ABSTRACT

Geological investigations of Herndon Bay, a Carolina bay in the Coastal Plain of North Carolina (USA), provide evidence for rapid basin scour and migration during Marine Isotope Stage (MIS) 3 of the late Pleistocene. LiDAR data show a regressive sequence of sand rims that partially backfill the remnant older portions of the bay, with evidence for basin migration more than 600 meters to the northwest. Basin migration was punctuated by periods of stability and construction of a regressive sequence of sand rims with basal muddy sands incorporated into the oldest rims. Single grain OSL ages place the initial formation of each sand rim from oldest to most recent as ca. 36.7 +/- 4.1, 29.6 +/- 3.1, and 27.2 +/- 2.8 ka. These ages indicate that migration and rim construction was coincident with MIS 3 through early MIS 2, a time of rapid oscillations in climate. The fact that Carolina bay basins can migrate, yet maintain their characteristic shape...
and orientation, demonstrates that Carolina bays are oriented lakes that evolved over time through lacustrine and eolian processes. This research also indicates that Carolina bays can respond rapidly during periods of climatic transition such as Dansgaard-Oeschger or Heinrich events.

**INTRODUCTION**

Carolina bays are shallow, oriented (NW-SE in the Carolinas), elliptically-shaped depressions occupied by ponds and wetlands and occur in large numbers throughout the Atlantic Coastal Plain (Raisz, 1934; Johnson, 1942; Prouty, 1952; Thom, 1970; Gamble and others, 1977; Kaczorowski, 1977; Stolt and Rabenhorst, 1987; Walker and Coleman, 1987; Bliley and Burney, 1988; Bennett and Nelson, 1991). Most Carolina bays have elevated sand rims composed of fine sand to gravel. Previous studies have demonstrated that these sediments were deposited by high-energy, lacustrine shoreface and eolian processes (Kaczorowski, 1977; Thom, 1977; Brooks and others, 1996; Grant and others, 1998).

Below we describe the geomorphic evolution of Herndon Bay, a multi-rim Carolina bay in southeastern North Carolina, USA (Figure 1), and relate this evolution to regional climate conditions prevailing during the late Pleistocene. This study used Light Detection and Ranging (LiDAR) data, geologic coring, sedimentological descriptions, ground-penetrating radar (GPR), and optically-stimulated luminescence (OSL) dating of multiple sand rims. The
findings reported here have broad implications for other oriented lakes and the likely geomorphic response of these landforms to future climate perturbations.

**Regional Geological Framework**

Herndon Bay lies in the Coastal Plain of the southeastern United States, ~130 km inland from the Atlantic Ocean and ~18 km east/southeast of the Sandhills region in the Upper Coastal Plain of North Carolina, USA (Daniels and others, 1978) (Figure 2). The bay is 1 km long along its long axis, and as wide as 0.65 km. Herndon Bay is bound by sand rims along the southeast margin, including several sets southeast of the current margin that appear to represent previous bay margins. Our analysis focused on these sand rims. At the lowest point, the basin at Herndon Bay sits at approximately 48 meters above mean sea-level (amsl) with peak elevation for sand rims at approximately 54 amsl. Thus, the landform has an elevation relief of approximately 6 meters between the lowest and highest points (Figure 3). Currently,
Figure 3. LiDAR imagery and elevation profiles for Herndon Bay: a) 3D LiDAR view [20 percent exaggeration], b) LiDAR planview showing elevation, GPR transect [white line], and Geoprobe core locations, c) and d) elevation profiles showing Geoprobe® core and OSL sample locations/depth. The LiDAR data are provided by the North Carolina Floodplain Mapping Program (http://www.ncfloodmaps.com/) and were collected using 3-5 meter point spacing and a vertical accuracy of less than or equal to 20 cm Root Mean Squares Error (RMSE).
Herndon Bay is dry and its basin is used as a large agricultural field. Many Carolina bays in the area (including Herndon Bay) were ditched and drained historically for this purpose.

The study area is within the Lumber River drainage basin, which is covered by a 2-3 meter thick unit of Quaternary quartz-dominated sand that is interpreted as various fluvial, lacustrine and eolian deposits (Soller and Mills, 1991). In the study area, marine muds of the Cretaceous Black Creek Group (Owens, 1989, 1990; Sohl and Owens, 1991) directly underlie the Quaternary deposits (Rhodes and Conrad, 1985). Elsewhere, throughout the region, shallow and discontinuous marine, shelly, medium- to coarse-grained sand of the late Miocene to early Pliocene Duplin Formation underlies the Quaternary deposits (Soller, 1988; Owens, 1990; Ewing and others, 2001; Zanner and others, 2003) (Figure 2a).

The geomorphology and shallow stratigraphic framework of the area are the cumulative result of Quaternary sea-level fluctuations (Cronin and others, 1981), glacio-isostatic adjustments (GIA) of the region (Peltier, 2004), dynamic topographic uplift (~0.06 mm/y) related to mantle processes (Rowley and others, 2013), and uplift (~0.24 mm/y) along the Mid- Carolina Platform High (a.k.a., the Cape Fear Arch) (Van de Plassche and others, 2014). Geomorphological features of the landscape include Quaternary marine terraces (which are mapped as the Duplin, Blear Bluff, Waccamaw, Penholoway, Socastee, and Wando Formations in ascending stratigraphic order; Soller, 1998; Owens, 1989) (Figure 2b). These terraces have been dissected by fluvial incision related to long-term uplift (My timescales), and episodic shorter term uplift and subsidence (GIA acting on 0.1 My timescales) accompanying base-level changes. The surficial sand sheet has been additionally modified by pedogenic, fluvial, eolian, and lacustrine processes; the latter two being most relevant to this study.

**Previous Work on Carolina Bays and Other Oriented Lakes**

Many hypotheses about Carolina bay (and other oriented lake) genesis have been promulgated over the years by scientists and non-scientists alike. Among these ideas, the more pervasive claims relate bay formation to low-angle meteor or comet impacts/air bursts (for example, Melton and Schriever, 1933). More recently, Firestone (2009) advanced a comet impact origin for Carolina bays promoting a hypothesis to explain the onset of the Younger Dryas (YD), some 13,000 years ago. While these claims persist, the data suggest that Carolina bays are best explained as oriented lakes.

Seminal work by Kaczorowski's (1977) on bay formation and evolution demonstrated that Carolina bays evolve through the interactions of strong, late Pleistocene directional winds on shallow, ponded water, producing oriented lakes; similar oriented lakes are a relatively common phenomenon globally. Through the use of wind table modeling, Kaczorowski demonstrated that strong prevailing winds (from the southwest in the Carolinas) were responsible for creating circulation cells that shaped natural depressions into ellipses and oriented bays perpendicular to prevailing wind. Dual circulation cells scoured basins and eroded opposite ends of the basin (perpendicular to directional winds) while depositing eroded sediment on the downwind side (northeast in the Carolinas) of the basin. These wind patterns were also responsible for producing sand rims which are typical shoreline lacustrine features composed of both water-lain and eolian deposits. Sand rims form primarily along the northeastern and southeastern portions of Carolina bays in the Carolinas. Multiple rims and variable sand rim placement around bays indicate variable wind directions may have been involved in rim formation.

Investigations of Carolina bays by Brooks and others, (2001, 2010) and Ivester and others, (2007, 2009) indicate that some Carolina bays are older than 100,000 ka and formed primarily during major climatic transitions from cooler/dryer to warmer/wetter conditions. Sediment analyses indicate that sand rims associated with Carolina bays are typical shoreline deposits (Brooks and others, 1996, 2001, 2010). At individual bays where concentric sand rims occur, dating shows that rims are progressively younger toward the center of the bay, reflecting a re-
gressive sequence (Brooks and others, 2001, 2010). Thus, contrary to the “Meteorite Theorists,” these previous studies confirm that bays evolved episodically over a long period of time, and that they are not single event features.

Oriented lakes have been studied in Alaska (e.g., Rex, 1961; Carson and Hussey, 1962), western Canada (Côté and Burn, 2002), the Amazon (Lombardo and Veit, 2014), Australia (Maher and Davis, 2009), and numerous other locations around the globe (Kaczorowski, 1977; Goudie and others, 1995; Gustavon and others, 1995; Burn, 2004; Holliday and others, 2008; Ashton and others, 2009; Maher and Davis, 2009). Each of these studies resulted in a determination that the primary driver of oriented lake formation is related to directional winds on shallow ponded water, thereby shaping unconsolidated sediments through lacustrine processes. Although many oriented lakes form as a result of reworking unconsolidated sediments, some oriented lakes form in karstic environments and are influenced by the antecedent structural framework or other subsurface features (for example, Allenby, 1989). May and Warne (1999) speculate that the initial depressions of Carolina bays in the Southeastern Atlantic Coastal Plain formed as silica-karst features related to significantly lowered water tables during the last glacial maximum (LGM). In their hypothesis, slow dewatering of the sand and clay-rich surface deposits resulted in desilicification and formation of surface depressions that were later shaped by water and eolian processes. More recently, Rodriguez and others, (2012) found charcoal lenses in sand rims from a “…conglomeration of multiple Carolina bays...” in North Carolina and suggested that burning of peat “…and subsequent hydrodynamic processes were associated with initial basin formation of these Carolina bays.”

**METHODS**

Our analysis relies on (1) sedimentology and stratigraphy examined from four cores and a ground penetrating radar (GPR) transect; (2) optically stimulated luminescence (OSL) age estimates from the bottoms of three of the cores; and (3) interpretation of LiDAR topography.

**Stratigraphy and Sedimentology**

Cores were collected using a truck-mounted 5410 Geoprobe® direct push system (Table 1). Three of the four locations correspond to the locations previously sampled for OSL dating. Cores were analyzed to determine basic lithologies and grain-size characteristics. All sediment cores were analyzed by the Department of Geosciences at East Carolina University in Greenville, North Carolina. After logging the cores, approximately 10 grams of sediment were ex-
tracted at intervals of significant changes in sediment composition, or at 10 cm intervals where sedimentological trends were evident. Samples were dried, and then sieved at 0.5 phi intervals from 4 phi to -2 phi using a Ro-tap for 15 minutes. Phi fractions were then weighed and entered into the GRADISTAT Excel spreadsheet (Blott and Pye, 2001) to calculate statistical information.

**Geophysics**

Ground penetrating radar (GPR) surveys were conducted using a Geophysical Survey Systems (©GSSI) SIR-3000 unit with 200MHz ©GSSI antennae. A recording window of 300 ns provided potential data acquisition to a depth of ~5-9 m estimated by Kirschhoff migration on the basis of a dielectric constant of 6-10. GPR data were collected using a ©GSSI survey wheel set at 20 scans per meter and 1024 samples per scan. Survey lines were georeferenced with a Trimble differential GPS. GPR data were processed using Radan v6.5 software (©GSSI), including bandpass filtering and gain-enhancement. Major reflectors were traced in order to improve visualization of sedimentary features and define radar facies. Surface normalization was based on LiDAR elevation data.

**Luminescence Dating**

Samples for luminescence dating were collected by first using a bucket auger to determine the thickness of sand rim deposits and to determine the basal contact with the underlying substrate. Once determined, another auger hole was excavated to the desired depth above the interval of interest for OSL sampling (about 30 cm above the unconformity between the Carolina bay sand and the underlying mud substrate). A separate core collector was inserted into the hole with a stainless steel core collector and driven into the sand with a slide hammer before being retrieved. The core collector barrel was sealed on both ends to prevent light contamination.

All optically-dated samples were processed in the University of Washington, Luminescence Dating Laboratory. Luminescence was measured on single grains of 180-212µm quartz, using a 532 nm laser at 45 W/cm² for stimulation. The equivalent dose (Dₑ) was determined by the single- aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000; Wintle and Murray, 2006). A dose recovery test was also performed to check on the appropriateness of procedures. A combined total of 1079 grains were measured for all three samples, but using a set of criterion for evaluating the signals from each grain, only 224 grains were accepted for analysis (a 20.8% acceptance rate). The distribution of Dₑ values was evaluated by the finite mixture model (Galbraith and Roberts, 2012), which sorts the distribution into single-aged components, and by radial graphs.

Dose rate was estimated by alpha counting, beta counting, and flame photometry (for% K), taken on bulk samples. Consistency of results suggested that the dose rate did not change through time. Moisture content was taken as 6 ± 3%, which is typical for sandy sediments in temperate climates. OSL ages are reported in years before AD 2014 to 1-sigma standard deviation.

**Light Detection and Ranging (LiDAR)**

Over the last few years, high resolution Light Detection and Ranging (LiDAR) elevation data have become available and have revealed Carolina bays in spectacular detail. This technology has revealed geomorphic structures within and around bays not visible before and are useful for reconstruction of Carolina bay geomorphology. LiDAR data for the study area are used to provide clues to the geomorphology and the geomorphic relationships, between Carolina bay basins, sand rims, and cross-cutting relationships as well as to provide detailed elevation transects between Carolina bay basins and sand rims. The LiDAR data are provided by the North Carolina Floodplain Mapping Program (http://www.ncfloodmaps.com/) and were collected using 3-5 meter point spacing with a vertical accuracy of less than or equal to 20 cm Root Mean Square Error (RMSE).
Table 2. Grain size statistics for core samples (Folk and Ward [phi] method) and sedimentary lithofacies.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (cm)</th>
<th>Mean Grain Size (Φ)</th>
<th>Standard Deviation (Φ)</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Sedimentary Lithofacies</th>
</tr>
</thead>
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<tr>
<td>HB1-60</td>
<td>60</td>
<td>0.9</td>
<td>0.63</td>
<td>0.13</td>
<td>1.15</td>
<td>USR</td>
</tr>
<tr>
<td>HB1-80</td>
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<td>0.67</td>
<td>0.93</td>
<td>0.38</td>
<td>1.4</td>
<td>USR</td>
</tr>
<tr>
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<td>0.97</td>
<td>0.65</td>
<td>0.1</td>
<td>1.14</td>
<td>USR</td>
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<td>HB1-120</td>
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<td>-0.01</td>
<td>1.08</td>
<td>USR</td>
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<td>0.27</td>
<td>0.96</td>
<td>USR</td>
</tr>
<tr>
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<td>0.2</td>
<td>1.33</td>
<td>USR</td>
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<td>195</td>
<td>2.19</td>
<td>1.2</td>
<td>-0.5</td>
<td>1.23</td>
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<td>0.17</td>
<td>0.89</td>
<td>USR</td>
</tr>
<tr>
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<td>0.85</td>
<td>0.25</td>
<td>1.07</td>
<td>USR</td>
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<tr>
<td>HB1-320</td>
<td>320</td>
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<td>0.96</td>
<td>0.07</td>
<td>1.05</td>
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<td>-0.2</td>
<td>0.62</td>
<td>BSR</td>
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<td>HB2-40</td>
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<td>0.89</td>
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<td>1.17</td>
<td>0.18</td>
<td>1.29</td>
<td>USR</td>
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<td>0.11</td>
<td>1.2</td>
<td>USR</td>
</tr>
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<td>0.12</td>
<td>1.17</td>
<td>USR</td>
</tr>
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<td>0.63</td>
<td>0.07</td>
<td>0.96</td>
<td>USR</td>
</tr>
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<td>USR</td>
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<td>HB2-300</td>
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<td>0.43</td>
<td>0.88</td>
<td>0.13</td>
<td>0.92</td>
<td>LSR</td>
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<td>0.62</td>
<td>BSR</td>
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<td>LSR</td>
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<td>0.76</td>
<td>0.35</td>
<td>1.5</td>
<td>LSR</td>
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<td>0.92</td>
<td>BSR</td>
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<td>1.21</td>
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<td>1.76</td>
<td>0.26</td>
<td>1.4</td>
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<td>1.01</td>
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<td>0.88</td>
<td>USR</td>
</tr>
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<td>0.87</td>
<td>USR</td>
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<td>HB4-110</td>
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<td>0.98</td>
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<td>1.47</td>
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</tr>
<tr>
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<td>1.74</td>
<td>0.19</td>
<td>1.42</td>
<td>BSD</td>
</tr>
</tbody>
</table>

1Sedimentary lithofacies are sedimentary units distinguished by analysis of grain-size parameters (see Fig. 5).

Upper Sand Rim (USR); Lower Sand Rim (LSR); and Basal Sand Rim (BSR).
CAROLINA BAY FORMATION AND EVOLUTION

Figure 4. Sedimentological logs for core samples, corrected for elevation and rim topography, showing major lithofacies and single-grain luminescence geochronology.

Legend:
- mud
- sand
- muddy sand
- gravel
- laminations
- organics/rootlets

Graphics Key
- sand
- slightly muddy sand
- muddy sand
- slightly sandy mud
- sandy mud
- laminated sand
- slightly gravelly sand
- Upper Sand Rim
- Lower Sand Rim
- Basal Sand Rim

Lithofacies Key
- OSL age
- Unconformity

HB1
- Extant bay basin
- 27.2 ± 2.8 ka
- Black Creek Group

HB2
- 29.6 ± 3.1 ka

HB3
- Remnant bay basin
- 36.7 ± 4.1 ka
- Black Creek Group

HB4
- Scoured Surface
Figure 5. a) Bivariate plots for Geoprobe® core samples from Herndon Bay: mean grain-size versus standard deviation (sorting); b) Bivariate plot of skewness versus standard deviation (sorting). Numbers refer to depth of samples in centimeters (see Table 2).
RESULTS

Below we discuss the results of a suite of analyses. These include descriptions of core stratigraphy, grain-size characteristics, analysis of sedimentary structures revealed by cores and geophysics, results of luminescence dating of sand rims, and an evaluation of evidence derived from the examination of LiDAR data.

Stratigraphy and Sedimentology

The sand rims at Herndon Bay are comprised primarily of medium to fine sand (laminated in some places), although there are some lithofacies of muddy sand, sandy mud, laminated sand, and slightly gravelly sand (Figure 4). Multiple contacts between sedimentological lithofacies are apparent from cores, particularly between units of laminated sand, gravelly sand, and muddy sand. Units of muddy sand are more apparent in the outer sand rims (HB3 and 4) and were encountered in many zones throughout the entire length of the cores. In the two innermost sand rims (HB1 and HB2), mud is virtually absent, and gravelly sand and laminated sand occur at the base of the cores (Figure 4). Overall, Herndon Bay sand rim samples are highly variable in their mean grain-size, standard deviation, skewness, and kurtosis (Table 2); however, bivariate analysis of grain-size data from each core reveal broad textural distinctions defined as upper sand rim (USR), lower sand rim (LSR), and basal sand rim (BSR). Sediments from HB2 and HB3 displayed textural distinctions between the USR, LSR, and BSR. In contrast, sediments from HB1 and HB4 displayed textural distinctions between only the USR and BSR (Table 2; Figure 5a and 5b). Generally, sediments within the middle to lower portions of each rim are the coarsest and better sorted. This finding contrasts with basal (BSR) sediments that tended to have a more variable texture, but were generally finer grained and more poorly sorted. In HB2 and HB3, the USR deposits are also typically finer and slightly more poorly sorted than LSR samples. These sedimentological distinctions are interpreted below as components of lacustrine and eolian depositional environments similar to shoreface deposits recorded for lake shorelines elsewhere (Thompson, 1990; Dott and Mickelson, 1995; Baedke and others 2004; and Johnston and others 2004).

Geophysics

The radar-stratigraphic character of each sand rim consists of a ~1-2.5 m thick zone of low amplitude reflection. The thickness of this low amplitude zone increases in the middle two sand rims (HB2 and HB3) and is thinnest on the innermost and outermost sand rims (HB1 and HB4). Below this zone is a ~2-3 m thick zone of very high amplitude with strong reflections and subtle indications of structure. This very high amplitude zone reveals the clearest evidence of distinct sedimentary structures in the form of slightly hummocky bedding, reactivation surfaces, and dipping clinoforms (Figure 6). Such indications of sedimentary structures are most clearly seen between sand rims HB2 and HB4. The GPR data also indicate dipping clinoforms between HB3 and HB4 that are inferred to be a buried sand rim or paloeshoreline, indicating progradation of rim deposits (Figure 6). At ~48 m above mean sea level (amsl), radar data are strongly attenuated by the underlying muddy Black Creek Group.

Luminescence Dating

Single grain OSL places the initial formation of each sand rim from oldest to most recent as ca. 36.7 +/- 4.1 (UW2788) for HB4, 29.6 +/- 3.1 (UW2787) for HB2, and 27.2 +/- 2.8 ka (UW2786) for HB1 (Tables 3-4). Looking at the radial graphs for samples UW2786 (HB1) and UW2787 (HB2), the distributions seem to be more evenly mixed than for the other sample
CHRISTOPHER R. MOORE AND OTHERS

Table 3. Concentrations of U, Th, K, beta dose rates, and total dose rate for Herndon Bay.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Core Depth (m)</th>
<th>238U (ppm)</th>
<th>233Th (ppm)</th>
<th>K (%)</th>
<th>Beta dose rate (Gy/ka)</th>
<th>Total dose rate (Gy/ka)</th>
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</thead>
<tbody>
<tr>
<td>UW2786</td>
<td>1.8-2.0</td>
<td>0.55±0.10</td>
<td>7.72±1.00</td>
<td>0.01±0.01</td>
<td>0.32±0.03</td>
<td>0.30±0.03</td>
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<tr>
<td>UW2787</td>
<td>3.0-3.3</td>
<td>0.35±0.10</td>
<td>8.26±1.03</td>
<td>0.02±0.01</td>
<td>0.26±0.04</td>
<td>0.30±0.03</td>
</tr>
<tr>
<td>UW2788</td>
<td>1.6-1.9</td>
<td>0.80±0.11</td>
<td>8.07±1.05</td>
<td>0.31±0.02</td>
<td>0.37±0.04</td>
<td>0.36±0.04</td>
</tr>
</tbody>
</table>

Moisture content was taken as 6 ± 3 percent, typical for sandy sediments in temperate climates (Brady 1974).

U, Th, and K values determined by alpha counting, beta counting, and flame photometry.

1UW, University of Washington, Luminescence Dating Laboratory.

Table 4. Luminescence dating results for Herndon Bay.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Equivalent dose (Gy)</th>
<th>Central age (Gy)</th>
<th>2σb (%)</th>
<th>3FMM –most common component (Gy)</th>
<th>Age (ka)</th>
<th>% error</th>
<th>4Basis for age</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW2786</td>
<td>21.4±1.2</td>
<td>21.4±1.2</td>
<td>34±5</td>
<td>16.7±1.1 (54%)</td>
<td>27.2 ± 2.8</td>
<td>10.1</td>
<td>Central Age</td>
</tr>
<tr>
<td>UW2787</td>
<td>22.9±1.3</td>
<td>22.9±1.3</td>
<td>32±5</td>
<td>17.0±1.5 (51%)</td>
<td>29.6 ± 3.1</td>
<td>10.3</td>
<td>Central Age</td>
</tr>
<tr>
<td>UW2788</td>
<td>32.4±2.6</td>
<td>22.7±2.4</td>
<td>80±8</td>
<td>32.4±2.6 (51%)</td>
<td>36.7 ± 4.1</td>
<td>11.3</td>
<td>Largest Component</td>
</tr>
</tbody>
</table>

1UW, University of Washington Luminescence Dating Laboratory.
22σb = over-dispersion
3FMM = finite mixture model shows the most common component with the proportion of all grains in parentheses.
4Age is calculated using a laboratory constructed spreadsheet based on Aitken (1985).

All given error terms are computed at one-sigma.

(Figure 7). The two defined components are about the same size. A weighted average (central age model of Galbraith and Roberts, 2012) yielding a Dc value half way between the two components provides the best estimate for depositional age for samples UW2786 and UW2787. Sample UW2788 (HB4) is dominated by older grains (Table 4). Because this sample is located on the outer rim, the OSL age should be older than that of the other two samples. This age estimate is provided by the largest component.

LiDAR

Analysis of LiDAR data for the study area reveals a cluster of Carolina bays (including Herndon Bay) with clear evidence for basin migration and construction of a regressive sequence of sand rims backfilling remnant basins (Figures 1 and 3). Migration of Carolina bays is
Figure 6. Surface-normalized GPR transect at Herndon Bay showing interpreted radar facies, location of cores, OSL samples, and the contact with underlying mud facies. Vertical range of sedimentary facies (USR, LSR, and BSR) based on analysis of grain-size data (Table 2 and Figure 5).
to the northwest with prominent sand rims primarily occurring along the southeastern margin of the landforms. Cross-cutting relationships also indicate differential rates of migration with truncation of some bay sand rims by adjacent Carolina bays. The implications for these cross-cutting relationships are discussed below.

**DISCUSSION**

In the following discussion, we present our interpretations of the various data sets from Herndon Bay, along with their implications for the geomorphic evolution of the landform. This is followed by a brief discussion of Carolina bay formation and evolution that draws on previous studies of Carolina bays and oriented lakes discussed earlier. While this research was not initiated to substantiate or refute the claims for an impact(s) origin for Carolina bays, it directly addresses these claims through the establishment of a high resolution OSL geochronology and through detailed sedimentological and geophysical descriptions. Together, these data provide an accurate assessment of the geological processes and evolution of Caro-
CAROLINA BAY FORMATION AND EVOLUTION

Herndon Bay

Herndon Bay is interpreted as having evolved rapidly under high-energy conditions favoring basin migration. The outer rims are interpreted as high-energy shoreface deposits, with rapid scour and rim development that included muddy sediments within an immature mixture of sand, mud, and gravel. GPR data reveal structural features of sand rims, including dipping clinoforms and evidence for a buried sand rim between cores HB3 and HB4 (Figure 6). The closeness in age of the various sand rims, as indicated by OSL age estimates (Table 4 and Figure 3), suggests that the muddy sand in...
the oldest sand rim is not pedogenic in origin, but rather is a primary sedimentary feature.

A comparison of grain-size and sorting data from Herndon Bay sand rims with data from the Central Savannah River Area (CSRA) of South Carolina (Moore and others, 2010) reveals that the Herndon Bay sand rim samples have more variable grain-size characteristics (Figure 8a). For example, measures of skewness for Herndon Bay samples are highly variable, but most samples are finely-skewed and their skewness overlaps with skewness values for bay rims in South Carolina (Figure 8b). Sedimentological data from grain-size analysis show the sediments at Herndon Bay to be less well-sorted and more variable, in contrast with single-rim and non-migrating Carolina bays in South Carolina (Moore and others, 2010). The relatively immature nature of the sediments at Herndon Bay is consistent with sand rim formation under high-energy conditions favoring basin migration, whereas single rim bays were more stable, enabling shoreline processes to operate more efficiently and produce better sorted sediments.

Single-grain OSL dating of three sand rims indicates a period of fairly rapid bay migration from approximately 41 to 24 ka, with the development of distinct sand rims in a regressive sequence occurring between ca. 8,000 and 16,500 years and over a distance of 370 m (Figures 3 and 4). If we assume gradual formation, this equates to a migration rate of between ~22 and 44 m per millennium towards the northwest; however, the distinct nature of the individual rims is consistent with punctuated and very rapid migration over short distances followed by periods of stability and rim formation. Standard deviations of the OSL age estimates overlap at 2-sigma, limiting the precision of estimated migration rates. Based on the position of the remnant bay basin (to the east), the extant basin has migrated ~600 m towards the northwest (Figure 3). With regard to the age of the remnant basin, the OSL ages from the sand rims dated here must be considered minimum ages since these sand rims and the period of migration indicated by our data postdate the formation of the older basin by an unknown amount of time.

With respect to the OSL data, the distribution of the equivalent dose ($D_e$) values for the youngest Herndon Bay samples, (UW2786 and UW2787) was not highly scattered (Table 4). The equivalent dose from the central age model was taken as the best estimate for determining when the sediments were last exposed to sunlight. The few older grains may represent some partial bleaching due to the rapid and high-energy basal scour during initial rim formation, and the few younger grains may represent post-depositional downward movement, via some form of bioturbation. The sample from the outer rim is more mixed, with a large older component (51% from the finite mixture model with a few additional older grains) and two smaller younger components (32%). The latter may represent post-depositional downward movement via bioturbation or may be partially an artifact of the samples being close to saturation (see Feathers and Pagonis, 2015). In this situation, grains dominated by a slower bleaching signal may underestimate the age. This possibility of a saturation artifact was not judged to be statistically significant for these samples, but some of the apparently younger grains did have a slower bleaching signal. The large component is taken as the best estimate for calculating the age when the sediments were last exposed to sunlight. The resulting OSL ages are in the correct chronological order if the outer rim accumulated first and the inner rim accumulated last (Table 4).

Evidence from Herndon Bay suggests that there were multiple periods of bay migration, which included scouring of the underlying mud (Figures 3c, 3d, and 4). Periods of stability were punctuated by periods of high-energy shoreline processes leading to bay basin migration, punctuated by sand rim development during intervals of stability; the net effect is a regressive sequence of sand rims (Figure 3). The OSL chronology indicates that rim construction and migration was between approximately 41 to 24 ka, coincident with late marine isotope stage (MIS) 3 and early MIS 2 (Figure 9). Elsewhere in the southeastern Atlantic Coastal Plain, eolian parabolic dunes in river valleys attest to wind speeds that were considerably greater than modern values, prevailing winds out of the west.
and southwest, and sparse tree-cover during this time (Markewich and Markewich, 1994; Ivester and others, 2001; Ivester and Leigh, 2003; Leigh and others, 2004; Leigh, 2008; Swezey and others, 2013; Markewich and others, 2015). Evidence for high-energy basin scour and rapid construction of multiple sand rims at Herndon Bay is consistent with strong prevailing winds and with ecological reconstructions of the Late Quaternary environment in the southeastern Atlantic Coastal Plain of the United States (for example, Watts, 1980; Delcourt and Delcourt, 1981, 1984; Goman and Leigh, 2003). Given the amount of sediments mobilized to produce the sand rims at Herndon Bay and the evidence for basin scour, periods of very strong surface winds are implied. Consistent with this, Swezey and others, (2013), using the methods of Hsu (1974), estimated that wind velocities during the LGM were at least 4 m/s in order to mobilize eolian dunes along the Savannah River in South Carolina and Georgia. Winds during pre-LGM stadials and stadial/interstadial transitions were likely of similar strength. A close inspection of the LiDAR data (Figures 1 and 3) reveals cross-cutting relations in the imagery, indicating some time difference in basin migration. For example, Herndon Bay cross-cuts, and therefore, post-dates the bays and rims immediately adjacent on both the south and north sides. Alternatively, all of these bays may have been migrating together, but with Herndon Bay cutting through and truncating sand rims of the small bay to the south and larger bay to the north as it moved towards the northwest. Herndon Bay appears to have breached or nearly breached the smaller bay to the south, possibly draining one or both. Another possibility is that some bays may have migrated at a faster rate than others. In this case, the smaller bay to the south appears to have migrated further and produced as many as six distinct sand rims. Speculatively, different rates of migration could be related to basin size, water depth, and/or timing of climate thresholds. The gap between the eastern remnant basin and the most recent sand rims for the smaller bay is similar to the gap noted for Herndon Bay and the
large bay to the northwest of Herndon Bay (Figure 3b). This similarity suggests that the timing for construction of the most recent set of three rims for the smaller bay may be similar to those reported here for Herndon Bay. Additional OSL dating of these sand rims is needed to address this timing.

**Carolina Bay Formation and Evolution**

The evidence from Herndon Bay, and other Carolina bays (Brooks and others, 1996; Grant and others, 1998; Ivester and others, 2007, 2009; Brooks and others, 2001), is fully consistent with Carolina bay formation as oriented lakes within the Coastal Plain of the southeastern United States, as demonstrated by the experimental work of Kaczorowski (1977). Those touting a catastrophic origin for Carolina bays often confuse and conflate original depression formation and explanations of Carolina bay geomorphology. Carolina bays are dynamic features that may erase and rework their original basin regardless of the origin of the original depression (Gamble and others, 1977). Carolina bays evolve over many millennia in the same way that a meandering river migrates through, reworks, and erases evidence of former chan-
Evidence of multiple sand rims and bay migration demonstrate this explanation most clearly. Thus, a catastrophic origin is neither supported by geological data, nor needed to explain features attributed to Carolina bays. All that is required to initiate formation of oriented lakes is unconsolidated and easily erodible sediments that overlie a relatively impermeable layer which allows water to pond within natural depressions. Shallow cover sands, interdune regions, eolian blowouts, or irregularities in the underlying impermeable muddy substrate (i.e., antecedent topography) may provide suitable original depressions. Figure 10 illustrates one scenario whereby interdune wetlands are transformed into Carolina bays. As shown by Kazrowski’s wind table model, strong winds on shallow water can easily rework and shape cover sands and, as demonstrated by this study, scour underlying muddy sediments into the oriented lake basins that are referred to colloquially as Carolina bays.

Granulometric data (Figures 5 and 8) support the interpretation that the sand rims represent shoreline deposits. For example, vertical trends with respect to sand rim elevation are similar to those observed along lacustrine shorelines elsewhere (for example, Thompson, 1990; Dott and Mickelson, 1995; Baedke and others 2004; and Johnston and others 2004). At Herndon bay, basal sand rim (BSR) sediments are more poorly sorted, and (for HB1 and HB2) more negatively skewed than overlying sediments. BSR sediments also generally have a finer mean
grain-size. These trends are consistent with subaqueous deposition on an upper shoreface or foreshore position. The variability in BSR sediments with their laminae, gravels, and muds suggests corresponding variations in wave energy conditions, with alternating episodes of scour, winnowing of fine sediments, and quiescence. Higher up in each core, upper sand rim (USR) sediments are better sorted, fine (positively) skewed, and have a coarser mean grain-size. These characteristics suggest the influence of eolian processes and are consistent with deposition on a backshore or dune. The eolian sands would have been sourced from the backshore or foreshore, especially during periods of lower water level. Intermediate lower sand rim (LSR) sediments are marked for HB2 and HB3 on the basis of a distinct grouping on the bivariate plots in Figure 5. The distinction of the LSR sediments may reflect an influence by storm waves and wave washover that is less dominant in USR sediments higher up the rim. The upper boundary of BSR sediments is at a similar elevation for HB1, HB2, and HB3, suggesting a consistent mean water level as the bay migrated. In contrast, the upper BSR sediments as well as the underlying mud are about 2 m higher at HB4. Sediments of HB1, the youngest sand rim, exhibit the greatest difference of all the cores in grain-size and skewness between the basal and upper sand rim deposits. This difference in grain-size and skewness here suggests a progressive winnowing of fines from the basal deposits and transport to the USR as the bay...
evolved and migrated.

An analysis of high-resolution LiDAR data reveals clear evidence of basin migration for many bays with multiple sand rims (usually southeastern sand rims). This process is analogous in some ways to lateral migration of a meandering stream, where fluvial erosion along the outside (higher energy) of the meander loop and deposition on the inside (lower energy) create a scroll-bar topography of ridges and swales that indicate stream migration. In the case of Carolina bays, Kaczorowski's wind table modeling suggests a similar mechanism for the construction of elliptical Carolina bays, with circulation cells in shallow ponded water eroding southeast and northwest margins and depositing lacustrine sand rims on the downwind side (northeastern margin) of the prevailing wind (Figure 11).

Carolina bay orientation in the Carolinas is perpendicular to prevailing southwest winds (Carver and Brook, 1989), but a significant role for winds out of the west and northwest is suggested for bay migration and the presence of well-developed southeastern sand rims. Strong prevailing winds from the southwest were principally responsible for bay shape, orientation, and the development of sand rims along the northeastern margins of bays, whereas seasonal and stronger westerly and northwesterly winds appear to have driven basin migration and development of multiple southeastern sand rims in a regressive sequence towards the northwest (Figure 11).

Following Kaczorowski (1977), a Carolina bay migration model was developed to explain processes that shape, orient, and lead to bay basin migration and the development of a regressive sequence of sand rims along the southeastern margin of Carolina bays (Figure 12). LiDAR data reveal that Carolina bay migration occurs principally in the Middle and Lower Coastal Plain of North and South Carolina. Expansive, flat terrain, along with easily eroded cover sands, facilitate the lateral movement of bays through migration. In the Upper Coastal Plain, bay migration is often restricted due to dissected terrain and antecedent topographic highs.

Carolina bay orientation is driven by prevailing wind patterns which shift with changing latitude from northern Florida to New Jersey and correlate very well with changes in basin orientation (Kaczorowski, 1977; Carver and Brook, 1989; Brooks and others, 2001). As illustrated in Figures 11 and 12, bay basins are scoured, shaped, and oriented as a result of wind-driven water circulation cells that erode symmetrically on bay margins perpendicular to prevailing winds, while rims build as high energy lacustrine shoreline features on the downwind side and parallel to prevailing winds. In this way, southwest winds scour and elongate bays into ellipses perpendicular to the prevailing wind, while producing a pronounced northeastern shoreline and sand rim. As stated by Kaczorowski (1977), rim development occurs when wind-driven water currents drop suspended and saltated sediments as they lose energy on the return loop inward towards the center of the basin (Figures 11 and 12a). Shoreline sediments are then reworked into rim deposits through lacustrine processes involving water-lain and eolian sedimentation, including sedimentation influenced by winds from the west and northwest.

It is unclear why westerly and northwesterly winds in the Carolinas appear to drive migration but do not reorient bay rims, whereas prevailing wind patterns from the southwest shape and orient bays but do not appear to drive bay migration. A possible clue comes from previous work by Grant and others, (1998) who developed a bay formation and evolution model based on data from bays at the U.S. Department of Energy's Savannah River Site (SRS). Their model suggests that the link between orientation by prevailing southwest winds and creation of large and/or multiple southeastern sand rims by westerly or northwesterly winds is the seasonal change in water levels (Grant and others, 1998). In this scenario, bay shape and orientation are controlled by southwesterly winds because these winds dominate during periods of higher water when circulation cells can do the most shaping and eroding of bay shorelines. A 15-year study of a Carolina bay in South Carolina showed that water levels were usually lowest in the late summer to early winter (Taylor
and Brooks, 1994). The seasonal change in water level would have been even more pronounced during the Pleistocene, as evidenced by the existence of braided streams in the southeastern United States (Leigh, 2004). Thus, lowered water levels in the past would have exposed the sandy beachface, and fall-winter westerly or northwesterly winds would have reworked sediments to produce more pronounced southeastern sand rims. Southeast rims may therefore have a greater proportion of eolian sediments than slightly less pronounced northeastern sand rims.

A wind-rose diagram (Figure 1) for Lumberton, North Carolina (just south of Herndon Bay), shows modern wind velocity and direction averaged for a period of 14 years. These data show prevailing winds from the southwest but with seasonal shifts to winds from the west and winds from the north and northeast. It is unclear how similar this wind pattern is compared to wind patterns prior to the LGM. However, southwest prevailing winds and westerlies are consistent with paleo-wind reconstructions based on analysis of parabolic dunes (for example, Markewich and Markewich, 1994; Leigh and others, 2004; Leigh, 2008; Swezey and others, 2013; Markewich and others, 2015) and with the orientation of Carolina bays in the region (for example, Thom, 1977; Carver and Brook, 1989). If strong winds out of the north or northeast were common in the Coastal Plain during the Late Pleistocene, then the geological evidence for this in the form of source-bordering dune directions or the location of Carolina bay sand rims is missing.

The fact that bays do not reorient themselves to strong westerly winds probably indicates a dynamic equilibrium between these patterns with dominance by southwesterly winds. It appears likely that winds out of the west and northwest act more to redistribute sediments seasonally from northeastern shoreface deposits, with overall net sedimentation accumulation occurring along northeastern and southeastern margins of bay basins, while net erosion and scour occur principally along the southwestern and northwestern margins. Figure 11a shows the cumulative erosion and deposition that occurs with prevailing and seasonal winds. Together, these processes lead to limited bay basin migration and formation of multiple sand rims for bays in some parts of the Coastal Plain (Figure 12b). The combined influence of prevailing and seasonal wind patterns, variable erosion and deposition caused by these different wind patterns, and hydrologic conditions explains migration to the northwest that is slightly offset from the long axis of Carolina bays (Figures 3b and 12a).

**Paleoclimate Implications**

Punctuated periods of rim formation and bay migration at Herndon Bay likely occurred during transitions from cooler/drier to warmer/wetter conditions from approximately 41 to 24 ka, coincident with Late MIS 3 through early MIS 2. During such transitions (i.e., periods of climate stress, instability, and changes to the biome) there is evidence elsewhere for increased fire frequency (for example, Marlon and others, 2009; Daniau and others, 2010) and subsequent opportunities for enhanced sediment mobility. Rapid construction of Carolina bay sand rims, migration, and basin scour likely occurred during these relatively brief transitional intervals between glacial stadials and interstadials. It was during such transitions that increased rainfall favored standing water in bay basins, strong winds were still prevalent (as evidenced by numerous OSL ages from parabolic eolian dunes in river valleys of South Carolina and Georgia for this time period) (Ivester and others, 2007; Brooks and others, 2010; Swezey and others, 2013; Markewich and others, 2015), grass and shrubs were prevalent along with sparse tree cover (for example, Watts, 1980; Brooks and others, 2001; Leigh, 2008), and fire frequency was most likely enhanced due to climate stress and changes in vegetation (for example, Marlon and others, 2009; Daniau and others, 2010). The transition back from an interstadial to a stadial may also have been conducive to rim construction and basin migration. Carolina bays may

1. See Johnson (1942, Figure 38, p. 206) for "Hypothetical distribution of wind-drifted sand rims..."
still have held considerable water during this transition, but with conditions rapidly moving towards reduced forest cover, increasing grasslands, reduced moisture with likely enhanced fire frequency during the transition, and stronger winds common to stadials (Watts, 1980; Markewich and Markewich, 1994; Brooks and others, 2001; Leigh, 2008; Marlon and others, 2009; Swezey and others, 2013; Markewich and others, 2015). Subsequently, conditions during full interstadials include greater overall moisture, increased vegetation, decreased wind velocity, and a reduced fire frequency relative to climate transitions (for example, Marlon and others, 2009)—all of which are unfavorable to active shoreline processes and rim development of Carolina bays and other oriented lakes. Conditions during full stadials are likewise less likely to be conducive to active bay formation due to reduced moisture and decreased water levels in basins.

The Greenland Ice Sheet Project 2 (GISP2) oxygen isotope record (Figure 9) suggests that the period coincident with the later part of MIS 3 and the early part of MIS 2, was a time of rapid oscillations in climate between warmer/wetter interstadials and colder/drier stadials known as Dansgaard-Oeschger [D-O] events (Dansgaard and others, 1993; Grootes and others, 1993; Severinghaus and others, 1998; Huber and others, 2006; Van Meerbeeck and others, 2009). Model simulations and comparison of climate conditions during MIS 3 and MIS 2 (for example, Broecker and others, 1985, 1990) suggest that there was abrupt warming in the North Atlantic “...with a resumption of the Thermohaline Circulation (THC) from a weak state during stadials to a relatively strong state during interstadials.” (Van Meerbeeck and others, 2009). More recent model simulations suggest an enhancement of seasonality in the Northern Hemisphere during MIS 3, with much warmer average summer temperatures (~4°C) than during the LGM due to an increase in insolation (Van Meerbeeck and others, 2009). Freshwater forcing appears to have been necessary to return to stadial conditions during MIS 3 by limiting or shutting down of THC (Van Meerbeeck and others, 2009). Heinrich events are related to this phenomena and to D-O events (Heinrich, 1988). During the Pleistocene, Heinrich events were associated with ice sheet expansion and collapse leading to large-scale ice rafting in the North Atlantic Ocean and further slowing or shutting down THC and intensification of stadial conditions (Maslin and others, 2001). These perturbations to the climate system, particularly D-O events during MIS 3, would have produced multiple periods of rapid climate change and instability on decadal to centennial time scales. Active rim formation and migration at Herndon Bay appears to have occurred from approximately 41 to 24 ka, coincident with late MIS 3 through early MIS 2, a period of rapid and pronounced climate oscillations (Dansgaard and others, 1993; Heinrich, 1988).

**CONCLUSIONS**

The data presented here show that Carolina bays are capable of limited basin migration, including high-energy, subaqueous scouring of the underlying substrate. At Herndon Bay, high-energy basin migration events are punctuated by periods of more stable shoreline processes leading to the construction of a regressive sequence of bay sand rims with basal muddy sand incorporated throughout the earlier rims (Figure 4). Younger rims (HB1 and HB2) lack muddy sands incorporated into the older rims (HB3 and HB4) during the initial period of high-energy basin scour and migration and reflect more typical sandy facies common to other Carolina bays in the region (Brooks and others, 1996; Grant and others, 1998; Brooks and others, 2001; Ivester and others, 2007, 2009).

The fact that Carolina bays can migrate, yet maintain their characteristic oval shape, orientation, and rim sequences demonstrates that these landforms are oriented lakes shaped by lacustrine and eolian processes. Clear evidence of basin scour into the underlying Cretaceous sandy mud, reveals that Carolina bays are capable of migrating while backfilling remnant basins with a regressive sequence of paleoshoreline deposits as the position of the basin margin changes through time. Geomorphic variables such as antecedent topography, cover sand
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thickness, and slope gradient likely control which Carolina bays migrate and which do not. The rapid nature of sand rim construction at Herndon Bay is indicated by OSL ages from the base of sand rims, and by sedimentological data showing that the oldest bay sand rims are composed of immature and poorly sorted sand and mud. GPR data show structural features typical of high-energy shoreface and beach ridge construction and progradation, whereas OSL ages suggest that rim formation and basin migration can occur rapidly when climatological and hydrologic thresholds are met—such as during transitions between colder/drier stadials and warmer/wetter interstadials.

The characteristics of Carolina bays, including basin shape, changes in basin orientation with latitude, and sand rims reflect long-term and pervasive environmental, climatological, and hydrological factors over millennia rather than from sudden or catastrophic events (Kaczorowski, 1977; Thom, 1977; Carver and Brook, 1989; Brooks and others, 1996; Grant and others, 1998; Brooks and others, 2001; Ivester and others, 2007, 2009; Brooks and others, 2010). The fact that practically all Carolina bays in a particular geographic region have nearly identical patterns of shape, orientation, and sand rim composition suggests similar processes working over long periods of time. This study also indicates that Carolina bays can respond rapidly, and appear to become more active during periods of climatic instability. While many nuances of bay evolution remain to be refined, the evidence at Herndon Bay clearly supports the concept that Carolina bays represent a regional example of a globally-occurring phenomenon: They are wind-oriented lakes shaped primarily by lacustrine processes. Efforts to further resolve details of bay evolution have the potential to reveal additional insights into the nature and timing of landscape response to climate change.

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