Chapter 2
Quaternary Eolian Dunes and Sand Sheets in Inland Locations of the Atlantic Coastal Plain Province, USA

Christopher S. Swezey

Abstract Quaternary eolian dunes and sand sheets that are stabilized by vegetation are present throughout many inland locations of the Atlantic Coastal Plain province (USA). These locations include river valleys, the Carolina Sandhills region, adjacent to Carolina Bays, and upland areas of the northern coastal plain. The eolian dunes are primarily parabolic in river valleys and in upland areas of the northern coastal plain, linear in the Carolina Sandhills region, and arcuate adjacent to Carolina Bays. Optically stimulated luminescence (OSL) ages from the eolian sands range from circa (ca.) 92–5 ka, revealing that they are relict features that are not active today. These sands have been degraded by vegetation and pedogenic processes, and are stabilized under modern environmental conditions. Most of the OSL ages are approximately coincident with the last glacial maximum (LGM), when conditions were generally colder, drier, and windier. Various features associated with these eolian dunes and sand sheets suggest that the winds that mobilized the sand blew from the northwest in the coastal plain region of Maryland and Delaware, and from the west in the coastal plain region of North Carolina, South Carolina, and Georgia. Most of the eolian dunes and sand sheets are composed of fine to medium sand, although a substantial silt component is present in the northern coastal plain, and a substantial coarse sand component is present in the Carolina Sandhills region. Eolian sand mobilization would have been facilitated by conditions of stronger wind velocity (at least 4–6 m/s), lower air temperature, lower air humidity, and (or) reduced vegetation cover. Eolian sediment mobilization appears to have occurred episodically at any given site, although sites that are farther south have preserved a greater proportion of eolian sands yielding pre-LGM ages (indicating that the southern landscapes farther from the ice sheet have experienced less reworking).

Keywords Quaternary · Aeolian · Dune · Carolina Bay · Carolina Sandhills · U.S.A.

C. S. Swezey (✉)
U.S. Geological Survey, Reston, VA, USA
e-mail: cswezey@usgs.gov

© Springer Nature Switzerland AG 2020

N. Lancaster, P. Hesp (eds.), *Inland Dunes of North America*,
Dunes of the World, https://doi.org/10.1007/978-3-030-40498-7_2

2.1 Introduction

In the eastern United States (U.S.), the Atlantic Coastal Plain province (Fig. 2.1) extends from New York to Florida, and contains strata and sediments of Cretaceous to Quaternary age. Until recently, much of the Quaternary record in this province has been considered to be relatively sparse, consisting primarily of a few onshore lacustrine and paludal records, some beach and barrier island complexes, and some offshore sand and mud. However, with the advent of optically stimulated luminescence (OSL) dating techniques and high-resolution topographic information from Light Detection and Ranging (LiDAR) data, new studies have revealed that the Quaternary record of Atlantic Coastal Plain province is much more extensive and complex than had previously been perceived. Some of these new studies have focused on fluvial settings (e.g., Leigh 2006, 2008; Suther et al. 2011), whereas others have focused on modern coastal settings (e.g., Mallinson et al. 2008; Scott et al. 2010; Timmons et al. 2010; Parham et al. 2013; Seminack and Buynevich 2013; Peek et al. 2014). One of the more surprising revelations from these new studies is the recognition of widespread Quaternary eolian sand dunes and sand sheets of approximately synchronous age throughout many inland locations of the U.S. Atlantic Coastal Plain province (e.g., Ivester et al. 2001; Ivester and Leigh 2003; Markewich et al. 2009; Swezey et al. 2013, 2016a, b).

Inland locations of the U.S. Atlantic Coastal Plain province are not settings in which one would typically expect widespread eolian sands because the modern climate is not conducive to eolian sediment mobilization. Indeed, most of these inland Quaternary eolian sediments are stabilized by vegetation, and the dune and sand sheet morphologies have been degraded by erosion and pedogenic processes. In other words, these eolian sediments are relict features from times when conditions were different from the modern environment. Although future work will undoubtedly reveal additional locations and features, this publication provides a summary of Quaternary eolian sand dunes and sand sheets in the following four inland settings of the U.S. Atlantic Coastal Plain province: (1) river valleys; (2) the Carolina Sandhills region; (3) Carolina Bays; and (4) upland areas of the northern Atlantic Coastal Pain.

2.2 Modern Climate

From northern Delaware to northern Florida, the modern climate of the Atlantic Coastal Plain province is humid and mesothermal with little or no water deficiency during any season (climate classification of Thornthwaite 1931, 1948). During January the mean temperature varies from ~0 °C in northern Delaware to ~12 °C in northern Florida, whereas during July the mean temperature varies from ~12 °C in northern Delaware to ~30 °C in northern Florida (Fig. 2.2). Precipitation occurs throughout the year, and mean annual precipitation ranges from ~110 cm in

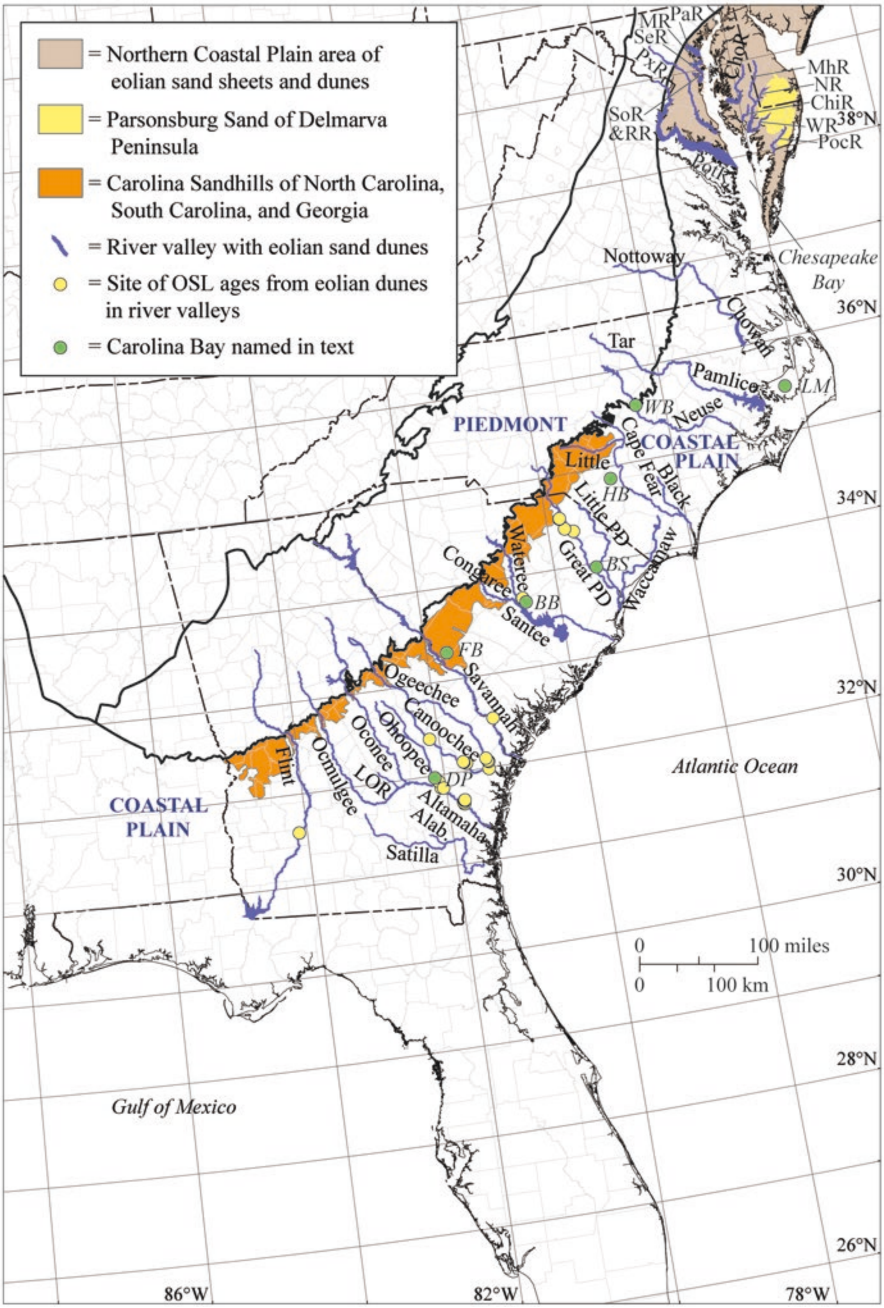


Fig. 2.1 Coastal Plain location map. The location of the Carolina Sandhills is from Griffith et al. (2001, 2002). *Alab*. Alabaha River, *BB* Big Bay, *BS* Bear Swamp, *ChiR* Chicomacomico River, *ChoR* Choptank River, *DP* Dukes Pond, *FB* Flamingo Bay, *Great PD* Great Pee Dee River, *HB* Herndon Bay, *Little PD* Little Pee Dee River, *LM* Lake Mattamuskeet, *LOR* Little Ocmulgee River, *MhR* Marsheyhope Creek, *MR* Magothy River, *NR* Nanticoke River, *PaR* Patapsco River, *PxR* Patuxent River, *PocR* Pocomoke River, *PotR* Potomac River, *RR* Rhode River, *SeR* Severn River, *SoR* South River, *WB* Wilson's Bay, *WR* Wicomico River

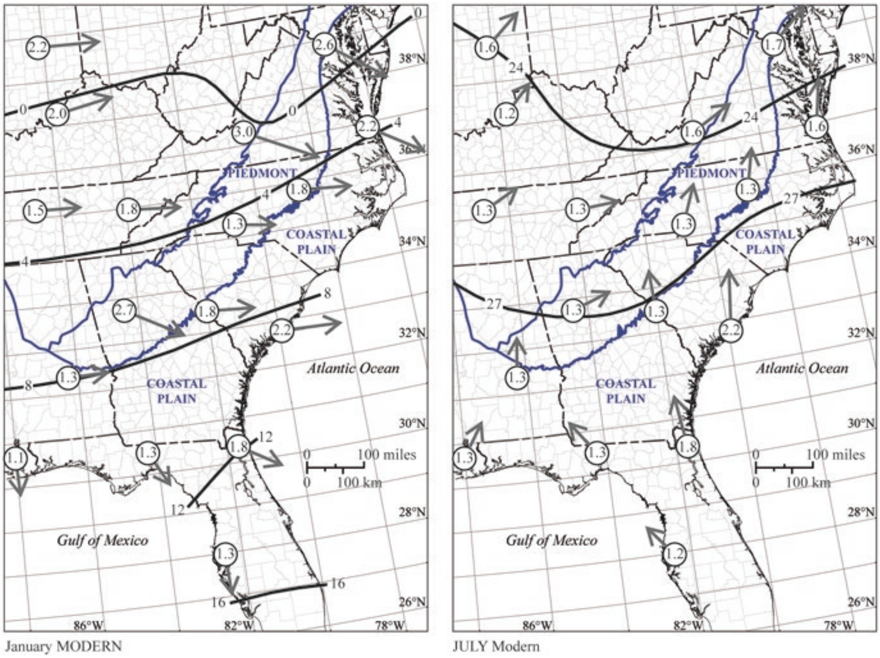


Fig. 2.2 Modern climate data of the southeastern United States. Mean temperature data in degrees Celsius are from Webb et al. (1993), and mean resultant wind data are from Baldwin (1975). The mean resultant wind is the vectorial average of all surface wind velocities and wind directions on the basis of hourly observations at a given place during the specified months for 1951–1960. The velocity of surface wind in meters per second (m/s) is written inside each circle, and is proportional to the length of the gray arrows

northern Delaware to ~140 cm in northern Florida (Fig. 2.2). Average annual free water surface (FWS) evaporation values range from ~92 cm in northern Delaware to ~122 cm in northern Florida (Farnsworth et al. 1982). Average annual potential evapotranspiration values range from ~74 cm in northern Delaware to ~107 cm in northern Florida (Fig. 2.2). These values yield ratios of annual precipitation to potential evapotranspiration (P:PE) that vary from 1.49 in northern Delaware to 1.31 in northern Florida. For reference, a P:PE ratio between 0.50 and 0.75 denotes a “sub-humid” climate in the UNESCO (1979) classification of arid regions.

The directions of surface winds in the southeastern United States vary seasonally (Fig. 2.2) and are governed primarily by the following three variables: (1) the westerlies; (2) the polar front jet stream; and (3) the Bermuda High. During winter, the westerlies and the polar front jet stream are stronger, the polar front jet stream moves to lower latitudes, and the Bermuda High is weaker (Sahsamanoglou 1990; Harman 1991; Davis et al. 1997). As a result, during winter the surface winds over the Atlantic Coastal Plain province blow predominantly from the west and west-northwest. Most precipitation during winter is frontal in association with the polar front jet stream where cold and dry continental air from Canada is in contact with warm and humid maritime air from the Gulf of Mexico (Court 1974; Soulé 1998; Katz et al. 2003). In contrast, during summer the westerlies and the polar front jet stream are weaker, the polar front jet stream moves to higher latitudes, and the Bermuda High is stronger (Sahsamanoglou 1990; Harman 1991; Davis et al. 1997). As a result, during summer the surface winds over the U.S. Atlantic Coastal Plain province blow from the south via the Bermuda High, bringing moisture to the Atlantic Coastal Plain from the Gulf of Mexico and (or) the Atlantic Ocean (Court 1974; Soulé 1998; Katz et al. 2003). Most precipitation during summer is associated with convection rather than fronts.

The mean resultant velocity of surface winds in the U.S. Atlantic Coastal Plain province is <3 m/s during any given month (Fig. 2.2), but there is some variability ("gustiness") around the mean. For example, wind velocities of 6 m/s or greater occurred ~8% of the time per whole year during the interval of 1981–2010 according to hourly data from the Metropolitan Airport at the city of Columbia, South Carolina (www.ncdc.noaa.gov; accessed 18 August 2016). In relatively warm low-latitude regions, however, typical threshold wind velocities for sustained eolian mobilization of 0.25–0.50 mm diameter quartz sand are 4–6 m/s (e.g., Hsu 1974), and therefore modern surface winds in inland locations of the Atlantic Coastal Plain province are really not sufficient for much sustained eolian sand transport.

2.3 Age Data

The age data presented in this paper were obtained by radiocarbon techniques and (or) luminescence techniques. Unless otherwise stated, the radiocarbon ages are reported in radiocarbon years (^{14}C yr) before present (BP), using the Libby half-life of 5568 years and with 0 ^{14}C year BP being equivalent to AD 1950. In contrast, the luminescence ages are reported in calibrated years (cal year) BP with 0 cal year BP being the year that a specific luminescence age was determined. The luminescence ages presented in this paper were compiled from different sources, and different authors used different statistical models to determine their best estimates of the ages. Where available, information on these different statistical models is given in Tables 2.1, 2.2, 2.3, and 2.4. For luminescence ages published for the first time in this paper (Table 2.2), the choice of statistical model that is thought to yield the most accurate age follows criteria discussed in Swezey et al. (2016b). In brief, if the dispersion was <25% (as determined by the R program radial plot, following Galbraith and Roberts 2012), then the preferred age was the age obtained by the weighted mean. If the dispersion was ≥25%, then the preferred age was the age obtained by the Minimum Age Model-3.

Table 2.1 OSL data from eolian dunes in river valleys of the U.S. Atlantic Coastal Plain province

Sample ID	References	State	River valley	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
UGA-DL-3	Leigh et al. (2004)	South Carolina	Great Pee Dee River	34.53512	−79.81282	unspec.	210–180	16.6 ± 1.8	unspec.
UGA-DL-4	Leigh et al. (2004)	South Carolina	Great Pee Dee River	34.53259	−79.81730	unspec.	190–160	20.2 ± 2.4	unspec.
UGA-DL-2	Leigh et al. (2004)	South Carolina	Great Pee Dee River	34.41460	−79.76242	26	210–180	15.0 ± 1.4	unspec.
UGA-4-SC34-Br.	Leigh (2008)	South Carolina	Great Pee Dee River	34.37303	−79.64535	unspec.	210	19.5 ± 1.8	unspec.
Wateree01	Ivester et al. (2002) and Brooks et al. (2010)	South Carolina	Wateree and Congaree Rivers	33.7900	−80.4852	64	unspec.	74.3 ± 7.1	unspec.
Wateree02	Ivester et al. (2002) and Brooks et al. (2010)	South Carolina	Wateree and Congaree Rivers	33.7866	−80.4891	69	unspec.	29.6 ± 2.4	unspec.
Wateree03	Ivester et al. (2002) and Brooks et al. (2010)	South Carolina	Wateree and Congaree Rivers	33.8008	−80.4989	72	unspec.	33.2 ± 2.8	unspec.
GAW 03a	Swezey et al. (2013)	South Carolina	Savannah River	32.49416	−81.19051	11	150	22.9 ± 1.7	Weighted
GAW 03b	Swezey et al. (2013)	South Carolina	Savannah River	32.49416	−81.19051	11	150	24.0 ± 1.2	Weighted
GAW 04a	Swezey et al. (2013)	South Carolina	Savannah River	32.49416	−81.19051	11	140	18.6 ± 0.1	MAM
GAW 04b	Swezey et al. (2013)	South Carolina	Savannah River	32.49416	−81.19051	11	140	19.1 ± 0.1	MAM
GAW05	Swezey et al. (2013)	South Carolina	Savannah River	32.54332	−81.26128	12	152	32.7 ± 2.1	Weighted
GAW06	Swezey et al. (2013)	South Carolina	Savannah River	32.54423	81.26348	12	148	32.9 ± 2.5	Weighted

GAW07	Swezey et al. (2013)	South Carolina	Savannah River	32.54423	−81.26348	12	20	24.1 ± 1.5	Weighted
GAW08	Swezey et al. (2013)	South Carolina	Savannah River	32.52192	−81.23143	12	96	30.8 ± 1.6	Weighted
GAW09	Swezey et al. (2013)	South Carolina	Savannah River	32.49084	−81.19570	9	78	21.5 ± 1.3	Weighted
GAW10	Swezey et al. (2013)	South Carolina	Savannah River	32.48911	−81.18024	8	40	31.3 ± 1.8	Weighted
GAW11	Swezey et al. (2013)	South Carolina	Savannah River	32.48457	−81.20333	9	60	10.2 ± 0.7	MAM
GAW12	Swezey et al. (2013)	South Carolina	Savannah River	32.42373	−81.15730	8	80	19.2 ± 1.2	Weighted
GAW13	Swezey et al. (2013)	South Carolina	Savannah River	32.43740	−81.14857	8	90	10.3 ± 0.7	Weighted
GAW30	Swezey et al. (2013)	South Carolina	Savannah River	32.55597	−81.27906	8	549	30.5 ± 2.2	Weighted
GAW36	Swezey et al. (2013)	South Carolina	Savannah River	32.50996	−81.22414	11	82	23.3 ± 1.9	Weighted
Dalhousie-DL17	Leigh (2008)	Georgia	Ogeechee River	32.09682	−81.37651	unspec.	210–185	45.3 ± 6.7	unspec.
Dalhousie-DL15	Leigh (2008)	Georgia	Ogeechee River	32.06689	−81.35625	unspec.	195	37.5 ± 2.8	unspec.
Dalhousie-DL18	Leigh (2008)	Georgia	Ogeechee River	32.05596	−81.34448	unspec.	210–185	31.4 ± 5.9	unspec.
Dalhousie-AI-22	Ivester et al. (2001)	Georgia	Canoochee River	32.38440	−82.12426	unspec.	350	24.3 ± 3.3	unspec.
Dalhousie-AI-4	Ivester et al. (2001)	Georgia	Canoochee River	32.08542	−81.68432	21	257–233	26.6 ± 2.3	unspec.
Dalhousie-AI-5	Ivester et al. (2001)	Georgia	Canoochee River	32.08001	−81.67687	unspec.	277–253	32.8 ± 3.3	unspec.
Dalhousie-AI-3	Ivester et al. (2001)	Georgia	Canoochee River	32.06734	−81.64418	19	200	25.8 ± 1.2	unspec.

(continued)

Table 2.1 (continued)

Sample ID	References	State	River valley	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
Dalhousie-AI-2	Ivester et al. (2001)	Georgia	Canoochee River	32.06552	−81.64565	20	201–183	29.9 ± 6.2	unspec.
Dalhousie-DL10	Leigh (2008)	Georgia	Canoochee River	31.97694	−81.35153	unspec.	200–175	34.0 ± 2.6	unspec.
Dalhousie-AI-18	Ivester et al. (2001)	Georgia	Ohoopee River	31.95195	−82.09706	52	177–153	77.4 ± 6.6	unspec.
Dalhousie-AI-15	Ivester et al. (2001)	Georgia	Ohoopee River	31.94299	−82.10378	32	127–103	23.6 ± 5.4	unspec.
UGA-BH-2	Leigh et al. (2004)	Georgia	Altamaha River	31.86451	−82.04860	25	210–180	18.6 ± 1.9	unspec.
UGA-BH5.2	Leigh et al. (2004)	Georgia	Altamaha River	31.86882	−82.08279	25	210–180	17.6 ± 2.6	unspec.
Dalhousie-AI-9	Ivester et al. (2001)	Georgia	Altamaha River	31.70031	−81.78545	16	227–203	45.0 ± 7.4	unspec.
Dalhousie-AI-11	Ivester et al. (2001)	Georgia	Altamaha River	31.69402	−81.79448	16	227–203	38.1 ± 5.0	unspec.
Dalhousie-AI-10	Ivester et al. (2001)	Georgia	Altamaha River	31.67538	−81.80657	16	235–225	4.9 ± 0.5	unspec.
Dalhousie-AI-12	Ivester et al. (2001)	Georgia	Altamaha River	31.67307	−81.80575	17	250	20.9 ± 1.2	unspec.
Dalhousie-AI-13	Ivester et al. (2001)	Georgia	Altamaha River	31.65689	−81.79436	14	250	16.2 ± 2.0	unspec.
Dalhousie-AI-6	Ivester et al. (2001)	Georgia	Flint River	31.57104	−84.13042	74	200	8.6 ± 0.9	unspec.
Dalhousie-AI-7	Ivester et al. (2001)	Georgia	Flint River	31.57104	−84.13042	74	325	15.8 ± 1.7	unspec.
Dalhousie-AI-8	Ivester et al. (2001)	Georgia	Flint River	31.56852	−84.13158	66	460	17.5 ± 1.7	unspec.

DEPTH Depth below land surface at which OSL sample was collected, *ELEV* elevation of land surface, *LAT* latitude, *LONG* longitude, *MAM* Minimum Age Model-3 (Galbraith and Laslett 1993; Galbraith et al. 1999), *Weighted* age in thousands of years (ka) ago using the weighted mean OSL value for equivalent dose (DE) determinations (similar to the Central Age Model of Galbraith et al. 1999), *unspec.* unspecified

Table 2.2 OSL data from eolian sand in the Carolina Sandhills region of the U.S. Atlantic Coastal Plain province

Sample ID	References	State	Site descript.	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
UGA-DB-TU4-90	Leigh (2008)	North Carolina	Bogwater, Fort Bragg	35.12665	−79.22776	unspec.	90	22.7 ± 5.9	unspec.
UGA-DB-TU4-153	Leigh (2008)	North Carolina	Bogwater, Fort Bragg	35.12665	−79.22776	unspec.	153	24.1 ± 6.1	unspec.
USGS1585	Swezey et al. (2016)	South Carolina	Site 3	34.56355	−80.13365	113	47–42	10.2 ± 0.8	MAM3
USGS1586	Swezey et al. (2016)	South Carolina	Site 3	34.56355	−80.13365	113	70–65	24.1 ± 2.2	MAM3
USGS1588	Swezey et al. (2016)	South Carolina	Site 5	34.56355	−80.10430	125	42	9.4 ± 0.8	Weighted
USGS1589	Swezey et al. (2016)	South Carolina	Site 5	34.56355	−80.10430	125	85	19.3 ± 1.6	MAM3
USGS1642	Swezey et al. (2016)	South Carolina	Site 4	34.55686	−80.12839	119	200	46.3 ± 3.1	MAM3
USGS1643	Swezey et al. (2016)	South Carolina	Site 4	34.55686	−80.12839	119	60	25.5 ± 2.3	MAM3
USGS1715	Swezey et al. (2016)	South Carolina	Site 6	34.62072	−80.05958	76	210	39.8 ± 2.7	MAM3
USGS1716	Swezey et al. (2016)	South Carolina	Site 6	34.62072	−80.05958	76	250	69.6 ± 5.6	Weighted
USGS1717	Swezey et al. (2016)	South Carolina	Site 6	34.62072	−80.05958	76	250	53.7 ± 5.1	MAM3
USGS1718	Swezey et al. (2016)	South Carolina	Site 2	34.52557	−80.22427	122	40	7.0 ± 0.9	MAM3
USGS1719	Swezey et al. (2016)	South Carolina	Site 2	34.52557	−80.22427	122	145	48.9 ± 7.7	Weighted

(continued)

Table 2.2 (continued)

Sample ID	References	State	Site descript.	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
USGS1720	Swezey et al. (2016)	South Carolina	Site 1	34.62237	−80.23235	125	90	49.8 ± 3.7	Weighted
USGS1721	Swezey et al. (2016)	South Carolina	Site 1	34.62237	−80.23235	125	160	9.2 ± 0.6	Weighted
USGS1722	Swezey et al. (2016)	South Carolina	Site 1	34.62237	−80.23235	125	210	10.9 ± 0.6	MAM3
USGS GAW-35	Previously unpublished	South Carolina	White Pond Dune	34.16364	−80.77531	91	90	92.3 ± 5.2	Weighted

DEPTH Depth below land surface at which OSL sample was collected, *ELEV* elevation of land surface, *LAT* latitude, *LONG* longitude, *MAM* Minimum Age Model-3 (Galbraith and Laslett 1993; Galbraith et al. 1999), *Weighted* age in thousands of years (ka) ago using the weighted mean OSL value for equivalent dose (DE) determinations (similar to the Central Age Model of Galbraith et al. 1999), *unspec.* unspecified

Table 2.3 OSL data from sand ridges of Carolina Bays in the U.S. Atlantic Coastal Plain province

Sample ID	References	State	Carolina Bay Name	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
UW2786 (core 1)	Moore et al. (2016)	North Carolina	Herndon Bay	34.8603	−78.9391	50.8	180–200	27.2 ± 2.8	CAM
UW2787 (core 2)	Moore et al. (2016)	North Carolina	Herndon Bay	34.8602	−78.9377	52.3	300–330	29.6 ± 3.1	CAM
UW2788 (core 4)	Moore et al. (2016)	North Carolina	Herndon Bay	34.8599	−78.9354	52.1	160–190	36.7 ± 4.1	LC
unspec.	Ivester et al. (2003) and Brooks et al. (2010)	South Carolina	Big Bay	33.7676	−80.4590	58	60–75	2.1 ± 0.3	unspec.
unspec.	Ivester et al. (2003) and Brooks et al. (2010)	South Carolina	Big Bay	33.7661	−80.4584	58	60–75	11.2 ± 0.9	unspec.
unspec.	Ivester et al. (2003) and Brooks et al. (2010)	South Carolina	Big Bay	33.7654	−80.4647	58	60–75	25.2 ± 1.9	unspec.
unspec.	Ivester et al. (2003) and Brooks et al. (2010)	South Carolina	Big Bay	33.7709	−80.4798	59	60–75	35.7 ± 2.6	unspec.
unspec.	Ivester et al. (2003) and Brooks et al. (2010)	South Carolina	Unnamed bay near Big Bay	33.7643	−80.4683	59	60–75	20.4 ± 1.6	unspec.
unspec.	Moore et al. (2012)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	35	5.0 ± 0.5	MAM
unspec.	Moore et al. (2012)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	50	9.2 ± 1.0	MAM
unspec.	Moore et al. (2012)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	65	11.5 ± 1.3	MAM
unspec.	Moore et al. (2012)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	78	15.5 ± 1.8	MAM
unspec.	Moore et al. (2012)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	95	13.1 ± 1.7	MAM

(continued)

Table 2.2 (continued)

Sample ID	References	State	Carolina Bay Name	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
unspec.	Ivester et al. (2002) and Brooks et al. (2010)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	unspec.	108.7 ± 10.9	unspec.
unspec.	Ivester et al. (2002) and Brooks et al. (2010)	South Carolina	Flamingo Bay	unspec.	unspec.	unspec.	unspec.	40.3 ± 4.0	unspec.
unspec.	Ivester et al. (2002) and Brooks et al. (2010)	South Carolina	Bay-40 (SRS 40)	unspec.	unspec.	unspec.	unspec.	77.9 ± 7.6	unspec.

CAM Central Age Model, *DEPTH* Depth below land surface at which OSL sample was collected, *ELEV* elevation of land surface, *LAT* latitude, *LC* Largest Component, *LONG* longitude, *MAM* Minimum Age Model-3 (Galbraith and Laslett 1993; Galbraith et al. 1999), *unspec.* unspecified

Table 2.4 OSL data from eolian dunes on upland areas of the northern Atlantic Coastal Plain province

Sample ID	Reference	Location	Site descript.	LAT (North)	LONG (West)	ELEV (m)	DEPTH (cm)	AGE (ka)	Preferred age model
UIC2020BL	Lowery et al. (2010)	Miles Point, Maryland	Tilghman Soil	unspec.	unspec.	unspec.	85	27.9 ± 1.6	unspec.
UIC2019BL	Lowery et al. (2010)	Miles Point, Maryland	Tilghman Soil	unspec.	unspec.	unspec.	90	29.5 ± 1.7	unspec.
UIC2014BL	Lowery et al. (2010)	Miles Point, Maryland	Miles Point Loess	unspec.	unspec.	unspec.	135	34.8 ± 2.0	unspec.
UIC2013BL	Lowery et al. (2010)	Miles Point, Maryland	Miles Point Loess	unspec.	unspec..	unspec.	137	40.9 ± 2.4	unspec.
UIC2013BL	Lowery et al. (2010)	Miles Point, Maryland	Pre-Loess Sequum	unspec.	unspec.	unspec.	148	41.1 ± 2.4	unspec.
UIC2013BL	Lowery et al. (2010)	Miles Point, Maryland	Pre-Loess Sequum	unspec.	unspec.	unspec.	161	40.6 ± 2.7	unspec.
UGA07 OSL-512	Markewich et al. (2009)	Brandywine2, Maryland	unspec.	38.66106	−76.86119	unspec.	66	19.2 ± 2.7	MEAN
UGA07 OSL-472	Markewich et al. (2009)	Fenwick, Maryland	Dune	38.64756	−77.10817	unspec.	unspec.	26.7 ± 3.1	MEAN
UGA07 OSL-479	Markewich et al. (2009)	Goose Bay, Maryland	Dune	38.51428	−77.26185	unspec.	183	30.4 ± 4.0	MEAN
UGA07 OSL-514	Markewich et al. (2009)	Goose Bay, Maryland	Dune	38.51428	−77.26185	unspec.	305	24.4 ± 4.1	MEAN
UGA07 OSL-478	Markewich et al. (2009)	Chapman Landing, Maryland	unspec.	38.62139	−77.11917	unspec.	unspec.	27.0 ± 3.3	MEAN
Pedon VA1	Feldman et al. (2000)	Pedon VA1, Virginia	Loess	38.68786	−77.31222	97	<51	13.8 ± 1.0	TL

DEPTH Depth below land surface at which OSL sample was collected, *ELEV* elevation of land surface, *LAT* latitude, *LONG* longitude, *MEAN* age in thousands of years (ka) ago using the mean OSL value for equivalent dose (DE) determinations, *TL* Thermoluminescence date, *unspec.* unspecified

2.4 Descriptions of Eolian Dunes and Sand Sheets

Vegetated (stabilized) eolian dunes and sand sheets of Quaternary age are found in many settings throughout inland locations of the U.S. Atlantic Coastal Plain province. These eolian sediments may be divided into the following four categories according to geographic location: (1) in river valleys; (2) in the Carolina Sandhills region; (3) adjacent to Carolina Bays; and (4) on upland areas of the northern Atlantic Coastal Plain.

2.4.1 Eolian Dunes in River Valleys

Vegetated (stabilized) eolian sand dunes are present within numerous river valleys in the U.S. Atlantic Coastal Plain province (Fig. 2.1). At the time of this writing, such dunes have been identified in river valleys of all of the eastern coastal states from Delaware to Georgia. On the Delmarva Peninsula (Delaware, Maryland, Virginia), eolian dunes are present in the valleys of the Choptank River, Chicamacomico River, Marsheyhope Creek, Nanticoke River, Wicomico River, and Pocomoke River (Denny and Owens 1979; Denny et al. 1979; Newell and DeJong 2011; Markewich et al. 2015), and on the east side of the Potomac River/Chesapeake Bay in Virginia (Mixon 1985). Elsewhere in Maryland, eolian dunes and (or) sand sheets are present in the valleys of the Patapsco River, Magothy River, Severn River, South River, Rhode River, Potomac River, and Patuxent River (Hack 1955; Markewich et al. 2009; Newell and DeJong 2011). On the mainland part of Virginia, eolian dunes are present in the valley of the Nottoway River (Powars et al. 2016). In North Carolina, eolian dunes are present in the valleys of the Chowan River, Tar River, Pamlico River, Neuse River, Black River, Little River, and Cape Fear River (Daniels et al. 1969; Thom 1970; Miller 1979; Soller 1988; Markewich and Markewich 1994; Markewich et al. 2015). In South Carolina, eolian dunes are present in the valleys of the Little Pee Dee River, Great Pee Dee River, Waccamaw River, Wateree River, Congaree River, Santee River, and Savannah River (Daniels et al. 1969; Thom 1970; Pickering and Jones 1974; Markewich and Markewich 1994; Brooks et al. 2010; Swezey et al. 2013). In Georgia, eolian dunes are present in the valleys of the Ogeechee River, Canoochee River, Ohoopee River, Little Ohoopee River, Oconee River, Ocmulgee River, Little Ocmulgee River, Altamaha River, Alabaha River, Satilla River, and Flint River (Thom 1970; Pickering and Jones 1974; Markewich and Markewich 1994; Ivester et al. 2001; Ivester and Leigh 2003).

In most publications, eolian dunes in river valleys of the Atlantic Coastal Plain are identified as sand of Quaternary age, but a formal stratigraphic formation name is not applied to the dunes. On the Delmarva Peninsula, however, both eolian sand dunes within river valleys and eolian sand dunes and sand sheets on upland terraces are mapped as the Quaternary Parsonsburg Sand (Denny and Owens 1979; Denny et al. 1979). Because the reference locality for the Parsonsburg Sand is located in an upland area of the Delmarva Peninsula (test hole Wi-Bg 11 at the north end of Parsonsburg Ridge, Wicomico County, Maryland; Rasmussen and Slaughter 1955), it is not appropriate to apply the Parsonsburg Sand nomenclature to the river valley sand dunes that have a discontinuous distribution from Delaware to Georgia. In other words, it is better to restrict the name Parsonsburg Sand to eolian sand in upland areas of the Delmarva Peninsula.

Despite their discontinuous distribution, eolian dunes in the river valleys show some consistent patterns with respect to geographic and stratigraphic location. For example, the eolian dunes are located on the east side of the modern river channels (Pickering and Jones 1974; Carver and Brook 1989; Markewich and Markewich 1994; Ivester and Leigh 2003; Swezey et al. 2013). An excellent example of such dunes is present in the valley of the Savannah River, Jasper County, South Carolina (Fig. 2.3). With respect to stratigraphic location, the eolian dunes in river valleys are located above unconformities on terraces within their respective valleys. Depending upon location, these terraces are composed of either (1) Quaternary sand, mud, and (or) peat of fluvial and paludal origin; or (2) pre-Quaternary sand and (or) mud upon which a paleosol has developed (Ivester and Leigh 2003; Swezey et al. 2013).

In many river valleys, the eolian dunes occur as groups of dunes or dune fields that are elongate parallel to the rivers. On the Delmarva Peninsula the linear ridges of eolian sand may be as much as 5 m high and up to 5 km long (Denny and Owens 1979), whereas in Georgia the linear ridges may be 2–14 m high and 6 to >100 km long (Ivester and Leigh 2003). At some locations, the eolian dunes in river valleys form multiple linear ridges that are parallel to the modern river channel. In river valleys where multiple eolian dune ridges are present, the western ridges typically have morphologies that are more distinct and regular (Ivester and Leigh 2003).

Many of the individual dunes in river valleys have parabolic shapes or infilled parabolic shapes, and the orientations of these dunes show a predictable geographic variability. In Maryland and Delaware, the tails of parabolic dunes point northwest (Denny and Owens 1979; Denny et al. 1979; Carver and Brook 1989; Markewich et al. 2009). In contrast, in North Carolina, South Carolina, and Georgia, the tails of parabolic dunes point west or southwest (Thom 1970; Carver and Brook 1989; Ivester and Leigh 2003; Swezey et al. 2013).

The height (sand thickness) of individual eolian dunes in river valleys generally increases towards the south. Specifically, dune height is typically 5 m or less in Virginia, Delaware, and Maryland, 2–10 m in North Carolina and South Carolina, and 2–14 m in Georgia. On the Delmarva Peninsula in Delaware and Maryland, eolian dunes in river valleys are either parabolic forms up to 1 m high or linear ridges up to 5 m high (Hack 1955; Denny et al. 1979; Denny and Owens 1979). On the Delmarva Peninsula in Virginia, however, some larger eolian dunes (6–15 m high) form linear and arcuate dune fields as much as 0.5 km wide and 3 km long parallel to the Chesapeake Bay shoreline (Mixon 1985). Farther south in North Carolina, eolian dune height is typically 1–7 m in the valley of the Cape Fear River (Soller 1988) and up to 5 m in the valley of the Neuse River (Daniels et al. 1969). In South Carolina, eolian dune height is up to 5 m in the valleys of the Great Pee Dee

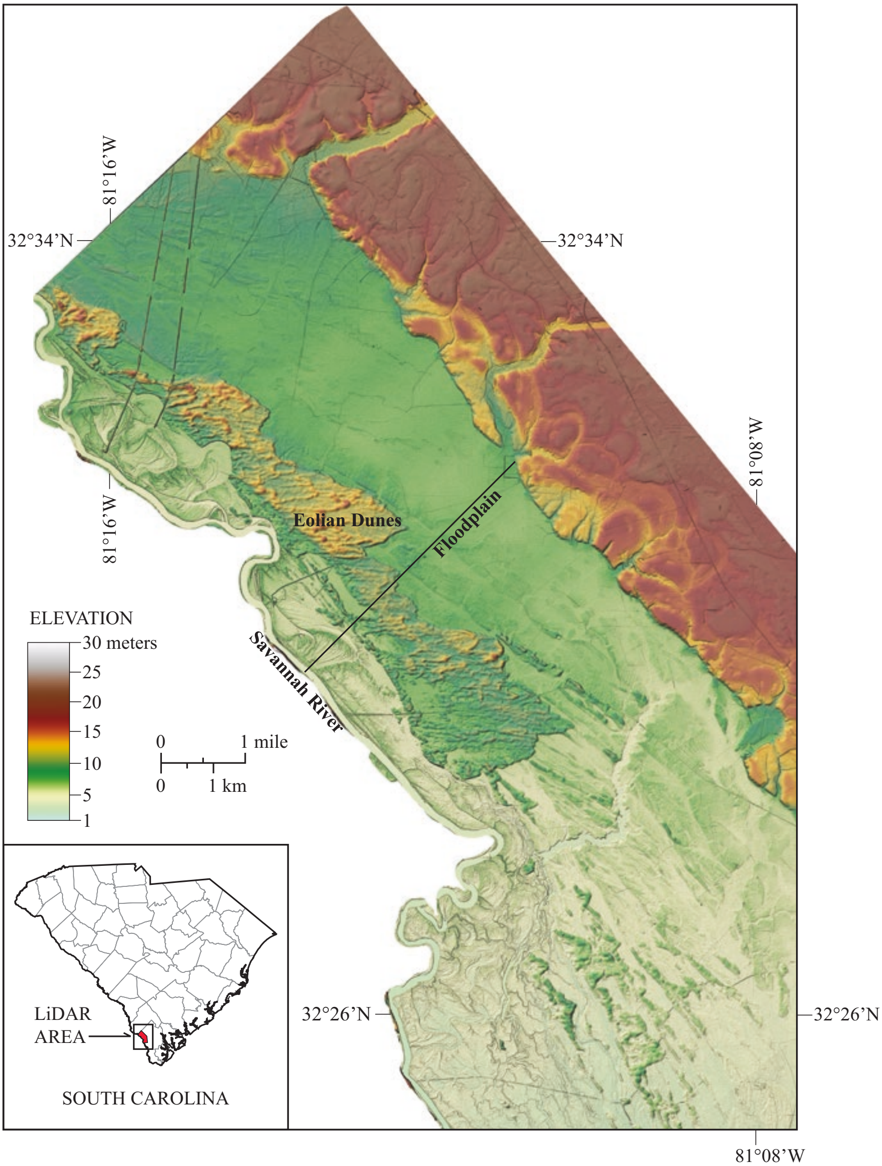


Fig. 2.3 LiDAR image of eolian dunes in the valley of the Savannah River, Jasper County, South Carolina (modified from Swezey et al. 2013). These dunes are located ~50–70 km inland from the coast, on the east side of the modern river channel. Elevations are given relative to sea level

River and Little Pee Dee River (Thom 1970), and 1–10 m in the valley of the Savannah River (Swezey et al. 2013). In Georgia, eolian dune height is 4–12 m in the valley of the Flint River (Ivester and Leigh 2003), 8 m in the valley of the Satilla River (Markewich and Markewich 1994), and 4–14 m in the valley of the Altamaha River (Ivester and Leigh 2003). Eolian dune height is typically 2–5 m in the valley of the Ohoopee River, and 2–4 m in the valley of the Canoochee River (Ivester et al. 2001; Ivester and Leigh 2003).

The eolian dunes in river valleys display many similarities with respect to grain size, sorting, and composition (Pickering and Jones 1974; Denny et al. 1979; Soller 1988; Markewich and Markewich 1994; Ivester and Leigh 2003; Swezey et al. 2013). Most dunes are composed of 95–100% sand and 0–5% mud, and the sand size is predominantly fine to medium sand. The eolian dune sand is typically moderately sorted to well sorted (following terminology of Folk and Ward 1957). Sand composition is typically 95–100% quartz, 0–5% feldspar (although feldspar content is usually <1%), and < 1% mica and opaque minerals. Most of the quartz sand grains have roundness values that range from subangular to rounded, and sphericity values that range from high sphericity to low sphericity (following terminology of Powers 1953).

Most eolian dunes in river valleys do not display obvious sedimentary structures, except for bioturbation by plant roots. However, large cross-bedding, parallel laminations, reactivation surfaces, and buried paleosols have been reported from some eolian dunes in the river valleys of Georgia (Ivester and Leigh 2003). Likewise, east-dipping cross-bedding has been reported from eolian dunes in the valley of the Congaree River in South Carolina (Johnson 1961), and cross-bedding has also been reported from eolian dunes in the valley of the Great Pee Dee River in South Carolina (Thom 1970).

Forty-six OSL ages have provided an absolute chronology for eolian sand dunes within river valleys of South Carolina and Georgia (Table 2.1, Fig. 2.4). These OSL ages range from circa (ca.) 54–5 thousand years ago (ka), although most of the ages range from ca. 35–15 ka. Only two ages are younger than 11 ka, and these two ages are from river valleys in southern Georgia. No OSL ages from eolian dunes in river valleys are younger than ca. 5 ka.

2.4.2 Eolian Dunes and Sand Sheets of the Carolina Sandhills

The Carolina Sandhills, which has long been recognized as a distinct geomorphologic province (e.g., Holmes 1893), is a 15–60 km wide physiographic region that extends ~700 km from the western border of Georgia across South Carolina to central North Carolina along the updip (inland) part of the Atlantic Coastal Plain province (Fig. 2.1). As described by Swezey et al. (2016b), the region is characterized by: (1) vegetated (stabilized) eolian sand dunes and sand sheets that are mapped as the Quaternary Pinehurst Formation; and (2) outcrops of Cretaceous strata consisting of sand, slightly indurated sandstone, conglomerate, and mud. The region is also

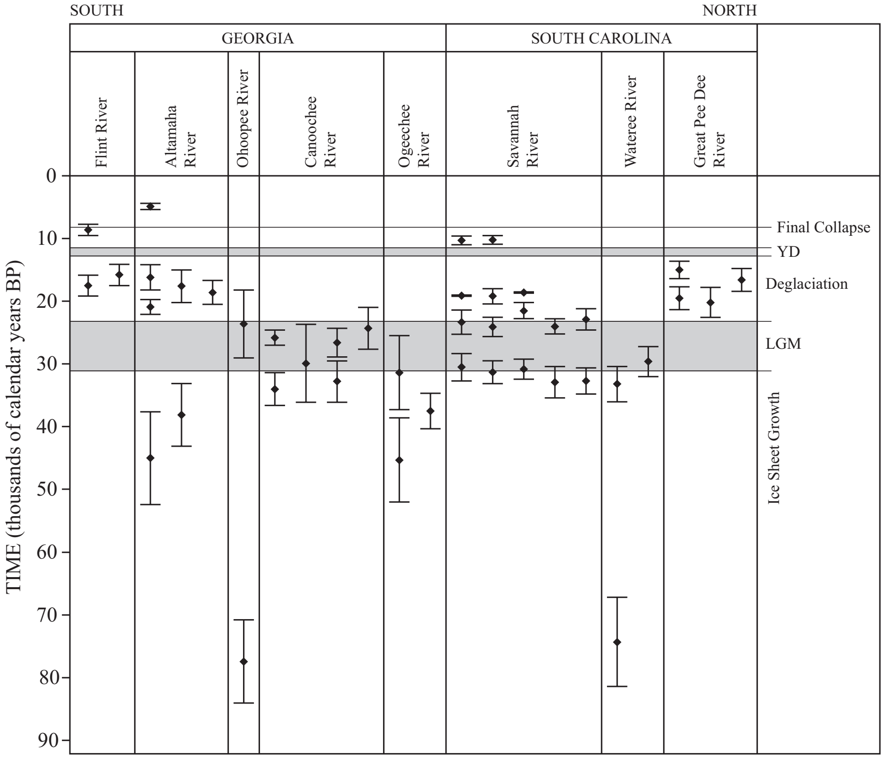


Fig. 2.4 OSL ages from eolian dunes in river valleys of the U.S. Atlantic Coastal Plain province. *LGM* Last glacial maximum, *YD* Younger Dryas event, *Final Collapse* Final collapse of the Laurentide Ice Sheet. Detailed age data are given in Table 2.1

notable for supporting an endangered ecosystem of longleaf pine (*Pinus palustris*) and wiregrass (*Aristida stricta*) that is maintained by frequent low-intensity fires (Earley 2004; Askins 2010).

The geology of the Carolina Sandhills has been studied in greatest detail in Chesterfield County, South Carolina (Fitzwater 2016; Swezey et al. 2016a, b). In this area, the Carolina Sandhills region is a relatively high plateau that is bounded to the west by Paleozoic schist of the Piedmont province and bounded to the east by the east-facing Orangeburg Scarp (Fig. 2.5), which is interpreted as having formed by marine wave erosion during the middle Pliocene (Dowsett and Cronin 1990). Throughout this area, Quaternary eolian sand (Pinehurst Formation) is present above an unconformity that caps the Cretaceous Middendorf Formation, which is a unit of sand, sandstone, conglomerate, and mud. Relief on this unconformity ranges up to 5 m in places, and the immediately underlying Cretaceous strata display pedogenic mottling and other paleosol characteristics.

In Chesterfield County, the Quaternary eolian sand (Pinehurst Formation) forms both dunes and sand sheets (Fitzwater 2016; Swezey et al. 2016a, 2016b). At most

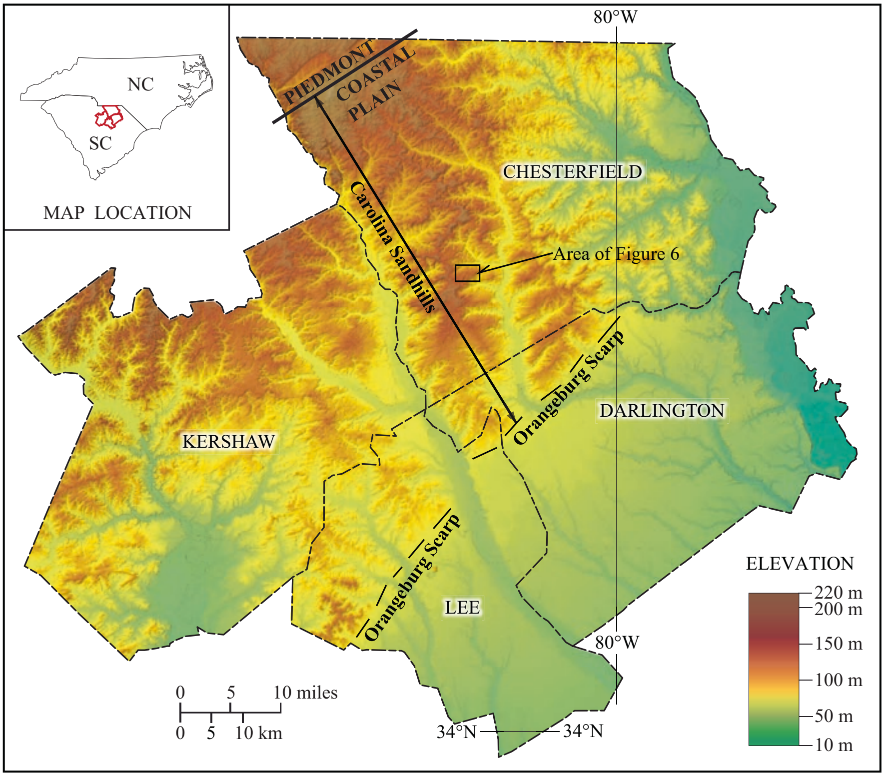


Fig. 2.5 LiDAR image of four counties in northern South Carolina, showing the Carolina Sandhills region in the inland (updip) part of the Coastal Plain province (modified from Swezey et al. 2016b). In this area, the Carolina Sandhills region is bounded on the west by the Piedmont province and is bounded on the east by the Orangeburg Scarp. Elevations are given relative to sea level

locations the sand is <2 m thick and forms a sand sheet of low relief, but in areas of higher elevation the sand can be up to 10 m thick and can form subdued hills of up to 6 m relief with steeper sides on the east and southeast (Fig. 2.6). The sand is grayish orange (10 YR 7/4; color nomenclature of Goddard et al. 1963). Grain sizes range from fine (lower) sand to coarse (lower) sand, but the most frequently occurring grain size of individual samples ranges from medium (upper) to coarse (lower) sand (0.35–0.59 mm diameter). Sorting values (σ_ϕ) range from moderately sorted to poorly sorted. The sand-size grains consist predominantly of quartz (99%) with 1% mica and opaque minerals. Most of the quartz grains of medium sand size and coarser are subrounded to subangular, ranging from high sphericity to low sphericity. Exposures of the sand display evidence of bioturbation by vegetation (plant roots), and pedogenic features such as soil lamellae and argillic horizons. Exposures do not display primary sedimentary structures, although ground-penetrating radar

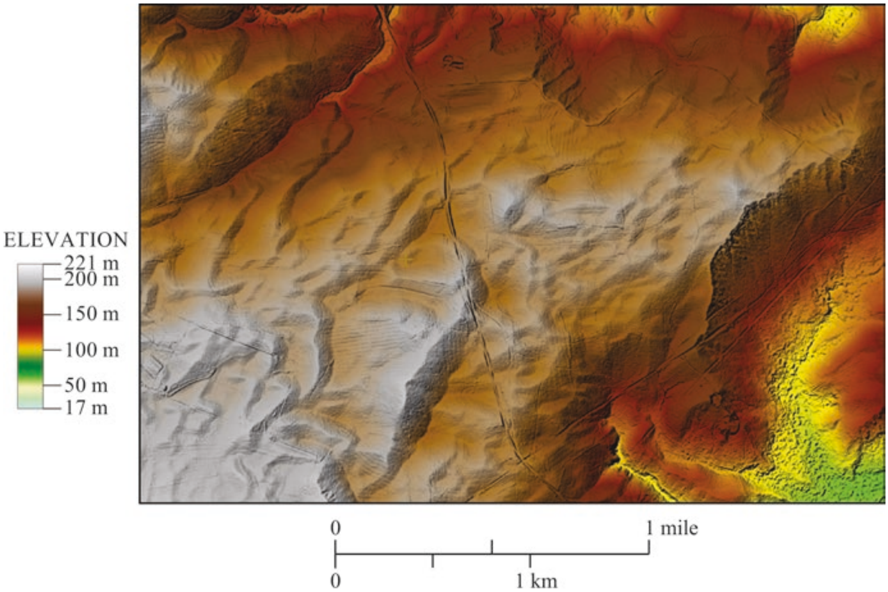


Fig. 2.6 Detailed LiDAR image showing eolian dune morphology in the Carolina Sandhills region, Chesterfield County, South Carolina (from Swezey et al. 2016b). Elevations are given relative to sea level

(GPR) traverses have revealed 2–5-m thick sets of southeast-dipping cross-bedding at depths below 2 m.

The thickness of the eolian sand (Pinehurst Formation) displays great variability across South Carolina. In contrast with Chesterfield County where the sand reaches a thickness of 10 m, in western Lexington County the sand can be up to 24 m thick (Doar and Howard 2010). In these Lexington County locations, exposures of the sand display cross-bedding, wind ripple laminations, deformed bedding, and paleosols with organic matter.

OSL data from the sand of the Pinehurst Formation have yielded Quaternary ages (Table 2.2, Fig. 2.7). Fourteen OSL ages have been obtained from the Pinehurst Formation in Chesterfield County of South Carolina (Swezey et al. 2016b), one OSL age (published here for the first time) has been obtained from an eolian sand dune on the south side of White Pond in Kershaw County of South Carolina, and two OSL ages have been reported from an eolian sand dune within the Carolina Sandhills at Fort Bragg in Cumberland County, North Carolina (Leigh 2008). Most of these OSL ages range from ca. 42–9 ka, although the full range of reported ages is ca. 98–6 ka. At the older end of the age spectrum, the OSL age of 92.3 ± 5.2 ka from White Pond is the oldest age yet obtained from the Pinehurst Formation. No reported OSL ages from the Pinehurst Formation are younger than ca. 6 ka.

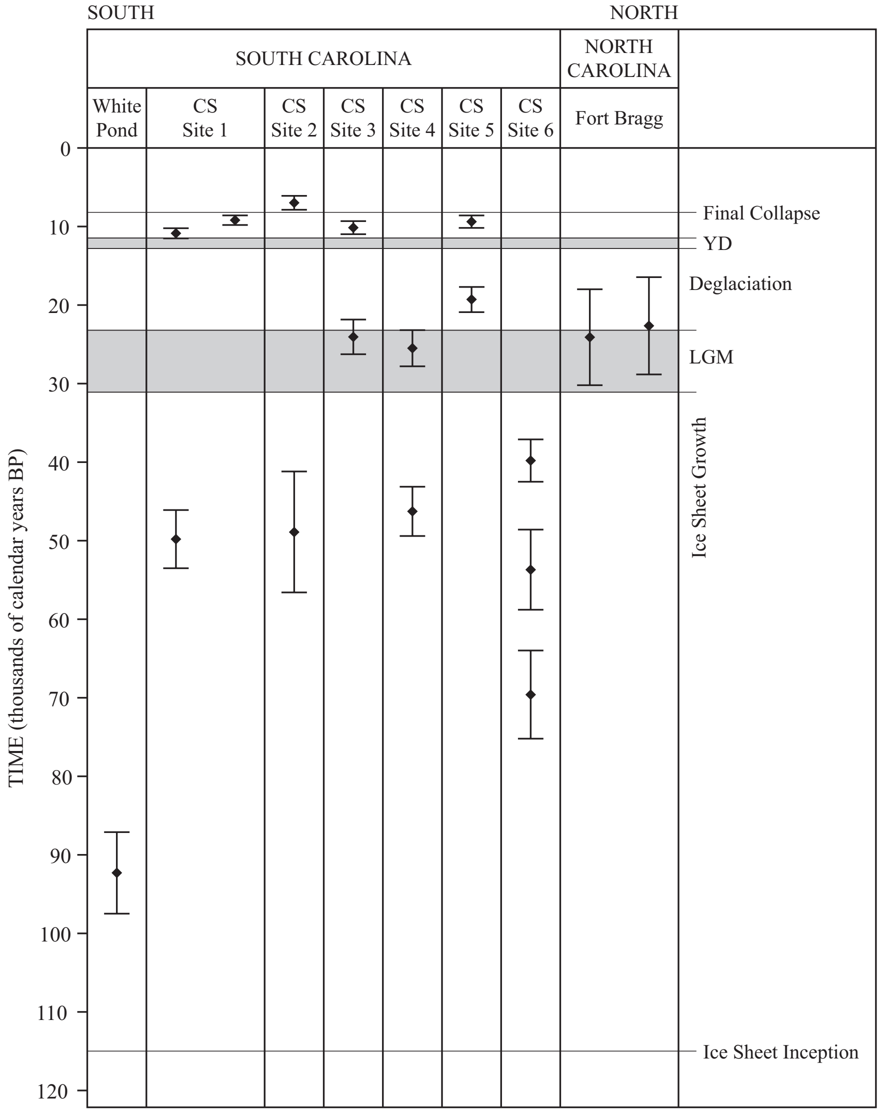


Fig. 2.7 OSL ages from the Carolina Sandhills region of the U.S. Atlantic Coastal Plain province. *LGM* Last glacial maximum, *YD* Younger Dryas event, *Final Collapse* Final collapse of the Laurentide Ice Sheet. Detailed age data are given in Table 2.2

2.4.3 *Eolian Dunes Associated with Carolina Bays*

Oriented low-relief oval depressions referred to as "Carolina Bays" are present throughout most of the U.S. Atlantic Coastal Plain province, and arcuate ridges (referred to as "sand ridges" or "sand rims") of sand (interpreted as eolian and lacustrine deposits) are present on the south and east margins of many of these depressions (e.g., Glenn 1895; Melton and Schriever 1933; Prouty 1952; Thom 1970; Bliley and Pettry 1979; Stolt and Rabenhorst 1987a, b; Bliley and Burney 1988; Grant et al. 1998; Moore et al. 2016). The Carolina Bays are situated on different geomorphologic surfaces of the coastal plain, although they are not present in recent sediments at the modern coast. Some Carolina Bays are isolated features, whereas others exhibit cross-cutting and nested relations whereby one Carolina Bay cuts across other Carolina Bays. Most Carolina Bays range from a few hundred meters to ~12 km across their long axis, and have relief ranging from 1–3 m (not including the sand ridges). Prouty (1952) estimated that there are ~500,000 Carolina Bays in the Atlantic Coastal Plain province extending over an area of ~83,000 square miles from southern New Jersey to northern Florida. Carolina Bays are especially abundant to the east of the Orangeburg Scarp in South Carolina and adjacent areas of North Carolina and Georgia. In this region, most Carolina Bays are oval with an NW-SE orientation, and many are occupied by ponds. Farther south in Georgia, Carolina Bays are less abundant and many are circular rather than oval.

Carolina Bays are primarily surficial features that do not have much of a subsurface expression. In a publication about several Carolina Bays in North Carolina, Gamble et al. (1977, p. 199) stated, "Power auger drilling indicates that the bedding and sediments underlying a bay are undisturbed." Subsurface studies with cores and augers of numerous Carolina Bays have revealed that they consist of a few meters of sand and (or) muddy sand that overlie an unconformity on an older fine-grained substrate that does not show any sign of disturbance or interruption (Thom 1970; Gamble et al. 1977; Bliley and Burney 1988; Rodríguez et al. 2012). The nature of the underlying substrate varies from location to location, but specific identified substrates include Pleistocene clay (Gamble et al. 1977; Rodríguez et al. 2012), saprolite that formed from felsic gneiss (Bliley and Burney 1988), sandy clay of the Pliocene Duplin Formation (Brooks et al. 2001), marl and shell-bearing limestone of the Pliocene Duplin Formation? (Thom 1970), Eocene sandy silt and clay (Brooks et al. 1996), and mud of the Cretaceous Black Creek Formation (Moore et al. 2016).

In North Carolina, detailed descriptions have been published for the following three Carolina Bays: (1) Lake Mattamuskeet; (2) Wilson's Bay; and (3) Herndon Bay. OSL samples from the sand ridges of Herndon Bay have yielded ages ranging from ca. 37–27 ka (Table 2.3).

Lake Mattamuskeet (Hyde County, North Carolina; Fig. 2.1) is a conglomeration of multiple Carolina Bays that form a lake. According to Rodríguez et al. (2012), the eastern margin of the lake is a 2.9–km-wide plain with several parabolic sand ridges that exhibit relief of ca. 0.5–2.0 m. The taller ridges are located farther to the east. Cores from the bay and from the sand ridges have revealed the presence of an underlying unit of Pleistocene gray clay to sandy clay (with marine shells and burrows) that is capped by an unconformity. Within the Carolina Bay, this gray clay to sandy clay is overlain by a 0.3–1.2 m thick unit of sand and sandy silt (interpreted as lacustrine deposits and paleosols). Cores from the sand ridges have revealed the presence of the same unit of sand and silty sand, overlain by a separate 2.6–2.9 m thick unit of silt, sandy silt, and silty sand (interpreted as paleosols, loess, prograding shoreline deposits, and eolian dune deposits). The unit of silt, sandy silt, and silty sand in a western sand ridge (closer to the bay margin) contained samples of charcoal and wood that yielded ages of ca. 5760 and 1270 ^{14}C year BP. The unit of silt, sandy silt, and silty sand in an eastern sand ridge (farther from the bay margin) contained samples of organic sediment and charcoal that yielded ages ranging from ca. 7750–2780 ^{14}C year BP.

Wilson's Bay (Johnston County, North Carolina; Fig. 2.1) is a Carolina Bay with a slightly oval NW-SE orientation (~750 m long and 600 m wide), and parabolic sand ridges of ~0.5–2 m relief on the northeast and southeast margins. According to Bliley and Burney (1988), hand augers and borings from the bay and from the sand ridges have revealed the presence of an underlying unit of saprolite that formed from felsic gneiss. This saprolite is capped by an unconformity with a thin bed (lag) of quartz gravel in some places. Within the bay, the saprolite (and quartz gravel lag) is overlain by a 1.5–3.2 m thick unit of sand, sandy silt, and silty sand (interpreted as lacustrine deposits). A sample of organic material within this unit yielded a radiocarbon age of ca. 21,920 ^{14}C year BP. Cores from the sand ridges revealed that the saprolite (and quartz gravel lag) at these locations is overlain by a 1.5–4.0 m thick unit of muddy sand, sand, and gravel.

Herndon Bay (Robeson County, North Carolina; Fig. 2.1) is an oval Carolina Bay that is oriented NW-SE (~1 km long and 0.65 km wide), with several parabolic sand ridges of 1.5–4 m relief on the southeast margin (Fig. 2.8). According to Moore et al. (2016), four cores each drilled into different sand ridges at successively greater distances from the bay margin revealed that the sand ridges are 2.5–4.5 m thick accumulations of predominantly fine to coarse sand that rest on an unconformity above mud of the Cretaceous Black Creek Formation. Coarse sand and slightly gravelly sand are present in the two more proximal sand ridges, whereas muddy sand and sandy mud are present in the two more distal sand ridges. Three OSL ages have been reported from these sand ridges (Table 2.3, Fig. 2.9). These four cores through the sand ridges are described as follows: (1) The core in the sand ridge closest to the bay (core 1) reached a total depth of 3.6 m in mud of the Black Creek Formation (drilling depths: 3.6–2.5 m), above which was a 0.7 m thick unit of laminated fine sand (drilling depths: 2.5–1.8 m) that yielded an OSL age of ca. 27 ka (sample UW2786; Table 3). Above the fine sand, the core recovered a 1.0 m thick unit of predominantly coarse sand (drilling depths: 1.4–0.4 m); (2) The core in the next sand ridge away from the bay margin (core 2) reached a total depth of 3.6 m and recovered a 0.8 m thick unit of predominantly coarse sand (drilling depths: 3.6–2.8 m) that yielded an OSL age of ca. 30 ka (sample UW2787; Table 2.3). Above the coarse sand, the core recovered another 0.8 m thick unit of predominantly coarse sand (drilling depths: 2.6–1.8 m), above which the core recovered a 0.7 m thick unit of medium sand (drilling depths: 1.1–0.4 m); (3) The core in the third sand ridge away from the bay margin (core 3) reached a total depth of 4.8 m in mud of the Black Creek Formation (drilling depths: 4.8–4.5 m), above which was a 1.6 m thick unit of predominantly medium sand (drilling depths: 4.5–2.9 m). This unit of medium sand was overlain by a 2.7 m thick unit of predominantly fine sand (drilling depths: 2.9–0.2 m); and (4) The core in the fourth (most distal) sand ridge

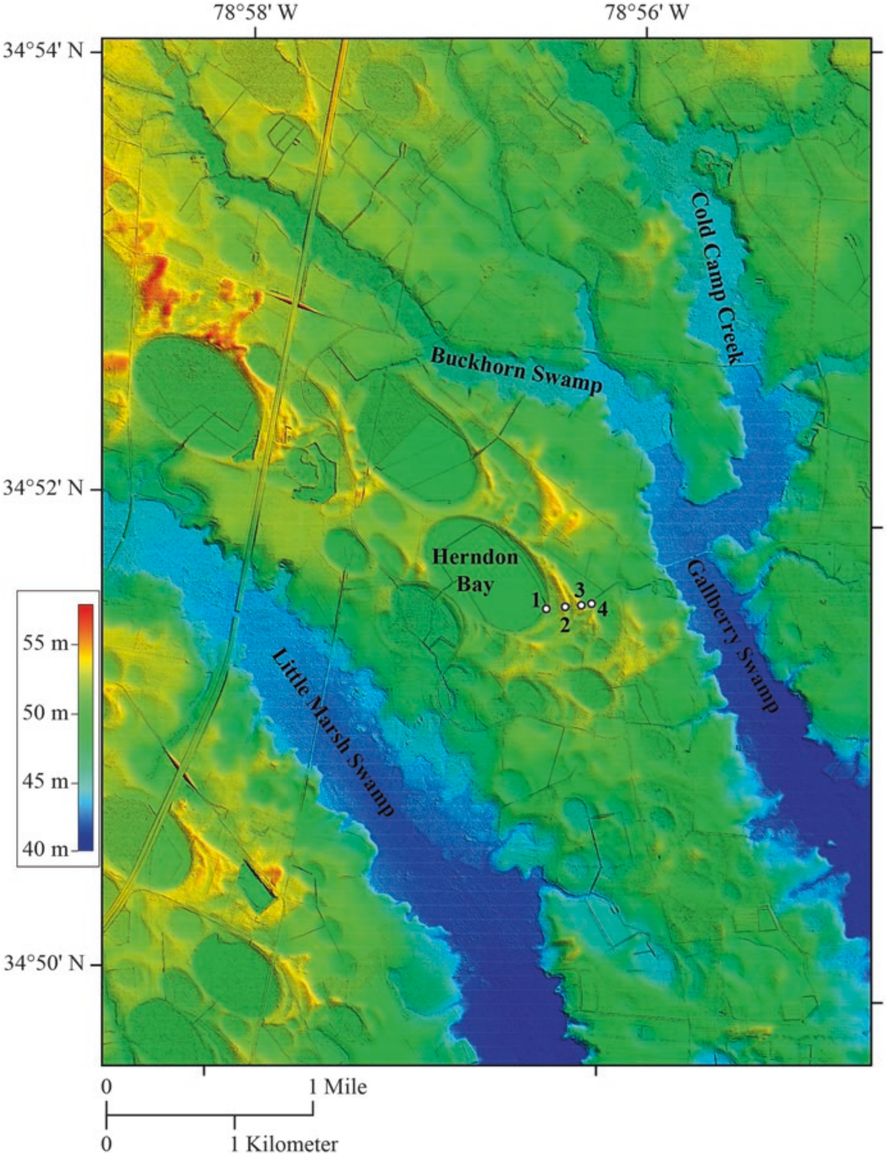


Fig. 2.8 LiDAR image of Herndon Bay, Robeson County, North Carolina. The white circles and adjacent numbers denote to sand ridge cores obtained by Moore et al. (2016). Elevations are given relative to sea level

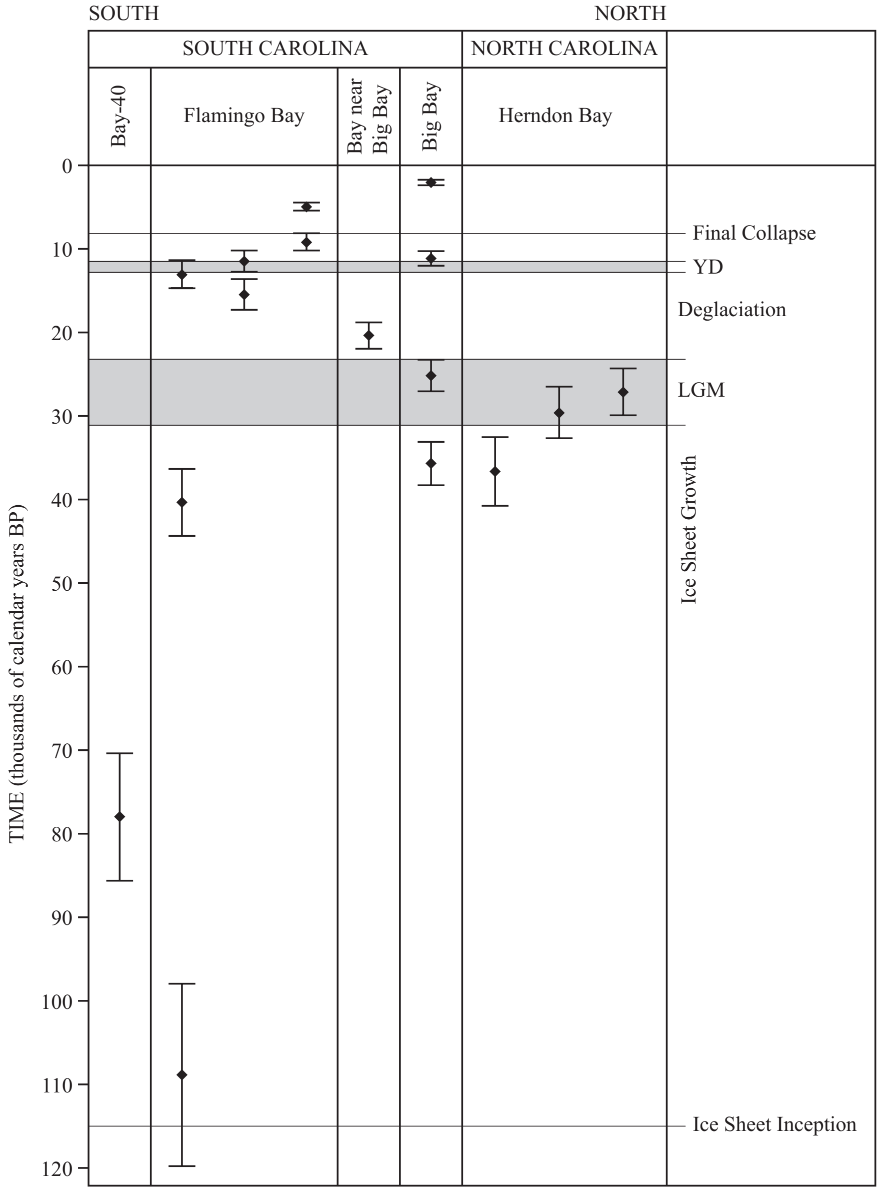


Fig. 2.9 OSL ages from sand ridges of Carolina Bays of the U.S. Atlantic Coastal Plain province. *LGM* Last glacial maximum, *YD* Younger Dryas event, *Final Collapse* Final collapse of the Laurentide Ice Sheet. Detailed age data are given in Table 2.3

from the bay margin (core 4) reached a total depth of 3.6 m in mud of the Black Creek Formation (drilling depths: 3.6–2.5 m), above which was a 1.1 m thick unit of predominantly fine to medium sand (drilling depths: 2.3–1.2 m) that yielded an OSL age of ca. 37 ka (sample UW2788; Table 3). This unit of fine to medium sand was overlain by 0.7 m thick unit of predominantly medium sand (drilling depths: 1.1–0.4 m).

In South Carolina and Georgia, several Carolina Bays are present within river valleys, and they exhibit cross-cutting relations with eolian dunes in these valleys. For example, Bear Swamp (Marion County, South Carolina; Fig. 2.1) is a Carolina Bay that is oriented NW-SE (ca. 1.2 km long and 0.8 km wide). This Carolina Bay is inset into a field of eolian dunes in the valley of the Great Pee Dee River (Fig. 2.10), and thus this bay must be younger than the dunes. Although OSL ages have not been published from these dunes, it is reasonable to assume that these dunes would yield OSL ages that are similar to those obtained from eolian dunes in other river valleys of the coastal plain. Ivester et al. (2001) described a similar setting in the valley of the Ohoopee River (Tattnall County, Georgia), where a Carolina Bay named Dukes Pond (Fig. 2.1) is inset within eolian dunes that have yielded an OSL age of ca. 23.6 ka (Table 2.1).

In South Carolina, detailed descriptions have been published for the following three Carolina Bays: (1) Big Bay; (2) an unnamed Carolina Bay immediately southwest of Big Bay; and (3) Flamingo Bay. OSL ages obtained from samples from the Carolina Bay sand ridges range from ca. 108.7–2.2 ka (Table 2.3). Where multiple sand ridges are present, older ages have been obtained from the sand ridges that are farther from the modern bay.

Big Bay (Sumter County, South Carolina; Fig. 2.1) is an oval Carolina Bay in the valley of the Wateree River on the north side of Big Bay Road in Sumter County, South Carolina (Fig. 2.11). The bay is oriented NW-SE (~5 km long and 3 km wide), and has several parabolic sand ridges of 1.5–3.5 m relief on the south and east margins. The western margin of Big Bay is covered by eolian sand in the form of a sand sheet with a few parabolic dunes. According to Ivester et al. (2002) and Brooks et al. (1996, 2010), this eolian sand has yielded three OSL ages. Within the confines of Big Bay, a sample from the sand sheet yielded an OSL age of ca. 74.3 ka and a sample from a parabolic dune yielded an OSL age of ca. 29.6 ka. At a distance ~1 km west of the inferred margin of Big Bay, a sample from a parabolic dune that is part of the same eolian sand deposit yielded an OSL age of ca. 33.2 ka. Brooks et al. (2001) described a core (drill hole D1/2; Fig. 2.11) drilled through the sand sheet within the confines of Big Bay that reached a total depth of 10.6 m in sandy clay of the Pliocene Duplin Formation (drilling depths: 10.6–9.0 m), above which was a 4.5 m thick unit of silty sand and sandy mud with abundant organic material (drilling depths: 9.0–4.5 m), above which was a 4.5 m thick unit of quartz sand (drilling depths 4.5–0 m).

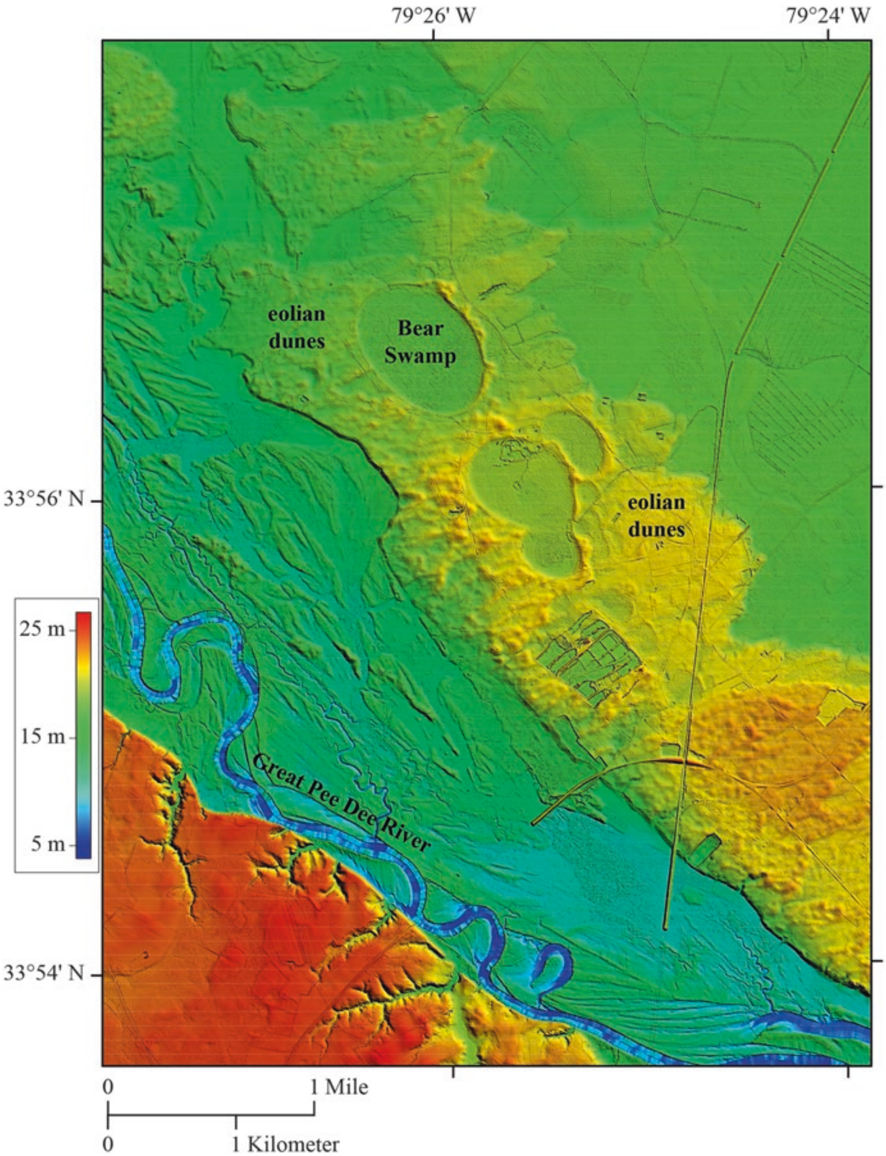


Fig. 2.10 LiDAR image of Bear Swamp, Marion County, South Carolina. Bear Swamp is a Carolina Bay inset into eolian dunes in the valley of the Great Pee Dee River. Elevations are given relative to sea level

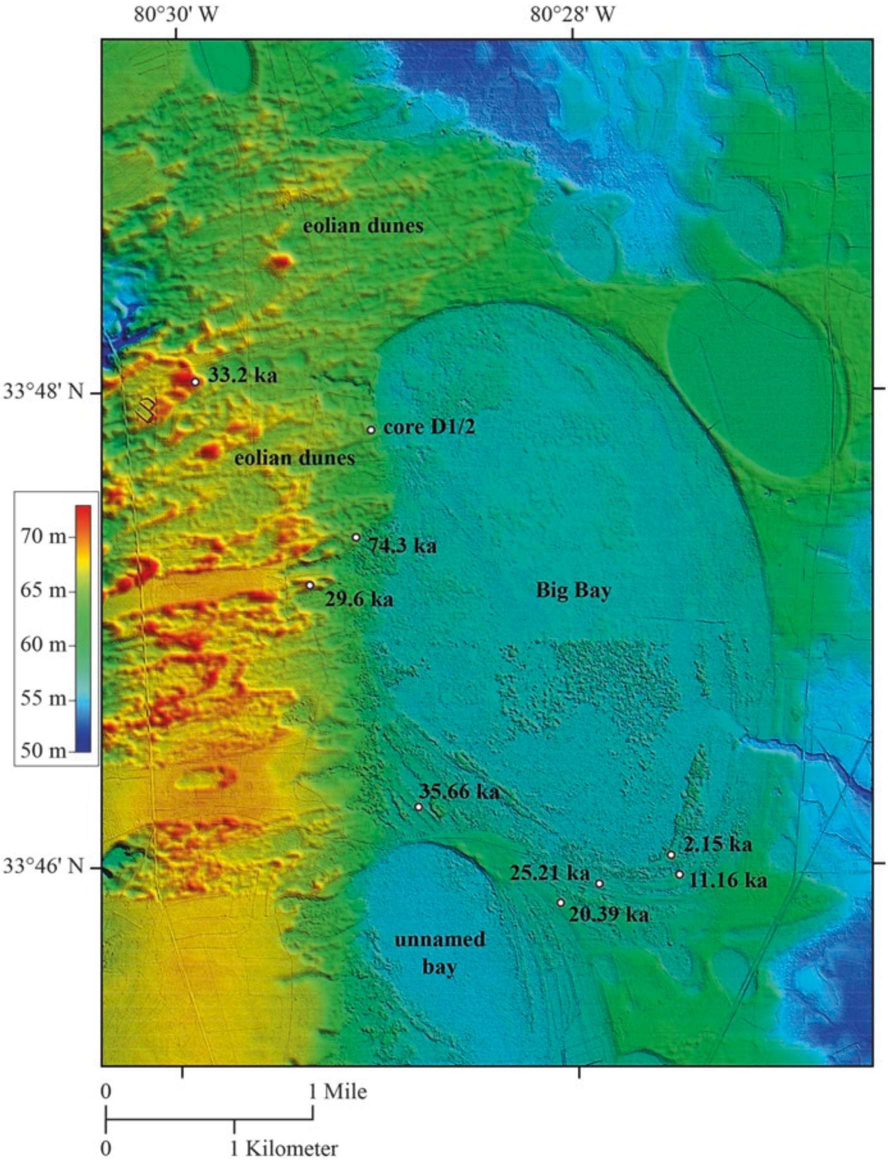


Fig. 2.11 LiDAR image of Big Bay, Sumter County, South Carolina. The white circles and adjacent numbers denote cores and OSL ages reported by Ivester et al. (2002) and Brooks et al. (1996, 2010). Elevations are given relative to sea level

Several OSL ages have been reported from sand ridges along the south and east margins of Big Bay (Brooks et al. 1996, 2010; Ivester et al. 2003). These OSL data are described as follows: (1) From the sand ridge closest to the bay, a sediment sample at 60–75 cm depth yielded an OSL age of 2.15 ± 0.30 ka (this age was reported as 2.2 ka by Brooks et al. 2010); (2) From the next sand ridge away from the bay margin, a sediment sample at 60–75 cm depth yielded an OSL age of 11.16 ± 0.90 ka (this age was reported as 11.3 ka by Brooks et al. 2010); (3) From the third sand ridge away from the bay margin, a sediment sample at 60–75 cm depth yielded an OSL age of 25.21 ± 1.9 ka (this age was reported as 25.4 ka by Brooks et al. 2010); and (4) From the fourth (most distal) sand ridge from the bay margin, a sediment sample at 60–75 cm depth yielded an OSL age of 35.66 ± 2.60 ka (this age was reported as 35.9 ka by Brooks et al. 2010).

Additional data are available from an unnamed Carolina Bay located immediately to the southwest of Big Bay, on the south side of Big Bay Road in Sumter County (Fig. 2.11). This unnamed bay is oriented NW-SE (~2 km long and 1 km wide), and has several parabolic sand ridges of 0.8–1 m relief on the south and east margins of the bay. Ivester et al. (2003) stated that sediment from a sand ridge associated with this bay yielded an OSL age of 20.39 ± 1.60 ka (this age was reported as 20.5 ka by Brooks et al. 2010). It is possible, however, that this sand ridge might be associated more appropriately with Big Bay than with the unnamed bay.

Flamingo Bay (Aiken County, South Carolina; Fig. 2.1) is an oval Carolina Bay that is oriented NW-SE (~0.6 km long and 0.5 km wide), with several parabolic sand ridges of 4–5 m relief on the east and south margins (Fig. 2.12). According to Brooks et al. (1996), a core (C1) taken within Flamingo Bay penetrated a 94-cm thick unit of quartz sand above a unit of sandy silt and clay that they referred to as a "BC soil horizon," which they interpreted as Eocene sediments that were subsequently altered by lateritic weathering. Charcoal samples from the unit of quartz sand within the Flamingo Bay yielded ages ranging from ca. 4505–2550 ^{14}C year BP. Brooks et al. (1996) also reported that a core (P25) through the highest part of a sand ridge on the eastern side of Flamingo Bay revealed a 1.85 m-thick unit of Quaternary quartz-rich medium sand, overlying an unconformity with evidence of lateritic weathering ("BC Soil Horizon") on a unit of Eocene sandy silt and clay. Additional cores on the western flank of this sand ridge revealed a similar stratigraphy, but with the addition of quartz pebbles on the unconformity. Moore et al. (2012) reported the following five OSL ages from a Flamingo Bay sand ridge composed of medium sand: (1) 5.0 ± 0.5 ka at ~35 cm depth; (2) 9.2 ± 1.0 ka at ~50 cm depth); (3) 11.5 ± 1.3 ka at ~65 cm depth; (4) 15.5 ± 1.8 ka at ~78 cm depth; and (5) 13.1 ± 1.7 ka at ~95 cm depth. In addition, Ivester et al. (2002) and Brooks et al. (2010) reported the following two OSL ages from sand ridges of Flamingo Bay: (1) 108.7 ± 10.9 ka; and (2) 40.3 ± 4.0 ka. Ivester et al. (2002) and Brooks et al. (2010) also reported an OSL age of 77.9 ± 7.6 ka from a sand ridge of a nearby Carolina Bay named Bay-40.

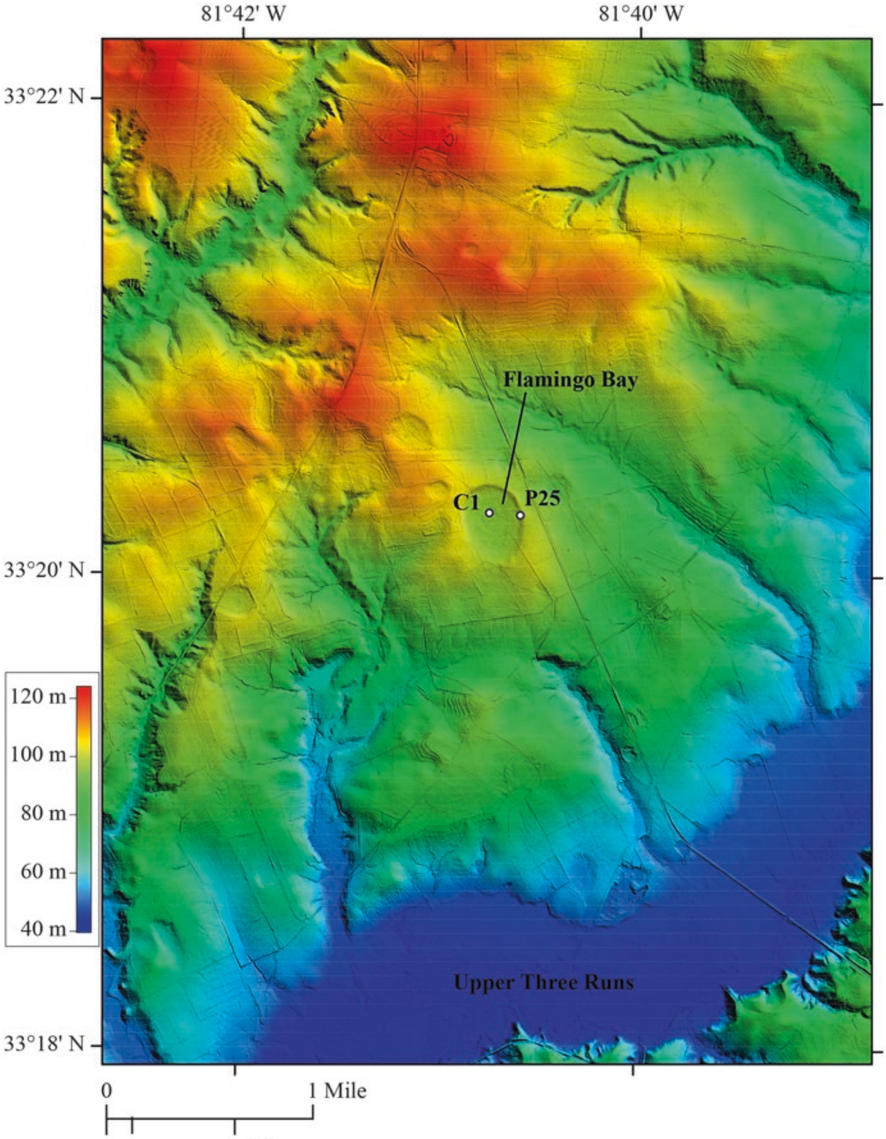


Fig. 2.12 LiDAR image of Flamingo Bay, Aiken County, South Carolina. C1 and P25 denote cores obtained by Brooks et al. (1996). Elevations are given relative to sea level

2.4.4 *Eolian Dunes and Sand Sheets on Upland Areas of the Northern Atlantic Coastal Plain*

Vegetated (stabilized) eolian sand dunes and sand sheets are present on many upland areas of the northern Atlantic Coastal Plain (Figs. 2.1 and 2.13). These eolian deposits are extensive and particularly well developed on the Delmarva Peninsula (Delaware, Maryland, Virginia) east of the Chesapeake Bay (Rasmussen and Slaughter 1955; Denny and Owens 1979; Denny et al. 1979; Mixon 1985; Lowery et al. 2010; Newell and DeJong 2011). Similar eolian sand and silt have also been identified on the Atlantic Coastal Plain west of the Chesapeake Bay (west of the Delmarva Peninsula) in Maryland (Hack 1955; Markewich et al. 2009). Farther north in Sussex County (Delaware), an approximately correlative unit of fine sand, silt, and clayey silt is mapped as the Cypress Swamp Formation and is interpreted as deposits of fresh-water bogs, swamps, marshes, ponds, floodplains, and eolian

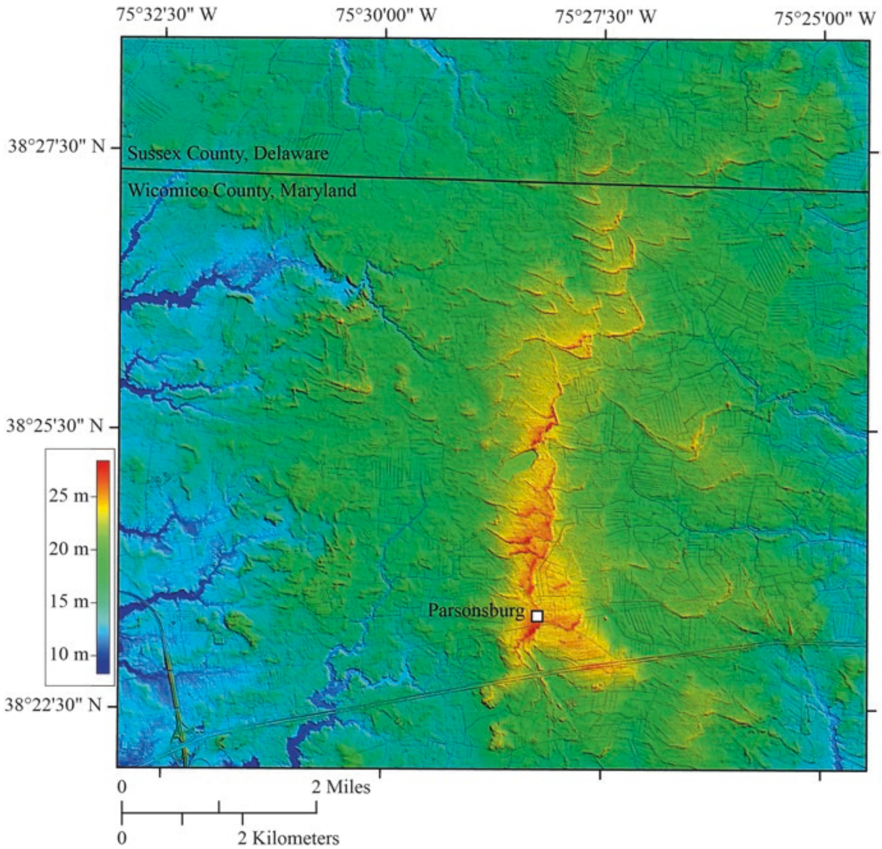


Fig. 2.13 LiDAR image showing parabolic dunes on the Delmarva Peninsula (Wicomico County, Maryland; Sussex County, Delaware). Elevations are given relative to sea level

dunes (Andres and Howard 2000). Quaternary eolian sand and (or) silt are also present in the Pine Barrens region of southern New Jersey (Newell and DeJong 2011; French and Demitroff 2012), around the western margin of the Atlantic Coastal Plain province in Mercer County of New Jersey (Stanford 1993), and in nearby areas west of the Atlantic Coastal Plain province in southeastern Pennsylvania (Carey et al. 1976).

According to Denny and Owens (1979) and Denny et al. (1979), eolian sand on the upland areas of the Delmarva Peninsula is typically 1.2–6 m thick, and overlies a variety of older units of sand and mud that range in age from Miocene to Quaternary (e.g., Pensauken Formation, Beaverdam Sand, Walston Silt, Omar Formation, Kent Island Formation). At most locations the eolian sand is composed of light brown to dark gray fine to medium sand, although clayey silt is present at some locations. The sand consists predominantly of quartz, with a small fraction of feldspar and opaque minerals. Most exposures of the sand display evidence of bioturbation and pedogenic features such as soil lamellae and argillic horizons. Evidence of primary sedimentary structures is absent in most exposures, although low-angle bedding is visible at the base of some exposures. Thin units of peaty sand within the Parsonsburg Sand have yielded several radiocarbon ages ranging from ca. 30,560–13,420 ^{14}C year BP. The upper surface of the eolian sand in the upland area of the central Delmarva Peninsula varies from a relatively flat surface to irregular mounds and sinuous ridges (Denny and Owens 1979; Denny et al. 1979). Some of the ridges are in the shape of parabolic dunes with tails that point to the northwest (Fig. 2.13).

On the west side of the Delmarva Peninsula (east side of the Chesapeake Bay), there are several exposures of eolian sand and sandy silt that may be correlative to the Parsonsburg Sand. In Northampton County (Virginia), for example, Mixon (1985) described irregular fields of 0.6–3 m high eolian sand dunes. Farther north in Kent County (Maryland), Foss et al. (1978) described a 0.5–2.1 m thick unit of Quaternary sandy silt (interpreted as loess) that overlies a "buried paleosol." In Talbot County (Maryland), Lowery et al. (2010, p. 1475) described two units of sandy silt (interpreted as loess) that overlie an unconformity (paleosol) on a "fine-sandy sequum formed in either fluvial/estuarine sediments or possibly coarse eolian deposits." The lower unit of sandy silt is ~1 m thick and is capped by an unconformity (paleosol), and the upper unit of sandy silt is ~0.8 m thick. Lowery et al. (2010) named the lower unit as the Miles Point Loess, upper unit as the Paw Paw Cove Loess, and the intervening paleosol as the Tilghman Soil. At a locality named Miles Point, the "fine-sandy sequum" immediately below the Miles Point Loess yielded two OSL ages of ca. 41 ka, the Miles Point Loess yielded two OSL ages of ca. 41 and 35 ka, and the Tilghman Soil yielded two OSL ages of ca. 29 and 28 ka (Table 2.4, Fig. 2.14). The Tilghman Soil also yielded four radiocarbon ages ranging from ca. 27,249–21,490 ^{14}C year BP (Lowery et al. 2010).

On the west side of the Chesapeake Bay (west of the Delmarva Peninsula), vegetated (stabilized) eolian sand and silt are present across several upland areas of the Maryland coastal plain. In upland areas of Prince Georges and Charles Counties of Maryland, Hack (1955) identified a < 2 ft. (0.6 m) thick unit of eolian fine sand that rests on an unconformity on Miocene sand, gravel, and loam. With the availability of LiDAR data, Markewich et al. (2009) were able to discern the presence of parabolic dunes among this eolian sand in Charles County. Relief of these parabolic dunes is 8–12 m, the axis length of the dunes is ~3 km, and the dune tails point to the northwest. At a site named Fenwick Shores/Piscataway, one sample of eolian sand yielded an OSL age of ca. 27 ka (Table 2.4, Fig. 2.14). At a site named Goose Bay, a ~4 m thick quartz-rich medium sand of eolian origin yielded two OSL ages of ca. 30 and 24 ka (Table 2.4, Fig. 2.14). This eolian unit rests on an unconformity above a ~0.9 m-thick estuarine deposit of quartz-rich medium to fine sand that fines up to clayey silt with organic-rich sediment and wood that yielded radiocarbon ages of ca. 26,270 and 20,500 ^{14}C year BP. Markewich et al. (2009) also reported OSL ages from eolian sand at two other sites in Charles County (Chapman Landing, Brandywine2). Eolian sand from the Chapman Landing site yielded an OSL age of 27 ka, and eolian sand from the Brandywine2 site yielded an OSL age of ca. 19 ka (Markewich et al. 2009).

In the Piedmont province immediately west of the Atlantic Coastal Plain province, sand and silty sand of possible eolian origin are present at several locations in central and northern Virginia. For example, on many of the interfluvial upland areas of Louisa County, the author has noted a < 0.5 m thick unit of possible eolian origin composed of quartz-rich very fine sand and silt that overlies deeply weathered Paleozoic metamorphic rocks. Similarly, on an interfluvial upland area in Prince William County, Feldman et al. (2000) described a ~0.5–1 m thick unit of silt (interpreted as loess) that overlies granitic saprolite. This silt yielded a thermoluminescence (TL) age of ca. 14 ka.

2.5 Interpretations of Eolian Dunes and Sand Sheets

When viewed as an ensemble, the eolian dunes and sand sheets in inland settings of the U.S. Atlantic Coastal Plain province show some interesting differences and similarities. For example, the eolian sediments are thought to have been derived from distinctly different sources in each of the four identified settings (river valleys; Carolina Sandhills; Carolina Bays; upland areas of the northern Atlantic Coastal Plain). Yet the eolian sediments show many similarities with respect to inferred timing of eolian mobilization, thus providing a common framework for interpretations of paleoclimate variables such as wind direction, wind velocity, and air temperature.

2.5.1 Eolian Dunes in River Valleys

Several previous studies have interpreted the eolian dunes in the river valleys as being derived from fluvial sand from the nearby river channels (e.g., Pickering and Jones 1974; Carver and Brook 1989; Markewich and Markewich 1994; Ivester et al.

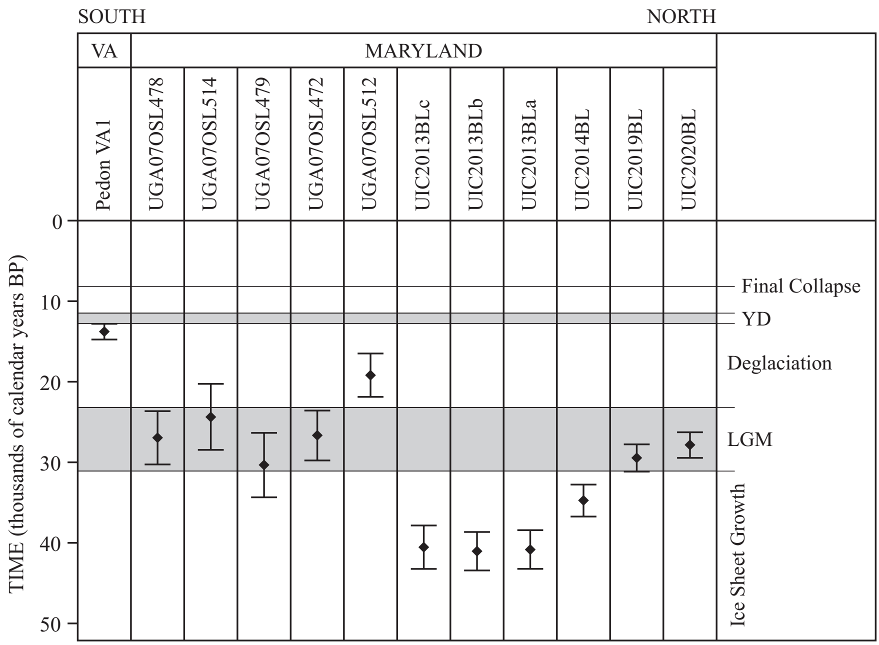


Fig. 2.14 OSL ages from eolian dunes on upland areas of the northern Atlantic Coastal Plain province. *LGM* Last glacial maximum, *YD* Younger Dryas event, *Final Collapse* Final collapse of the Laurentide Ice Sheet. Detailed age data are given in Table 2.4

2001; Ivester and Leigh 2003; Swezey et al. 2013). There must have been enough variability in climate and river discharge such that the fluvial sand could be mobilized into eolian dunes, which migrated away from the river channels until they became stabilized. The eolian dunes, however, are located only 1–5 km from the modern river channels, indicating that the dunes did not travel very far from their sediment sources before becoming stabilized.

OSL ages from eolian dunes in the river valleys range from ca. 84–5 ka and the majority of these ages are approximately coincident with the last glaciation in the northern hemisphere (Fig. 2.4), assuming the date of inception of the Laurentide Ice Sheet to be ca. 115 ka (Mix 1992; Kleman et al. 2010) and the date of final collapse of the Laurentide Ice Sheet to be ca. 8.2 ka (Barber et al. 1999; Shuman et al. 2002). The great range of OSL ages suggests that eolian sediment mobilization was episodic during this time. Most of the OSL ages range from ca. 35–14 ka and are approximately coincident with the last glacial maximum (LGM) and the time of deglaciation before the Younger Dryas (YD) event, assuming the LGM to be ca. 31,100 to 23,200 calibrated years before present [reported by Clark et al. 2009 as 26.5 to 19–20 ka in radiocarbon years before present, and converted to calibrated years using the program CALIB 6.1.1 (available at http://calib.qub.ac.uk/calib) in conjunction with Stuiver and Reimer 1993 and Reimer et al. 2009], and assuming the YD event to be 12,800 to 11,500 cal year BP (Alley et al. 1993).

At the older end of the age spectrum, OSL ages of 77.4 ± 6.6 ka from the valley of the Ohoopee River and 74.3 ± 7.1 ka from the valley of the Wateree River provide evidence of eolian sand mobilization well before the LGM (Fig. 2.4). For some reason, the eolian sand at these locations was not reworked during the LGM or later. There are apparent gaps in the river valley OSL ages from ca. 67–14 ka, and from ca. 14–11 ka. Eolian sand may have been stabilized during these times, but it is also possible that additional OSL ages may fill in these gaps. It is also important to realize that the OSL ages indicate not the total time of eolian sand mobilization but only the time that eolian sand was last exposed to sunlight. At the young end of the age spectrum, an OSL age of ca. 5 ka from the Altamaha River may attest to some isolated eolian sand remobilization in this area, or perhaps may be attributed to the effects of post-depositional bioturbation exposing sand grains to sunlight.

No OSL ages from eolian sand in the river valleys are younger than ca. 5 ka (Fig. 2.4), and thus it appears that since this date the sand has been stabilized by vegetation and subjected to pedogenic processes. This final stabilization of the dunes is thought to have been caused by a change to a less arid climate along with a general increase in air temperature, decrease in wind velocity, and increase in vegetation density (Swezey et al. 2013). Most exposures of the dunes do not display sedimentary structures except for traces of bioturbation by plant roots, suggesting that the dunes have been stabilized for a duration long enough for vegetation to obliterate primary sedimentary structures.

Most eolian dunes in the river valleys are parabolic dunes, which is a morphology that is usually associated with an adequate sand supply, moderate vegetation cover, and a unidirectional wind regime for sand-mobilizing winds (McKee and Bigarella 1979; Lancaster 1995; Hugenholtz et al. 2008; Hugenholtz 2010). Pollen data also support the interpretation of some vegetation being present during the last glaciation and deglaciation (e.g., Watts 1980a, b; Delcourt and Delcourt 1984, 1985; LaMoreaux et al. 2009; Spencer et al. 2017). With regards to wind directions, the tails of parabolic dunes point to the northwest in the northern coastal plain (Delaware, Maryland), suggesting that the winds that mobilized the sand in this area blew from the northwest. In contrast, the tails of parabolic dunes point to the west in the central and southern coastal plain (North Carolina, South Carolina, Georgia), suggesting that the winds that mobilized the sand in this area blew from the west. Some climate models (e.g., Kutzbach et al. 1998) have proposed that surface winds in the southeastern United States blew from the west during the LGM winter and from the southeast during the LGM summer (e.g., Kutzbach et al. 1998), prompting speculation that eolian dune mobilization may have occurred preferentially during the winter (Swezey et al. 2016b).

Very few eolian dunes have been reported from river valleys in central and southern Virginia, which is the area where winds from the northwest (Delaware, Maryland) are presumed to have converged with winds from the west (North Carolina, South Carolina, Georgia). Quaternary eolian sand has been reported from the Cactus Hill and Rubis Pearsall archeological sites, both of which are located in the upper coastal plain part of the Nottoway River valley in Sussex County, Virginia (Wagner and McAvoy 2004; Feathers et al. 2006; Macphail and McAvoy 2008;

Markewich et al. 2009). These sands have yielded OSL ages ranging from ca. 23.7–7.4 ka (Feathers et al. 2006), which are generally coincident with the ages of numerous eolian sands described in this paper. However, the criteria cited for determining an eolian origin of these sands are now considered to be non-diagnostic criteria (Swezey 1998; Swezey et al. 2016b), and LiDAR data in this area show primarily fluvial sand bars rather than fields of large and obvious eolian dunes such as are present in North Carolina, South Carolina, and Georgia. If eolian sand is present at the Cactus Hill and Rubis Pearsall sites, then this sand is likely to be a relatively thin deposit reworked from underlying fluvial sediments. Some fields of eolian dunes, however, may be present in the Nottoway River valley even farther downstream near the Virginia–North Carolina border (Powars et al. 2016).

2.5.2 Eolian Dunes and Sand Sheets of the Carolina Sandhills

The unconsolidated sand (Quaternary Pinehurst Formation) of the Carolina Sandhills is interpreted as eolian dunes and sand sheets derived from sand of the underlying Cretaceous strata (Fitzwater 2016; Swezey et al. 2016a, 2016b). This interpretation of sand source is supported by the spatial association of the Quaternary and Cretaceous units, and the fact that the two units have similar grain sizes and similar abundance and composition of opaque minerals. Furthermore, the poor sorting suggests that sand of the Pinehurst Formation has not traveled far from its source.

OSL ages from the eolian sand (Pinehurst Formation) are approximately coincident with the last glaciation in the northern hemisphere (Fig. 2.7). The great range of OSL ages (ca. 98–6 ka) suggests that eolian sediment mobilization was episodic during this time. Most of the OSL ages, however, range from ca. 42–9 ka and are approximately coincident with the interval from the latter stages of ice sheet growth (leading to the LGM) to the Final Collapse of the Laurentide Ice Sheet. At the older end of the age spectrum, an OSL age of 92.3 ± 5.2 ka from White Pond (South Carolina) provides evidence of eolian sand mobilization well before the LGM. The southern location (greater distance from the influences of the Laurentide Ice Sheet) may have helped to prevent eolian sand at this location from being reworked during the LGM or later. There are apparent gaps in the Carolina Sandhills OSL ages from ca. 87–75 ka, 64–59 ka, 37–30 ka, and 17–12 ka. Eolian sediment may have been stabilized during these times, but it is also possible that additional OSL ages may fill in these gaps. As stated above, the OSL ages indicate not the total time of eolian sand mobilization but only the time that the sand was last exposed to sunlight.

No OSL ages from the Pinehurst Formation are younger than ca. 6 ka, and thus it appears that since this date the sand has been stabilized by vegetation and subjected to pedogenic processes. As with eolian dunes in the river valleys, this final stabilization of eolian sand in the Carolina Sandhills region is thought to have been caused by a change to a less arid climate along with a general increase in air temperature, decrease in wind velocity, and increase in vegetation density (Swezey et al. 2016b). Most exposures of the dunes do not display sedimentary structures except for traces of bioturbation by plant roots, suggesting that the dunes have been stabilized for a duration long enough for vegetation to obliterate primary sedimentary structures.

Several paleoclimate variables may be inferred from characteristics of the Pinehurst Formation (Swezey et al. 2016b). For example, the predominance of sand sheets over dunes is attributed to the coarse grain size and to the likely presence of some vegetation when the sand was mobilized. Eolian mobilization of coarse sand would have been facilitated by colder air temperatures, such as are inferred for the LGM. The dune morphologies and cross-bedding suggest that winds that mobilized the sand blew from the west and (or) northwest. These inferred wind directions are most consistent with both modern January wind directions (Baldwin 1975) and inferred LGM January wind directions (Kutzbach et al. 1998), suggesting that eolian sand mobilization may have occurred preferentially during the winter (when the air temperatures would have been lower, thus facilitating the eolian mobilization of coarse sand). Furthermore, the relatively coarse grain size suggests that eolian sand mobilization during the LGM winter would have required wind velocities of at least 4–6 m/s, after taking into account the effects of colder air temperatures on eolian sand transport (Swezey et al. 2016b).

2.5.3 Eolian Dunes Associated with Carolina Bays

Most geologists interpret the Carolina Bays as relict geomorphologic features that formed via a combination of eolian and lacustrine processes (e.g., Livingstone 1954; Thom 1970; Stolt and Rabenhorst 1987a, b; Bliley and Burney 1988; Grant et al. 1998; Moore et al. 2016). Some of the sediments from Wilson's Bay are interpreted specifically as deposits that formed when ice in a lacustrine basin expanded and was thrust against the bay shoreline (Bliley and Burney 1988). The evidence that Carolina Bays are relict features comes from observations that: (1) modern drainages cut across some Carolina Bays; (2) some Carolina Bays are nested within other bays and show various cross-cutting relations with other Carolina Bays; and (3) Carolina Bays are not present in recent sediments at the modern coast. Furthermore, the wide range of OSL ages and the observation that some Carolina Bays show cross-cutting relations with other Carolina Bays and with eolian dunes in river valleys demonstrates that the Carolina Bays did not form during a single event. Theories of origin related to meteorite impacts (e.g., Melton and Schriever 1933; MacCarthy 1937; Prouty 1952) may be ruled out because the OSL ages show a wide range of values and because there is no evidence of disturbance of the underlying strata. Likewise, theories of origin related to traditional karst phenomena (e.g., Smith 1931) may be ruled out because of the absence of limestone beneath most Carolina Bays.

OSL ages from eolian sand ridges of the Carolina Bays range from ca. 109–2 ka, but most of the ages are approximately coincident with the last glaciation in the northern hemisphere (Fig. 2.9). The great range of OSL ages suggests that eolian sediment mobilization was episodic during this time. Most of the OSL ages range from ca. 40–11 ka and are approximately coincident with the LGM through the Younger Dryas (YD) event. At the older end of the age spectrum, OSL ages of 108.7 ± 10.9 ka from a sand ridge of Flamingo Bay and 77.9 ± 7.6 ka from a sand ridge of Bay-40 (both located in South Carolina) provide evidence of eolian sand mobilization well before the LGM. The southern location (greater distance from the influences of the Laurentide Ice Sheet) may have helped to prevent the eolian sand at these two locations from being reworked during the LGM or later. There are apparent gaps in the sand ridge OSL ages from ca. 98–86 ka, and from ca. 70–44 ka. Eolian sediment may have been stabilized during these times, but it is also possible that additional OSL ages may fill in these gaps. At the young end of the age spectrum, an OSL age of 2.1 ± 0.3 ka from a sand ridge of Big Bay may attest to some isolated eolian sediment remobilization in this area, or perhaps may be attributed to the effects of post-depositional bioturbation exposing sand grains to sunlight. Bioturbation seems likely because this ca. 2 ka age is much younger than any other OSL ages reported from eolian sand of the inland coastal plain.

In addition to the range of OSL ages, stratigraphic relations provide exceptionally clear evidence that the Carolina Bays did not form during one specific event of limited duration. For example, there are certain locations where eolian sand dunes in a river valley overlie parts of a Carolina Bay, and thus that Carolina Bay must be older than the overlying eolian sand (e.g., Big Bay; Fig. 2.11). There are other locations where a Carolina Bay is inset into eolian sand dunes in a river valley, and thus that Carolina Bay must be younger than the underlying eolian sand (e.g., Bear Swamp; Fig. 2.10). Additional evidence of the episodic nature of Carolina Bay genesis comes from the observation by Ivester et al. (2007) that the sand ridges of any specific Carolina Bay yield systematically younger OSL ages towards the center of the bay, confirming that the bays are not the product of a single event of limited duration.

The OSL ages indicate that the Carolina Bays formed during approximately the same time interval as the eolian dunes and sand sheets in the river valleys and in the Carolina Sandhills region. In other words, the Carolina Bays are relict features that formed when air temperatures were cooler, wind velocities were greater, and vegetation density was reduced. Very similar oriented lakes are present today in many high-latitude regions such as Alaska (Fig. 2.15), Canada, Russia, and the Falkland Islands (e.g., Rex 1961; Carson and Hussey 1962; Coté and Burn 2002; Wilson et al. 2002; Hinkel et al. 2005, 2012; Arp et al. 2011; Karlsson et al. 2012; Morgenstern et al. 2013; Zhan et al. 2014). These high-latitude oriented lakes are thermokarst lakes that developed as a result of thaw and collapse of frozen ground, with subsequent modification by lacustrine and (or) eolian processes. Most studies of thermokarst lakes have been conducted in the continuous permafrost zone of northern Alaska, but thermokarst lakes are also present in zones of discontinuous permafrost such as the boreal forest regions of central Alaska and northern Quebec (Jorgenson et al. 2012; Coulombe et al. 2016). In the Barrow region of northern Alaska, the dominant wind direction is from the east to northeast, and this wind generates gyres that promote erosion of the north and south shores of the

Fig. 2.15 Google Earth image of oriented thermokarst lakes near Barrow, Alaska

thermokarst lakes, leading to the elongate orientation of the lakes (Zhan et al. 2014). In other words, the orientation of thermokarst lakes is governed by patterns of wind-driven circulation and longshore drift, whereby sediment accumulates on the down-wind (lee) side of the lakes and the lakes expand by erosion in zones that are oriented 50° to the wave approach or approximately perpendicular to the dominant wind direction (Rex 1961; Carson and Hussey 1962; Zhan et al. 2014). Many of these thermokarst lakes in northern Alaska have modified an older, stabilized substrate of eolian sand (Carter 1981).

2.5.4 *Eolian Dunes and Sand Sheets on Upland Areas of the Northern Atlantic Coastal Plain*

Eolian sand dunes and sand sheets on upland areas of the northern Atlantic Coastal Plain were deposited relatively close to the southern margin of the Laurentide Ice Sheet during the LGM. These sands were probably remobilized from any loose sediment that was available in the area, and their location near the southern margin of the ice sheet is similar to extensive deposits of Quaternary eolian sand and loess in the midwest United States, as well as in Europe and in China (e.g., Sun et al. 1998; Zeeberg 1998; Kasse 2002; Zhou et al. 2009; Yang and Ding 2013; Kalińska-Nartiša et al. 2015; Bertran et al. 2016).

OSL ages from eolian sand on upland areas of the northern Atlantic Coastal Plain range from ca. 44–3 ka, but most of the ages are approximately coincident with the last glaciation in the northern hemisphere (Fig. 2.14). The great range of OSL ages suggests that eolian sediment mobilization was episodic during this time. Most of the OSL ages, however, range from ca. 44–20 ka and are approximately coincident with the interval from the latter stages of ice sheet growth (leading to the LGM) to the LGM. No OSL ages older than ca. 44 ka have been reported from eolian sands in this area, and it may be that the northern location (closer distance to the influences of the Laurentide Ice Sheet) may have facilitated the remobilization any older (pre-44 ka) eolian sand during the LGM or later. At the young end of the age spectrum, there is an individual OSL age of 13.8 ± 1.0 ka from Virginia (Feldman et al. 2000), but this age is not anomalously younger than other OSL ages from eolian sands in the area.

Although most of the eolian sediment of the northern Atlantic Coastal Plain has the morphology of sand sheets, some parabolic dunes are present on the Delmarva Peninsula. As mentioned above, the parabolic dune morphology is usually associated with an adequate sand supply, moderate vegetation cover, and a unidirectional wind regime for sand-mobilizing winds (McKee and Bigarella 1979; Lancaster 1995; Hugenholtz et al. 2008; Hugenholtz 2010). The tails of these parabolic dunes point to the northwest, suggesting that the winds that mobilized the sand in this area blew from the northwest. This orientation of the parabolic dunes is consistent with that of other vegetated parabolic dunes even farther north and west in central Pennsylvania (Chase 1977).

2.6 Discussion

The various Quaternary inland eolian dunes and sand sheets of the U.S. Atlantic Coastal Plain province have yielded a broadly similar range of OSL ages (ca. 92–5 ka), suggesting that there are regional controls on eolian sediment behavior in the area (Fig. 2.16). These controls appear to be certain climate-related parameters because most of the OSL ages are approximately coincident with growth of the Laurentide Ice Sheet and the LGM in the northern hemisphere. Eolian sediment mobilization appears to have been more common during times of cooler air temperatures (coincident with drier air and greater velocities of surface winds). Despite the broadly synchronous chronology, however, it is likely that eolian sediment mobilization was episodic at any given site. This episodic mobilization of eolian sand may have occurred on a variety of millennial and sub-millennial scales. For example, the orientations of parabolic dunes south of Virginia are consistent with climate models of surface wind directions during the LGM winter, and are opposite the inferred wind directions during the LGM summer (Fig. 2.17), thus suggesting

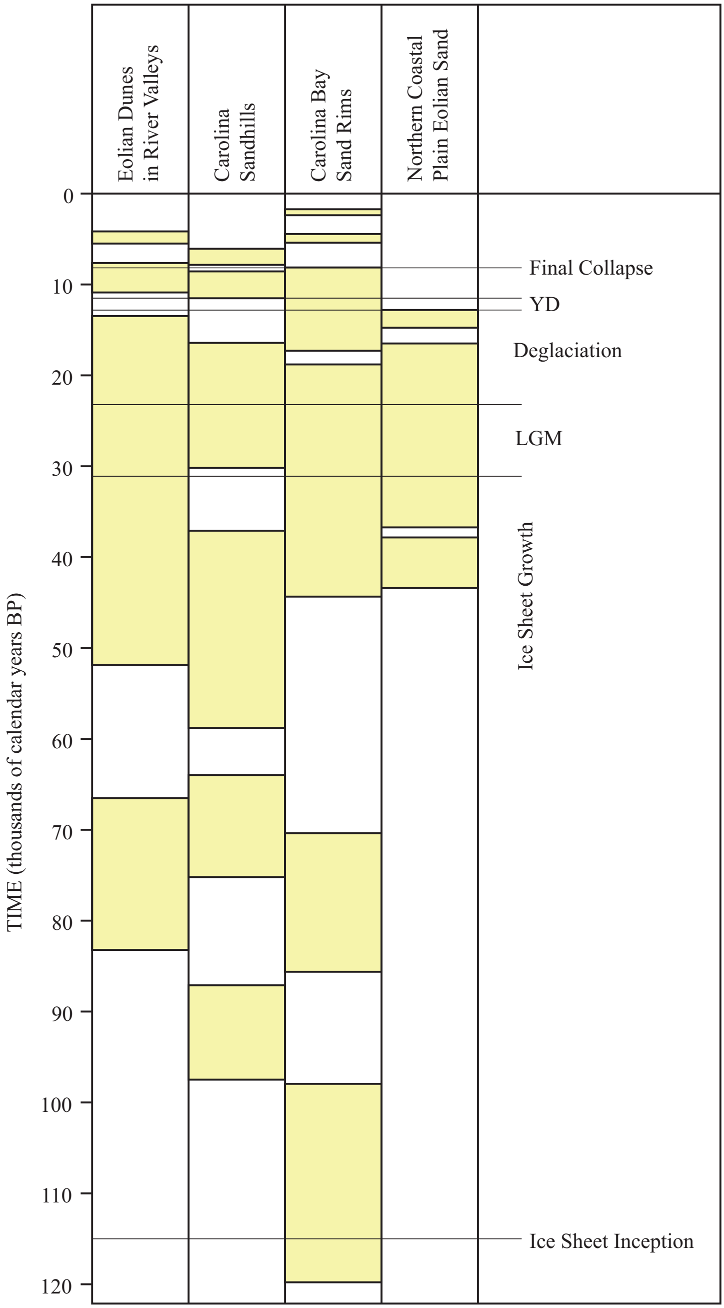
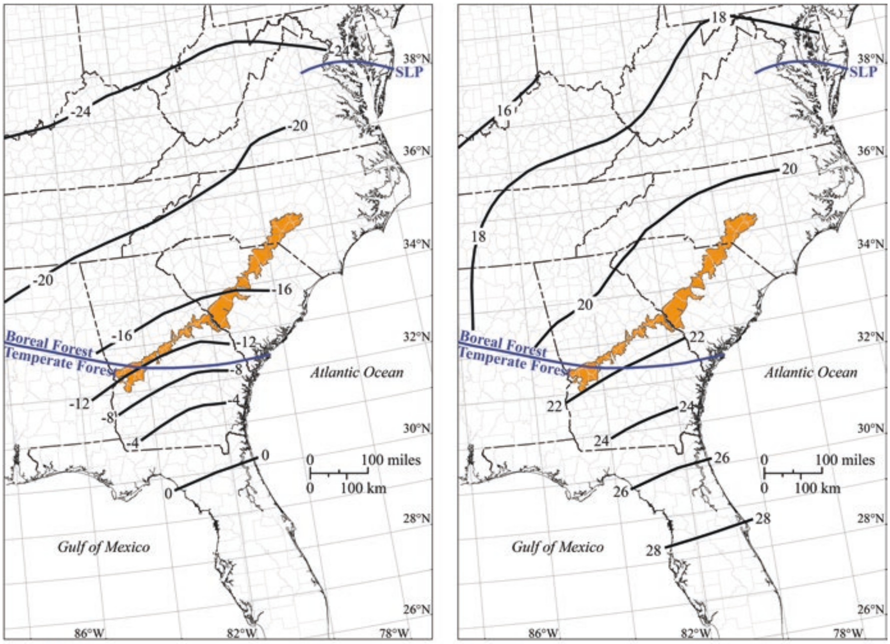


Fig. 2.16 Correlation chart showing the time span of OSL ages (including ranges of uncertainty) from eolian sand associated with Atlantic Coastal Plain river valleys, the Carolina Sandhills region, Carolina Bays, and upland areas of the northern coastal plain. These data are compiled from Tables 2.1, 2.2, 2.3, and 2.4. *LGM* Last glacial maximum, *YD* Younger Dryas event, *Final Collapse* Final collapse of the Laurentide Ice Sheet



January LGM
(Surface winds generally from the west; Kutzbach et al., 1998)

July LGM
(Surface winds generally from the southeast; Kutzbach et al., 1998)

Fig. 2.17 Last glacial maximum (LGM) climate data of the southeastern United States. Mean temperature data in degrees Celsius are from Jackson et al. (2000), and surface wind data are from Kutzbach et al. (1998). *SLP* Southern limit of LGM permafrost in the Atlantic Coastal Plain province (from French et al. 2009). Although the southern limit of permafrost during the LGM is typically thought to have been located in central or northern Virginia (French et al. 2009; French and Miller 2014), discontinuous and sporadic permafrost probably extended much farther south. Boreal forest-temperate forest boundary is from Woodcock and Wells (1990)

that eolian dune mobilization may have occurred preferentially during the winter (Swezey et al. 2016b).

Although the OSL ages from eolian sand of the inland Atlantic Coastal Plain range from ca. 92–5 ka, these ages alone do not allow one to distinguish many separate and distinct episodes of eolian sediment mobilization (Fig. 2.16). There is an apparent gap in the OSL ages from ca. 64–59 ka, but it is also possible that additional OSL ages may fill in this gap. There is also an anomalously young OSL age of ca. 2 ka from Big Bay (South Carolina) that is possibly the result of post-depositional bioturbation exposing sand grains to sunlight. At the older end of the age spectrum, it is somewhat unusual to have abundant Quaternary eolian sand of pre-Younger Dryas age preserved across a broad geographical area. In contrast, most OSL ages reported from Quaternary eolian sand in the northern and western United States are younger than the Younger Dryas event (e.g., Arbogast et al. 2015; Halfen et al. 2016). A similar pattern is seen in North Africa, where many Quaternary eolian sands have yielded relatively young ages (Swezey 2001; Bristow and

Armitage 2016). Although there is evidence of widespread eolian sand mobilization in North Africa during the LGM (e.g., Sarnthein 1978), much of this eolian sand was subsequently remobilized during the YD event. This pattern of widespread remobilization, however, is not the case in the U.S. Atlantic Coastal Plain province, where many eolian sands have yielded OSL ages that are substantially older than the YD event. Likewise, numerous OSL ages that are substantially older than the YD event have been reported from Quaternary eolian sand of the Gulf of Mexico Coastal Plain (Otvos 2004). In other words, the OSL ages reveal a general pattern of greater preservation of older eolian sediment with increasing distance from the LGM glacial front, demonstrating that the landscape of the southeastern United States is a generally older landscape that has not been reworked as readily as some other landscapes. During the YD event, the nature of the vegetation that stabilized eolian sand in the southeastern United States may have changed, but the landscape did not lose all of the stabilizing vegetation such that there was complete reworking of older eolian sand.

Despite the broadly synchronous OSL ages, the different settings of Quaternary inland eolian sand display some differences in geomorphology and sediment grain size. Eolian dune morphologies are primarily parabolic in river valleys and on upland areas of the northern Atlantic Coastal Plain, whereas eolian dune morphologies are linear but of relatively short length in the Carolina Sandhills region. Eolian sand sheets are common in the northern Atlantic Coastal Plain (e.g., Delmarva Peninsula) and in the Carolina Sandhills region, and arcuate ridges of eolian sand are common adjacent to many of the Carolina Bays. Most of these eolian sediments are fine to medium sand, with the exception of: (1) the Carolina Sandhills, where the eolian sediments are primarily medium (upper) to coarse (lower) sand; and (2) the northern Atlantic Coastal Plain, where the eolian sand sheets contain a substantial silt component. The relatively coarse size of eolian sand of the Carolina Sandhills is attributed to the relatively coarse size of the underlying Cretaceous sediments from which the eolian sand was derived, and the substantial silt component of the eolian sediments of the northern Atlantic Coastal Plain is attributed to greater proximity to the Laurentide Ice Sheet, which would have generated abundant silt.

The parabolic dune morphologies and the relative abundance of eolian sand sheets suggest that some vegetation was present when the eolian sand was mobilized. Both parabolic dunes and eolian sand sheets are often associated with moderate vegetation cover (McKee and Bigarella 1979; Kocurek and Nielson 1986; Lancaster 1995; Hugenholtz et al. 2008; Hugenholtz 2010). Furthermore, in the case of the Carolina Sandhills, the presence of paleosols with organic matter within the eolian sand implies the presence of vegetation that was capable of producing organic litter (Swezey et al. 2016b). Pollen data also support the interpretation of some vegetation being present during the last glaciation and deglaciation (e.g., Watts 1980a, b; Delcourt and Delcourt 1984, 1985; LaMoreaux et al. 2009; Spencer et al. 2017). This vegetation is thought to have been primarily a boreal forest of spruce and pine, with a tree cover that was much less dense than in modern boreal forests (Watts 1980a, b; Taylor et al. 2011). The southern limit of this boreal forest during the LGM is estimated to have been located near 33°N latitude (Woodcock and Wells 1990), which is near the southern limit of both the Carolina Sandhills and the Carolina Bays (Fig. 2.17).

Additional paleoclimate data are available from the orientations of the parabolic dunes. The tails of parabolic dunes point to the northwest in the northern Atlantic Coastal Plain (Delaware, Maryland), suggesting that the winds that mobilized the sand in this area blew from the northwest. In contrast, the tails of parabolic dunes point to the west in the central and southern Atlantic Coastal Plain (North Carolina, South Carolina, Georgia), suggesting that the winds that mobilized the sand in this area blew from the west. These wind directions inferred from dune shapes are consistent with climate models by Kutzbach et al. (1998) suggesting that surface winds in the southeastern United States blew generally from the west during the LGM winter and from the southeast during the LGM summer (Fig. 2.17). Thus, the results of these climate models have prompted speculation that eolian dune mobilization may have occurred on a seasonal basis, preferentially during winter (Swezey et al. 2016b).

Information about the velocity of paleo-winds may be obtained from the grain sizes of the eolian sediment. In the Carolina Sandhills region, the most frequently occurring grain size of individual eolian sand samples ranges from 0.35–0.59 mm diameter. In relatively warm low-latitude climates, 0.25–0.50 mm diameter quartz sand typically requires threshold wind velocities of 4–6 m/s for sustained eolian mobilization (e.g., Hsu 1974). For 0.25–0.33 mm diameter quartz sand, a threshold wind velocity of 6 m/s has been used for calculations of eolian sediment drift potential (e.g., Fryberger and Dean 1979). In the southeastern United States, however, the mean velocity of modern surface winds is 1.3–2.2 m/s. Therefore, although there is some variability around these mean values, the mean velocity of modern surface winds is generally not sufficient for sustained eolian mobilization of sand in inland locations of the southeastern United States. Cold winds, however, are more effective at eolian transport than warm winds (Selby et al. 1974; McKenna Neuman 1989, 1993, 2003, 2004), and wind tunnel experiments have shown that -12 °C air can entrain particles 40–50% larger in diameter than +32 °C air (McKenna Neuman 2003). Thus, eolian mobilization of sand in inland locations of the U.S. Atlantic Coastal Plain province would have required much greater wind velocities and (or) colder air temperatures than are present today. Swezey et al. (2016b) estimated that sustained eolian mobilization of sand in the Carolina Sandhills region would have required wind velocities of at least 4–6 m/sec during the LGM winter, and would have required even greater wind velocities during the LGM summer. Furthermore, they postulated that eolian dune mobilization may have occurred preferentially during the winter, because the dune morphologies are not consistent with the inferred wind directions proposed by climate models of the LGM summer (Swezey et al. 2016b).

Finally, the distribution of the Carolina Bays (and their associated eolian sand ridges) may provide information about both paleo-wind directions, the former distribution of frozen ground, and an upper boundary on temperature in the southeastern United States during the last glaciation. The OSL ages indicate that Carolina

Bays are relict features that formed during approximately the same time as the eolian dunes and sand sheets in the river valleys and in the Carolina Sandhills region. Both the formation of thermokarst lakes and the mobilization of eolian sand in the Atlantic Coastal Plain province would have required cooler air temperatures, greater wind velocities, and reduced vegetation density. The southern limit of continuous permafrost during the LGM is generally thought to have been located in central or northern Virginia approximately 230–320 km south of the LGM ice margin (French et al. 2009; French and Miller 2014), but the distribution of Carolina Bays suggests that permafrost (possibly discontinuous and/or sporadic) may have extended much farther south. For comparison, during the last glaciation, permafrost in Europe is thought to have extended 800–1200 km south of the LGM ice margin, and permafrost in Asia is thought to have extended 2000–4500 km south of the LGM ice margin (Vandenberghe et al. 2014; Ballantyne 2018). Furthermore, pollen data from the southeastern United States suggest that the southern limit of boreal forest during the LGM was located in central to southern Georgia (Fig. 2.17). These interpretations are consistent with evidence of LGM iceberg scour on the upper continental slope offshore the coasts of South Carolina, Georgia, and eastern Florida (Hill et al. 2008; Hill and Condron 2014). In other words, all of these features suggest that the southeastern United States became very cold, dry, and windy during the LGM. Much of the landscape appears to have been covered by a sparse boreal forest, discontinuous and sporadic permafrost probably extended south into Georgia (where Carolina Bays are present), and eolian sand mobilization appears to have occurred episodically (preferentially during winter) wherever loose sediment was available throughout most of the U.S. Atlantic Coastal Plain province.

2.7 Conclusions

The modern Atlantic Coastal Plain province of the eastern United States is not very conducive to widespread eolian sediment mobilization because of relatively low surface wind velocities, relatively dense vegetation, and a humid and mesothermal climate with average air temperatures ranging from ~0 °C to ~30 °C (depending upon location and season). Quaternary eolian dunes and sand sheets that are stabilized by vegetation, however, are present at many inland locations throughout the coastal plain. These locations include river valleys, the Carolina Sandhills region, adjacent to Carolina Bays, and upland areas of the northern coastal plain. In river valleys, eolian dunes are primarily parabolic and are located to the east of the modern river channels. In Maryland and Delaware, these parabolic dunes are composed of fine to medium sand and silty sand, and dune tails point northwest. In North Carolina, South Carolina, and Georgia, these parabolic dunes are composed of fine to medium sand, and dune tails point west. In the Carolina Sandhills region, eolian dunes are linear, and are composed of medium (upper) to coarse (lower) sand. Arcuate ridges of fine to medium eolian sand are located on the east and south sides of many shallow depressions known as Carolina Bays, which are most abundant east of the Orangeburg Scarp in South Carolina and in adjacent areas of North Carolina and Georgia. In upland areas of the northern coastal plain (e.g., Delmarva Peninsula), eolian dunes and sand sheets are composed of fine to medium sand and silty sand, and the dunes are parabolic with tails pointing to the northwest.

OSL ages reveal that these eolian dunes and sand sheets are relict features that were active episodically from ca. 92–5 ka. These dunes and sand sheets have been degraded by vegetation and pedogenic processes, and are stabilized under modern environmental conditions. Most of the OSL ages from these sands are approximately coincident with the LGM, when conditions would have been generally colder, drier, and windier. During this time, discontinuous and sporadic permafrost may have extended south into Georgia (where Carolina Bays are present). The presence of parabolic dunes and the abundance of eolian sand sheets suggest that some vegetation was present when the eolian sand was mobilized (and pollen studies suggest that this vegetation was a sparse boreal forest). Furthermore, the orientations of the parabolic dunes and the locations of the Carolina Bay eolian sand ridges suggest that the winds that mobilized the sand blew from the northwest in the coastal plain region of Maryland and Delaware, and that these winds blew from the west in the coastal plain region of North Carolina, South Carolina, and Georgia. These inferred wind directions are consistent with climate models for the LGM winter, suggesting that eolian sand mobilization may have occurred preferentially during winter. Eolian mobilization of the relatively coarse sand in the Carolina Sandhills region would have been facilitated by colder air temperatures during winter.

The OSL ages reveal a general pattern of greater preservation of older eolian sand towards the south (farther from the glacial front). In other words, the southern location (greater distance from the influences of the Laurentide Ice Sheet) may have helped to prevent some eolian sand from being reworked during the LGM or later. This observation suggests that the landscape of the southeastern United States is a generally older landscape that has not been reworked as readily as some other landscapes. During the YD event, for example, the nature of the vegetation that stabilized eolian sand in the southeastern United States may have changed, but the landscape did not lose all of the stabilizing vegetation such that there was complete reworking of all older eolian sand (and resetting of OSL ages). At any given site, however, eolian sand mobilization appears to have occurred episodically from ca. 92–5 ka, facilitated by conditions of sand availability, stronger wind velocity, lower air temperature, lower air humidity, and (or) reduced vegetation cover.

Acknowledgements The author extends sincere thanks to Nicholas Lancaster for the invitation to contribute this chapter. He also thanks Steven Cahan, Kelsey Ciarrocca, and Christopher Garrity for their invaluable work with the LiDAR images, Bradley Fitzwater and G. Richard Whittecar (Old Dominion University) for collaborative field work in the Carolina Sandhills region of Chesterfield County (South Carolina), William R. Doar III (South Carolina Geological Survey) for guidance among the sandhills of Lexington County (South Carolina), and Shannon Mahan (USGS) for answering many questions about OSL analyses. Many thanks also go to Andrew Ivester and Christopher Moore for general discussion and exchange of ideas during the past few years. This manuscript benefitted from reviews by Selene Deike, by USGS geologists Miriam Jones and Kevin Kincare, and by journal editors Nicholas Lancaster and Patrick Hesp. Any use of trade, firm, or

product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Alley R, Meese D, Shuman C, Gow A, Taylor K, Grootes P, White J, Ram M, Waddington E, Mayewski P, Zielinski G (1993) Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. Nature 362:527–529

Andres AS, Howard CS (2000) The Cypress Swamp Formation, Report of Investigations, vol 62. Delaware Geological Survey, Newark, 13p

Arbogast AF, Luehmann MD, Miller BA, Wernette PA, Adams KM, Waha JD, O'Neil GA, Tang Y, Boothroyd JJ, Babcock CR, Hanson PR, Young AR (2015) Late-Pleistocene paleowinds and aeolian sand mobilization in north-central lower Michigan. Aeolian Res 16:109–116

Arp CD, Jones BM, Urban FE, Grosse G (2011) Hydrogeomorphic processes of thermokarst lakes with grounded-ice and floating-ice regimes on the Arctic coastal plain, Alaska. Hydrol Process 25:2422–2438

Askins AH (2010) Carolina Sandhills National Wildlife Refuge comprehensive conservation plan. U.S. Fish and Wildlife Service–Southeast Region, Atlanta, Georgia, 234p

Baldwin JL (1975) Weather Atlas of the United States. Gale Research Company, Detroit, 262p

Ballantyne CK (2018) Periglacial Geomorphology. Wiley, New York, 465p

Barber DC, Dyke A, Hillaire-Marcel C, Jennings AE, Andrews JT, Kerwin MW, Bilodeau G, McNeely R, Southon J, Morehead MD, Gagnon J-M (1999) Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. Nature 400:344–348

Bertran P, Liard M, Sitzia L, Tissoux H (2016) A map of Pleistocene aeolian deposits in western Europe, with special emphasis on France. J Quat Res 31:844–856

Bliley DJ, Burney DA (1988) Late Pleistocene climatic factors in the genesis of a Carolina Bay. Southeast Geol 29:83–101

Bliley DJ, Pettry DE (1979) Carolina bays on the eastern shore of Virginia. Soil Sci Soc Am J 43:558–564

Bristow CS, Armitage SJ (2016) Dune ages in the sand deserts of the southern Sahara and Sahel. Quat Int 410:46–57

Brooks MJ, Taylor BE, Grant JA (1996) Carolina Bay geoarchaeology and Holocene landscape evolution on the Upper Coastal Plain of South Carolina. Geoarchaeology 11:481–504

Brooks MJ, Taylor BE, Stone PA, Gardner LR (2001) Pleistocene encroachment of the Wateree River sand sheet into Big Bay on the Middle Coastal Plain of South Carolina. Southeast Geol 40:241–257

Brooks MJ, Taylor BE, Ivester AH (2010) Carolina Bays: time capsules of culture and climate change. Southeast Archaeol 29:146–163

Carey JB, Cunningham RL, Williams EG (1976) Loess identification in soils of southeastern Pennsylvania. Soil Sci Soc Am J 40:745–750

Carson CE, Hussey KM (1962) The oriented lakes of Arctic Alaska. J Geol 70:417–439

Carter LD (1981) A Pleistocene sand sea on the Alaskan Arctic Coastal Plain. Science 211:381–383

Carver RE, Brook GA (1989) Late Pleistocene paleowind directions, Atlantic Coastal Plain, U.S.A. Palaeogeogr Palaeoclimatol Palaeoecol 74:205–216

Chase CM (1977) Central Pennsylvania sand dunes. Pa Geol 8(3):9–12

Clark PU, Dyke AS, Shakun JD, Carlson AE, Clark J, Wohlfarth B, Mitrovica JX, Hostetler SW, McCabe AM (2009) The last glacial maximum. Science 325:710–714

Coté MM, Burn CR (2002) The oriented lakes of Tuktoyaktuk Peninsula, western Arctic coast, Canada: a GIS-based approach. Permafr Periglac Process 13:61–70

Coulombe O, Bouchard F, Pienitz R (2016) Coupling of sedimentological and limnological dynamics in subarctic thermokarst ponds in northern Québec (Canada) on an interannual basis. Sediment Geol 340:15–24
Court A (1974) The climate of the conterminous United States. In: Bryson RA, Kare FK (eds) Climates of North America. Elsevier, Amsterdam, pp 193–343
Daniels RB, Gamble EE, Boul SW (1969) Eolian sands associated with coastal plain river valleys—some problems in their age and source. Southeast Geol 11:97–110
Davis RE, Hayden BP, Gay DA, Phillips WL, Jones GV (1997) The North Atlantic subtropical anticyclone. J Clim 10:728–744
Delcourt PA, Delcourt HR (1984) Late Quaternary paleoclimates and biotic responses in eastern North America and the western North Atlantic Ocean. Palaeogeogr Palaeoclimatol Palaeoecol 48:263–284
Delcourt HR, Delcourt PA (1985) Quaternary palynology and vegetational history of the southeastern United States. In: Bryant VM Jr, Holloway RG (eds) Pollen Records of Late-Quaternary North American Sediments. American Association of Stratigraphic Palynologists Foundation, Dallas, pp 1–37
Denny CS, Owens JP (1979) Sand dunes of the central Delmarva Peninsula, Maryland and Delaware. U.S. Geological Survey Professional Paper 1067-C, 15p
Denny CS, Owens JP, Sirkin LA, Rubin M (1979) The Parsonsburg Sand in the central Delmarva Peninsula, Maryland and Delaware. U.S. Geological Survey Professional Paper 1067-B, 16p
Doar WR III, Howard CS (2010) Geologic map of the Steedman quadrangle, Aiken and Lexington Counties, South Carolina. South Carolina Geological Survey Geologic Quadrangle Map GQM-49, 1 sheet
Dowsett HJ, Cronin TM (1990) High eustatic sea level during the middle Pliocene: evidence from the southeastern U.S. Atlantic Coastal Plain. Geology 18:435–438
Earley LS (2004) Looking for Longleaf: The Fall and Rise of an American Forest. The University of North Carolina Press, Chapel Hill, 336p
Farnsworth RK, Thompson ES, Peck EL (1982) Evaporation Atlas for the Contiguous 48 United States. National Oceanic and Atmospheric Administration (NOAA) Technical Report NWS 33, 26p. and 4 plates
Feathers JK, Rhodes EJ, Huot S, Mcavoy JM (2006) Luminescence dating of sand deposits related to late Pleistocene human occupation at the Cactus Hill Site, Virginia, USA. Quat Geochronol 1:167–187
Feldman SB, Zelazny LW, Pavich MJ, Millard HT Jr (2000) Late Pleistocene eolian activity and post-depositional alteration on the Piedmont of northern Virginia. Southeast Geol 39:183–198
Fitzwater BA (2016) Reevaluating the geologic formations of the Upper Coastal Plain in Chesterfield County, South Carolina: M.S. thesis, Old Dominion University, Norfolk, Virginia, 189p
Folk RL, Ward WC (1957) Brazos River point bar: a study in the significance of grain size parameters. J Sediment Petrol 27:3–26
Foss JE, Fanning DS, Miller FP, Wagner DP (1978) Loess deposits of the eastern shore of Maryland. Soil Sci Soc Am J 42(2):329–334
French H, Demitroff M (2012) Late-Pleistocene paleohydrography, eolian activity and frozen ground, New Jersey Pine Barrens, eastern USA. Neth J Geosci 91:25–35
French HM, Miller SWS (2014) Permafrost at the time of the Last Glacial Maximum (LGM) in North America. Boreas 43:667–677
French HM, Demitroff M, Newell WL (2009) Past permafrost on the mid-Atlantic Coastal Plain, eastern United States. Permafr Periglac Process 20:285–294
Fryberger SG, Dean, G (1979) Dune forms and wind regime. In: McKee E (ed) A Study of Global Sand Seas. U.S. Geological Survey Professional Paper 1052, pp 137–169
Galbraith RF, Laslett GM (1993) Statistical models for mixed fission track ages. Nucl Tracks Radiat Meas 21:459–470
Galbraith RF, Roberts RG (2012) Statistical aspects of equivalent dose and error calculation and display in OSL dating: an overview and some recommendations. Quat Geochronol 11:1–27

Galbraith RF, Roberts RG, Laslett GM, Yoshida H, Olley JM (1999) Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: part I experimental design and statistical models. Archaeometry 41:339–364
Gamble EE, Daniels RB, Wheeler WH (1977) Primary and secondary rims of Carolina Bays. Southeast Geol 18:199–212
Glenn LC (1895) Some notes on Darlington (S. C.), 'bays.'. Science 2(41):472–475
Goddard EN, Trask PD, De Ford RK, Rove ON, Singewald JT Jr, Overbeck RM (1963) Rock-Color Chart. Geological Society of America, New York, New York
Grant JA, Brooks MJ, Taylor BE (1998) New constraints on the evolution of Carolina Bays from ground-penetrating radar. Geomorphology 22:325–345
Griffith GE, Omernik JM, Comstock JA, Lawrence S, Martin G, Goddard A, Hulcher VJ, Foster T (2001) Ecoregions of Alabama and Georgia. U.S. Geological Survey, Reston, Virginia, 1:1,700,000 scale map, 1 sheet
Griffith GE, Omernik JM, Comstock JA, Schafale MP, McNab WH, Lenat DR, MacPherson TF, Glover JB, Shelburne VB (2002) Ecoregions of North Carolina and South Carolina. U.S. Geological Survey, Reston, Virginia, 1:1,500,000 scale map, 1 sheet
Hack JT (1955) Geology of the Brandywine area and origin of the upland of southern Maryland. U.S. Geological Survey Professional Paper 267-A, 41p
Halfen AF, Lancaster N, Wolfe S (2016) Interpretations and common challenges of aeolian records from North American dune fields. Quat Int 410:76–95
Harman JR (1991) Synoptic climatology of the Westerlies: process and patterns. Association of American Geographers, Washington, DC, 80p
Hill JC, Condron A (2014) Subtropical iceberg scours and meltwater routing in the deglacial western North Atlantic. Nat Geosci 7:806–810
Hill JC, Gayles PT, Driscoll NW, Johnstone EA, Sedberry GR (2008) Iceberg scours along the southern U.S. Atlantic margin. Geology 36:447–450
Hinkel KM, Frohn RC, Nelson FE, Eisner WR, Beck RA (2005) Morphometric and spatial analysis of thaw lakes and drained thaw lakes in the western Arctic Coastal Plain, Alaska. Permafr Periglac Process 16:327–341
Hinkel KM, Sheng Y, Lenters JD, Lyons EA, Beck RA, Eisner WR, Wang J (2012) Thermokarst lakes on the Arctic Coastal Plain of Alaska: geomorphic controls on bathymetry. Permafr Periglac Process 23:218–230
Holmes JA (1893) Geology of the sand-hill country of the Carolinas. Geol Soc Am Bull 5:33–35
Hsu SA (1974) Computing eolian sand transport from routine weather data. In: Proceedings of the 14th Coastal Engineering Conference, 24–28 June 1974, vol 2. Copenhagen, Denmark, pp 1619–1626
Hugenholtz CH (2010) Topographic changes of a supply-limited inland parabolic sand dune during the incipient phase of stabilization. Earth Surf Process Landf 35:1674–1681
Hugenholtz CH, Wolfe SA, Moorman BJ (2008) Effects of sand supply on the morphodynamics and stratigraphy of active parabolic dunes, Bigstick Sand Hills, southwestern Saskatchewan. Can J Earth Sci 45:321–335
Ivester AH, Leigh DS (2003) Riverine dunes on the Coastal Plain of Georgia, USA. Geomorphology 51:289–311
Ivester AH, Leigh DS, Godfrey-Smith DI (2001) Chronology of inland eolian dunes on the Coastal Plain of Georgia. Quat Res 55:293–302
Ivester AH, Godfrey-Smith DI, Brooks MJ, Taylor BE (2002) Carolina Bays and inland dunes of the southern Atlantic Coastal Plain yield new evidence for regional paleoclimate. Geol Soc Am Abstr Programs 34(6):273–274
Ivester AH, Godfrey-Smith DI, Brooks MJ, Taylor BE (2003) Concentric sand rims document the evolution of a Carolina Bay in the middle coastal plain of South Carolina. Geol Soc Am Abstr Programs 35(6):169
Ivester A.H., Brooks, M.J., Taylor, B.E., 2007. Sedimentology and ages of Carolina Bay sand rims: Geol Soc Am Abstr Programs 39(2): 5

Jackson ST, Webb RS, Anderson KH, Overpeck JT, Webb T III, Williams JW, Hansen BCS (2000) Vegetation and environment in eastern North America during the last glacial maximum. Quat Sci Rev 19:489–508
Johnson HS Jr (1961) Fall line stratigraphy Northeast of Columbia, S.C. Geol Notes 5:81–87
Jorgenson MT, Kanevskiy M, Shur Y, Osterkamp T, Fortier D (2012) Thermokarst lake and shore fen development in boreal Alaska. In: Proceedings of the 10th International Conference on Permafrost, vol 1, pp 179–184
Kalińska-Nartiša E, Thiel C, Nartišs M, Buylaert J-P, Murray AS (2015) Age and sedimentary record of inland eolian sediments in Lithuania, NE European Sand Belt. Quat Res 84:82–95
Karlsson JM, Lyon SW, Destouni G (2012) Thermokarst lake, hydrological flow and water balance indicators of permafrost change in Western Siberia. J Hydrol 464-465:459–466
Kasse C (2002) Sandy aeolian deposits and environments and their relation to climate during the Last Glacial Maximum and Lateglacial in northwest and central Europe. Prog Phys Geogr 26:507–532
Katz RW, Parlange MB, Tebaldi C (2003) Stochastic modeling of the effects of large-scale circulation on daily weather in the southeastern U.S. Clim Chang 60:189–216
Kleman J, Jansson K, De Angelis H, Stroeven AP, Hättestrand C, Alm G, Glasser N (2010) North American ice sheet build-up during the last glacial cycle, 115–21 kyr. Quat Sci Rev 29:2036–2051
Kocurek G, Nielson J (1986) Conditions favorable for the formation of warm climate aeolian sand sheets. Sedimentology 33:795–816
Kutzbach J, Gallimore R, Harrison S, Behling P, Selin R, Laarif F (1998) Climate and biome simulations for the past 21,000 years. Quat Sci Rev 17:473–506
LaMoreaux HK, Brook GA, Knox JA (2009) Late Pleistocene and Holocene environments of the southeastern United States from the stratigraphy and pollen content of a peat deposit on the Georgia Coastal Plain. Palaeogeogr Palaeoclimatol Palaeoecol 280:300–312
Lancaster N (1995) Geomorphology of Desert Dunes. Routledge, London, 290p
Leigh DS (2006) Terminal Pleistocene braided to meandering transition in rivers of the southeastern USA. Catena 66:155–160
Leigh DS (2008) Late Quaternary climates and river channels of the Atlantic Coastal Plain, southeastern USA. Geomorphology 101:90–108
Livingstone DA (1954) On the orientation of lake basins. Am J Sci 252:547–554
Lowery DL, O'Neal MA, Wah JS, Wagner DP, Stanford DJ (2010) Late Pleistocene upland stratigraphy of the western Delmarva Peninsula, USA. Quat Sci Rev 29:1472–1480
MacCarthy GR (1937) The Carolina Bays. Bull Geol Soc Am 48:1211–1226
Macphail RI, McAvoy JM (2008) A micromorphological analysis of stratigraphic integrity and site formation at Cactus Hill, an early Paleoindian and hypothesized pre-Clovis occupation in south-central Virginia, USA. Geoarchaeology 23:675–694
Mallinson D, Burdette K, Mahan S, Brook G (2008) Optically stimulated luminescence age controls on late Pleistocene and Holocene coastal lithosomes, North Carolina, USA. Quat Res 69:97–109
Markewich HW, Markewich W (1994) An overview of Pleistocene and Holocene inland dunes in Georgia and the Carolinas – morphology, distribution, age, and paleoclimate, U.S. Geological Survey Bulletin 2069. 32p
Markewich HW, Litwin RJ, Pavich MJ, Brook GA (2009) Late Pleistocene eolian features in southeastern Maryland and Chesapeake Bay region indicate strong WNW-NW winds accompanied growth of the Laurentide ice sheet. Quat Res 71:409–425
Markewich HW, Litwin RJ, Wysocki DA, Pavich MJ (2015) Synthesis on Quaternary aeolian research in the unglaciated eastern United States. Aeolian Res 17:139–191
McKee ED, Bigarella JJ (1979) Sedimentary structures in dunes. In: McKee E (ed) A Study of Global Sand Seas. U.S. Geological Survey Professional Paper 1052, pp 83–134
McKenna Neuman C (1989) Kinetic energy transfer through impact and its role in entrainment by wind of particles from frozen surfaces. Sedimentology 36:1007–1015

McKenna Neuman C (1993) A review of aeolian transport processes in cold environments. Prog Phys Geogr 17:137–155
McKenna Neuman C (2003) Effects of temperature and humidity upon the entrainment of sediment particles by wind. Bound-Layer Meteorol 108:61–89
McKenna Neuman C (2004) Effects of temperature and humidity upon the transport of sedimentary particles by wind. Sedimentology 51:1–17
Melton FA, Schriever W (1933) The Carolina "Bays"–are they meteorite scars? J Geol 41:52–66
Miller W III (1979) Stratigraphic framework of the Wharton Station dune field, easternmost Beaufort County, North Carolina. Southeast Geol 20:261–273
Mix AC (1992) The marine oxygen isotope record: constraints on timing and extent of ice-growth events (120–65 ka). In: Clark PU, Lea PD (eds) The Last Integlacial-Glacial Transition in North America. Geological Society of America Special Paper 270, pp 19–30
Mixon RB (1985) Stratigraphic and geomorphic framework of uppermost Cenozoic deposits in the southern Delmarva Peninsula, Virginia and Maryland. U.S. Geological Survey Professional Paper 1067-G, 53p
Moore CR, Brooks MJ, Ivester AH, Ferguson T, Feathers JK (2012) Radiocarbon and luminescence dating at Flamingo Bay (38AK469): implications for site formation processes and artifact burial at a Carolina Bay. Legacy 16(1):16–21
Moore CR, Brooks MJ, Mallinson DJ, Parham PR, Ivester AH, Feathers JK (2016) The Quaternary evolution of Herndon Bay, a Carolina Bay on the Coastal Plain of North Carolina (USA): implications for paleoclimate and oriented lake genesis. Southeast Geol 51:145–171
Morgenstern A, Ulrich M, Günther F, Roessler S, Fedorova IV, Rudaya NA, Wetterich S (2013) Evolution of thermokarst in East Siberian ice-rich permafrost: a case study. Geomorphology 201:363–379
Newell WL, DeJong BD (2011) Cold-climate slope deposits and landscape modifications of the mid-Atlantic Coastal Plain, eastern USA. In: Martini IP, French HM, Alberti AP (eds) Ice-Marginal and Periglacial Processes and Sediments, Geological Society, London, Special Publication 354. pp 259–276
Otvos EG (2004) Prospects for interregional correlations using Wisconsin and Holocene aridity episodes, Northern Gulf of Mexico coastal plain. Quat Res 61:105–118
Parham PR, Riggs SR, Culver SJ, Mallinson DJ, Rink WJ, Burdette K (2013) Quaternary coastal lithofacies, sequence development and stratigraphy in a passive margin setting, North Carolina and Virginia, USA. Sedimentology 60:503–547
Peek KM, Mallinson DJ, Culver SJ, Mahan SA (2014) Holocene geologic development of the Cape Hatteras region, Outer Banks, North Carolina, USA. J Coast Res 30:41–58
Pickering SM, Jones RC (1974) Morphology of aeolian parabolic sand features along streams in southeast Georgia. Geol Soc Am Abstr Programs 6(4):387–388
Powars DS, Edwards LE, Johnson GH, Berquist CR (2016) Geology of the Virginia Coastal Plain: new insights from continuous cores and geophysical surveys. In: Bailey CM, Sherwood WC, Eaton LS, Powars DS (eds) The Geology of Virginia, Virginia Museum of Natural History, Special Publication 18. Martinsville, pp 193–240
Powers MC (1953) A new roundness scale for sedimentary particles. J Sediment Petrol 23:117–119
Prouty WF (1952) Carolina Bays and their origin. Geol Soc Am Bull 63:167–224
Rasmussen WC, Slaughter TH (1955) The ground-water resources. In: The Water Resources of Somerset, Wicomico, and Worcester Counties, Maryland Department of Geology, Mines and Water Resources Bulletin 16, pp 1–170
Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE (2009) IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51:1111–1150

Rex RW (1961) Hydrodynamic analysis of circulation and orientation of lakes in northern Alaska. In: Raasch GO (ed) Geology of the Arctic – Proceedings of the First International Symposium on Arctic Geology, vol 2. University of Toronto Press, Toronto, pp 1021–1043

Rodríguez AB, Waters MN, Piehler MF (2012) Burning peat and reworking loess contribute to the formation and evolution of a large Carolina-bay basin. Quat Res 77:171–181

Sahsamanoglou HS (1990) A contribution to the study of action centres in the North Atlantic. Int J Climatol 10:247–261

Sarnthein M (1978) Sand deserts during glacial maximum and climatic optimum. Nature 272:43–46

Scott TW, Swift DJP, Whittecar GR, Brook GA (2010) Glacioisostatic influences on Virginia's late Pleistocene coastal plain deposits. Geomorphology 116:175–188

Selby MJ, Rains RB, Palmer RW (1974) Eolian deposits of the ice-free Victoria Valley, southern Victoria Land, Antarctica. N Z J Geol Geophys 17:543–562

Seminack CT, Buynevich IV (2013) Sedimentological and geophysical signatures of a relict tidal inlet complex along a wave-dominated barrier: Assateague Island, Maryland, U.S.A. J Sediment Res 83:132–144

Shuman B, Bartlein P, Logar N, Newby P, Webb T III (2002) Parallel climate and vegetation responses to the early Holocene collapse of the Laurentide ice sheet. Quat Sci Rev 21:1793–1805

Smith LL (1931) Solution depressions in sandy sediments of the coastal plain in South Carolina. J Geol 39:641–652

Soller DR (1988) Geology and tectonic history of the lower Cape Fear River valley, southeastern North Carolina. U.S. Geological Survey Professional Paper 1466-A, 60p

Soulé PT (1998) Some spatial aspects of southeastern United States climatology. J Geogr 97:142–150

Spencer J, Jones KB, Gamble DW, Benedetti MM, Taylor AK, Lane CS (2017) Late-Quaternary records of vegetation and fire in southeastern North Carolina from Jones Lake and Singletary Lake. Quat Sci Rev 174:33–53

Stanford SD (1993) Late Cenozoic surficial deposits and valley evolution of unglaciated northern New Jersey. Geomorphology 7:267–288

Stolt MH, Rabenhorst MC (1987a) Carolina Bays on the eastern shore of Maryland: I. Soil characterization and classification. Soil Sci Soc Am J 51:394–398

Stolt MH, Rabenhorst MC (1987b) Carolina Bays on the eastern shore of Maryland: II. Distribution and origin. Soil Sci Soc Am J 51:399–405

Stuiver M, Reimer P (1993) Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35:215–230

Sun J, Ding Z, Liu T (1998) Desert distributions during the glacial maximum and climatic optimum: example of China. Episodes 21(1):28–31

Suther BE, Leigh DS, Brook GA (2011) Fluvial terraces of the Little River Valley, Atlantic Coastal Plain, North Carolina. Southeast Geol 48:73–93

Swezey C (1998) The identification of eolian sands and sandstones. Comptes Rendus de l Academie des Sciences 327(8):513–518

Swezey C (2001) Eolian sediment responses to late Quaternary climate changes: temporal and spatial patterns in the Sahara. Palaeogeogr Palaeoclimatol Palaeoecol 167:119–155

Swezey CS, Schultz AP, Alemán González W, Bernhardt CE, Doar WR III, Garrity CP, Mahan SA, McGeehin JP (2013) Quaternary eolian dunes in the valley of the Savannah River, Jasper County, South Carolina. Quat Res 80:250–264

Swezey C.S, Fitzwater BA, Whittecar GR (2016a) Geology and geomorphology of the Carolina Sandhills, Chesterfield County, South Carolina. In: Doar III WR (ed) Gold, Structures, and Landforms in Central South Carolina – Field Guides for the GSA Southeastern Section Meeting, Columbia, South Carolina, 2016. Geological Society of America Field Guide 42, pp 9–36

Swezey CS, Fitzwater BA, Whittecar GR, Mahan SA, Garrity CP, Alemán González WB, Dobbs KM (2016b) The Carolina Sandhills: Quaternary eolian sand sheets and dunes along the updip margin of the Atlantic Coastal Plain province, southeastern United States. Quat Res 86:271–286

Taylor BE, Rich FJ, Brooks MJ, Ivester AH, Clement CO (2011) Late Pleistocene and Holocene vegetation changes in the Sandhills, Fort Jackson, South Carolina. Southeast Geol 48:147–163
Thom BG (1970) Carolina Bays in Horry and Marion Counties, South Carolina. Geol Soc Am Bull 81:783–814
Thornthwaite CW (1931) The climate of North America according to a new classification. Geogr Rev 21:633–655
Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94
Timmons EA, Rodriguez AB, Mattheus CR, DeWitt R (2010) Transition of a regressive to a transgressive barrier island due to back-barrier erosion, increased storminess, and low sediment supply: Bogue Banks, North Carolina, USA. Mar Geol 278:100–114
UNESCO (1979) Map of World Distribution of Arid Regions. United Nations Educational, Scientific and Cultural Organization (UNECSO) Programme on Man and the Biosphere (MAB) Technical Notes 7, Explanatory Note (54p.) and Map (1 sheet at scale of 1:25,000,000)
Vandenberghe J, French HM, Gorbunov A, Marchenko S, Velichko AA, Jin H, Cui Z, Zhang T, Wan X (2014) The last permafrost maximum (LPM) map of the Northern Hemisphere: permafrost extent and mean annual air temperatures, 25–17 ka BP. Boreas 43:652–666
Wagner DP, McAvoy JM (2004) Pedoarchaeology of Cactus Hill, a sandy Paleoindian site in southeastern Virginia, U.S.A. Geoarchaeology 19:297–322
Watts WA (1980a) Late-Quaternary vegetation history at White Pond on the inner Coastal Plain of South Carolina. Quat Res 13:187–199
Watts WA (1980b) The late Quaternary vegetation history of the southeastern United States. Annu Rev Ecol Syst 11:387–409
Webb T III, Bartlein PJ, Harrison SP, Anderson KH (1993) Vegetation, lake levels, and climate in eastern North America for the past 18,000 years. In: Wright JE Jr, Kutzbach JE, Webb T III, Ruddiman WF, Street-Perrott FA, Bartlein PJ (eds) Global Climates since the Last Glacial Maximum. University of Minnesota Press, Minneapolis, pp 415–467
Wilson P, Clark R, Birnie J, Moore DM (2002) Late Pleistocene and Holocene landscape evolution and environmental change in the Lake Sulivan area, Falkland Islands, South Atlantic. Quat Sci Rev 21:1821–1840
Woodcock DW, Wells PV (1990) Full-glacial summer temperatures in eastern North America as inferred from Wisconsinan vegetational zonation. Palaeogeogr Palaeoclimatol Palaeoecol 79:305–312
Yang L-R, Ding Z-L (2013) Expansion and contraction of Hulun Buir Dunefield in north-eastern China in the last late glacial and Holocene as revealed by OSL dating. Environ Earth Sci 68:1305–1312
Zeeberg J (1998) The European sand belt in eastern Europe–and comparison of late glacial dune orientation with GCM simulation results. Boreas 27:127–139
Zhan S, Beck RA, Hinkel KM, Liu H, Jones BM (2014) Spatio-temporal analysis of gyres in oriented lakes on the Arctic Coastal Plain of northern Alaska based on remotely sensed images. Remote Sens 6:9170–9193
Zhou Y, Lu H, Zhang J, Mason JA, Zhou L (2009) Luminescence dating of sand-loess sequences and response of Mu Us and Otindag sand fields (North China) to climatic changes. J Quat Res 24:336–344