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## PRESERVATION OF TRACE FOSSILS AND MOLDS OF TERRESTRIAL BIOTA BY INTENSE STORMS IN MID–LAST INTERGLACIAL (MIS 5c) DUNES ON BERMUDA, WITH A MODEL FOR DEVELOPMENT OF HYDROLOGICAL CONDUITS

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### ABSTRACT

We document massive deposition of carbonate sands along the south shore of Bermuda that were emplaced during one or two great storms during the last interglacial. As determined by their stratigraphic position and geochronological data, these deposits formed during marine isotope substage (MIS) 5c ca. 100 ka ago. Within a leeward set of eolian beds, evidence of a living landscape was preserved that includes delicate footprints of a shorebird (*Scolopacidae*, *Catoptrophorus*) preserved in frothy dune forest beds. In the same stratigraphic unit, outlines of a standing forest of palm trees (*Sabal bermudana*), some evidently with fronds in place, were molded in the fine carbonate dune sand. All available evidence points to an MIS 5c sea level positioned several meters below the present datum, which would require great intensity of storms to transport such voluminous deposits well above present sea level. Waves and storm currents transported loose sediments from the shallow shelf onto the shore, where hurricane winds piled up sand sufficiently deep to bury established forests of 8- to 10-m-tall trees. Evidence of such powerful storms preserved in the rock record is a measure of the intensity of past hurricanes, and a possible bellwether of future storm events. Entombment of the trees involved rapid burial and cementation creating external molds in limestone, a process that is important in the development of vertical hydrological conduits commonly observed in eolianites.

### INTRODUCTION

In an open ocean setting 1040 km ESE of Cape Hatteras, North Carolina (Fig. 1), the subaerial portion of the Bermuda platform is fully exposed to a variety of storm systems, including westerly trade winds, Western Atlantic storms (so-called nor'easters), and tropical hurricanes. The literature on intense storms during the Quaternary generally centers on overwash of coarse sediments into back-barrier environments during the mid to late Holocene (e.g., Donnelly et al., 2001; Nott, 2004; Stone and Orford, 2004 and papers therein; Mann et al., 2009). The burial of trees in rapidly accreting coastal carbonate dunes (eolianites) may also create long-lasting vertical conduits in limestone. Elsewhere these have been known to develop into highly indurated columns composed of mixed materials; a process we describe in a model.

Bermuda is a relatively small (56 km<sup>2</sup>) oceanic island that preserves an extensive record of interglacial coastal sedimentation, modulated by sea-level changes throughout the Quaternary. The island formations mapped by Vacher et al. (1989) were later correlated with marine isotope stages (MIS) through independent U/Th dating (Harmon et al., 1983; Ludwig et al., 1996) and aminostratigraphic techniques (Hearty et al., 1992, 2004; Hearty and Olson, 2010), with some subsequent minor modifications of the stratigraphic column (Hearty, 2002; Table 1). A litho-, chrono-, and biostratigraphic framework based on limestones

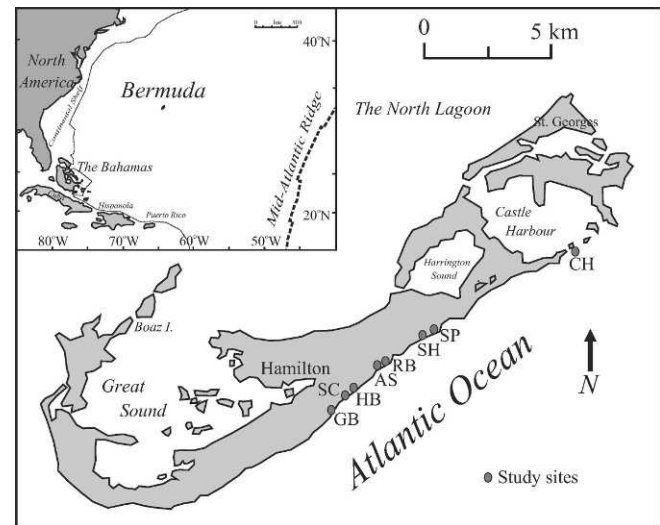


FIGURE 1—Located 1040 km ESE of Cape Hatteras, North Carolina (inset), Bermuda has a current land area of 56 km<sup>2</sup>. Study sites along the South Shore of Bermuda (individual sections in Fig. 3) are as follows: GB = Grape Bay; SC = Southcourt Ave., HB = Hungry Bay, AS = Ariel Sands; RB = Rocky Bay (type section), SH = Saucos Hill, SP = Spittal Pond, and CH = Charles Island.

and fossils (Hearty et al., 1992; Hearty and Olson, 2010) provides a reliable means to correlate and date most of the deposits from the island.

Interglacial highstands are represented in Bermuda by subtidal and intertidal marine facies marking the approximate position of ancient shorelines, and wind-deposited eolianite facies farther inland. Intercalated and oxidized red or orange *terra rossa* soils developed during glacially lowered stands of sea level (Vacher et al., 1995). During pauses in dune accretion, perhaps coinciding with minor sea-level regressions during interglacials, tan to gray protosols (Vacher and Hearty, 1989) formed when plants and animals actively colonized dune surfaces. These interdune intercalations may contain rhizoliths (*sensu* Kraus and Hasiotis, 2006), land snails, invertebrate, and vertebrate fossils.

Bermuda has a rich paleontological record, with hard parts of vertebrates, including birds, reptiles, bats, and numerous terrestrial invertebrates (e.g., land snails and crabs) preserved in a wide variety of sedimentary environments (e.g., eolianite, protosols, foreshore deposits, cave and fissure fills, pond sediments), ranging in age from early to middle Pleistocene to late Holocene (Olson et al., 2005). While both continental and marine birds are known from abundant bones and even fossilized eggs (Olson and Hearty, 2003; Olson et al., 2005), bird trackways have not been previously documented from Bermuda, although plant impressions are noted in the literature (e.g., Verrill, 1902; Livingston, 1944; Vacher and Rowe, 1997).

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TABLE 1—Correlation table of nomenclature associated with the stratigraphy of Bermuda.

Vacher et al. (1989); Hearty et al. (1992)	Hearty (2002); Hearty and Olson (2010) [sedimentary facies]	Hearty et al. (2004)	(MIS) correlation
Recent	Recent	Unit uv to z Admiral's Cave	1–4
Southampton Fm.	Southampton Fm. [eolianite and multiple protosols]	Unit u; Wilkinson Q High fissure	5a
	Hungry Bay Fm. (former Pembroke dune) [eolianite, protosol, plant body fossils, and bird tracks]		5c
	Harrington soil [weak reddened paleosol]		5e/5c
Pembroke dune	Devonshire marine (max. + 6–9 m), including Spencer's Pt. [foreshore, eolianite, multiple protosols] Rocky Bay Formation	Unit s/t	Late 5e
Harrington soil	Mid-5e regression [protosol]	Unit r/s	Middle 5e
Devonshire marine or dune	Grape Bay Mb (former Belmont marine (+2.5 m) of Rocky Bay Formation) [marine, eolianite, "palmetto stumps" in upper levels]	Unit p/q/r	Early 5e
Shore Hills Geosol	Red geosol (?) [complex paleosol]	Unit o/~p Crane fauna	Late 6 to early 5e
Belmont marine and dune (+2.5 m)	Harvey Rd Q [eolianite]		7 (now 5e)
Ord Rd. Geosol	Ord Rd. Geosol [complex paleosol]	Middle Pleistocene	8
U. Town Hill	Upper Town Hill [eolianite with multiple protosols]		9
Paleosol	Harbour Road Geosol [red to orange paleosol]		10
L. Town Hill	Lower Town Hill [foreshore, eolianite, multiple protosols]		11
Big Red soil (BRS): Castle Harbour geosol [deep red, thick, clayey paleosol in solution pipes in Walsingham eolianite]			12–26?
Walsingham Fm.	Walsingham Fm. [eolianite with multiple protosols]	Early Pleistocene	27/35?

Dune accretion and island growth occurred asymmetrically on the Bermuda platform (Fig. 1). As the broad North Lagoon effectively de-energizes wave intensity along the north shore, significant sediment flux and shoreline deposition from the north occurred only during shifts to significantly higher-than-present sea levels, before accommodation could be filled, such as during late MIS 5e and 11 (Hearty et al., 1999, 2007; Olson and Hearty, 2009). Furthermore, prevailing winds and the source of the strongest storms are mainly from the southern quadrants. Hence, cumulative land accretion, mostly through dune deposition, has been greater on the stormy and higher energy southern exposure, accounting for the present-day asymmetrical orientation of the Bermuda islands (56 km<sup>2</sup>) on the 650 km<sup>2</sup> platform (Fig. 1).

#### Importance of Storms in Preservation of Trace Fossils and External Molds

On Bermuda, storm events have clearly played an important role in the formation and preservation of trace fossils and the impressions of plants through rapid and voluminous sedimentation, as opposed to slowly accreting dunes that would be constantly bioturbated by plants and animals that largely destroy primary eolian physical sedimentary structures (bedding), along with any traces of organisms that may have been present. Such heavily bioturbated sands are common as protosols within eolianites. On the other hand, exceptional circumstances are necessary to preserve continuous sets of foresets in 3-dimensional dune architecture. Conditions must prevail under which deposition is too rapid to allow reworking and destruction of dune bedding by physical processes or bioturbation. We, therefore, view extensive, uninterrupted sets of foreset bedding as an indication, not of decadal-type hurricanes, but extreme events that might occur only a few times during an interglacial period.

In Bermuda, several authors interpreted sediment- or soil-filled pipes as fossilized palmetto stumps (Verrill, 1902; Livingston, 1944; Vacher and Rowe, 1997), although Herwitz (1993) and Herwitz and Muhs (1995) reinterpreted these as being attributable to stemflow driven, top-down limestone dissolution that formed vertical conduits. Below, we revive the original bottom-up interpretation of palmetto stumps as the external molds of tree trunks (Hearty, 2002) that were later filled with a mixture of sediment types. Curran and White (2001) and Curran et al. (2008) investigated the extent of terrestrial trace and body fossils on

several islands in the Bahamas, while Kindler et al. (2008) described bird trackways in Eleuthera.

Additional evidence in the Bahamas for great storms and rising seas at the end of MIS 5e comes from vast chevron ridges over flatlands of several islands in which extensive oolitic sands entombed palmettos and standing trees (Neumann and Hearty, 1996). Also, late in MIS 5e, waves catapulted giant boulders onto present 20-m-high ridges on open-ocean coasts (Hearty, 1997). Although deposition by tsunami cannot be excluded, Hearty and Neumann (2001), based primarily on the internal structure of the chevron ridges, suggested that storm waves were the most likely process concurrently depositing both the boulders and chevron ridges. Some authors contend that the boulders, now at the crest of a complex middle and late Pleistocene eolianite ridge (Hearty, 1997), rolled down from an easterly ridge and came to rest on younger units, or alternatively, that the boulders are tower karst, peaks of limestone left as relicts from deep karst erosion of a higher eolianite ridge (Mylroie, 2008, p. 71 and 73, and his fig. 13). There is no evidence, however, of a hypothetical elevated landscape to cause such rolling, or from which the karst towers could have been fashioned. Furthermore, old and high rocks as hypothesized would not fit stratigraphically or diagenetically into the geologic context of the site. Primary dune morphology is preserved even in the oldest (MIS 11) of the eolianite deposits (Hearty, 1998; Hearty et al., 1999) and there is no evidence of deep surficial karst erosion in the area.

#### Eolianites in Bermuda

Carbonate eolianites of Bermuda are composed of skeletal fragments of once-living organisms that include marine taxa inhabiting the shallow shelf such as mollusks, corals, foraminifera, calcareous algae, and echinoderms. These fragments are comminuted by various processes and reduced to sand, transported to the shore by currents, and into dunes farther landward by wind. As dunes become inactive and colonized by organisms, induration takes place rapidly over tens to hundreds of years. Massive seas and intense winds episodically deposit sediments well above mean sea level because Bermuda lies in the path of major western Atlantic storms. Consequently, a large proportion of the present-day Bermuda is formed of wind-deposited calcareous dunes. Exposed lee-side foreset bedding and lower-angle eolian bed forms are



**TABLE 2**—Amino acid data from whole-rock (WR) and *Poecilozonites* land snails from Charles Island. See Figure 2 for stratigraphic position and aggregate mean values for associated deposits.

AAL#	Field #	Material	1st run	2nd run	Mean	St. dev.
Unit I (A) and III (B)						
4359 A	OCL-04	WR	0.285	0.275	0.280	0.007
4359 B	OCL-04	WR	0.260	0.271	0.266	0.008
				Mean	0.273	0.009
Unit II						
4588	UCH1b	Land snail	0.398	0.395	0.397	0.002
4589	UCH1b	Land snail	0.466	0.464	0.465	0.001
4590	UCH1b	Land snail	0.486	0.482	0.484	0.003
4591	UCH1b	Land snail	0.390	0.389	0.390	0.001
4592	UCH1b	Land snail	0.479	0.490	0.490	0.008
				Mean	0.445	0.048

AAL# = Amino Acid Laboratory number at Northern Arizona University (D. Kaufman, Director); Field # = field number; St. dev. = 1 standard deviation (1 $\sigma$ ).

of the HBF deposits (Fig. 2; Table 2) correlate with *Poecilozonites* from the Southampton Formation ( $0.40 \pm 0.04$  (N = 36) (Hearty et al., 1992), which, along with marine facies, are correlated with MIS 5a (Vacher and Hearty, 1989; Ludwig et al., 1996; Dorale et al., 2010). The Harrington Member postdates MIS 5e (120 ka) and is correlated with a sea level regression during late MIS 5e, 5d and perhaps into MIS 5c (Hearty, 2002). Thus, the preferred correlation of the HBF, including the former Pembroke Member and Charles Island deposits, is with MIS 5c around 100 ka ago, based on stratigraphy and AAR values.

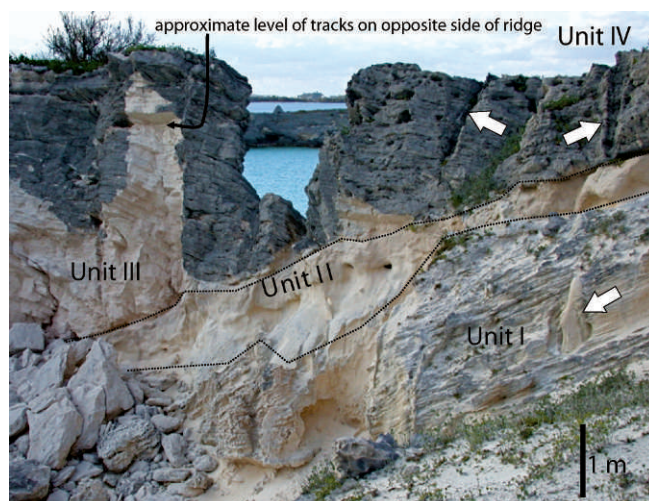
The extension of foreset bedding below the present datum and absence of any washover or stillstand marine facies above the Harrington soil (until late Southampton time) indicates a sea level somewhat lower than the present one at the time of deposition of both Units I and III of the HBF. Sea level was well above the platform margin, however, as platform flooding is required for substantial bioclastic sediment formation and subsequent transport to the shore ( $\sim -20$  m). These observations are supported by previous studies on Bermuda that identified a sea level during MIS 5c at  $\sim -10$  to  $-15$  m (Vollbrecht, 1990; Hearty, 2002).

We maintain that all the trace fossil- and mold-bearing deposits we describe in Bermuda are the result of powerful and sustained storms (see also Olson and Hearty, 2009). This view is based on the volume and lack of complexity of the eolian deposits, the sedimentary conditions of burial, and exquisite preservation of delicate footprints of birds.

Such a massive sediment flux indicates powerful and prolonged storms accompanied by a large and constant supply of available sediment, probably late in the highstand cycle. Extreme storm conditions blur the interface between air, sea, and sand and result in deposition of wet, air-filled sediment, cascading over the crest and into the lee of coastal dunes. In this case, we describe extreme storm deposits from Bermuda characterized by extensive, uninterrupted sets of slumping eolian foresets composed of poorly sorted and high-porosity sediment that rapidly buried terrigenous landscapes.

#### Trace Fossils and External Molds Preserved by Intense Storms During MIS 5

**Description of Bird Tracks.**—A trackway was preserved on the bedding planes of a huge tilted slab ( $23^{\circ}$ – $27^{\circ}$ ) of indurated calcarenite that was detached from the outcrop on Charles Island (CH on Fig. 1) during the high seas generated by Hurricane Fabian on 5 September 2003. Four stratigraphic units are exposed (Fig. 4): two thick eolianites, each capped by weak soils, numbered I–IV from base to top of the section. The trackway occurs midway in a lenticular eolianite of Unit III (thin arrow Fig. 4) that varies laterally in thickness between 2 and 7 m.



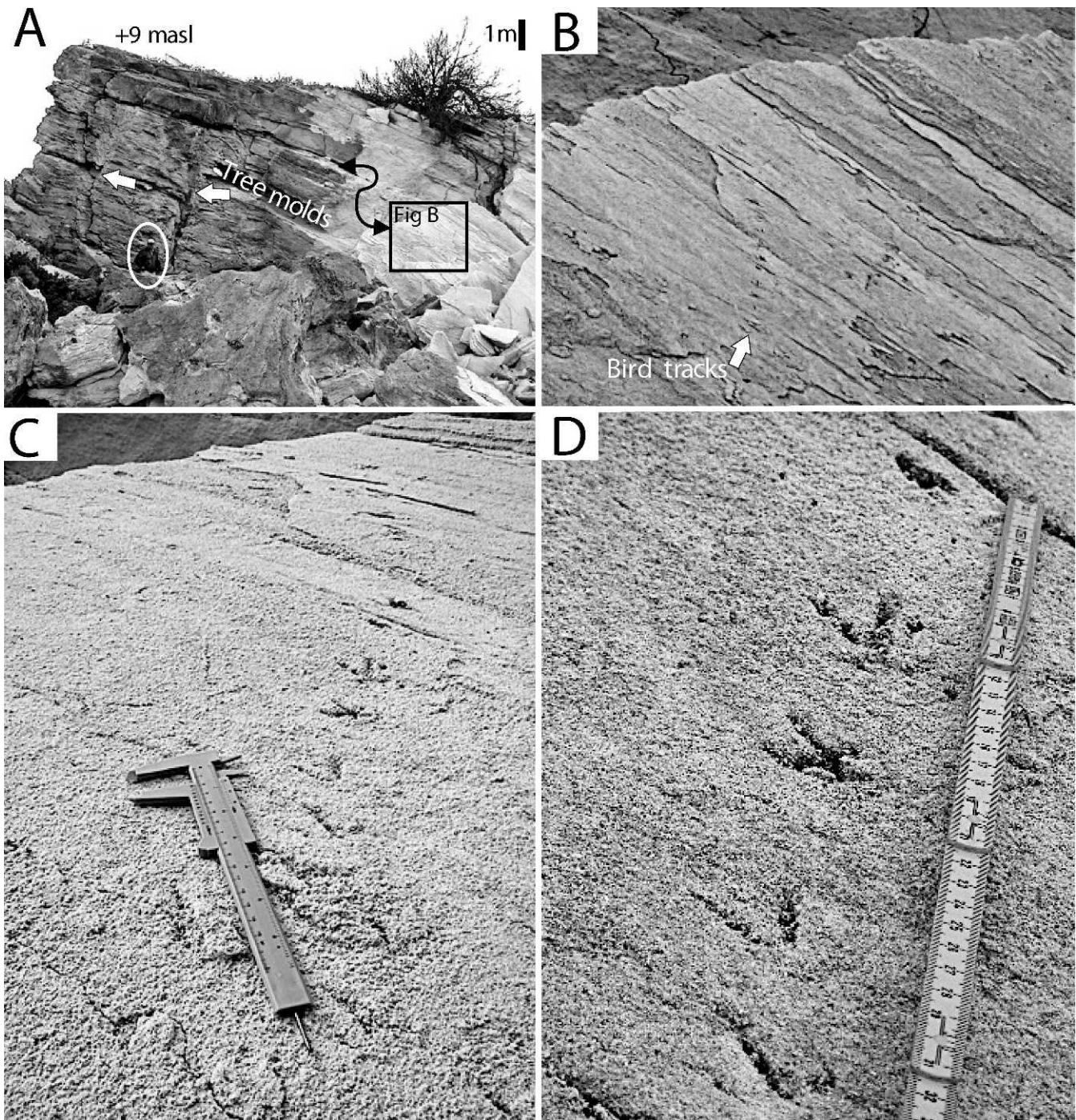
**FIGURE 4**—Landward (northward) view of south side of Charles Island showing stratigraphy and major units. Approximate stratigraphic level of bird trackways indicated by thin black arrow. Possible casts of standing trees identified by larger arrows.

In its present position, the tabular bed imprinted with the trackway is nearly vertical, but when in place would have been inclined at  $\sim 25^{\circ}$  in foreset dune beds near the top of the exposure. The surface is that upon which the bird actually walked, not a counterslab. Olson visited the locality on 30 April 2004 and took photos, notes, and measurements. Olson and Hearty returned to the site on 21 February 2005 and made further observations and photographs and collected additional samples for dating. Unfortunately, due to the unstable and precarious position of the fallen block, images of the trackway from a vertical perspective could not be obtained.

The trackway consists of 7 or 8 visible 3-toed footprints, obviously avian, extending  $\sim 0.5$  m in a relatively straight line (Fig. 5). There was no imprint of the hallux (hind toe) or the metatarsal pad and lengths of the toes were extrapolated from the estimated point of convergence of the three toes. The stride—distance between tracks made by the same foot—is  $\sim 14$  cm, making the step (distance between tracks made by alternate feet)  $\sim 7$  cm. The length of the middle toe (and thus the total length of the track) was 33.5 mm and the lateral toes  $\sim 29$  mm. The widths of the tracks were  $\sim 40$  mm. Some prints preserved faint impressions of the edge of a web between the toes. This did not extend to the tips of toes, however, indicating a semipalmate condition of the foot. Other possible footprints of the same size are on the same surface as the trackway, but these are so obscure that absent the distinct set of tracks, their possible identity as footprints would probably have gone unrecognized.

**Interpretation of the Bird Tracks.**—The size and spacing of the footprints indicate a medium-large wading or shore bird. The semipalmate webbing is a highly diagnostic trait. Such birds as gulls would be fully webbed, whereas herons, ibises, and such large shorebirds as godwits (*Limosa*) and curlews (*Numenius*) would show little to no webbing (Ray, 1678). The willet (*Catoptrophorus semipalmatus*), among the larger species of North American shorebirds, as its specific name implies, has the toes only partly webbed (Coues, 1903, p. 137, fig. 49), very much as in the Bermuda trackway.

The size and spacing of the tracks are close to what would be expected for a willet. Length measurements (mm) of the toes of four fluid-preserved specimens were as follows: digit III 37–39 (10%–16% larger than tracks); digit II 30–32 (0.3%–10% larger); digit IV 31–35 (10%–20% larger). The discrepancy with the tracks could arise from imprecision in knowing from where to measure at the posterior end of the toe in the museum specimens (i.e., which part of the foot actually touches the sediment surface) and also from possible shrinkage of the



**FIGURE 5**—Montage of trackway views in Hungry Bay Formation at Charles Island, Bermuda, St. Georges Parish, south side (mouth) of Castle Harbour located at  $32^{\circ} 20.312' N$ ;  $64^{\circ} 40.306' W$ . A) exposure on north side of Charles Island showing eolianite slab with the bird trackways. Oval indicates standing person partially hidden by rock. Thin black arrow in A indicates approximate stratigraphic level of the slab before collapse. Apparent tree molds are indicated by larger arrows. B–D) General and more detailed views of the trackway (2003 photos).

wet sand of the tracks upon drying. The fossil tracks were quite similar in overall preservation—imprints of three anterior toes but no hallux or metatarsal pad—to those shown by Elbroch and Marks (1999, p. 126) for a willet walking in mud.

In walking birds, the femur is held horizontally and is essentially fixed, so that forward movement involves swinging at the knee joint (Gatesy, 1995), with the length of the stride becoming a function of the length of the tibiotarsus; thus, as S.L. Olson (unpublished data, 1990) has determined from field studies, the length of a step in an avian trackway is roughly equivalent to the length of the bird's tibiotarsus.

Willetts vary in size geographically (western birds are larger) and sexually (females larger) as well as individually (Lowther et al., 2001). The length (mm) of the tibiotarsus (from the proximal articular surface to the distal condyles) in skeletal specimens of willets was as follows: males 70.1–83.3 (mean 75.5,  $n = 7$ ; females 79.1–87.8 (mean 84.1,  $n = 13$ ). Thus, the length of the step in the Bermuda trackway ( $\sim 70$  mm) would fit reasonably well with a willet, particularly one walking slowly. Elbroch and Marks (1999, p. 126) give somewhat higher values, although they mistakenly use the word stride when the word step, as defined above, was intended.

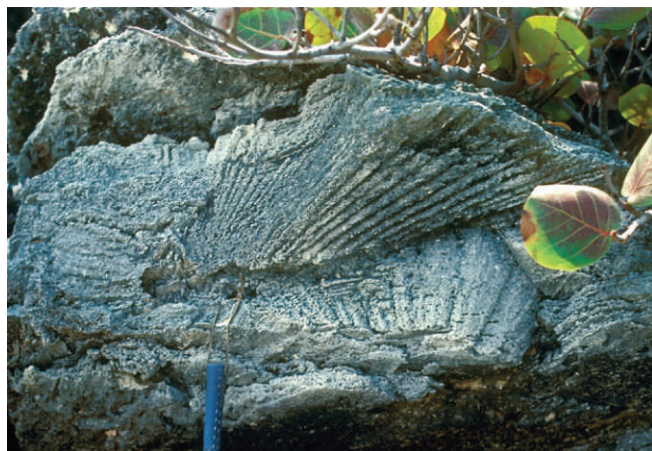


FIGURE 6—Corrugations typical of molds of palmetto fronds at Grape Bay, Bermuda. The hammer handle in the lower left of the photo is 3.5 cm wide.

Willetts occur in Bermuda only as rather uncommon but regular migrants, almost entirely in fall migration with peak abundance from July through September (Amos, 1991), generally coinciding with the early half of the North Atlantic hurricane season. In migration they inhabit beaches and shorelines and could be expected to take refuge from storms by walking to the lee side of beach dunes.

The trackway is preserved in tabular beds composed of medium to fine bioclastic sand of Unit III on foreset bedding dipping to the north at  $\sim 23^{\circ}$ – $27^{\circ}$ , very near the angle of repose (Fig. 5B). The bird trackway traverses the foreset bed, climbing obliquely at an angle equally dividing strike and dip. The beds were clearly wet and of fine sediment texture, as preservation of detailed foot impressions (Figs. 5C–D) would not have been possible in dry or coarser sediment, particularly when inclined near the angle of repose. If the sand were dry when imprinted, no detail would be preserved. If the trackway were exposed for days or weeks, the sand would dry and run on a  $25^{\circ}$  slope, and detail would be lost or completely obliterated. To preserve these details, imprint, burial, and preservation must have been nearly synchronous.

Jackson et al. (2010) have shown that moisture content of the medium (=substrate) has a great effect on the preservation of tracks, with the best preservation being in moist, as opposed to dry or saturated, sand. From the detailed sole or flow marks on the foreset beds (e.g., Fig. 5B), the wet sand was apparently shifting and sliding during the height of the storm, ultimately attaining the angle of repose. The trackway was then buried by an additional 1–2 m of dune sand perhaps as the storm waned, indicating that foul weather continued for some time after the bird traversed the lee side of the dune. Immediately adjacent to the beds containing the trackway, several hollow tree molds  $\sim 4$  m high are also observed in the deposits (wide arrows; Figs. 4, 5A).

We conclude that the late Pleistocene avian trackway on Charles Island, Bermuda, represents the path of a lone bird, likely a willet (*Catoptrophorus semipalmatus*, Scolopacidae), sheltering from the effects of a major storm on the lee side of a beachridge. The period of willetts' main abundance in Bermuda coincides with the late summer or early fall hurricane season. Hitherto, there has been no evidence of this species in the fossil record of Bermuda (Olson et al., 2005).

*Palmetto Fronds.*—Impressions of what we and others have interpreted as palm fronds occur along South Shore coastal exposures between Grape Bay, Southcourt Avenue, and Castle Roads (southern entrance to Castle Harbour) (Fig. 1). Most commonly observed in the dune sand are linear corrugations of significant number (Figs. 6, 7A–B). These molds are characterized by 2- to 3-cm-wide, zigzag patterns, radiating from a curving central axis or petiole (Figs. 7A–B). Impressions sometimes occur stacked, like cards, standing vertically in arching planar zones up to 50–100 cm wide. The corrugated interfaces are readily exploited by erosion (Fig. 6). The impressions of

the fronds crosscut the dune bedding planes, which are generally dipping to the north. This implies that the plants were standing upright when they were buried, as opposed to lying flat on the ground as in the case of dead, detached fronds. The striking similarity of these traces compared with living palmetto fronds, including the arching petiole (Figs. 7A–B), precludes their formation as solutional *rillenkarren* as suggested by Herwitz (1993).

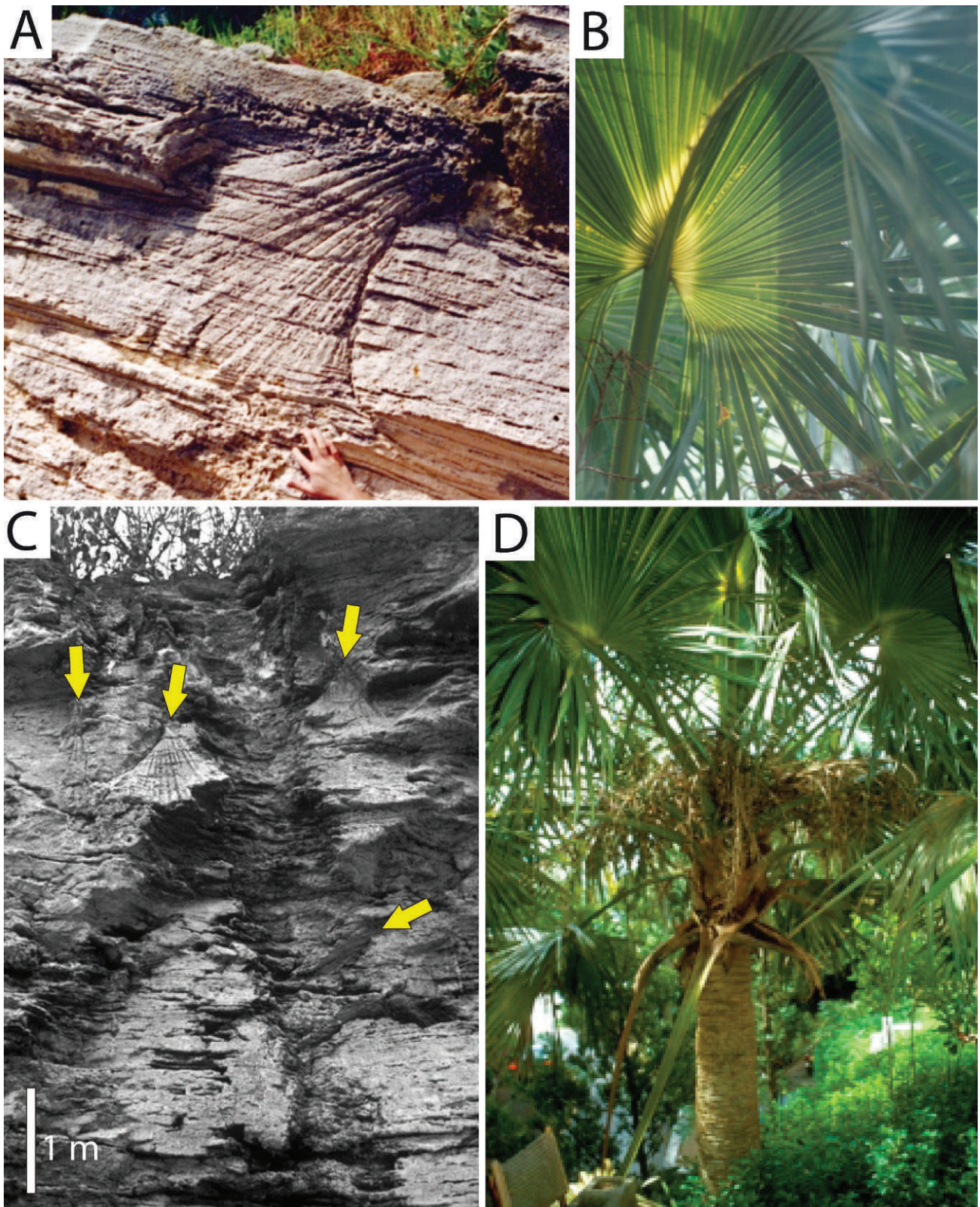
*A Buried Forest of Sabal Palm?*—Spectacular mold features exposed within a vertical cliff section (Figs. 7C, 8A–B) at Hungry Bay—documented photographically in May 1989—have since been destroyed during cliff erosion by several storms since the 1990s. Numerous near-vertical, cylindrical, empty or partially filled molds, 30–60 cm in diameter, in various orientations (vertical, sloping, and horizontal), and more than 8 m tall were exposed in the cliff section  $\sim 30$  m length along the shore. Directly associated with the trunk molds were the corrugated frond impressions described above. In some cases the fronds are pointing downward from near the top of the cylindrical structures (Figs. 7C, 8) as if they were hanging from the trunk when buried.

Because of their consistent diameters ( $\sim 50$  cm) and association with the radiating corrugations, many of the cylindrical forms are interpreted as trunks of the endemic Bermuda palmetto, *Sabal bermudana*, which lives on the islands today. Although we have no knowledge of the morphometrics of mature virgin forests of *S. bermudana* in times past, their length and trunk diameters and the association with corrugated fronds invites an association with the endemic *S. bermudana*, living examples of which average 25 cm in trunk diameter (Britton, 1918, p. 56). This association is highly likely as the only other common endemic tree of Pleistocene Bermuda was *Juniperus bermudiana*, which has a quite different morphology.

An entire forest of *S. bermudana* was rapidly buried beneath more than 8–10 m of uninterrupted, thick and broad sets of cascading dune sand in both windward and leeward sets. We suggest that a single depositional event buried the plants while either alive or standing dead with leaves still attached. *Sabal bermudana* palms are well adapted to salt, sand, and partial burial and presumably could survive most conditions short of complete burial. Many of the trees were standing while the fronds were still attached to crown of the tree, based on the orientation of the molds (Fig. 7C). Other tree impressions were oriented horizontally at different levels (circular molds in Fig. 8B), indicating they had fallen before burial as in an established mature palm forest, although perhaps they were toppled or broken off during the storm. The basal soils in which the trees grew are not exposed, although sinuous plant traces (Fig. 8B) that could be from roots were observed in the outcrop.

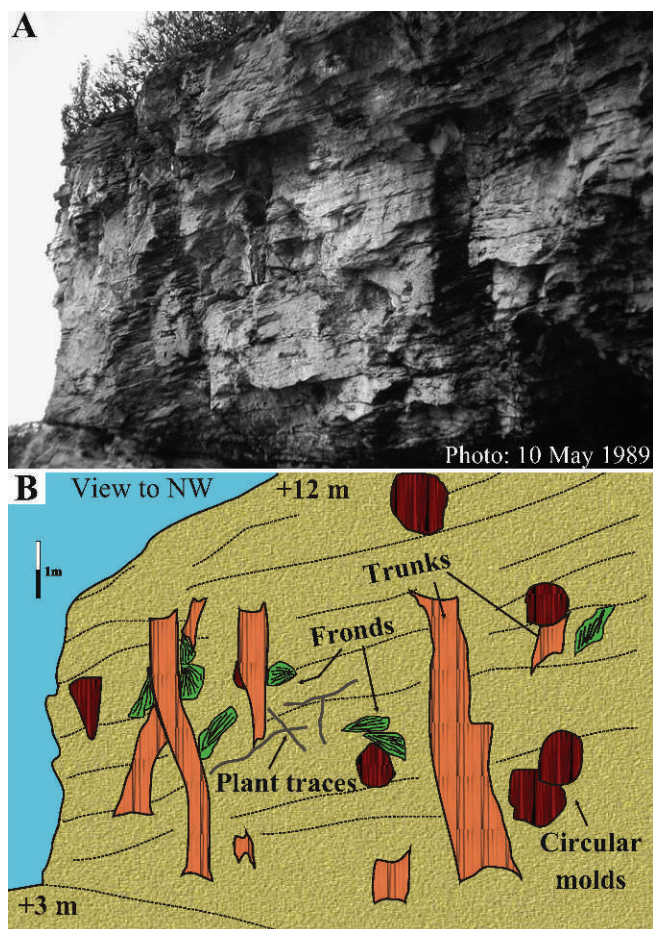
#### Summary of Evidence for Abnormally Intense Storms

Evidence for great storms, perhaps no more than two, along the south shore of Bermuda in MIS 5c consists of: (1) continuous, uninterrupted sets of foreset bedding in 3-dimensional architecture, whereas any cessation of deposition would be made evident by protosols, the absence of foreset beds or changes within them, structureless sand, or erosional discontinuities; (2) complete and rapid burial of standing trees 10 m in height with fronds still attached; (3) entombment of palmettos indicating live burial of vertical fronds as opposed to the dead and decaying leaves expected with partial or shallow burial; (4) preservation of avian trackways on a  $25^{\circ}$  slope made in wet sand and buried before they could dry and be blown away; (5) with maximum sea level being well below present, land transport of sediments must have been due to high energy sources in order to deposit such great volumes on land above present sea level; and (6) the existence of only one (or possibly two at Charles Island) homogenous facies units composed only of parallel foresets in the entire HB formation during a highstand of several thousand years. Only exceptional events could account for the coincidence of such circumstances.



**FIGURE 7**—Plant impressions and modern counterparts in rocks correlated with the Hungry Bay Formation of mid last interglacial age (MIS 5c). A) corrugated impression of a frond with arching petiole at Southcourt Avenue (Feb 2005 photo; hand for scale); B and D) The modern endemic palm *Sabal bermudana*. The trunk in view D is approximately 40 cm in diameter. C) Hollow tree mold with fronds (arrows), many pointing downward from apex of the trunk (at Hungry Bay, 10 May 1989 photo).





**FIGURE 8**—Preservation of a forest of trees at Hungry Bay. A) photograph showing several hollow and refilled casts of suspected buried *Sabal bermudana* forest. B) Sketch interpreting the above photograph showing standing and fallen trunks and a large number of frond molds and rhizomorphs.

#### A Model for Tree Mold-Cast Conduit Formation and Evolution

Bermuda offers exquisite examples of tree molds that exhibit youthful stages (<125 ka) of evolution and diagenesis of vertical hydrological conduits within carbonate dunes. Combined with similar but older (ca. 400 ka) features in more advanced stages of development at the Pinnacles in Western Australia at Nambung National Park (NNP) (Lowry, 1973; McNamara, 1995; Hearty and O'Leary, 2008; Lipar, 2009), we can develop an empirical model to explain the initial formation and evolution of conduits created by burial of standing trees in dunes (Fig. 9).

**Stage I: Burial of Trees and Initial Conduit Formation.**—Dune sand may accrete with sufficient speed during intense storms to bury living trees growing landward of the coastal beach-dune ridge. Rapid deposition and large volumes of sediment are considered essential to the process, as initial cementation of dune sand and molding of the trunk must occur while the standing trunk is intact, previous to or during its subsequent decay.

Highly soluble aragonite is abundant in the vadose environment of the dune that would precipitate around the trees as a result of the release of abundant organic acids from decaying plant material. Fluid flow and precipitation of  $\text{CaCO}_3$  as calcrete would occur along the cylindrical plane of the tree trunks forming molds deep within the dunes. Curran et al. (2008; Fig. 5C) observe that calcrete rinds may begin to form while the trees are still living.

Vadose solutions tracking along the mold-cast interface would also move laterally and irregularly, filling voids and penetrating some of the

enclosing dune sediments. The result would be cementation and induration of dune bedding beyond the circumference of the original mold (Fig. 10A).

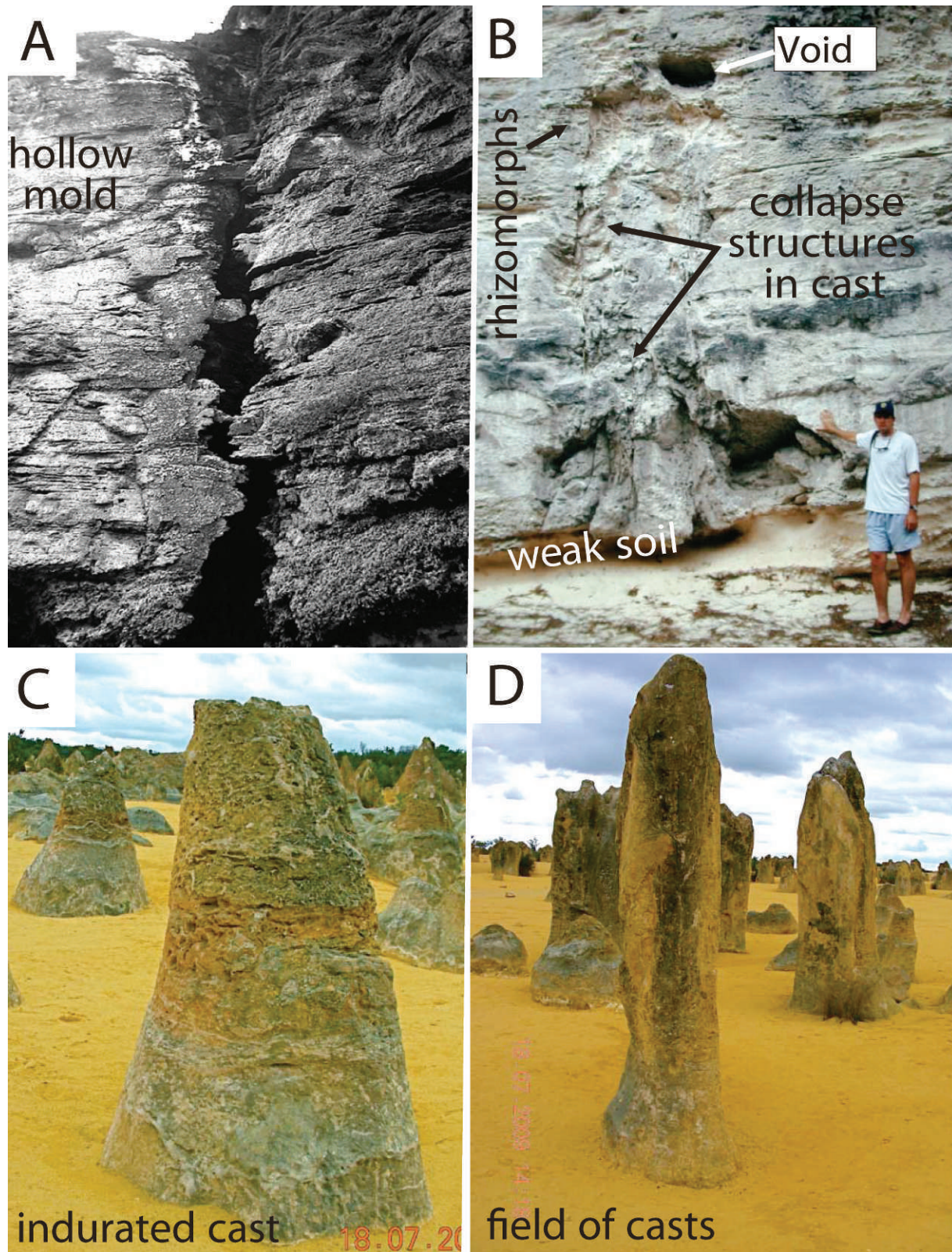
**Stage II: Tree Decay and Initial Infilling of Void.**—Molds within carbonate sand (Fig. 9A) are progressively filled by a mixture of materials collapsing, seeping, precipitating, and slowly entering into the voids (Fig. 9B) as the tree begins to decay. The variety of infilling materials (Fig. 9C) reflects polygenetic processes within the dune, the cylindrical void, and at the surface over a considerable amount of time. Materials deposited in the voids created by the decaying trunks early in the process might include: (a) carbonate sand from adjacent unconsolidated dunes or younger overlying dunes (often preserving as hourglass-like sand-flow cross-bedding within the casts); (b) quartz sand from continental dunes migrating across the landscape in the case of Western Australia. Materials deposited later might include: (c) breccia and rhizoliths from plants growing on the dune surface whose roots exploit the conduit for moisture and nutrients; (d) reddened soils and silts including atmospheric dust, translocated downward (Fig. 9C); and (e) micrite or microcrystalline calcite progressively filling interstitial pores.

**Stage III: Cementation and Calcretization.**—Over tens to hundreds of thousands of years, secondary plant growth and roots exploit the conduit by wedging and breaking the rock, eventually to form a network of rhizoliths and brecciated limestone. Progressive thickening of calcrete tubes and lenses would occur over time, just as they thicken in soils and calcrete capping the dune limestone (Hearty, 1998). Seasonal wetting and drying, and precipitation of vadose solutions, would progressively fill voids with micrite. The result is a slightly distorted replica of the morphology of the original tree, generally tapering upward from the base of the dune, reflecting the initial formation of casts from the bottom up. Irregular cementation of high-angle hourglass bedding within and adjacent dune bedding beyond the margin of the original trunk would explain the numerous observations of cross-bedding within and around the Western Australia pinnacles (Grimes, 2009; Lipar, 2009).

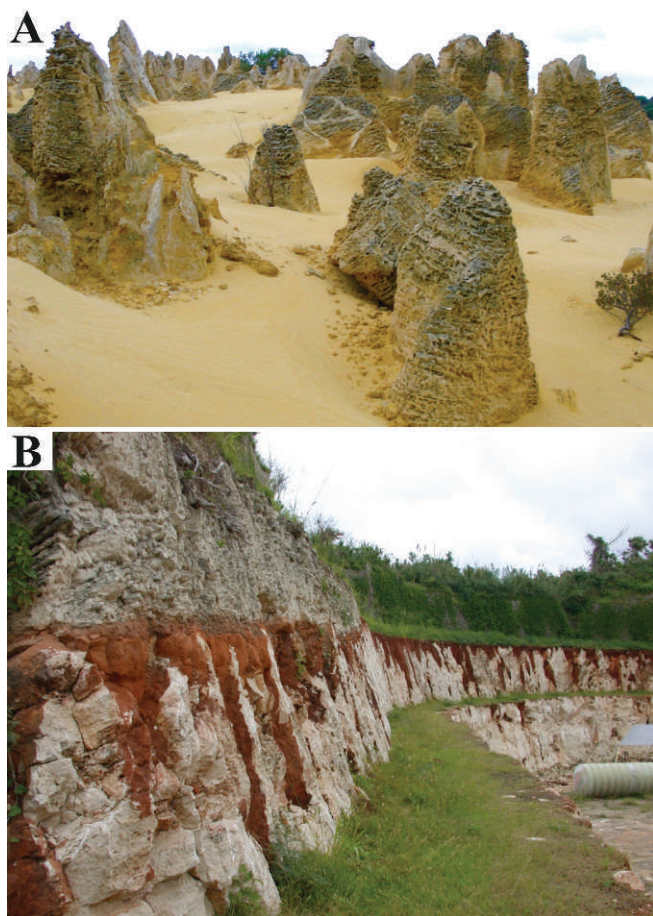
**Stage IV: Exhumation and Sculpting.**—Over several hundred thousand years (multiple subsequent glacial-interglacial cycles) the vertical casts become highly indurated as a complex aggregate of polygenetic sedimentary components (Figs. 9C–D). At the eolianite surface, a pedogenic calcrete may progressively thicken to several decimeters over this same time interval. The high level of induration of the filled tree cast would extend into the surrounding aeolianite matrix (Hearty and O'Leary, 2008; Lipar, 2009). In the case of the Pinnacles at NNP in Western Australia, subsequent erosion by wind and water removed the softer eolianite matrix, leaving the stronger pinnacles in positive relief (Figs. 9C–D) often with a relict cap of calcrete indicating the approximate position of the original dune surface.

#### Alternative Models for Conduit Formation and Development

There is ongoing debate regarding the formation of vertical conduits in limestone, but we suggest that the confusion originates from two distinct processes that slightly converge in their morphological end products. The fundamental question distinguishing those processes is the initial formation of the void within the limestone. Are conduits formed over hundreds of thousands of years by dissolution and diagenesis of limestone forming a solution pipe, or are they formed instantaneously (geologically) by molding and subsequent casting of vertical tree trunks? We emphasize that our conduit model above differs significantly in both fundamental process and time scale from the pedogenic evolution of solution pipes that develop in such aging limestone (see discussion in Herwitz, 1993; Lundberg and Taggart, 1995) as the Big Red Soil (BRS) in the early Pleistocene Walsingham Formation of Bermuda (Hearty, 2002) (Fig. 10B), which clearly is not a fossilized relict of a buried forest.



**FIGURE 9**—Successive stages of evolution of mold and cast tree forms. A) Stage I: unfilled mold of palmetto in 100 ka eolianite at Hungry Bay, Bermuda. B) Stage II: mostly filled cast of a large tree mold and cast in Nassau, Bahamas, 125 ka dune (note large void and rhizomorphs at top of cast). C) Stage III/IV: horizontally filled cast at Nambung National Park (NPN, Western Australia) showing tapered upward trunk morphology—pinnacle molds and casting are estimated to have been initiated ca. 400 ka (Hearty and O’Leary, 2008). D) Stage III/IV: field of pinnacles at NNP with conical or cylindrical morphology that have weathered out of softer sediments—millennia of subsequent exposure to wind abrasion and sand-blasting have sculpted the Pinnacles at NNP into a myriad of unique shapes.



**FIGURE 10**—Contrasting processes and time scales. A) advanced stage of bottom-up evolution of molds and casts over a several hundred thousand years at the Pinnacles of Western Australia. Note cemented cross-bedding around margins of casts. B) example of top-down development of solution pipes in recrystallized limestone filled with deep red soils (Big Red Soil of Hearty, 2002) in the upper several meters of the Walsingham Formation (>1 Ma?) capped by the Town Hill Formation (MIS 11) in Wilkinson Quarry, Bermuda.

**Solution Pipes and Top-Down Formation of Conduits.**—The formation of solution pipes is dominated by dissolution and pedogenesis forming enlarging vertical shafts in limestone that are simultaneously (syngenetically?) filled with soils, rhizoliths, and eventually *terra rossa* soils (Lundberg and Taggart, 1995; Grimes, 2009). This process might be described as top-down conduit formation because the development of the pipes enlarge from the surface downward, perhaps initially guided by hydrologic stemflow from plants. As observed in well-developed soils and karst surfaces of numerous Quaternary sections (Hearty et al., 2005; Hearty and O’Leary, 2008; Olson and Hearty, 2009), this top-down pedogenic process results in meter-scale deep shafts, narrowing with depth and filled with red or deep red clayey soil (such as the BRS), formed on a time scale of over 0.5 to over 2.0 Ma (Fig. 10B). In this latter case, if the enclosing softer dune matrix were removed by erosion, the top-down, calcrete-lined, conical solution pipes would be top-heavy, break off at their bases, and ultimately be strewn about horizontally as a lag on the erosion surface, not vertically standing as strong pillars in the case of the pinnacles. The solution pipes are generally filled with *terra rossa* clayey soil, unless excavated by inundation or drained by encountering subsurface voids.

At the Pinnacles at NNP in Western Australia, one group favors initial, early development of conduits from the land surface downward of the limestone by dissolution (Lowry, 1973; McNamara, 1995; Grimes, 2009).

**Tree Molding and Casting: Bottom-Up Formation of Conduits.**—In contrast (Hearty and O’Leary, 2008 and herein), we argue that the composition and morphology of the pinnacles at NNP indicate an initial bottom-up origin and evolution of conduits from tree molds and casts. Formation of the conduit can occur as quickly as cementation takes place in as little as a few hundred to a few thousand years (Halley and Harris, 1979; Curran et al., 2008). In our bottom-up model, pedogenesis and dissolution play a secondary role as they are only related to thickening of calcrete in the subsurface and translocation of soil material from the surface to build the cast. With removal of the enclosing dune matrix, the calcrete-hardened casts would be left standing vertically as in the case of the pinnacles of Western Australia.

## CONCLUSIONS

During the mid last interglacial period, as powerful storms, probably late summer hurricanes, slammed the southerly coast of Bermuda, extensive dunes were deposited along nearly 10 km of coastline at a time when sea level was above the platform margin, yet well below the present datum. The voluminous sediment deposition, perhaps amplified by waves along a steep shelf margin, has been dated to MIS 5c around 100 ka ago. The slurry of sea, sand, and air at the height of an intense oceanic storm discharged huge volumes of sediment on land. Within the dunes, delicate footprints of a willet (*Catoptrophorus semipalmatus*) were imprinted on soft, wet sand at the onset of hurricane conditions, then immediately buried. Vivid impressions of fronds presumably of *Sabal bermudana* are preserved extensively throughout the deposit. Hollow or partially filled molds of tree trunks represent the rapid burial of entire standing trees in a mature forest while still alive or recently dead.

The extent and consistent character of the foreset bedding of the HBF eolianites suggest an exceptionally powerful storm that deposited over 8 m of sediment on land during perhaps a single event that occurred when sea level was positioned well below present. To the east at Charles Island, the thick eolianites are interrupted by a well-developed protosol containing abundant snails, suggesting reestablishment of vegetative cover and slope stability, implying more than one storm event. Thus, we suggest that the entire HBF on land in Bermuda may have been deposited in as few as two intense storms that occurred during the MIS 5c highstand.

Perhaps due to convergent forms, there is debate and considerable confusion surrounding the origin of vertical conduits in limestone. The evolutionary stages we suggest here differ considerably from stemflow, or other means of concentration of fluids that through karstic processes and pedogenesis, dissolve vertical shafts in limestone that are generally backfilled with clayey *terra rossa* soils. The rapid burial, molding and subsequent casting of tree structures, the evolution of the resulting vertical conduit, and the ultimate possible exhumation comprise the various stages of a model that explains such features in Quaternary dunes. Understanding the processes and speed of entombment of coastal landscapes may provide a bellwether of future storminess associated with the continuing natural rise of the MIS 1 sea level with possible exacerbation by anthropogenic global change.

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