shoreface to backshore deposits showing fenestrae-rich beach beds at about +5 m above modern sea level. Unit II is

Figure 3. Southeastern end of the Boiling Hole exposure; background cliff height is 20 m. The dotted line emphasizes the boundary between Units I and II which is dipping towards the southwest (modified from Kindler and Hearty, 1995).

attributed to MIS 5e because of its stratigraphic position and the presence of elevated beach facies (Kindler and Hearty, 1995), and also because it yielded whole-rock amino-acid ratios that are consistent with the beginning of the last interglacial period (Hearty, 1998; Hearty and Kaufman, 2000). Unit III overlies Unit II along the back

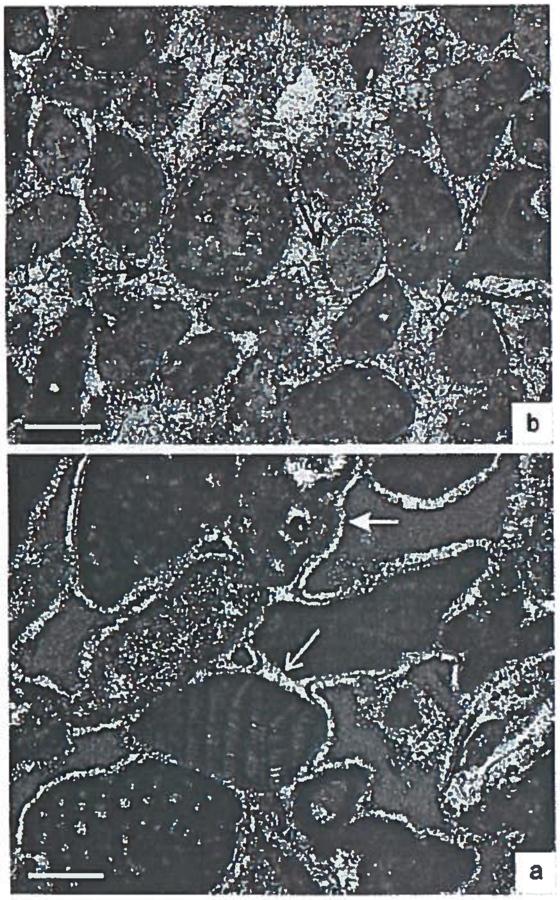

Figure 4. a) Sample EL 169. Microscopic view of the middle Pleistocene (Unit I, MIS 13?) bioclastic eolianite exposed on the southeastern end of the Boiling Hole outcrop. Note the pronounced diagenetic alteration of constituent grains (e.g., peneroplid fragment in lower left corner and Halimeda *clast above center). Note also the early generation of meteoric vadose cement (thin arrow) and the late generation of isopachous fibrous rims (thick arrow) likely precipitated during a later sea-level event. b) Sample EL 64. Microscopic view of the middle Pleistocene (Unit I, MIS 11?) peloidal limestone exposed on the northwestern end of the Boiling Hole outcrop. Note extensive, late meteoric sparry cement. Thin arrow points to remnants of an early isopachous fibrous rim of marine origin. Thick arrow indicates polygonal boundaries suggesting this rock was cemented in a phreatic setting. Scale bars = 200 µm.*

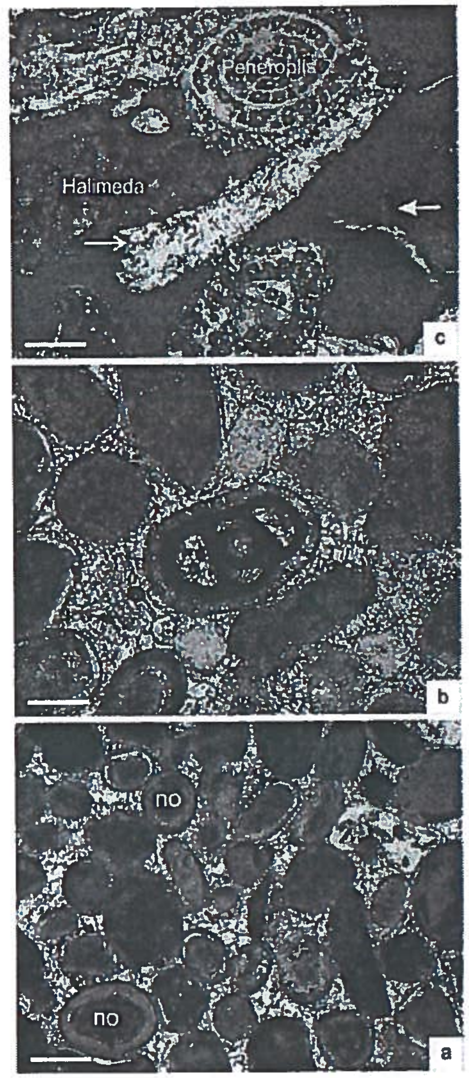

Figure 5. a) Sample EL 205. Microscopic view of last interglacial oolitic deposits (Unit II, MIS 5e) at Boiling Hole. Note the abundance of normal (i.e. thickly coated ooids = no) compared to Fig. 4B; scale bar = 200 µm. b) Sample EL 204. Peculiar radial ooid with a miliolid nucleus. Such ooids are typical of a low energy setting (Land et al., 1979); scale bar = 100 µm. c) Sample EL 69. Microscopic view of the upper Pleistocene bioclastic eolianite (Unit III, MIS 5a). Note the good preservation of bioclasts compared to the middle Pleistocene eolianite (Figure 4a). Note also meteoric meniscus cement (thin arrow) binding the grains and incipient alveolar texture of pedogenic origin (thick arrow); scale bar = 200 µm.

wall of the Boiling Hole cove. In this exposure, a thin calcrete occurs between the two units, whereas at Whale Point, 3.5 km to the NW, they are separated by a 30 cm thick paleosol. Unit III consists of small (up to 3 m high) bioclastic eolianites (Figure 5c) bearing numerous root casts and it is capped by a calcrete. Constituent grains have retained their original mineralogy (aragonite or high-Mg calcite). This difference in petrographic characteristics, the presence of an intervening paleosol, and distinctive whole-rock amino-acid ratios (Hearty, 1998), all indicate that Unit II and Unit III represent separate depositional events and suggest a correlation of the latter unit with MIS 5a.

METHODS

For this study, the geometry, stratigraphy and sedimentology of Unit II were reexamined in detail in the field. Particular attention was given to bounding surfaces and physical sedimentary structures that provide useful information on sediment transport vectors and past depositional environments. A new stratigraphic section was logged at cm-scale on the southeastern flank of the Boiling Hole cove and sedimentological investigations were carried out in the sea cave carved in the back wall of the exposure. The newly discovered footprints were documented and measured according to current vertebrate ichnological standards and methods (e.g., Leonardi, 1987). Track length was measured axially from the tip of digit III along the axis of digit III to the most posterior trace of the heel pad. Width was measured between the tips of digits II and IV. Tracings and a silicon cast of the trackway were made.

RESULTS

The new stratigraphic section logged at the southeastern end of the Boiling Hole cove (Figures 3 and 6) only displays the lowermost two lithological units exposed in the area.

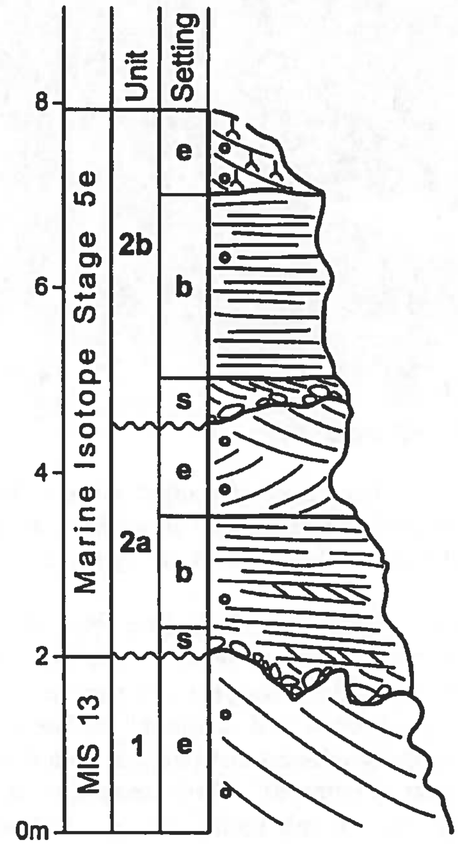

Figure 6. Stratigraphic section logged in the southeastern end of the Boiling Hole exposure. Precise location is indicated on Fig. 3. Setting column: s = subtidal, b = beach, e = eolian. Dots indicate sample locations. Inverted Ys correspond to rhizomorphs (modified from Kindler and Hine, 2008).

Unit I is visible from sea level up to an elevation of 2 m. It consists of a well-cemented, iron-stained, bioclastic eolianite exhibiting large-scale foresets dipping steeply towards the southwest (Figure 7). The upper surface of this rock body is highly irregular and rises towards the

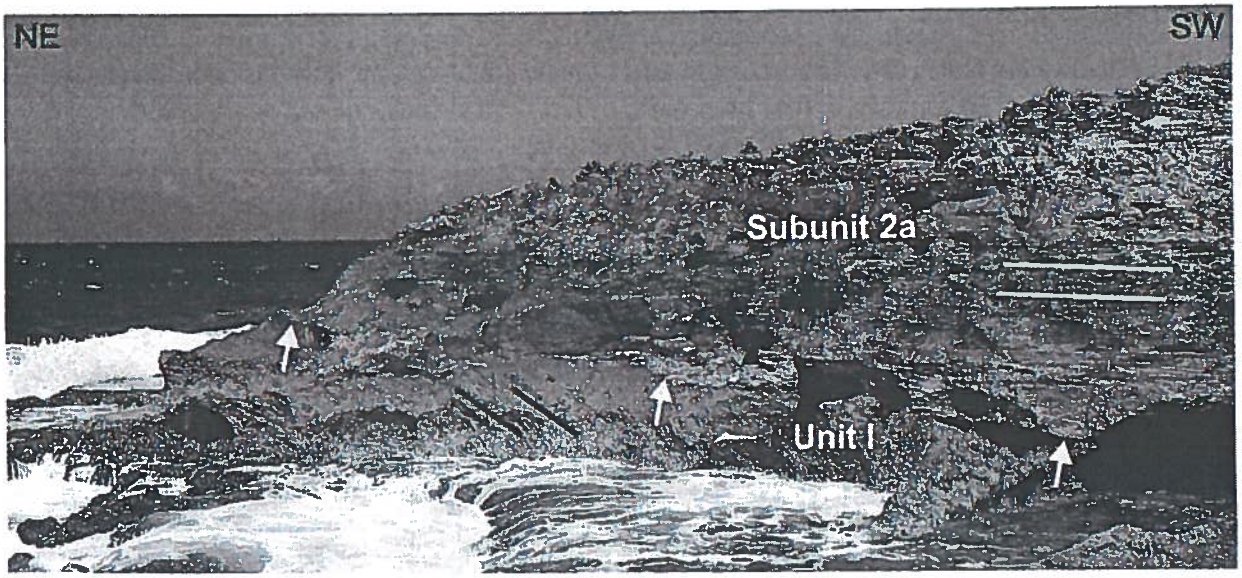

Figure 7. Basal part of studied section. Arrows point to the boundary between Units I and II which rises towards the northeast. Black lines in Unit I correspond to the dip of eolian foresets. White lines in Unit II (subunit 2a) show the dip of beach beds.

northeast (Figure 7). The oolitic-peloidal Unit II is 6 m thick here and includes two shallowing-upward depositional sequences separated, at about 4 m, by a pronounced erosional surface dipping towards the southwest and overlain by a thin conglomerate (Figure 6). Each sequence includes subtidal, beach and eolian facies, identified by sedimentary structures characteristic of these depositional environments (Fig. 6). The subtidal deposits display small-scale cross beds generated by the action of waves and currents. The overlying beach sediments are represented by large-scale, fenestrae-rich, planar cross beds with a low-angle dip towards the southwest (Figure 7) and occur between 2.5 and 3.3 m in the lower sequence and between 5 and 7 m in the upper one. The eolian beds dip mainly towards the southwest and further comprise unusual polygonal structures with a diameter of up to 0.5 m, already observed by Kindler and Hearty (1995), and resembling prism or desiccation cracks (Demicco and Hardie, 1994). The lower sequence disappears towards the back end of the cove (i.e. towards the southwest) where the section described by Kindler and Hearty (1995) was logged. The basal beach beds from the upper sequence form the floor of the large sea cave carved in the back wall of the Boiling Hole cove. Near the southeastern entrance of the cave, the upper surface of one of these beds exhibits bird tracks (Figures 8, 9 and 10).

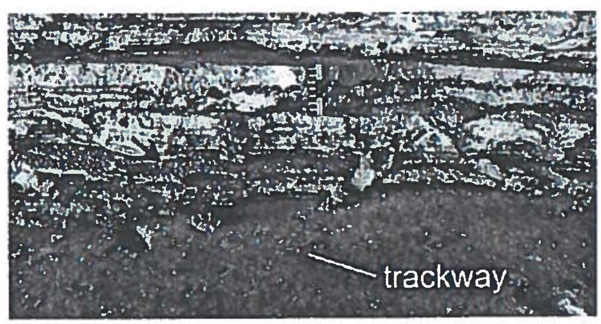

Figure 8. Partial view of the trackway site near the southeastern entrance of the back-wall cave at Boiling Hole. Note the occurrence of small wave ripples in the beds overlying the surface where the tracks are exposed (black arrow). Small wave ripples characterize the lower intertidal and upper subtidal environments.

These tracks are preserved in an oolitic grainstone comprising an early generation of isopachous fibrous cement of marine origin, rare cubic molds that could represent an early halite cement, as des-

Figure 9. Part of the bird trackway showing footprints T2 to T7 (Figure 10). Footprint T7 (far left) is the best preserved track. It has relatively broad digits and a wide divarication, but it shows no evidence for webbing of the foot.

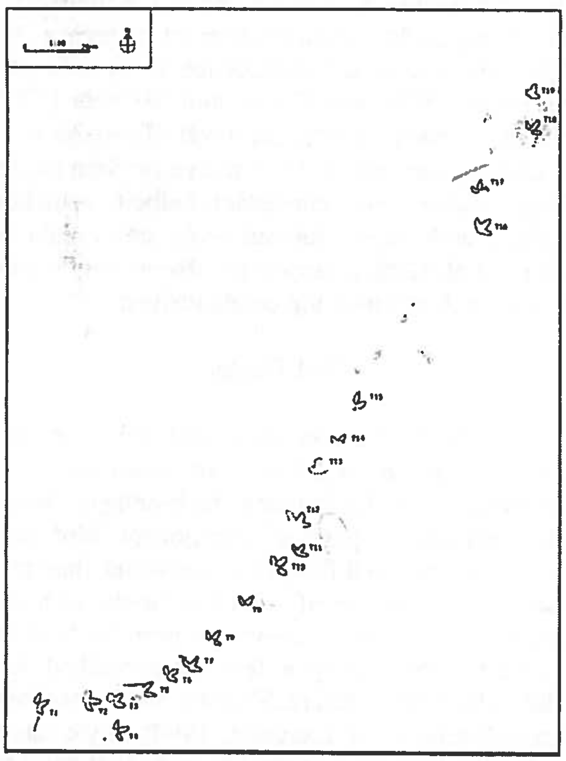

Figure 10. Site map of the bird footprint-bearing paleosurface. Most of the footprints can be attributed to the over 2-m long trackway. Between the footprints T15 and T16, the bird probably walked over a slightly drier substrate. This might explain why only some shallow imprints of the third digit are visible.

cribed by Davaud and Strasser (1984), and late blocky spar precipitated in a meteoric phreatic setting (Figure 11). On the footprint-bearing surface, a total of 19 bird tracks were recognized. Some of the prints are moderately to fairly well preserved, but none show anatomical details such as digital nodes or webbing traces. Nonetheless, all footprints are believed to be true tracks, as it is very unlikely that underprints would form in an unlaminated oolitic grainstone. All but one (footprint T4) can be attributed to the about 2 m long trackway (Figure 10). However, as the left and right footprints could not clearly be identified, pace and stride length have not been measured. Between footprints 15 and 16, several footprints are poorly defined and only some shallow longitudinal grooves that could be the prints of the third digit, were observed. Footprint length varies from 3 to 5.5 cm (average 4.2 cm), and width from 4.5 to 7 cm (average 6 cm). Digit III usually is the most deeply impressed (up to 0.8 cm). The digits are relatively broad and their tips are U- to V-shaped and without claw impressions. Tracks with three digit prints mostly have a relatively pronounced heel region where the three digits merge together.

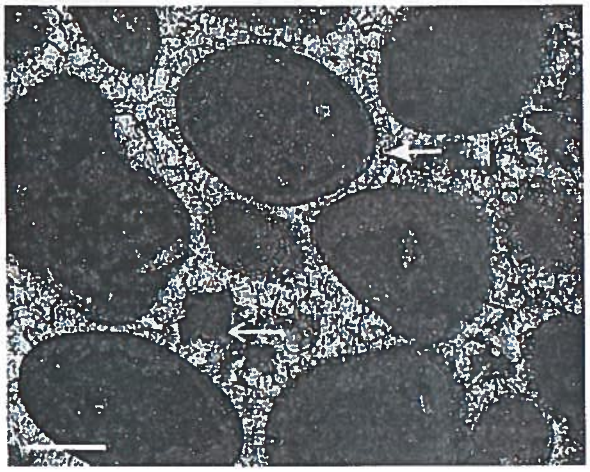

Figure 11. Sample EL 220. Thin-section of the oolitic grainstone bed ontop of which the bird tracks are imprinted. Thin arrow points to a square-shaped pore possibly resulting from the dissolution of a halite crystal. Thick arrow indicates partly preserved fibrous rim likely corresponding to an early marine cement. Note partially leached ooids and widespread late sparry cement; scale bar = 200 μm.

DISCUSSION

MIS 5e Sea Level

The recognition of two vertically stacked shallowing-upward sequences in the MIS 5e strata from the Boiling Hole supports earlier reports on the occurrence of two distinctive sea-level highstands in the Bahamas region during the last interglacial period (Chen et al., 1991; Hearty and Kindler, 1993, 1995; Neumann and Hearty, 1996; White et al., 1998; Wilson et al., 1998; Carew and Mylroie, 1999). Due to the lack of suitable material (e.g., *in situ* coral specimens), these sequences could not be precisely dated with the U-series methods. Nonetheless, the intervening erosional surface at 4 m can tentatively be correlated with the sea-level lowstand defined by White et al. (2001) as the Devil's Point Event, and dated at about 125-124 ka. Thus, based on Chen et al.'s (1991) data, the first sequence (sequence 5eII; White et al., 2001) could have been deposited between 130 and 125 ka and the second one (sequence 5eI; White et al., 2001) between 124 and 119 ka. However, the ages of these two depositional/sea-level events ultimately may have to be shifted towards younger values due to recoil-related processes that in most cases, add excess daughter isotopes to the coral framework (Fruijtier et al., 2000; Thompson and Goldstein, 2005). The major point of interest of the MIS 5e record from the Boiling Hole is the occurrence of well-expressed beach facies that, even more than coral reefs, provides a precise estimate of past sea-level stands. Thus, the elevation of beach bedding suggests that mean relative sea level stood at about +3 m (i.e. between 2.5 and 3.3 m) during deposition of sequence 5eII, and at +6 m (i.e. between 5 and 7 m) during accumulation of sequence 5eI. Consideration of the subsidence rates estimated by Lynts (1970) and Carew and Mylroie (1995) places the early eustatic sea-level highstand at +5 m and the later one at +8 m above modern datum. These values are consistent, albeit somehow higher, with those derived from coral data by White et al. (2001), despite the uncertainty related to the depth at which the corals thrived.

Bird Tracks

The bird tracks described here represent the first reported occurrence of fossil vertebrate footprints from the Bahama Archipelago. Moreover, previous reports of Pleistocene bird footprints are few. All footprints are wider than long that is characteristic of shorebird tracks (Abbassi and Lockley, 2004). Among modern birds of the Charadriiformes, only a few have webbed feet. The ichnotaxon *Charadriipeda* bears webbing traces (Sarjeant and Langston, 1994) so we cannot assign the Bahamian footprints to this ichnotaxon, even if webbing might have been present and simply not preserved in the Boiling Hole examples, due to their occurrence in relatively coarse-grained sediment. The Bahamian tracks do match closely with the ichnotaxon *Avipeda,* that is characterized by three forward directed digits of similar length with a total interdigital spacing of less than 95° (Sarjeant and Langston, 1994). For these reasons, we tentatively assign the Bahamian tracks to this ichnotaxon, using the designation cf. *Avipeda.* Although the tracks are moderately well preserved, we do not elect to erect a new ichnotaxon or ichnospecies at this time.

Figure 12. Shorebird trackway exposed on a modern sand shoal on the leeward side of Long Island, GBB, Bahamas. Note the association of the tracks with small, bifurcating wave ripples. Pen is 15 cm in length.

Observations by one of us (HAC) of similar tracks on a modern sand flat on the bank side of Long Island, Bahamas (Figure 12) indicates that the cm-sized tridactyle footprints exposed in the Boiling Hole cave were likely produced by a shorebird species common today in the Bahamas. It is suggested that the trackmaker belonged to the Order Charadriiformes and was quite possibly one of the following: American oystercatcher (*Haematopus palliates*), greater yellowlegs (*Tringa melanoleuca*), black-necked stilt (*Himantopus mexicanus*), or stilt sandpiper (*Calidris himantopus*). Nonetheless, the precise trackmaker species cannot be identified with the evidence presently in hand. The preservation of the bird footprints in an oolitic grainstone is surprising, as is the conservation of the large polygonal prism or desiccation cracks in the associated eolianites (Kindler and Hearty, 1995). Figure 12 shows that such footprints remain discernible for a few hours to days in cohesive sand, just a few centimeters above the normal high tide line. Subsequent burial by younger (? subtidal) sediment in a low-energy setting could ensure their preservation in the fossil record. In the Boiling Hole case, the footprint-bearing sands could have been quickly cemented by halite crystals precipitated out of marine pore waters, as documented in upper intertidal deposits of Holocene age from Bimini (Davaud and Strasser, 1984), and then rapidly buried and preserved, by a younger sediment layer. The rare occurrence of square pores (Figure 11), possibly resulting from the dissolution of early halite crystals, appears to support this hypothesis.

Origin of Ooids and Sediment Transport

The dip of MIS 5e beach deposits (Figure 7) strongly suggests that their constituent grains originated from the interior of the bank, to the southwest. The eolian strata dip in the same direction. However, they are not foresets, as figured earlier in Kindler and Hearty (1995) and Hearty (1998), but backsets draped over the pre-existing middle Pleistocene topography. Thus, their component particles were also brought up from the bank interior from the west, and not from the open ocean side by the prevailing easterly winds, as previously interpreted. Further, the unusual occurrence of radial ooids (Figure 5b) in these deposits suggests a relatively low-energy production locus (Land et al., 1979; Flügel, 2004), thus strengthening a bank-side source for these deposits. The case is even clearer at Cotton Hole (Figure 2), 1 km to the northwest, where bankward-dipping beach sediments exposed on the ocean-facing cliffs can be traced all the way to the bank-facing shoreline of the island. The Boiling Hole outcrop reveals that a large amount of sediments dating from the last interglacial period has been transported onto the island from the west, opposite to the main transport vector (from east to west) that is prevailing on GBB today. Moreover, ooids were not carried eastward during a single and catastrophic depositional event, such as a storm or a northwesterly gale, but by a sustained flux from the west that lasted long enough for the shoreline to prograde significantly towards the southwest.

CONCLUSIONS

The MIS 5e deposits exposed at the Boiling Hole cove on Eleuthera comprise two superimposed shallowing-upward sequences of coastal deposits separated by an erosional surface and exhibiting beach facies beds at about 3 and 6 m, respectively. These beach beds dip towards the southwest, i.e. towards the bank interior. A bedding plane surface at 5 m displays a 2 m long bird trackway consisting of moderately well-preserved tridactyle footprints that we tentatively assign to the ichnotaxon *Avipeda*. These footprints are the first report of fossil footprints from the Bahama Archipelago, and they were likely formed by an extant shorebird of the Order Charadriiformes. The occurrence of two MIS 5e depositional sequences at the Boiling Hole site adds further evidence to confirm that the last interglacial period was characterized by two sedimentation events corresponding to distinct highstands of sea level, and one erosional phase corresponding to an intervening regression. The Boiling Hole sequences can thus probably be correlated to the 5eII and 5eI sequences defined by White et al. (2001), and further record eustatic sea-level highstands at about +5 and +8 m, respectively, that is somewhat higher than the elevations estimated so far from coral-age data. The dip of the beach beds towards the southwest and the presence of radial ooids generated in a low-energy environment show that, at this locality, a fairly large amount of oolitic sediment was transported from west to east during a significant time period of MIS 5e. This transport direction is opposite to the main sediment transport vector operating on GBB today, demonstrating that the present is not necessarily the key to the past.

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