PROCEEDINGS OF THE 14TH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
Fredrick D. Siewers and Jonathan B. Martin

Production Editor:
Fredrick D. Siewers

Gerace Research Centre
San Salvador Island, Bahamas
2010

Front Cover Photograph – “Kelly and the Veggiemorphs” courtesy of Jon Martin

Back Cover Photograph – “Luigi” courtesy of Erin Rothfus

A & A Printing Inc., Tampa, FL

ISBN 0-935909-90-7

SOIL COLLUVIUM AND ELEVATED FOSSIL ALGAL-MICROBIAL MAT NEAR ALICE TOWN (ELEUTHERA, BAHAMAS): POSSIBLE EVIDENCE FOR EXTREME EVENTS AND A HIGH SEA LEVEL DURING THE MIDDLE HOLOCENE

Fabienne Godefroid, Pascal Kindler, and Elias Samankassou
Section of Earth and Environmental Sciences
University of Geneva
1205 Geneva, Switzerland

ABSTRACT

New sedimentological, petrographic and geochronological data obtained from a thin laminar crust and a superimposed reddish, clay-rich conglomerate layer exposed in central Eleuthera, Bahamas, suggest they represent, respectively, an algal-microbial mat and a colluvial deposit of middle Holocene age, which sheds new light on eustatic and climatic events during this time period.

Located on the ocean-facing coast of Eleuthera, near Alice Town, the studied exposure comprises one 30 cm-thick reddish layer consisting of a laminated micritic crust, at the base, and a clay-rich conglomerate, at the top, interstratified between two thicker limestone units. Like most similar occurrences in the Bahamas, this composite bed has been interpreted as a Wisconsinian paleosol separating Sangamonian and Holocene peritidal carbonate deposits. Our detailed study of this outcrop yielded the following results. The lower portion of the exposure consists of oolitic-bioclastic calcarenites deposited in a beach setting, locally overlain by rhizolith-rich bioclastic calcarenites accumulated in a foredune environment. Amino-acid ratios and stratigraphic relationships suggest a correlation with Marine Isotope Stage 5e for the beach facies, and with MIS 5a for the eolian facies. At about +2 m, these calcarenites are capped by a 1 to 5 cm-thick, laminated, micritic crust, which includes micron-sized spherulites of cyanobacterial origin and probable remnants of bryophytes. This crust yielded a ^{14}C age of 6,470 ± 30 a BP (= 7,375 ± 55 cal a BP). The overlying clay-rich conglomerate layer comprises blocks of various sizes and origins, and lacks a horizontal zonation and pedogenic textures. The uppermost unit of the exposure is made of an eolian bioclastic calcarenite, and yielded a ^{14}C age of 5,480 ± 30 years BP (6,289 ± 26 cal a BP).

The short time interval (ca. 1,000 years) established for the deposition of the reddish conglomerate layer, as well as the lack of soil horizons and pedogenic textures, suggest it corresponds to a debris-flow deposit resulting from an extreme event (tsunami wave or exceptional rainfall) during the middle Holocene. This case further demonstrates that red brecciated beds interstratified in Bahamian carbonates do not always represent glacial paleosols. The microbial and algal structures found in the studied crust show that laminated calcretes may not all have a pedogenic origin. This particular example, which is similar to algal-microbial mats forming along the shores of ponds and lakes in the Bahamas today, could indicate that sea-level was about 2 m higher than present during the middle Holocene, confirming earlier reports from Andros Island and the Exuma Islands.

INTRODUCTION

Fossil coastal deposits of Quaternary age are common along most of the world's tropical shorelines and provide information about climate and sea-level changes that can be used to better understand future climatic and eustatic trends (e.g. Strasser and Strohmenger, 1997; Meischner et al., 1995). The Bahamas archipelago is a particularly suitable location for such studies, because its numerous islands mostly consist of Pleistocene and Holocene carbonates that are very sensitive to even minor environmental changes (e.g. Hattin and Warren 1989; Kindler, 1992, 1995; Kindler and Hearty, 1996). The overall stratigraphic record of the Bahamas includes two types of lithological units (Carew and Mylroie, 1985, 1995a, 1997; Kindler and Hearty 1997; Hearty and Kaufman, 2000): (1) meter-thick, coastal carbonate deposits which accumulate during interglacial periods, when the flat-topped Bahamian platforms are partially or totally flooded, and (2) thin reddish layers, commonly interpreted as terra-rossa paleosols, that essentially form during glacial intervals, when the banks are exposed to pedogenic and karstification processes.

Paleosols are important and are widely used in Bahamian stratigraphy, because their position relative to coastal carbonate units is a primary criterion for correlating these with a specific interglacial period (Beach and Ginsburg, 1980; Carew and Mylroie, 1995a; Kindler and Hearty, 1997; Hearty and Kaufman, 2000). Nonetheless, as already reported by Carew and Mylroie (1991) and Rossinsky et al. (1992), caution is required when using this criterion because (1) paleosol formation can span several interglacial/glacial cycles, resulting in a composite paleosol; (2) pedogenic processes may act simultaneously both on the surface and at a certain depth in the parent rock (penetrative calcretes; Rossinsky et al., 1992; Aalto and Dill, 1996), thus duplicating a paleosol horizon; and (3) soil material can be washed down into horizontal phreatic conduits, giving the false impression there are several paleosol horizons, whereas there is only one.

Bahamian carbonate units mostly consist of coastal dune deposits (i.e. eolianites), but include also significant beach and shallow-marine sediments that precisely record the elevation of ancient sea stands (e.g. Garrett and Gould, 1984; Hearty and Kindler, 1995; Neumann and Hearty, 1996; White et al., 2001; Kindler et al., 2008). Up to now, no unequivocal perched beach or marine deposit of Holocene age has been found in the Bahamas, apparently corroborating coral- and peat-based eustatic curves for the Caribbean region (Lighty et al., 1982; Toscano and Macintyre, 2003) which suggests that sea level never exceeded the modern datum during this time period. Nonetheless, fossil ghost-crab burrows (*Psiloichnus upsilon*), which characterize the intertidal zone, have been reported at about 2 m above modern occurrences in ~3 ky-old backshore sediments on the ocean side of Lee Stocking Island (Exumas; White and Curran, 1993). In addition, perched subtidal muds of middle Holocene age have been recovered at several locations on the tidal flats of Andros Island, indicating that sea-level could have been 1.5 to 2 m above the modern datum around 3,000 years ago (Bourrouilh-Le Jan, 2007). Finally, elevated root casts of turtle grass exposed on the NE end of Key Biscayne (South Florida) suggest a Holocene sea-level highstand at least 0.5 m higher than present in the Caribbean region (Froede, 2002). Collectively, these data show that middle to late Holocene relative sea-level history is not well constrained in the Bahamas and Caribbean, as is also the case in the Gulf of Mexico (e.g. Blum et al., 2001).

This paper presents new sedimentological, petrographic and geochronological data from an exposure located near Alice Town, on Eleuthera Island, that (1) allow further discussion on the significance of paleosols in the stratigraphic record of the Bahamas islands, and (2) provide new information on the relative elevation of sea-level in the Caribbean region during the middle Holocene.

SETTING

Eleuthera is a long and narrow (140 x 2-5 km) island located along the NE corner of Great

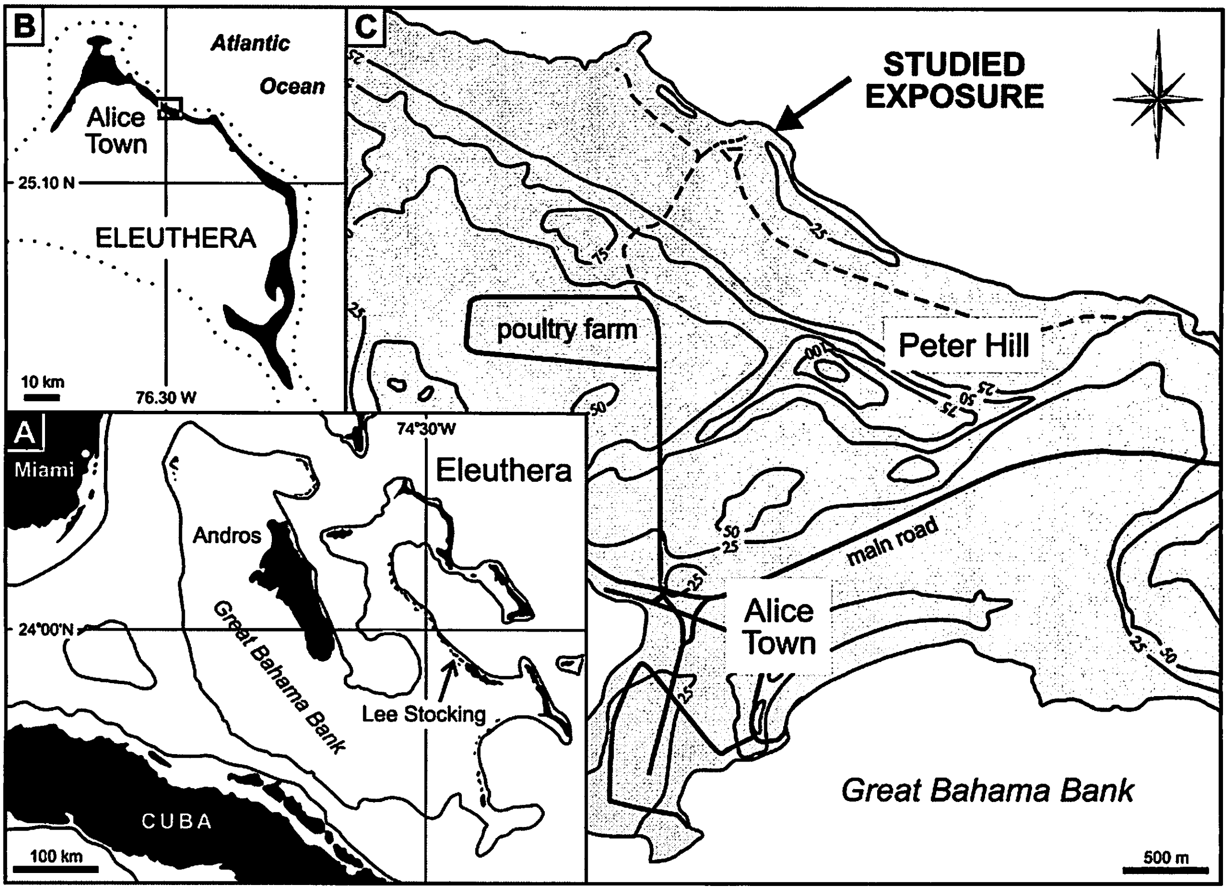

Figure 1. Situation maps of the studied area: a) location of Eleuthera on Great Bahama Bank; b) location of the studied exposure near Alice Town in central Eleuthera; c) topography near the studied outcrop (elevation in feet above sea level); note the presence of a fairly high hill (by Bahamian standards) to the SE of the exposure.

Bahama Bank (GBB; Figs. 1a and b). This region is considered as tectonically passive (Sheridan et al., 1988) and is only affected by slow subsidence (1.6 cm/10^3 years; Lynts, 1970; Mullins and Lynts, 1977; Carew and Mylroie, 1995b), linked to thermally induced sedimentary loading (Pindell, 1985). Possibly active compressive features, related to the convergence between the North and South American tectonic plates, have nonetheless been identified in the subsurface to the West of GBB (Masaferro et al., 1999). The stratigraphic record exposed on Eleuthera extends from the middle Pleistocene to the late Holocene (Kindler and Hearty, 1997; Hearty 1998; Hearty and Kaufman, 2000). Pleistocene limestone units (Kindler and Hearty, 1995; Hearty 1998; Kindler et al., 2008; Godefroid et al., this volume) and intervening paleosols (Foos and Bain, 1995; Michaud, 1999; Ersek, 2004; Nawratil de Bono, 2008) exposed on the island have been rather well studied. In contrast, to our knowledge, no detailed investigation has ever focused on the Holocene rock bodies that crop out along Eleuthera's shorelines.

The studied exposure, referred to as the Hatchet Bay section, is located on the ocean-facing coast of central Eleuthera, near Alice Town (Figs. 1b and c). The exposure forms a small headland (the Hatchet Bay headland) between two embayments (Fig. 1c), and consists of flat indurated rocks, at the base, overlain by poorly lithifed to sandy vegetated deposits, at the top. Maximum elevation reaches about +5 m. Of importance is the presence of significant relief, called Peter Hill (125 feet, 40 m; Fig 1c), about 1 km to the SE of the studied section.

METHODS

This paper builds upon earlier observations made by Pascal Kindler and two of his former students (Michaud, 1999; Nawratil de Bono, 2008). It relies on a multi-method approach combining stratigraphy, sedimentology, petrography, micromorphology and geochronology (amino-acid racemization and ^{14}C dating). After identifying the main stratigraphic units of the outcrop, physical and biogenic sedimentary structures were examined in the field to obtain information on past depositional environments and ancient sea-level stands. Sampling was made at closely spaced intervals in each unit. All samples were impregnated with blue-stained epoxy resin, thin sectioned, and examined with a petrographic microscope to further constrain the depositional setting, determine the early diagenetic history, and identify the possible imprint of pedogenic processes on each stratigraphic unit. Geochronological analyses relying on the amino-acid racemization (AAR) method were performed on whole-rock samples at the Amino Acid Geochronology Laboratory in Northern Arizona University. This method is based on the interconversion of amino acids from one chiral form (the L -laevo amino acids-) to a mixture of L- and D- (dextro) forms. The extent of racemization is measured by the ratio of D/L isomers and increases as a function of time and temperature. In our case, we used the ratio of D-alloisoleucine/L-isoleucine (or A/I ratio) to get a relative age of carbonate units. More details on the whole-rock AAR method can be found in Hearty and Kaufmann (2000; 2009). Whole-rock ^{14}C dating analyses were performed at the Physics Institute of the University of Bern (Switzerland) on three putative Holocene samples. ^{14}C ages younger than 22,000 a BP have been corrected with the INTCAL04 calibration curve (Reimer et al., 2004) to account for the secular variations in atmospheric ^{14}C level (no curve exists for older ages).

RESULTS

Stratigraphy and sedimentology

The Hatchet Bay section exhibits three stratigraphic units, including from base to top: (1) a well-indurated limestone; (2) a composite, red-colored unit comprising a thin micritic crust, at the base, and a conglomerate with a clayey matrix, at the top; and (3) a poorly lithified and cross-stratified calcarenite (Fig. 2). Like many similar successions in the Bahamas, e.g. Singer Bar Point on San Salvador (McCartney, 1987), these units have been interpreted in the past (Michaud, 1999) as a Sangamonian marine deposit, a Wisconsinian paleosol, and a Holocene eolianite, respectively. More detailed examination of this exposure shows that it actually comprises five stratigraphic units (Fig. 3) that are described below.

Unit 1 crops out extensively along the

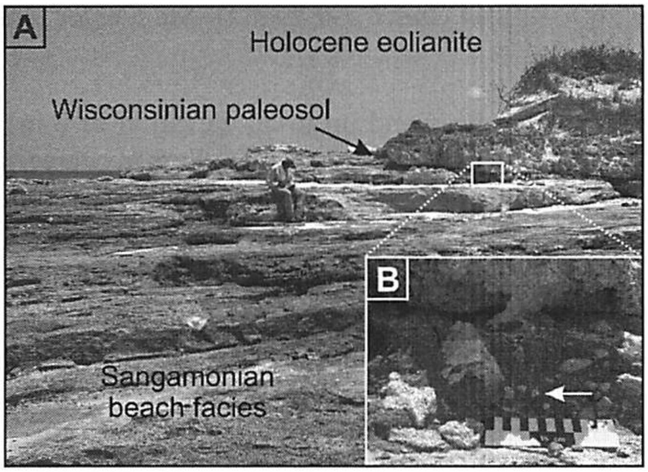

Figure 2. a) general view of the Hatchet Bay section presenting an earlier interpretation of the exposed units; b) close-up view of the middle unit showing its chaotic aspect; white arrow points to a specimen of the terrestrial snail Helix sp. Man is about 1.4 m tall in sitting position.

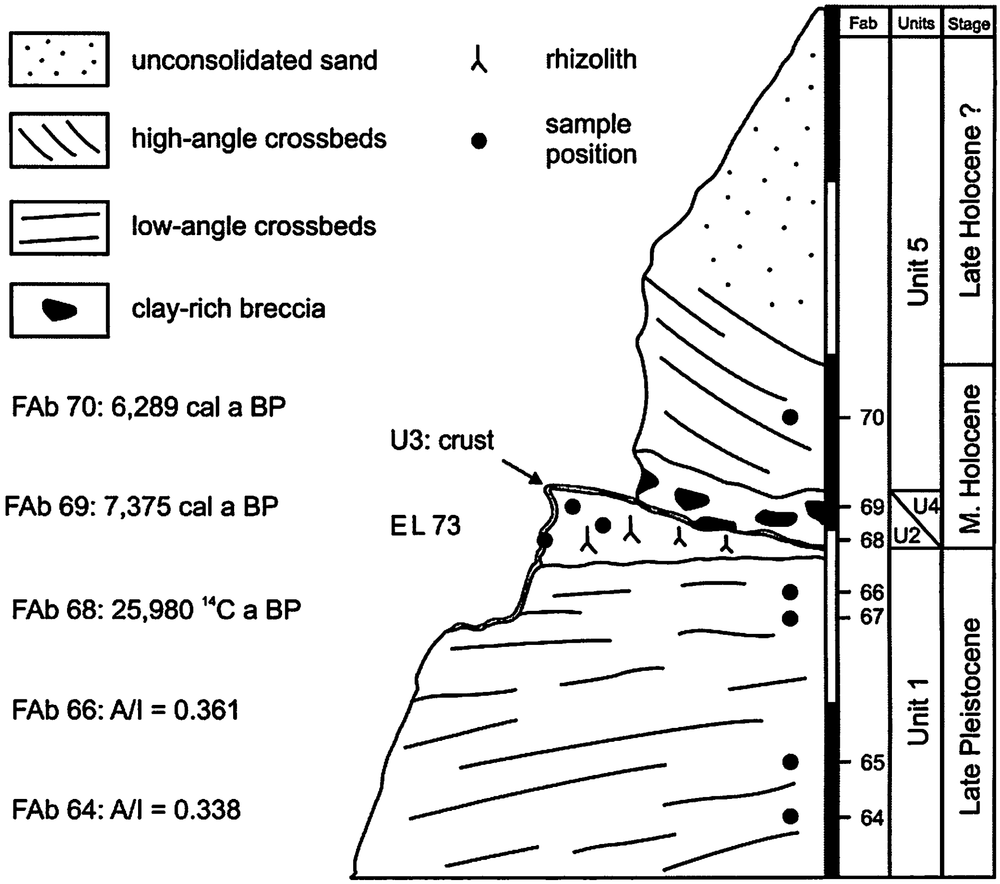

Figure 3. Logged stratigraphic section. Black and white scale bars = 1 m; column Fab = newly collected samples. EL 73 = sample collected by P. Kindler in Unit 2 (see Fig. 5). See text for further sedimentological description.

Hatchet Bay headland up to an elevation of 2 m (Figs. 2a, 3 and 4). It consists of medium to coarse-grained, laminated oolitic/peloidal limestone with bioclasts showing large-scale, low-angle crossbeds with a seaward dip, grading upsection to planar beds (Fig. 2a). Fenestral porosity is common in the upper part of the unit, whereas dm-scale dissolution pits, lined with brown micritic material, are preserved in its lower part. Bioclasts (mostly *Halimeda*, porcellaneous foraminifers, and mollusk fragments) are most abundant in coarse-grained laminae and in the upper part of the unit, whereas ooids and peloids form finer-grained laminae and predominate its lower portion. Cements include an early generation of fibrous rims (not always preserved) and a late generation of equant low-Mg calcite forming menisci at grain contacts and filling small pore spaces. Pedogenic overprint can be observed in some thin-sections in the form of alveolar structure, calcitized root cells, and rhizoliths (Klappa, 1980). The upper surface of Unit 1 is corrugated, showing a ca. 1 m-deep depression on the landward side of the headland (Fig. 2a).

Unit 2 forms one small, dm-thick lenticular body consisting of pedogenized, coarse-grained bioclastic calcarenite that partially covers Unit 1 on the seaward side of the headland (Figs. 3 and 4). This rock unit further displays poorly preserved cross stratification and numerous rhizoliths. Unit 2 is composed of bioclasts (> 80 %), including benthic foraminifers, green and red algae,

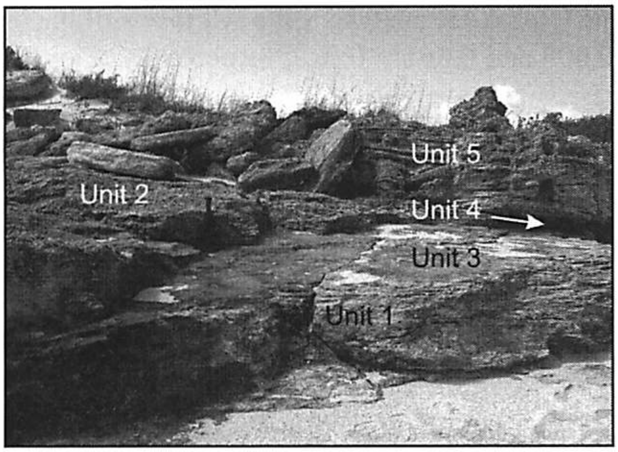

Figure 4. Detailed view of the northern (seaward) side of the Hatchet Bay exposure showing all stratigraphic units. Hammer is 36 cm long.

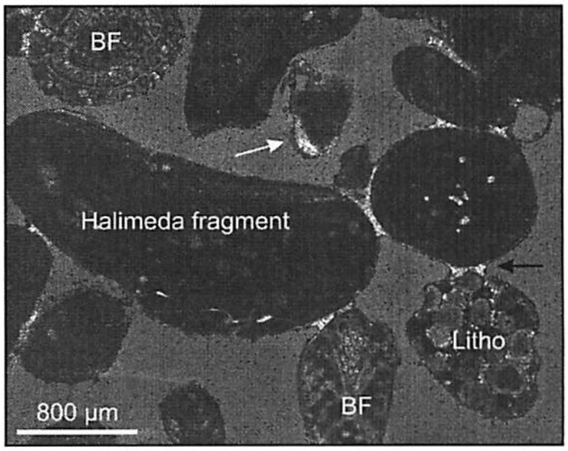

Figure 5. Sample EL 73. Photomicrograph of Unit 2. Note coarse-grained bioclastic fragments, meniscus (black arrow) cements and gravitational (white arrow) cements typical of vadose fresh-water diagenesis, and oolitic lithoclast (Litho) reworked from Unit 1. BF = benthic

mollusk, coral, serpulid and rare echinoid debris, micritized grains, and ~3 % of oolitic grainstone lithoclasts, probably reworked from Unit 1 (Fig. 5). Gravitational, meniscus, and "capillary-fringe" sparry cements bind the grains (Fig. 5). Alveolar structure (Klappa, 1980) and needle-fiber calcite are the most common pedogenic features present in this unit.

Exposed at about +2 m, Unit 3 is represented by a 1 to 5 cm-thick, beige to orange laminated calcitic crust with a smooth undulating upper surface, which caps and penetrates the underlying limestone units (Figs. 3, 4 and 6). Close examination of this crust reveals two microfacies types (Figs. 6b and 7): (1) dark, dense, vaguely laminated micrite, rich in Fe oxides, including rare, small (15 to 50 µm) subspherical structures consisting of radially arranged low-Mg calcite fibers (Figs. 6c and 7), and (2) more porous, beige micrite containing enigmatic amalgamated peloid-like structures that locally display the remnant of a cellular texture (Figs. 6b and 7). These two microfacies form 2 to 4 mm-thick laminae. Type 1 microfacies (dense micrite) predominates in the upper portion of the crust; type 2 microfacies (beige micrite) locally forms small columnar structures (Cs in Fig. 6b), and is more common in its lower part. The lower boundary of the crust is sharp, truncating or moulding the constituent grains of the underlying limestone, none of which has been incorporated or "digested" in the crust. Its upper boundary with the overlying Unit 4 is also sharp.

Unit 4 is a 20 to 40 cm-thick, poorly sorted, matrix-supported breccia layer (Figs. 2b, 3, 4 and 8) that covers all underlying units and is mostly found in the m-scale depression on the backside of the Hatchet Bay headland (Fig. 2a). This conglomeratic layer is characterized by a reddish clay-rich matrix (5 to 20%, chlorite, kaolinite, vermiculite; Nawratil de Bono, 2008), containing also organic matter and white sand grains. Cm to m-scale breccia elements include fragments of limestone derived from Units 1 and 2, calcrete clasts from Unit 3, black pebbles, terrestrial snails (*Helix sp.*, Fig. 2b), blackened plant debris (Fig. 8), and marine shells. The deposit is very chaotic:

clasts and blocks do not show any particular orientation in the matrix. No pedogenic horizon and rhizolith networks have been observed in this unit. About three meters in thickness, Unit 5 is made of fine-grained, *Homotrema*-rich, bioclastic calcarenite. Its basal part is moderately lithified and displays bioturbation (crab burrows) and bioerosion (insect and mollusk borings, Fig. 8) features, as well as meter-scale, high- and low-angle cross-stratification (Fig. 4), whereas its upper portion is unlithified and partly vegetated (Figs. 2a and 4). Thin-section examination of samples collected from the lower portion of Unit 5 reveals a fine-grained, very porous, bioclastic grainstone with some ooids and peloids. Constituents are bound by minor sparry cement forming menisci at grain contacts.

Geochronology

Two whole-rock samples collected from Unit 1 for AAR analysis gave A/I ratios of 0.338 ± 0.009 and 0.361 ± 0.028, respectively (Fig. 3). These values average at 0.349, which is consistent with the data obtained by Nawratil de Bono (2008) from the same unit (0.342 ± 0.001). Whole-rock samples collected from Units 2, 3 and 5 (Fig. 3) yielded conventional ^{14}C ages of 25,980 ± 120 a BP, 6,470 ± 30 a BP and 5,480 ± 30 a BP, respectively. After correction with the Reimer et al. (2004) calibration curve, calendar ages of 7,375 ± 55 a BP and 6'289 ± 26 a BP were obtained for Units 3 and 5, respectively.

DISCUSSION

Ancient depositional settings

Characterized by low-angle, seaward-dipping beds in its lower part, planar beds and widespread fenestral porosity in its upper part, and common early fibrous rim cement, Unit 1 can,

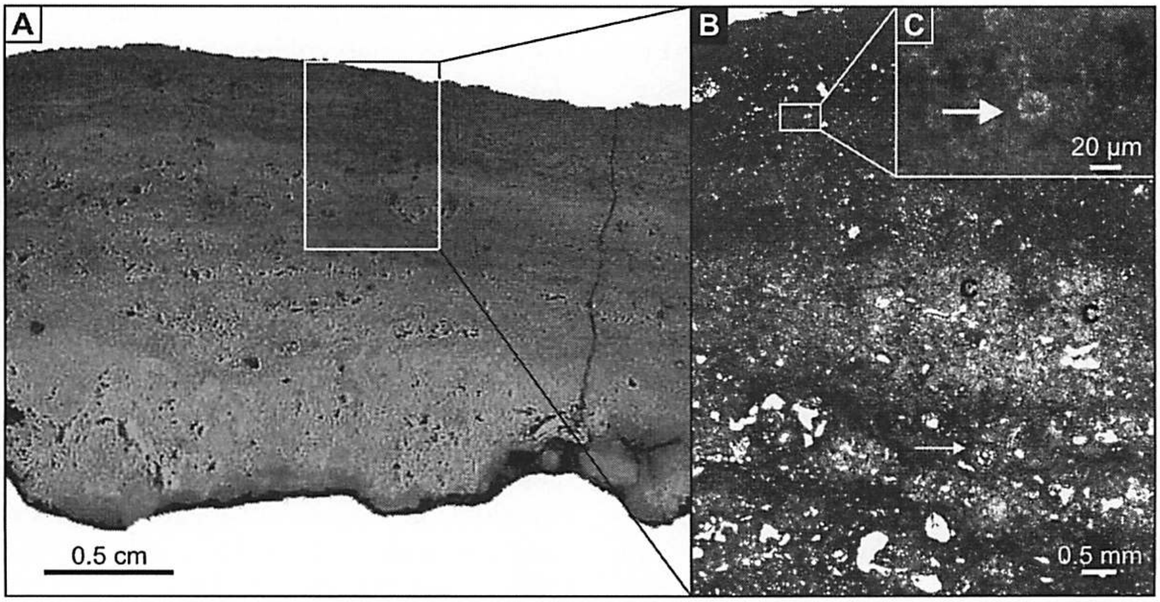

Figure 6. Laminated crust forming Unit 3 at different magnifications: a) slabbed crust sample; note dark dense zone at the top overlying a more porous zone below; b) thin-section view of Fig. 6a showing the two micritic microfacies composing the crust; note dark oxide stains in the dense zone, and columnar aggregates (black Cs) of peloid-shaped structures, interpreted as bryophyte remnants, in the underlying porous layer; thin arrow points to preserved cell structure; c) small subspherical structure (thick arrow) with radially arranged calcite fibers interpreted a spherulite of cynobacterial origin.

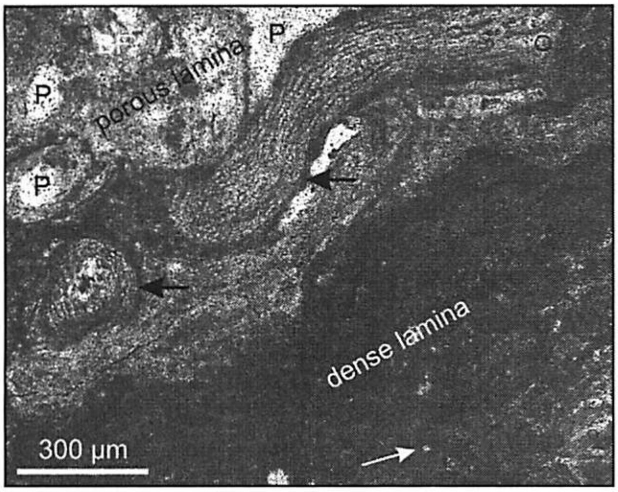

Figure 7 Thin-section view of laminated crust forming Unit 3. Dense undulating micritic lamina with spherulite (white arrow) is visible in the lower right-hand side of the photo, whereas porous lamina (P = pores) including rounded fragments with a cellular texture interpreted as bryophyte remnants (black arrows) can be seen in the upper left-hand corner of the image.

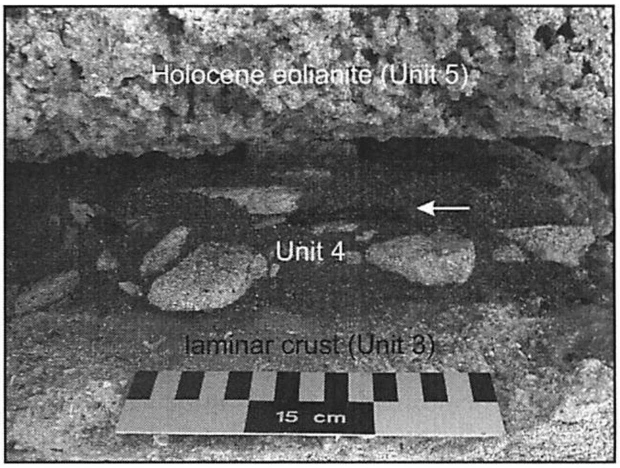

Figure 8 Close-up on Unit 4 conglomerate. Note clay-rich matrix with white sand grains, poor sorting of limestone clasts, carbonized plant fragment (white arrow), and sharp contact with underlying micritic crust. Sponge-like texture of Holocene eolianite corresponds to insect and mollusk borings.

with a fair amount of certainty, be interpreted as a fossil beach, grading upward to a berm.

Unit 2 likely corresponds to an ancient vegetated, incipient dune (protodune), due to the occurrence of numerous rhizoliths, fresh-water vadose cements (Fig. 5), and abundant pedogenic features (Nawratil de Bono, 2008). Despite the lack of a well-defined boundary between Units 1 and 2, the latter is probably not genetically related to the former because it is much coarser-grained and more bioclastic. In addition, Unit 2 contains some oolitic-peloidal lithoclasts likely derived from Unit 1 (Fig. 5), indicating this unit was lithified prior to the deposition of the younger protodune.

Unit 3 can unmistakably be described as a laminated crust or a laminar calcrete. Similar low-Mg calcite crusts are widespread on the top of Pleistocene limestones in the Bahamas (e.g. Kornicker, 1958) and in South Florida (e.g. Multer and Hoffmeister, 1968), and their origin (algal versus pedogenic) has been hotly debated for almost 60 years (e.g. Kornicker, 1958; Multer and Hoffmeister, 1968; Bourrouilh, 1977; Wright, 1989; Nawratil de Bono, 2008). Both microfacies comprising Unit 3 include remnants of biological activity, indicating this unit does not result from physico-chemical carbonate precipitation alone. No clear evidence of pedogenic features (micrite-lined root tubes, alveolar septal structure; Bain and Foos, 1993) has been observed in thin section. The peloidal aggregates with a cellular texture found in the beige micrite (microfacies 2, Figs. 6b and 7) can be interpreted as variously oriented sections of bryophytes (i.e. mosses; Bourrouilh, 1977). The small spherical structures consisting of radially arranged calcite crystals occurring in the dense micrite microfacies (Fig. 6c) likely correspond to spherulites produced by cyanobacterial activity (Verrecchia, 1994; Verrecchia et al., 1995). The occurrence of these biogenic features, the lack of typical pedogenic textures, and the laminated aspect of the crust (Fig. 6a) strongly suggest that Unit 3 corresponds to a fossil algal/microbial mat, and not to a pedogenic calcrete. This mat was certainly formed at the lithosphere/hydrosphere or lithosphere/atmosphere interface, and not at depth in a soil profile, because bryophytes and cyanobacteriae need light for photosynthesis. We observed similar active mats on the shores of Moray Pond near James Point (Eleuthera; Fig. 9).

Its sharp basal contact on multiple substrates, its location in a topographic depression, as well as the lack of horizons and pedogenic textures suggest that the reddish conglomeratic layer forming Unit 4 is a colluvial deposit reworking, in part, older soil material, and not a paleosol per se. The reworked material probably originates from the flanks of the neighbouring Peter Hill (Fig. 2c). Resedimentation of this material could have been caused by large waves related to major storms, by a tsunami (e.g. Kelletat et al., 2004), or by a protracted episode of rainfall.

Finally, meter-scale high-angle cross-bedding, insect borings (Fig. 8), and meteoric vadose cements identify the bioclastic limestone forming Unit 5 as an eolianite.

Age of studied units

Based on the A/I ratios measured from whole-rock samples, Unit 1 is correlated with aminozone E2 (Hearty and Kaufman, 2000, 2009), corresponding to the late part of the last interglacial period (Marine Isotope Stage 5e). Unit 1 can thus be further interpreted as regressive beach and berm sediments deposited at the onset of the late MIS 5e sea-level fall, about 116 ka ago (Muhs, 2002). The conventional ^{14}C age of 25,980 ± 120 a BP obtained from Unit 2 could not be adjusted with the Reimer et al. (2004) calibration curve. This age correlates with the last glacial period, more precisely with the boundary between MIS 3 and MIS 2 (Bassinot et al., 1994), when sea level was about 100 m below the present elevation (Rohling et al., 1998). It is unlikely that marine particles could have been transported from that elevation along the steep slopes of GBB

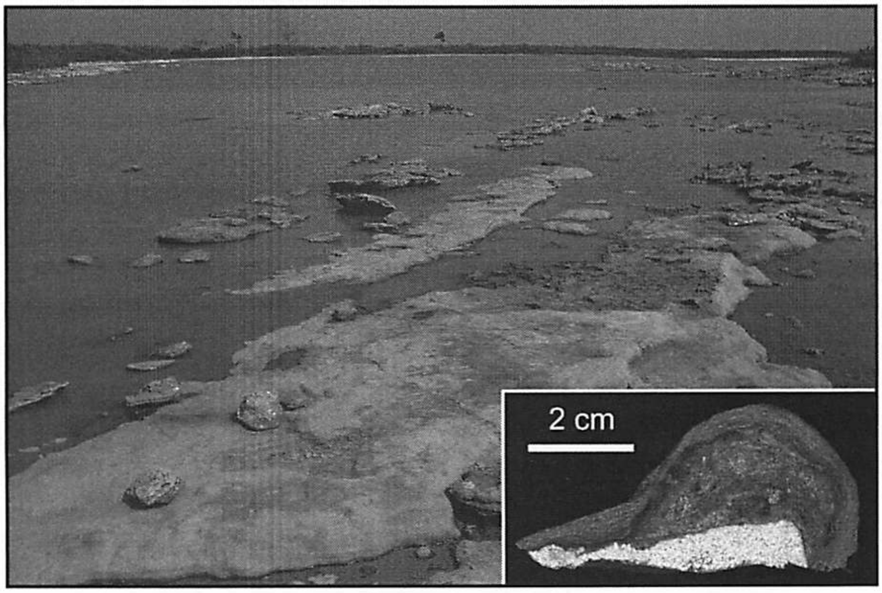

Figure 9 View of Moray Pond, near James Point (Eleuthera). The shores of this pond consist of mat-covered beachrock. Inset: slabbed mat sample showing a porous zone at the base and a dense laminated zone at the top. This zonation is identical to that observed on Unit 3 samples. Note that pond elevation corresponds to modern sea level.

to be deposited on the platform top. Based on its petrography and sedimentological characteristics, Unit 2 is more plausibly correlated with similar deposits of MIS 5a (ca. 80 ka BP) age (Hearty and Kindler, 1993; Kindler and Hearty, 1996). The obtained age probably results from contamination by a small (5%) amount of young carbon (Bowen, 1988). The calendar ages of 7,375 ± 55 a BP and 6,289 ± 26 a BP obtained from Units 3 and 5 are in stratigraphic order and correlate with the middle Holocene. These two values provide constraints on the age of the intervening clay-rich conglomerate (Unit 4), and further confirm our interpretation of this unit as a colluvial deposit, rather than a paleosol, which would have needed much more time than ca. 1,000 yrs to reach such a level of maturity. The age of Unit 3 will be further discussed in the next section. The age of Unit 5 is consistent with the age of the first major accumulation of marine sands on the Bahamian platforms (6,700 – 5,700 cal a BP; Hearty and Kaufman, 2009). In most cases, the early pulse of Holocene sedimentation in the Bahamas is characterized by the abundance of ooids and peloids (Kindler, 1992; 1995; Hearty and Kaufman, 2009). The predominance of bioclasts in Unit 5 suggests favourable conditions for the development of reefs or seagrass meadows in this area at that time.

Significance of paleosols and colluvial deposits in Bahamian stratigraphy

This example from Hatchet Bay demonstrates that reddish conglomerate layers (e.g. Unit 4) interstratified in Bahamian limestones need to be carefully studied to figure out whether they represent a paleosol or a fossil colluvium. This distinction is fundamental because the former results from processes that act on a rocky substrate during a protracted interruption of carbonate sedimentation, usually corresponding to a sea-level lowstand, whereas the latter correspond to a geologically instantaneous event. Paleosols thus have a stratigraphic significance (Carew and Mylroie, 1995a; Kindler and Hearty, 1997; Hearty and Kaufman, 2000) and, providing some caution (Carew and Mylroie, 1991), can be used to reconstruct late Quaternary sea-level and climate fluctuations in the Bahamas. This is not the case of colluvial deposits which may be formed at any time. Paleosols usually present the following characteristics: (1) the boundary with the underlying carbonate unit, which is commonly disturbed by roots, is gradual; (2) included clasts are usually angular and have the same composition as the underlying parent rock; (3) a vertical zonation and pedogenic horizons are commonly observed; and (4) the lateral extent of a paleosol is generally wide. In contrast, colluvium deposits can be identified by (1) a sharp, locally erosive, lower boundary; (2) included particles of various sizes and nature, and not necessarily related to the underlying rock unit; (3) the lack of pedogenic horizons or vertical zonation; and (4) a localized extent.

Implications regarding the Holocene sea-level history

The biogenic laminar crust (Unit 3) exposed at Hatchet Bay shows that, contrary to common thinking (Boardman et al., 1995; Carew and Mylroie, 1995a; Kindler and Hearty, 1995), all laminated calcretes occurring in the stratigraphic record of the Bahamas islands are not necessarily of pedogenic origin. This is important because soil-related crusts always form in a supratidal setting, whereas algal/microbial mats can develop in marine, lacustrine, subtidal, intertidal or supratidal environments. This is demonstrated by a possible modern equivalent of the Hatchet Bay crust at Moray Pond (Fig. 9), which occurs within one meter of present-day sea level. From this observation, we infer that the studied fossil algal/microbial mat could be a further indicator of a higher than present sea level during the middle Holocene, thus corroborating earlier reports by White and Curran (1993) from Lee Stocking Island and by Bourrouilh-Le Jan (2007) from western Andros.

The (single) age measured from the Hatchet Bay crust (7,375 ± 55 a BP) is slightly older than the age inferred for the (disputed) sea-level highstand along the US Gulf Coast (6.8 to 4.8 ka BP; Blum et al., 2001), but it could have been slightly biased by a hard-water effect (Worsley, 1990), especially if the crust was formed in a lacustrine setting. By contrast the elevation of the Hatchet Bay crust (ca. + 2 m) is consistent with the elevation of the middle Holocene highstand identified by Blum et al. (2001) along the coast of Central Texas.

CONCLUSIONS

The reddish layer exposed at the Hatchet Bay section, long considered as representing a typical paleosol of last glacial age between Sangamonian and Holocene calcarenite deposits, actually consists of a laminated crust of biogenic (algal and/or microbial) origin at the base and a reddish conglomeratic colluvial deposit with a clay-rich matrix at the top.

The colluvial deposit likely results from the resedimentation of an ancient paleosol during a high-energy event (storm or tsunami wave, or major rainfall episode) between 7.4 and 6.3 cal ka ago. This case further demonstrates that all reddish layers interstratified in Bahamian calcarenite units do not necessarily represent protracted intervals of subaerial exposures corresponding to sea-level lowstands.

The biogenic nature of the studied crust shows that laminated calcretes occurring in the Bahamas – South Florida region (and elsewhere) may not all have a pedogenic origin. In addition, this particular example, which is very similar to algal/microbial mats forming along the shores of ponds and lakes in the Bahamas today, could indicate that sea-level was about 2 m higher than present during the middle Holocene.

ACKNOWLEDGMENTS

We would like to thank F. Gischig and P. Desjacques (University of Geneva) for their technical help, the Swiss National Science Foundation for supporting this research (grant n° 200020-113356), and the staff of the Gerace Research Centre for logistical support and their friendly welcome. All the people who worked with us at the HB section (C. Nawratil de Bono, I. Cojan, C. Kurth, T. Michaud, F. Prognon, M. Brentini, G. Viret, and P.J. Hearty) are acknowledged for their contributions. Sample preparation, ^{14}C dating, and sample age calibration was performed at the Physics Institute of the University of Bern (Switzerland). Last, but not least, we thank D.S. Kaufman, Northern Arizona University, for providing amino-acid racemization data at a collaborative price, and J. Bright for analyzing the samples.

REFERENCES

Aalto, K.R., and Dill, R.F., 1996, Late Pleistocene stratigraphy of a carbonate platform margin, Exumas, Bahamas: Sedimentary Geology, v. 103, p. 129-143.

Bain, R.J., and Foos, A.M., 1993, Carbonate microfabrics related to subaerial exposure and paleosol formation, in Rezak, R., and Lavoie, D.L., eds, Carbonate Microfabrics: Springer, New York, p. 19-27.

Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackleton, N.J., and Lancelot, Y., 1994, The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal: Earth and Planetary Science Letters, v. 126, p. 91-108.

Beach, D.K., and Ginsburg, R.N., 1980, Facies succession of Pliocene-Pleistocene carbonates, Northwestern Great Bahama Bank:

American Association of Petroleum Geologists Bulletin, v. 64, p. 1634-1642.

Blum, M.D., Misner, T.J., Collins, E.S., Scott, D.B., Morton, R.A., and Aslan, A., 2001, Middle Holocene sea-level rise and highstand at +2 m, central Texas coast: Journal of Sedimentary Research, v. 71, p. 581-588.

Boardman, M.R., McCartney, R.F., and Eaton, M.R., 1995, Bahamian paleosols: origin, relation to paleoclimate, and stratigraphic significance, in Curran, H.A. and White, B., eds, Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300, p. 33-49.

Bourrouilh, F., 1977, Les particules du Pléistocène Bahamien et de sa croûte: sédimentologie et diagenèse: Sedimentary Geology, v. 17, p. 247-284.

Bourrouilh-Le Jan, F., 2007, Very high energy sedimentation (supratidal hurricane deposits) and Mid-Holocene highstand on carbonate platforms, Andros, Bahamas: an alternative view: Sedimentary Geology, v. 199, p. 29-49.

Bowen, D.Q., 1988, Quaternary Geology. A stratigraphic framework for multidisciplinary work: Pergamon Press, Oxford, England, 237 p.

Carew, J.L., and Mylroie, J.E., 1985, The Pleistocene and Holocene stratigraphy of San Salvador Island, Bahamas, with reference to marine and terrestrial lithofacies at French Bay, in Curran, H.A., ed., Pleistocene and Holocene carbonate environments on San Salvador Island, Bahamas: Geological Society of America, Annual meeting guidebook, Ft. Lauderdale, FL, CCFL Bahamian Field Station, p. 11-61.

Carew, J.L., and Mylroie, J.E., 1991, Some pitfalls in paleosol interpretation in carbonate sequences: Carbonates and Evaporites, v. 6, p. 69-74.

Carew, J.L., and Mylroie, J.E., 1995a, Depositional Model and Stratigraphy for the Quaternary Geology of the Bahamas Islands, in Curran, H.A. and White, B., eds, Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300, p.58-32.

Carew, J.L., and Mylroie, J.E., 1995b, Quaternary tectonic stability of the Bahamian archipelago: evidence from fossil coral reefs and flank margin caves: Quaternary Science Reviews, v. 14, p. 145-153.

Carew, J.L., and Mylroie, J.E., 1997, Geology of The Bahamas, in Vacher, H.L. and Quinn, T.M., eds, Geology and hydrogeology of carbonate islands: Developments in Sedimentology, v. 54, Elsevier, Amsterdam, p. 91-139.

Ersek, V., 2004, Analyses of common elements and oxides in the paleosols of the Bahamas and of the Northern Mariana islands, unpublished M.S. thesis: Mississippi State University, 110 pp.

Foos, A.M., and Bain, R.J., 1995, Mineralogy, chemistry, and petrography of soils, surface crusts, and soil stones, San Salvador and Eleuthera, Bahamas, in Curran, H.A. and White, B., eds, Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300, p. 223-232.

Froede, C.R. Jr., 2002, Rhizolith evidence in support of a late Holocene sea-level highstand at least 0.5 m higher than present at Key Biscayne, Florida: Geology, v. 30, p. 203-206.

Garrett, P., and Gould, S.J., 1984, Geology of New Providence Island, Bahamas: Geological Society of America Bulletin, v. 95, p. 209-220.

Hattin, D.E., and Warren, V.L., 1989, Stratigraphic analysis of a fossil Neogoniolithon-capped patch reef and associated facies, San Salvador, Bahamas: Coral Reefs, v. 8, p. 19-30.

Hearty, P.J., 1998, The geology of Eleuthera island, Bahamas: a rosetta stone of Quaternary stratigraphy and sea-level history: Quaternary Science Reviews, v. 17, p. 333-355.

Hearty, P.J., and Kaufman, D.S., 2000, Whole-rock aminostratigraphy and Quaternary sea-level history of the Bahamas: Quaternary Research, v. 54, p. 163-173.

Hearty, P.J., and Kaufman, D.S., 2009, A Cerion-based chronostratigraphy and age model from the central Bahama Islands: amino acid racemization and 14C in land snails and sediments: Quaternary Geochronology, v. 4, p. 148-159.

Hearty, P.J., and Kindler, P., 1993, New perspectives on Bahamian geology: San Salvador Island, Bahamas: Journal of Coastal Research, v. 9, p. 577-594.

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

Kelletat, D., Scheffers, A., and Scheffers, S., 2004, Holocene tsunami deposits on the Bahaman Islands of Long Island and Eleuthera: Zeitschrift für Geomorphologie, N.F., v. 48, p. 519-540.

Kindler, P., 1992, Coastal response to the Holocene transgression in the Bahamas: episodic sedimentation versus continuous sea-level rise: Sedimentary Geology, v. 80, p. 319-329.

Kindler, P., 1995, New data on the Holocene stratigraphy of Lee Stocking Island (Bahamas) and its relation to sea-level history, in Curran, H.A. and White, B., eds, Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300, p. 105-116.

Kindler, P., Curran, H.A., Marty, D., and Samankassou, E., 2008, Multiple sedimentary sequences, bird tracks and lagoon beaches in last interglacial oolites, Boiling Hole, North Eleuthera, Bahamas, in Park, L. and Freile, B., eds, Proceedings of the 13th Symposium on the Geology of the Bahamas and other carbonate regions, Gerace Research Centre, San Salvador, Bahamas, p. 169-181.

Kindler, P., and Hearty, P.J., 1995, Pre-Sangamonian eolianites in the Bahamas? New evidence from Eleuthera Island: Marine Geology, v. 127, p. 73-86.

Kindler, P., and Hearty, P.J., 1996, Carbonate petrography as an indicator of climate and sea-level changes: new data from Bahamian Quaternary units: Sedimentology, v. 43, p. 381-399.

Kindler, P., and Hearty, P.J., 1997, Geology of The Bahamas: architecture of Bahamian Islands, in Vacher, H.L. and Quinn, T.M., eds, Geology and hydrogeology of carbonate islands: Developments in Sedimentology, v. 54, Elsevier, Amsterdam, p. 141-160.

Klappa, C.F., 1980, Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance: Sedimentology, v. 27, p. 613-629.

Kornicker, L.S., 1958, Bahamian limestone crusts: Gulf Coast Association of Geological Societies Transactions, v. VIII, p. 167-170.

Lighty, R.G., Macintyre, I.G., and Stuckenrath, R., 1982, Acropora Palmata reef framework: a reliable indicator of sea level in the Western Atlantic for the past 10,000 years: Coral Reefs, v. 1, p. 125-130.

Lynts, G.W., 1970, Conceptual model of the Bahamian platform for the last 135 million years: Nature, v. 225, p. 1226-1228.

Masaferro, J.L., Poblet, J., Bulnes, M., Eberli, G.P., Dixon, T.H., and McClay, K., 1999, Palaeogene-Neogene/present day(?) growth folding in the Bahamian foreland of the Cuban fold and thrust belt: Journal of the Geological Society, London, v. 156, p. 617-631.

Meischner, D., Vollbrecht, R., and Wehmeyer, D., 1995, Pleistocene sea-level yo-yo recorded in stacked beaches, Bermuda south shore, in Curran, H.A. and White, B., eds, Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper, n° 300, p. 295-309.

McCartney, R.F., 1987, Origin and diagenesis of paleosols in the Bahamas, unpublished M.S. Thesis: Miami University, Oxford, Ohio, 88 pp.

Michaud, T., 1999, Géologie, stratigraphie et étude physico-chimique des paléosols de la région de North-Eleuthera (Bahamas), unpublished M.S. thesis: University of Geneva, 91 pp.

Muhs, D.R., 2002, Evidence for the timing and duration of the last interglacial period from high-precision uranium-series ages of corals on tectonically stable coastlines: Quaternary Research, v. 58, p. 36-40.

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

Multer, H.G., and Hoffmeister, J.E., 1968, Subaerial laminated crusts of the Florida Keys: Geological Society of America Bulletin, v. 79, p. 183-192.

Nawratil de Bono, C., 2008, Pétrographie, micromorphologie et minéralogie des paleosols pléistocènes d'Eleuthera, Bahamas: enseignements paléoclimatiques, stratigraphiques et sédimentologiques: Terre & Environnement, v. 75, 26 pp. + CD-Rom.

Neumann, A.C., and Hearty, P.J., 1996, Rapid sea-level changes at the close of the last interglacial (substage 5e) recorded in Bahamian island geology: Geology, v. 24, p. 775-778.

Pindell, J.L., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and proto-Caribbean: Tectonics, v. 4, p. 1-39.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, RL, Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, B.C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., and Weyhenmeyer, C.E., 2004, INTCAL04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP: Radiocarbon, v. 46, p.1029-1058.

Rohling, E.J., Fenton, M., Jorissen, F.J., Bertrand, P., Ganssen, G., and Caulet, J.P., 1998, Magnitudes of sea-level lowstands of the past 500,000 years: Nature, v. 394, p. 162-165.

Rossinsky, V., Jr., Wanless, H.R., and Swart, P.K., 1992, Penetrative calcretes and their stratigraphic implications: Geology, v. 20. p. 331-334.

Sheridan, R.E., Mullins, H.T., Austin, J.A. Jr., Ball, M.M., and Ladd, J.W., 1988, Geology and geophysics of the Bahamas, in Sheridan, R.E., and Grow, J.A., eds., The Geology of North America, vol. I-2, The Atlantic Continental Margin: U.S. Geological Society of America, p. 329-364.

Strasser, A., and Strohmenger, C., 1997, Early diagenesis in Pleistocene coral reefs, southern Sinai, Egypt: response to tectonics, sea-level and climate: Sedimentology, v. 44, p. 537-558.

Toscano, M.A., and Macintyre, I.G., 2003, Corrected western Atlantic sea-level curve for the last 11'000 years based on calibrated 14C dates from Acropora palmata framework and intertidal mangrove peat: Coral Reefs, v. 22, p. 257-270.

Verrecchia, E.P., 1994, L'origine biologique et superficielle des croûtes zonaires: Bulletin de la Société Géologique de France, t. 165, n° 6, p. 583-592.

Verrecchia, E.P., Freytet, P., Verrecchia, K.E., and Dumont, J.L., 1995, Spherulites in calcrete laminar crusts: biogenic CaCO3 precipitation as a major contributor to crust formation: Journal of Sedimentary Research, v. A65, p. 690-700.

White, B., and Curran, H.A., 1993, Sedimentology and ichnology of Holocene dune and backshore deposits, Lee Stocking Island, Bahamas, in White, B., ed., Proceedings of the Sixth symposium on the Geology of the Bahamas, Bahamian Field Station, San Salvador, p. 181-191.

White, B., Curran, H.A., and Wilson, M.A., 2001, A sea-level lowstand (Devils' Point Event) recorded in Bahamian reefs: comparison with other last interglacial climate proxies, in Greenstein, B.J. and Carney, C.K., Proceedings of the Tenth Symposium on the Geology of the Bahamas and other carbonate regions, Gerace Research Centre, San Salvador, Bahamas, p. 109-128.

Worsley, P., 1990, Radiocarbon dating: principles, application and sample collection, in Goudie, A., Anderson, M., Burt, T., Lewin, J., Richards, K., Whalley, B., and Worsley, P., eds, Geomorphological Techniques, Unwin Hyman, London, p. 383-393.

Wright, V.P., 1989, Terrestrial stromatolites and laminar calcretes: a review: Sedimentary Geology, v. 65, p. 1-13.