Aeolian Research 62 (2023) 100877

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Late Quaternary eolian dune-field mobilization and stabilization near the Laurentide Ice Sheet limit, New Jersey Pine Barrens, eastern USA

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A R T I C L E I N F O

Keywords:
Cold-climate
Dune stabilization
Optical dating
Grain morphoscopy
Last Glacial Maximum
Atlantic Coastal Plain

A B S T R A C T

Well-preserved stabilized dune fields are widespread in the New Jersey Pine Barrens, northern Atlantic Coastal Plain, USA. In this area, which was unglaciated throughout the Quaternary, quartz-rich Miocene–Pleistocene age fluvial and marginal marine sands provided source sediments for eolian mobilization. Parabolic and transverse dunes within fluvial source-bordering dune fields in small-river watersheds migrated to the east-southeast (110–125°) over unconsolidated sands and gravels. The short eolian transport distance of most dune-field sand in the presence of moderately to sub-rounded quartz grains with low sphericity indicates eolian abrasion and dune-sand fashioning occurred within a short duration of transport. Although the absolute duration of eolian transport remains unknown, dune stabilization occurred about 23–17.5 ka, with a weighted mean of 19.5 ± 0.5 ka from six dated dunes. Dune stabilization coincided with northward retreat of the Laurentide Ice Sheet from its maximum position at ~41.500° N (~100 km north of the study area), to ~41.375°N (~200 km north). The well-preserved dune morphology and narrowly constrained ages suggest rapid dune stabilization. Dune-forming katabatic winds from the WNW declined abruptly with northward migration of the ice sheet, accompanied by climatic amelioration and stabilization by vegetation. A short-lived period of eolian mobilization may have been associated with a temporary increase in sand availability from adjacent fluvially derived sediments. Post-depositional processes included soil eluviation, with dissolution features and breakage blocks on quartz grains signifying long-term *in-situ* soil weathering.

Introduction

Unlike contemporary eolian dune dynamics within semi-arid and desert settings, past eolian processes in periglacial (cold, non-glacial) areas remain less well understood (Seppälä, 2004; Wolfe, 2013; Woronko et al., 2015; Zieliński et al., 2016). Both in Europe and in North America, eolian sediment mobilization occurred within unglaciated regions beyond the margins of the last glacial ice sheets. In North America, dune fields and related eolian research are abundant within the unglaciated central and southern United States (Johnson et al., 2020; Mason et al., 2020), and along the eastern mid-latitudes of the Atlantic Coastal Plain (Markewich et al., 2015; Swezey, 2020). In Europe, eolian process were widespread under periglacial conditions, as inferred from the European 'sand belt' that extended from the Netherlands and Belgium in the west, across Germany, southern Denmark, and Poland, and into Russia in the east (Zeeberg, 1998; Kasse, 2002; Kalińska-Nartiša et al., 2015). European researchers have a long tradition of undertaking ice-marginal Quaternary dune studies (Högbom, 1923; Cailleux, 1942; Seppälä, 1972; Bernhardson et al., 2019), and many studies have occurred especially in Poland (Mycielska-Dowgiałło, 1965; Zieliński, 2003; Woronko et al., 2015). In North America, less well recognized are the paleo-dune systems that occurred along the margins of the Laurentide Ice Sheet (LIS) margin (Wolfe et al., 2004; Demitroff et al., 2012; French and Demitroff, 2012; Arbogast et al., 2015; Schaetzl et al., 2018). One example of such eolian dune systems is the New Jersey Pine Barrens dune fields of the U.S. northern Atlantic Coastal Plain (Fig. 1), where dune mobilization occurred under periglacial conditions at a time for which no full contemporary analogs exist due to the greater seasonality, sparse vegetation, intense insolation, and proximity to continental ice sheets (French, 2000; Vandenberghe, 2011; Demitroff et al., 2012).

https://doi.org/10.1016/j.aeolia.2023.100877
Received 3 February 2023; Received in revised form 20 May 2023; Accepted 22 May 2023
Available online 7 June 2023
1875-9637/

To date, no study of Pleistocene dune extant, beyond brief notes of observations, has been undertaken in southern New Jersey. To address this issue, this study applies detailed mineralogical, sedimentological, and geochronological methodologies to interpret the construction, mobilization, and stabilization of eolian dune fields in an ice marginal setting near the Laurentide Ice Sheet limit. The study focuses on eolian dune fields in the New Jersey Pine Barrens, which evolved during the last glacial episode on sandy Neogene-age-derived unconsolidated sediments of the U.S. northern Atlantic Coastal Plain. Within the context of past eolian and periglacial processes operating in the Pine Barrens, this paper has the following objectives: 1) to assess the timing of dune-field stabilization in relation to the position of the Laurentide Ice Sheet; 2) to discuss the influence of sediment sources and transport distances on the evolution of eolian sediments and dune fields; and 3) to improve the understanding of dune-field dynamics in the context of past environmental conditions.

Background

During the Late Wisconsinan Marine Isotope Stage 2 (MIS 2; ~28–11.7 ka), the southeastern limit of the LIS extended to within 50 km of the northernmost boundary of the New Jersey Pine Barrens (Fig. 1B) (Demitroff, 2016), providing proximal conditions for periglacial processes. Indeed, recent field investigations confirm earlier statements by Newell et al. (2000) and French and Demitroff (2001) that relict, well-developed periglacial features occur in southern New Jersey. French et al. (2003, 2005), French et al. (2007) and Merritts and Rahnis (2022) provide evidence of both deep seasonal frost and past permafrost in this area, including the presence of frost fissures related to permafrost aggradation and thermokarst structures associated with permafrost degradation. French and Demitroff (2012) further suggest that braided paleochannels, common throughout major watersheds in the Pine Barrens, are the result of reduced substrate permeability arising from the presence of permafrost. Evidence also exists for persistent winds, manifested in the form of eolian sand dunes, sand sheets (Newell et al., 2000; French and Demitroff, 2012), and ventifacts (Newell and Wyckoff, 1992; Demitroff, 2016). Strong katabatic winds during the Late Glacial Maximum (LGM) are surmised to have extended across the U.S. northern Atlantic Coastal Plain (Markewich et al., 2015). The presence of the continental ice sheet was also a potent influence in regions beyond the limit of katabatic winds, with alteration in regional wind patterns expressed for hundreds of kilometers south of the ice sheet along the southeastern Atlantic Coastal Plain. Sediment-transporting winds aided the development of eolian dune fields across the U.S. Atlantic Coastal Plain from Delaware to Georgia (Denny et al., 1979; Markewich and Markewich, 1994; Ivester et al., 2001; Ivester and Leigh, 2003; Markewich et al., 2009, 2015; Swezey, 2020; Swezey et al., 2013, 2016; Fig. 1A), and into the Gulf of Mexico (Otvos, 2004, and Otvos and Price, 2001). Based on this large assemblage dunes throughout the Atlantic Coastal Plain, Swezey et al. (2013) suggested that wind velocities must have been greater during the LGM than at present.

Exposed sediments and strata in the New Jersey Pine Barrens are predominantly marine, fluvial, and terrestrial sands of Miocene–Pleistocene age. Throughout much of the Pine Barrens, the exposed substrate is quartz-rich sand, mapped as the Lower-Middle Miocene (~10 Ma) Cohansey Formation (10–30 + m thick) and interpreted as fluvial-

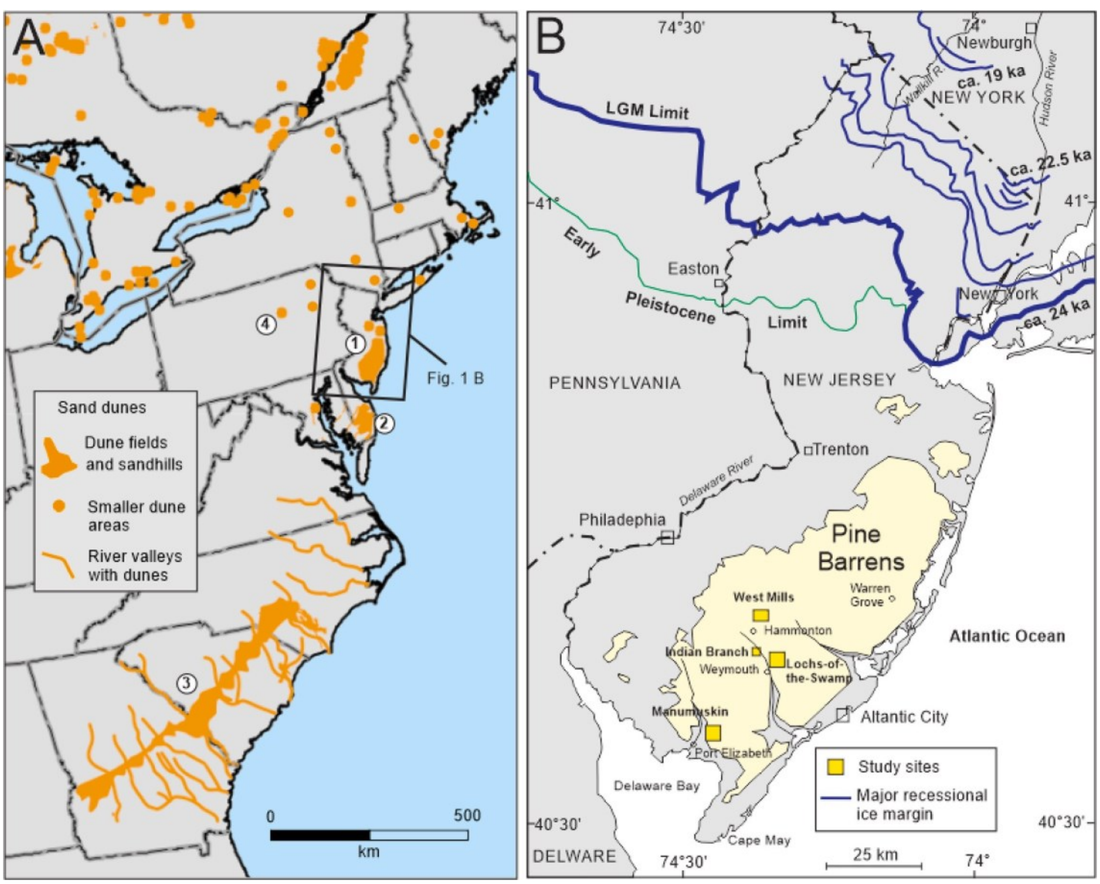


Fig. 1. Sand dunes in eastern North America. A) Distribution of dune fields, smaller dune areas and river valleys with dunes (from Wolfe et al., 2009 with additions from Chase, 1977; Lookingbill et al., 2013; and Swezey, 2020). Numbered locations refer to dune areas mentioned in text including: 1) New Jersey Pine Barrens; 2) Delmarva Peninsula; 3) Carolina Sandhills; and 4) dune area near Lewisburg, Pennsylvania. A) New Jersey Pine Barrens (as per McCormick and Andresen, 1963), fields sites, and past glacial limits and ice margins (Stanford et al., 2021) showing major recessional ice margins between 24 and 19 ka. LGM = Last Glacial Maximum.

channel, deltaic, and marginal marine deposits (Newell et al., 2000). The Cohansey Formation and is overlain at higher elevations in the southern Pine Barrens by arkosic sands and gravels (3–20 m thick) that are mapped as the Upper Miocene Bridgeton Formation and interpreted as major river discharge delta-plain, channel-fill deposits (Newell et al., 2000). At elevations of 20–30 m asl, Pleistocene-aged surficial sands and gravels are interpreted as colluvial and alluvial sediments, which grade eastward and southward at 15–20 m asl into sands interpreted as braided-channel deposits (Newell et al., 2000). Surficial deposits from the weathered and eroded upland units surround the lower slopes, merging with the margins of younger (Quaternary) sands and muds that are interpreted as marginal marine sediments (Newell et al., 2000). Associated Quaternary high-stand terraces are present on the eastern and southern edges of the Pine Barrens at elevations of up to 8 m (Stanford, et al., 2016).

Eolian dune fields are widespread at the surface and are superimposed upon all older deposits. No ice-contact glacial deposits or outwash sediments pertaining to Pleistocene glacial ice extents have been identified in the area. This lack of glacial ice-contact and outwash deposits is likely the result of the New Jersey Pine Barrens remaining unglaciated and an Inner Coastal Plain cuesta that blocked Pleistocene glacial outwash from entering the Pine Barrens (Demitroff, 2016), diverting sediments through the Delaware and Hudson Rivers (Fig. 1B).

The New Jersey Pine Barrens presently supports a cool temperate forest, with pine (*Pinus* spp.) and oak (*Quercus* spp.) being the dominant forest compositional mix for at least the last 8,000 years (Southgate Russell, 2000). Watts (1979) found a predominance of spruce (*Picea* spp.) and birch (*Betula* spp.) pollen near Warren Grove, New Jersey (Fig. 1B), within organic silt dating to >12,000 cal yr BP. However, Pleistocene-aged pollen and larger plant macrofossils remain conspicuously absent from the local sediments (Potzger, 1945, 1952; Whitehead, 1965; Buell, 1970; Florer, 1972; Watts, 1979, 1983; Hartzog, 1982; Russell and Stanford, 2000; Sirkin, 1967, 1977, 1986; Sirkin et al., 1970). The widespread presence of Pleistocene-aged ventifacts identified in the Pine Barrens (French et al., 2003; French and Demitroff, 2012; Demitroff, 2016) attest to unvegetated or sparsely vegetated periods with strong winds resulting in abrasion by saltating sand.

Early geological investigations in the Pine Barrens noted eolian dune forms but suggested that they were limited in extent and widely scattered (Tedrow, 1986; Stanford, 2003, 2011, 2012). Newell et al. (2000) noted the occurrence of eolian deposits, but that “only the thickest sand dunes and extensive sheets of windblown sand are shown on the maps”. The full extent of these eolian dunes only became fully apparent with bare-earth light detection and ranging (LiDAR) digital elevation models (DEMs) introduced by USGS in 2010 (Figs. 2, 3). This new imagery revealed the presence of numerous inland eolian dunes that are now stabilized by vegetation (Demitroff et al., 2012; Stanford, 2016, 2017, 2020a & Stanford, 2020b), many of which are hairpin (i.e., elongate) parabolic dunes (Demitroff et al., 2012; French and Demitroff, 2012). South of the Pine Barrens, remote sensing imagery has revealed similar eolian dune forms in adjacent Delaware, Maryland, and Virginia (Newell and Clark, 2008; Markewich et al., 2009; Newell and DeJong, 2011; Swezey, 2020).

In addition to larger eolian dune forms, lunettes, which are small crescent-shaped anchored dunes (Shaw and Thomas, 1997; Hesp and Smyth, 2019), are also apparent (Fig. 3B). In the Pine Barrens, lunettes can form partial rims around small (~100–200 m wide) round-to-oval closed-basin ephemeral ponds (Wolfe, 1953; 1956), colloquially referred to as ‘spungs’ and interpreted as deflation basins (French and Demitroff, 2001). These closed basins are a northern variant of Carolina Bays, which are also commonly partially sand-rimmed (Ivester, 2007; Moore et al., 2016; Swezey, 2020). French and Demitroff (2001) interpret the rims as dune deposits of fine sandy sediments eroded by wind from the basin floor.

The modern climate of southern New Jersey is characterized by moderately cold winters and warm, humid summers with ~1100 mm of precipitation annually, falling primarily as rain; average temperatures range from 29 to 32 °C in July to −1 to −4 °C in January. New Jersey’s geographic position in the mid-latitudes often places it near the jet stream and prevailing westerly winds, particularly outside of summer months (Runkle et al., 2022). The strongest winds are typically associated with storms, which also carry heavy precipitation. The modern fluvial regime is comprised of meandering river channels, commonly incised within older braidplain stream deposits (French and Demitroff, 2012), with much of the area consisting of swamps.

Soils in New Jersey are predominantly ultisols, with about equal

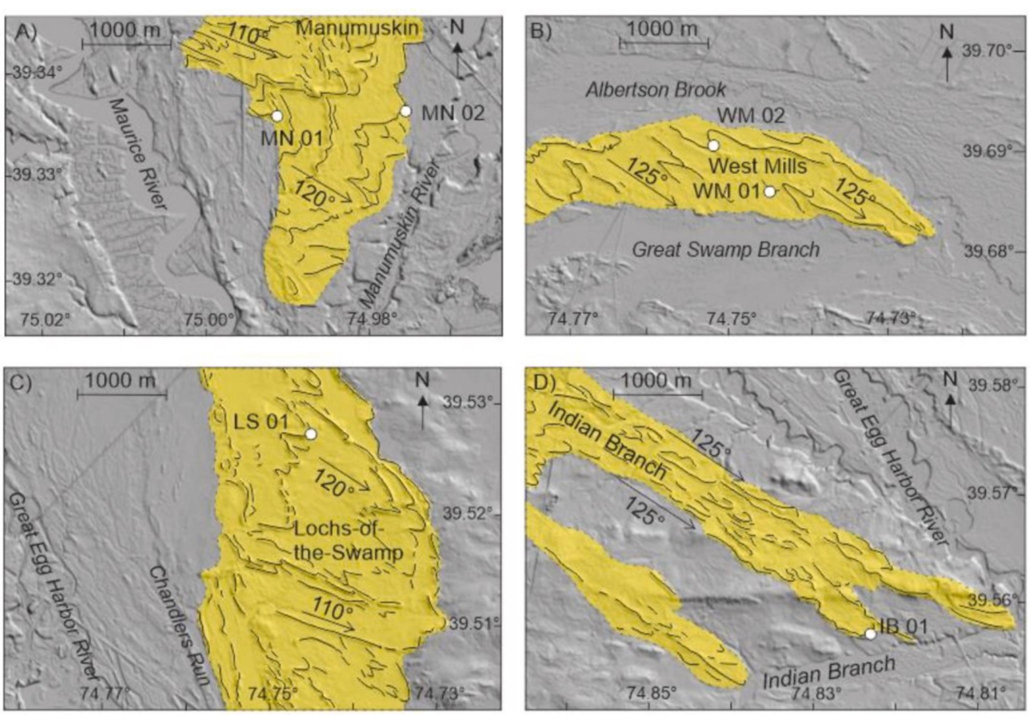


Fig. 2. Dune field study sites (yellow shading) within the southern New Jersey Pine Barrens with optical dating sample locations (white dots): A) Munumuskin; B) West Mills; C) Lochs-of-the-Swamp; D) Indian Branch. Dune crestlines drawn to highlight morphology with directional arrows indicating net-sediment transport by wind as interpreted from dune morphology. Base maps are Southern New Jersey LiDAR, © 2022 Boyd Ostroff (reproduced with permission). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

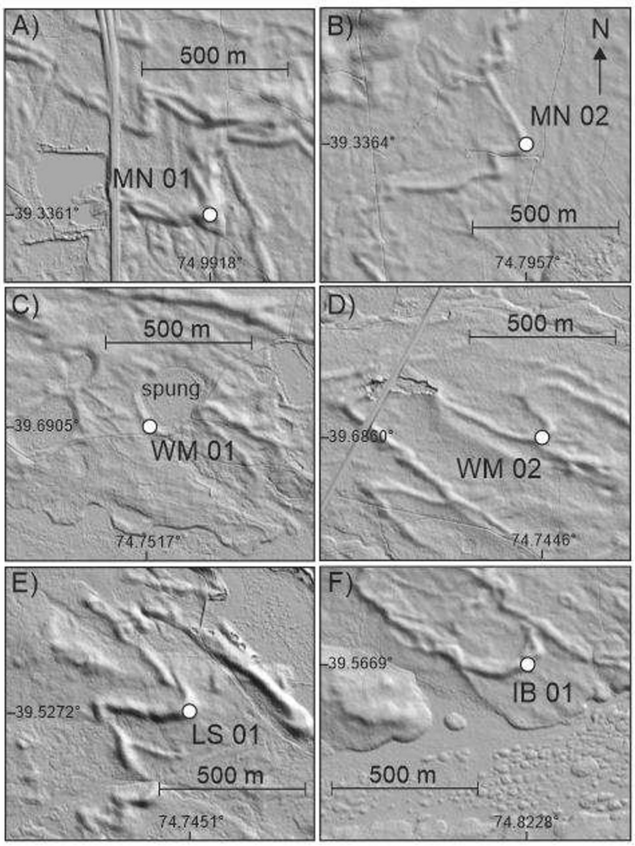


Fig. 3. LiDAR DEMs showing details at optical dating sample locations of parabolic dune-head morphologies (A, B, D, E, F). Note lunette ridge adjacent to deflation basin or 'spung' (C) and circular mounds (F) interpreted as patterned ground (French et al., 2003). Base maps are Southern New Jersey LiDAR, © 2022 Boyd Ostroff (reproduced with permission).

coverage of spodosols and entisols comprising ~40% of the total land area (USDA, 2008). Within the eolian dune fields, temperate pine-oak forests with well-drained quartz-rich sands are mainly underlain by sandy, spodic soils. The three main soils series are Evesboro sands occurring on higher relief dunes and fluvio-marine sands, Lakehurst sand occurring on dunes and sandy fluvio-marine deposits, and Lakewood sands occurring on low-relief eolian dunes and fluvio-eolian sheet sands. These soils occur on deep, loose, excessively drained sands with rapid permeability, low water capacity, high acidity, low fertility, and low organic content (USDA, 2008). The Evesboro soil series occurs on slopes of 0–40% (commonly 0–5%), and is taxonomically classified as a Mesic, coated Typic Quartzipsamment (typical profile—A/AB/Bw/C). The Lakehurst occurs on slopes of 0–5%, and is taxonomically classified as a Mesic, coated Aquodic Quartzipsamment (typical profile Oi/A/E/Bh/Bc/C/Cg). The Lakewood series occurs on slopes of 0–15% (commonly 0–5%), and is classified as a Mesic, coated Spodic Quartzipsamment (typical profile—A/E/Bh/BC/C1/C2). The Lakewood soil, in addition to containing an upper bleached light-gray sand, may include strong-brown and brownish yellow sand with large roots, common spheroidal iron-cemented nodules, and dark streaks in old root channels (USDA, 1971). All soils may contain quartzose pebbles up to 10 cm in diameter.

Study sites

Well-established dune fields in the New Jersey Pine Barrens commonly occur close to river-valleys, indicating a potential association between past fluvial and eolian activity. Therefore, four dune fields (Fig. 2) were selected for investigation from three small (<1500 km^2) river watersheds, including: 1) the Maurice River—Manumuskin dune field; 2) the Mullica River—West Mills dune field; and 3) the Great Egg Harbor River—Lochs-of-the-Swamp dune field and Indian Branch dune field. These sites are in substantially undisturbed conditions, being used primarily for forestry because the sandy soils do not support conventional agriculture (Demitroff, 2007, 2014).

Manumuskin dune field

The Manumuskin dune field, north of Port Elizabeth (Fig. 1B), is bounded to the west by the Maurice River and to the east by the Manumuskin River (Fig. 2A). The dunes are stabilized by vegetation. The near-surface sediments are medium-grained, moderately sorted, quartz-rich sands (interpreted as eolian), varying from one-to-several meters thick (Newell et al., 2000). The dune field resides on a 3–5-m thick unit of quartz-rich sand to pebbly gravel, mapped as the late Sangamonian–Early Wisconsinan Cape May Formation that are interpreted as marginal marine deposits, and underlain by finer-grained sand and mud interpreted as estuarine deposits (Newell et al., 2000). Fluvial terraces occur at an elevation of ~5 m above sea level (asl) and are eroded by younger terraces to the west at an elevation of ~3 m asl (Fig. 2A). These terraces are generally underlain by 1–2 m layer of alluvium consisting of very fine-to-coarse sand and containing sparse gravel (Newell and Wychoff, 1992). The Sangamonian marine highstand (MIS 5e) was ~8 m above present sea level (Stanford et al., 2016), which arguably limits the maximum age of terrestrial exposure and eolian deposits to MIS 5e in this area.

Stabilized dunes rise to a maximum height of ~4 m above the surrounding interdune areas (Table 1). They consist of several prominent southeast-trending parabolic dune crestlines and sub-parallel dune ridges (Fig. 2A). The interdune sediments consist of ~1 m thick moderately sorted, medium sand, interpreted as interdune eolian sands, which are underlain by moderately sorted medium-to-coarse sand interpreted as fluvial sediments. Rare quartz pebbles occur in the unit of fine-to-medium (eolian) sand and are more abundant in the underlying unit of medium-to-coarse (fluvial) sand. A dispersed pebble lag occurs at the unconformable contact between the unit of fine-to-medium (eolian) sands and the underlying unit of medium-to-coarse (fluvial) sands (Newell and Wyckoff, 1992).

West Mills dune field

The West Mills dune field lies north of Hammonton (Fig. 1B) and is bounded to the north by Albertson Brook and to the south by Great Swamp Branch of the Nescochague Creek, both tributaries of the Mullica River (Fig. 2B). The dunes are stabilized by vegetation and the dune sands vary from 1 to 3 m thick (Table 1). Near surface sands are predominantly quartz-rich, medium-grained, and moderately sorted. The dune field resides at an elevation of ~14 m asl and locally overlies a unit of sand and gravel that is interpreted as Pleistocene colluvium and alluvium, including anastomosing braided-channel deposits, derived from older slope deposits, and bedrock units including the Bridgeton and Cohansey Formations (Newell et al., 2000). These quartz-rich sand and gravel sediments are generally <2 m thick, but up to 8 m, and are typically weathered with deep textural B-horizons. Relict cryoturbation features and sand wedges are common in these Quaternary deposits (Newell et al., 2000). Newell and Wyckoff (1992) noted the presence of a large alluvial fan here and suggested that its architecture is indicative of active-layer and permafrost-thaw dynamics.

Stabilized dunes rise between 1.5 and 3 m above the interdune surfaces, and consist of wavy, elongate, discontinuous dunes, interpreted as parabolic, with merged arms being common (Fig. 2B). The dunes consist of quartz-rich, moderately sorted, medium sands, interpreted as eolian. This unit of medium sand overlies poorly sorted sand and gravel, interpreted as fluvial and colluvial. Interdune eolian sand-sheet deposits are <1 m thick, with a ventifact-pebble lag deposit (Demitroff, 2016)

Table 5
Dune field sediment and morphological characteristics.

Dune field	Settings	Dune and related feature morphologies	Eolian sediment thickness	Eolian transport direction (towards)	Eolian transport distance
Manumuskin	Bordering the Maurice River valley and locally underlain by Cape May marginal marine sands.	Well-developed sub-parallel ridges with parabolic dune crest lines 1.5–4 m high. Eolian sand underlain by dispersed pebble lag.	Interdunes ~1 m; dunes ~1.5–4 m	110–120°	1–2.5 km
West Mills	Bordering Albertson Brook valley (tributary of the Mullica River), and locally underlain by Pleistocene colluvial & alluvial sediments.	Wavy, narrow, sub-parallel ridges, with some parabolic dune crests 1.5–3 m high. Lunettes formed adjacent to local spungs. Eolian sand underlain by ventifact lag.	Interdunes ~0.2–0.5 m; dunes ~1.5–3 m	125°	1–1.5 km
Lochs-of-the-Swamp	Bordering the Great Egg Harbor River valley, and locally underlain by Bridgeton Formation and Pleistocene colluvial & alluvial sediments.	Well-developed sub-parallel ridges with parabolic dune crest lines with borders to 2.5–4.5 m high. Eolian sand underlain by discontinuous pebble lag.	Interdunes ~0.5–1 m; dunes 2.5–5 m	110–120°	1.5–2.5 km
Indian Branch	Bordering Great Egg Harbor River valley (Hospitality Branch and tributaries), and locally underlain by Bridgeton Formation and Pleistocene colluvial & alluvial sediments.	Elongate (i.e., hairpin) parabolic dunes & smaller individual parabolic dunes 1.5–2.5 m high.	Interdunes <0.5 m; dunes 1.5–2.5 m	125°	4.5–6 km

occurring at the contact between the unit of fine-to-medium sand (eolian) and the underlying unit of sand and gravel. Newell and Wyckoff (1992) have interpreted this ventifact lag as indicative of a period of deflation that preceded the deposition of eolian sands. In addition, several small 'spung' deflation basins occur within the dune field with linear ridges characteristic of lunettes (Fig. 2B).

Lochs-of-the-Swamp dune field

Lochs-of-the-Swamp dune field resides northeast of Weymouth (Fig. 1B), bounded to the west by Chandlers Run within the Great Egg Harbor River valley, at ~9 m asl (Fig. 2C), extending eastward for ~2.5 km (Table 1). The dunes are stabilized by vegetation, the dune field sand varies from 2.5 to 5 m thick, and with moderately sorted, medium-grained quartz-rich sand. At an elevation of ~15 m asl, stabilized dunes generally overlie a unit of quartz-rich poorly sorted sand and gravel that is interpreted as Pleistocene colluvial and alluvial sediments (Newell et al., 2000). This lower unit may include minimal soil development with lamellae, humate accumulations, and local chromic B-horizons ranging from 0.5 to 3 m thick, or a thicker (2–8 m) unit with more-abundant weathering, soil development, involutions, deformation, and infill features and that are characteristic of frozen-ground (Newell et al., 2000). Newell and Wyckoff (1992) also noted the presence of alluvial fans with anastomosing braided channels developed within these deposits in this area. A poorly sorted sand with silt and clay with poorly rounded gravel (mapped as a Bridgeton Formation Miocene aged fluvial-deltaic deposit) locally underlies portions of the dune field (Newell et al., 2000). The stabilized dunes rise to a maximum height of ~6 m above the surrounding interdune area and consist of several parabolic dune crestlines and sub-parallel dune ridges.

Indian Branch dune field

Indian Branch dune field lies northwest of Weymouth (Fig. 1B), residing south of both the Great Egg Harbor River and the Hospitality Branch, with Indian Branch to its south and east (Fig. 2C, D). The dunes are stabilized by vegetation, the dune field sand varies from 1.5 to 2.5 m thick with interdune areas <0.5 m thick (Table 1). Sands are quartz-rich, moderately sorted with medium grain size. The dune field extends for ~4.5–6 km southeast of White Oak Branch, a tributary of Hospitality Branch. Much of the Indian Branch dune field resides over quartz-rich, moderately sorted sands of the Cohansey Formation, interpreted as marginal marine deposits, and poorly sorted gravels of the Bridgeton Formation, interpreted as fluvial channel-bar deposits (Newell et al., 2000). At the study site, the dune sand overlies quartz-rich sands and gravels, interpreted as lower Pleistocene colluvial and alluvial valley deposits, possessing weathering, soil development, frost wedges, and perturbation features that are characteristic of frozen-ground (Newell et al., 2000). These dunes occupy about the same elevational terrace as the Lochs-of-the-Swamp dune field. Patterned ground contained within the paleochannel of Indian Branch is well defined at this location (French et al., 2003: 263, Fig. 3F) and overlying sands have been optically dated to 28.2 ± 2.8 ka (Demitroff, 2010, Demitroff et al., 2012). The Indian Branch dune field consists primarily of wavy, elongate (i.e., hairpin) stabilized parabolic dunes.

Methods

Field methods

For this study, forested field sites were accessed on-foot and locations were geo-referenced using a hand-held GPS receiver. Prior to sampling, exposed sections and augured shallow test pits were investigated to ascertain the thickness of eolian sands of the underlying sediments and that nature of stratigraphic contacts. Dune and lunette sample locations were selected based on topographic expression, as noted on LiDAR-derived DEMs (Figs. 2 and 3) and morphological observations in the field. Elevations and dune heights were determined from the LiDAR-derived data. Dune sample sites represented heads of stabilized dunes, along central crestlines on the stoss side of degraded slip-face slopes. These areas, which typically represent the highest local topography, considered to be sites where former dune sands were well exposed to eolian transport and thus reasonable locations to assess terminal depositional ages of sand dunes immediately prior to dune stabilization.

Sample pits were hand-dug to between 1.3 and 1.6 m depth to expose soil and stratigraphic profiles. Observed sections were qualitatively documented in the field for soil Munsell color, saturation, sorting, and grain size to assess appropriate depths for optical dating sampling, based on depths to undisturbed/minimally disturbed C horizons. Primary sedimentary structures were not observed in the sample profiles investigated, possibly owing, in part, to overprinting by soil processes and bioturbation by plant roots as noted by Swezey et al. (2020) in the Carolina Sandhills (Fig. 1A).

Sediment samples from exposed sections were collected for laboratory determination of grain-size distribution, mineralogy, and grain morphology. Samples were typically collected from 0.3, 0.6, and 1.3 m depths unless depth-constrained by the local groundwater table. Dune samples for optical dating were obtained from a depth of 1.3 m, whereas the lunette sample (WM-04) was obtained from a depth 0.6 m to ensure sampling within these thinner eolian deposits and to be above the local groundwater table (Table 2). Optical dating samples were collected using a metal pipe (~6 cm diam. × ~25 cm long), with a metal end cap

Table 2
Eolian sample locations, elevations, heights, optical dating sample depth, and ages. Additional detail related to the optical ages can be found in Table S7.

	Site	Latitude (deg N)	Longitude (deg W)	Location	Elevation (m asl)	Height (m)	Depth (m)	Optical age (ka)[a]
MN-01	Manumuskin	39.336135	74.991735	dune head	8.0	3.2	1.3	18.9 ± 1.3
MN-02	Manumuskin	39.336242	74.975613	dune head	7.0	1.5	1.3	19.1 ± 1.3
WM-01	West Mills	39.685952	74.794204	lunette	15.5	1.2	0.6	19.3 ± 1.3
WM-02	West Mills	39.691375	74.751566	dune head	18.5	2.3	1.3	21.7 ± 1.3
LS-01	Lochs-of-the-Swamp	39.527224	74.744962	dune head	22.5	4.5	1.3	18.8 ± 1.3
IB-01	Indian Branch	39.556981	74.823006	dune head	22.0	2.5	1.3	19.0 ± 1.3

[a] Optical ages expressed as thousands of years (ka) before CE 2020. Analytical uncertainties are ±1 sigma.

on the outfacing end of the pipe. The pipe was pressed against the freshly exposed face and hammered into sediment until it was flush with the exposure and would not penetrate further. The pipe was extracted from the face and a second end cap applied, avoiding direct exposure to sunlight. The pipe was labelled with the sample number, along with directions of in and out regarding the face of exposure. Samples for moisture content and dosimetry were obtained from surrounding sediments and from 15 cm above and below the sample depth.

At Manumuskin, samples from two parabolic dune heads, located at the eastern and western edges of the dune field, were collected for optical dating (Fig. 3A, B). At West Mills, a sample (sample WM-02) was collected from a stabilized parabolic dune head (Fig. 3C) at the northeastern edge of the dune field, and a second sample was collected from a stabilized lunette dune ridge (WM-01; Fig. 3D). At Lochs-of-the-Swamp, a sample (LS-01) was obtained from a large parabolic dune near the center of the dune field (Fig. 3E), and at Indian Branch a sample (IB-01) was collected at a terminal parabolic dune adjacent to Indian Branch (Fig. 3F).

Optical dating

Optical dating is a technique that provides the burial age of sediments by determining the time elapsed since their last exposure to sunlight (Huntley et al., 1985; Lian and Roberts, 2006). Eolian sediments are ideal for optical dating because wind transport of grains typically ensures complete sun exposure and re-setting of the luminescence signal prior to burial (Wintle, 1993). All laboratory procedures were conducted in an environment with controlled lighting specific to preparation and analysis of optical dating samples. Sample preparation was conducted at the Luminescence Dating Laboratory at the University of the Fraser Valley (Abbotsford, British Columbia, Canada) and included treatment with hydrogen peroxide and hydrochloric acid to remove any organic matter and dissolve any carbonates, respectively, sieving to attain the 180–250 μm diameter fraction, and heavy liquid separation to isolate the quartz fraction. A hydrofluoric acid treatment was used to remove any remaining feldspar and to etch away grain surfaces that had been affected by alpha radiation. Luminescence measurements were made at the Desert Research Institute Luminescence Laboratory (DRILL) using Risø TL/OSL DA-20 readers (see Supplementary Section S1 for measurement details).

Equivalent dose (*De*) for all quartz aliquots from all the samples were determined using a modified single aliquot regenerative-dose (SAR) technique (Murray and Wintle, 2000; 2003). Preliminary measurements on single grains showed that <5% of grains in these samples yielded a signal bright enough for dating, hence all *De* measurements were conducted on 1 mm diameter multi-grain aliquots of ~15 grains each. The dating experiments were conducted using measurement parameters determined based on preheat plateau and dose-recovery tests (See Supplementary Section S1 for details). Up to 96 aliquots were measured per sample to obtain a minimum of 35 accepted *De* determinations for age modelling. Overdispersion values, kernel density estimates (KDE), and radial plots (Supplementary Section S1, Table S7 and Fig. S3) were used to assess the distribution of aliquot *De* values for evidence of partial bleaching, and to remove any outlying *De* values.

Radioisotope concentrations in these samples were unusually low, and for that reason concentrations were measured by a variety of methods and by two different laboratories. Sample U, Th, and K contents were determined by neutron activation analysis (NAA), delayed neutron activation analysis (DNAA), and inductively coupled plasma mass spectrometry (ICP-MS) (Supplementary Section S1, Table S3 and S4). Dose rates were calculated using the weighted mean radionuclide concentrations obtained from all three analyses (Supplementary Section S1, Table S5). See Supplementary Section S1 for details regarding dose rates, water contents, dose responses, and dose recovery tests.

Mineralogy and grain-size analysis

Grain mineralogy was determined to assess the relative proportion of minerals in sand samples, and to assess the potential for allochthonous material imported into the study area.

Mineralogical analyses were performed on samples obtained from the depth of sampling for optical dating at the Advanced Microanalysis Centre, Saskatchewan Research Council (Canada). Whole ground samples were analyzed using a Bruker D4 Endeavor X-ray diffractometer with a Cu source. Mineralogical results were provided as weight percent (wt %), with detection limits for minerals of 1–3 wt%.

Grain-size distribution was determined to assess characteristics of eolian sediments and to determine the relative proportion of grains that may have been transported by saltation or suspension. Grain size and sorting were described according to methods of Folk and Ward (1957). Grain-size analysis was performed using two methodologies for comparative purposes. For 6 samples at the depth of sampling for optical dating, grain-size analysis was performed at the Geological Survey of Canada (GSC) Sedimentology Laboratory using a Retsch Technology Camsizer digital image analyzer to analyze sand-sized particles (2000–63 μm) and a Beckman Coulter Counter LS13-320 digital image analyzer to analyze the silt–clay fraction. Prior to measurement, samples were washed through sieves of 2000 and 63 μm, with the >2000 μm retained for bulk-weight measurement and the remaining separations retained for analysis of the respective fractions. Samples were pretreated with sodium hexametaphosphate for dispersion, and the sand-sized fraction underwent ultrasonic dispersion (sonification) for 20 s at 40% power level prior to analysis in the Camsizer to disaggregate grains.

An additional 18 samples underwent grain-size analysis using a Malvern, Mastersizer 3000 laser analyzer (0.01–3500 μm) at the Institute of Geography, Pedagogical University of Cracow, Poland. These samples first underwent sonification within the Mastersizer to disaggregate grains and remove coatings. In the field it was noted that sediment samples contained variable proportions of silt-sized particles. Consequently, the grain-analysis results may vary with the extent of sonification, with higher sonification resulting in a high proportion of fine-grained sediment derived from separation and disaggregation of particle-coatings. The following three different sonification levels were used to compare results: no sonification, 20 s at 40% level; and 60 s at high level (see Supplementary Section S4, Table S1). The mean of three measurements for each level of sonification was used as the final value.

Grain shape, morphoscopy, and microtextures

Multiple criteria are typically employed in assessing past environments of sedimentary deposits. The absence of apparent stratification at the study sites limits criteria, such as wind-ripple stratification (Swezey, 1998), to assess of past sedimentary deposition. In such circumstances other stratigraphic and sedimentological criteria including descriptive statistics of grain size, sorting, and distribution, and grain shape (e.g., Powers, 1953; Folk and Ward, 1957) are commonly employed. In Europe, micro-analytical techniques, including grain shape, morphoscopy, and microtextures are also routinely and effectively applied to assessing differing transport/weather processes of sediments, including eolian sands. Cailleux (1942) originally demonstrated that grain surface micromorphology may provide a means to assess environmental conditions of grain transport history and post-depositional processes. Early studies by Kuenen (1959, 1960) and Kuenen and Perdok (1962) suggested that the classification of Cailleux (1942) may not always be valid or determined objectively, necessitating the advancements of Go´zdzik (1980), with further refinements by Mycielska-Dowgiallo and Woronko (1998). These advancements have been useful in assessing past environmental history of sediments, particularly eolian sand.

Methods including roundness and surface characteristics have demonstrated utility in assessing past environmental history of sediments, particularly eolian sand. Recent micromorphological analysis of grain surfaces has been used to assess several environment variables, including: i) the duration and type of grain-transport processes from the initial to the full-stage development of surface microstructures; ii) the degree of morphological change from the grain source sediments; and iii) the intensity of mechanical and chemical weathering in post-depositional environments (e.g., Mahaney, 2002; Mol´en and Eyles, 2014; Woronko, 2016; Woronko and Pisarska-Jamroz˙y, 2016; Kˇriˇzek et al., 2017). Particularly relevant to this study is the use of grain surface roundness as an indicator of eolian transport distance, with roundness commonly intensifying in direct response to increased distance of grain transport (Mycielska-Dowgiallo, 2001; Woronko et al., 2017). In addition, quartz-grain shape can be a useful sedimentological attribute for reconstructing depositional and transport conditions, including distinguishing between eolian and fluvial transport processes and assessing the relative duration of grain transport under these processes (Chmielowska et al., 2021).

In the Pine Barrens of New Jersey, Miocene–Pleistocene surficial sedimentary deposits and associated chronological histories are well mapped and interpreted (Newell et al., 2000). This geological context is useful in assessing the application of micro-analytical techniques to the past environmental settings and to the relative duration of eolian transport of the sand dune deposits.

Morphoscopy and microtextures of quartz-sand grains

For 17 samples, representing all tested dune fields, morphoscopy of quartz-sand grains in two fractions (0.5–0.8 and 0.8–1.0 mm) was done using the morphoscopic method of Cailleux (1942) as modified by Mycielska-Dowgiallo and Woronko (1998). In each case, 100–150 randomly selected grains were first cleaned in 10% HCl acid, washed with distilled water, then analyzed as prescribed. Based on 9-degree scale of roundness by Krumbein (1941), quartz sand grains were classified into three class of degree of roundness (0.1–0.2; 0.3–0.6; and 0.7–0.9) and combined with grain-surface characteristics. The reduction of classes in the degree of roundness according to Krumbein scale, limits the subjectivism that was postulated by Kuenen (1959, 1960) and Kuenen and Perdok (1962). Using the modified method of Mycielska-Dowigiallo and Woronko (1998), seven grain types were distinguished (Table 3), and their characteristics used to interpret the sediment environmental residency, duration of transport, and subsequent of post-depositional processes.

For selected samples, quartz-grain microtexture analysis was conducted using scanning electron microscope (SEM) images on quartz-grain samples separated into 0.50–0.80 and 0.80–1.00 mm size fractions. Microtextures were studied at magnifications from 100 to 4000x. Grains were analyzed for roundness and microtextures to assist in interpreting sedimentary environments (Mahaney, 2002; Vos et al., 2014).

Table 3
Grain shape and surface characteristics, with environmental interpretation, as per modified Cailleux analysis by Mycielska-Dowgiallo and Woronko, 1998.

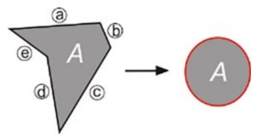
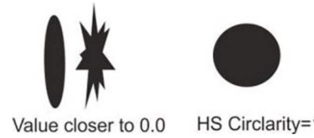
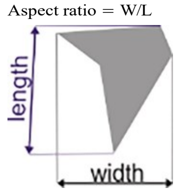
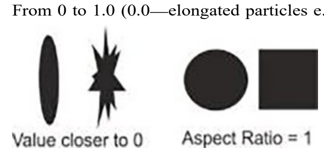
GRAIN TYPE	KRUMBEIN ROUNDNESS	GRAIN SURFACE CHARACTERISTICS	ENVIRONMENTAL INTERPRETATION
RM *rond-mat*	0.7–0.9	Well-rounded with completely matt surface	Long-term (>1,000 years) high-energy collisions in an eolian environment
EM/RM *transitive rond-mat*	0.3–0.6	Matt surface only on convex parts of grains	High-energy collisions in an eolian environment; sub-rounded grains indicate shorter duration of eolian processes than RM
EL *mousse-luisants*	0.7–0.9	Very well-rounded with smooth, featureless surface, shiny on the entire surface	Dissolving and abrasion by transport control in fluvial or beach environment; very well-rounded grains indicate long duration of processes
EM/EL *Transitive mousse-luisants*	0.3–0.6	Moderately rounded, smooth-shiny surface	Dissolving and abrasion by transport in fluvial or beach environment; moderately rounded grains
C *cass´e*	–	Crushed/broken	Crushing in all types of environments
NU *uon-us´es*	0.1–0.2	All surfaces are fresh, corners are sharp & angular	Crushing in glacial environment; in situ mechanical weathering—e.g., frost weathering
Other *une autre*	0.1–0.9	Intensive weathered surface by silica precipitation or solution; no transport trails	Crushing in all types of environments desert or periglacial environment

Automatic particle-shape image analysis

Grain shape is one of the most important parameters used in identifying sedimentary environments, transport conditions (including length), and sediment origin (e.g., Joo et al., 2018; Zielin´ski et al., 2016; Tunwal et al., 2018). Grain shape was used with the modified analysis of Mycielska-Dowgiallo and Woronko (1998), to assess the degree of eolian transport and grain fashioning. Quartz-sand grains from 9 samples (using 120–181 grains), representing all dune fields, were examined for automatic particle-shape image analysis (APIA) using a Malvern Morphologi G3SE analyzer (see Supplementary Section S2).

The APIA provides automatic scanning of the surface of a three-dimensional (3D) particle and a conversion into a corresponding two-dimensional (2-D) image. The analyzer measures particles in the size range from 10.0 to 0.5 μm. APIA is an objective method, where shape parameters ranging from 0 to 1 are compared. Quartz-grain shapes were measured for High Sensitivity (HS) circularity and aspect ratio parameters, which most precisely describe the particle shapes (Chmielowska et al., 2021). HS circularity corresponds to the degree of grain roundness and aspect ratio describes the degree of grain sphericity (Table 4).

Table 4
Shape parameters used to study sand grains with the Morphologi G3SE analyzer.

Shape parameter	Equation	Range
High sensitive circularity	HS circularity = $4\pi A/P^2$ A—area P—perimeter as sum of segment lengths Σ(a + b + c + d + e + d)  	From 0 to 1.0 (0.0—very narrow elongated particles; 1.0—perfect circle) 
Aspect ratio	Aspect ratio = W/L  	From 0 to 1.0 (0.0—elongated particles e.g., rod; 1.0—circular, isometric) 

Results

Dune morphology, stratigraphy, and optical ages

Manumuskin dune field

The parabolic dune morphology is indicative of sediment-transporting winds from the west-northwest (Fig. 2A), with net sediment transport direction (towards) between 110 and 120° (Table 1). In interdune areas throughout the Manumuskin dune field, ~1 m thick fine-to-medium quartz-rich sand (interpreted as eolian) overlies a unit of medium sand (interpreted as fluvial; Newell et al., 2000). Rare quartz pebbles were noted in eolian sediments and in underlying sands but did not form a sediment supply-inhibiting pavement and at the contact.

In the southern Manumuskin area, three auger pits within thin dune and interdune areas encountered ~1 m-thick unit of moderately sorted quartz-rich medium sands, interpreted as eolian (moderately to sub-rounded quartz grains with low sphericity), at the surface, overlying moderately sorted, medium-to-coarse, quartz-rich sands with occasional granules and small pebbles. The Maurice River has exposed 1–3 m of moderately sorted medium eolian sands underlain by ~2 m of medium-to-coarse sand, probably fluvial, with dispersed pebbles. A dispersed gravel lag was noted at the base of the well-sorted medium eolian sands.

Of the two dunes dated at Manumuskin, the first was a stabilized parabolic dune of ~3 m relief located at the western end of the dune field. The dune straddles a terrace of the Maurice River valley, interpreted a braided fluvial channel deposit that migrated southeast off the alluvial surface onto the quartz-rich sand-to-pebbly gravels of late Sangamonian–Early Wisconsinan Cape May Formation, interpreted as marginal marine deposits (Newell et al., 2000). The sampled dune section (Fig. 4A) revealed a very gray (10YR4/1) sand unit (0–20 cm depth), underlain by a yellowish brown (10YR5/6) root-rich layer of (20–70 cm depth), in turn underlain by yellow (10YR7/6) sand with few roots (70–140 cm depth). Sampled sand was medium-grained, moderately sorted, and quartz-rich (99.7%). The profile was similar to the Lakehurst soil series (see Supplementary Section S3). An OSL dating sample (MN-01) at 130 cm returned an age 18.9 ± 1.3 ka (Table 2).

The second dune dated at Manumuskin was located on the eastern side of the dune field and is interpreted as having migrated onto late Sangamonian–Early Wisconsinan Cape May Formation (interpreted as marginal marine deposits) (Newell et al., 2000). The stabilized parabolic dune has ~2 m relief and has migrated southeastward. The sampled section (Fig. 4B) revealed an organic horizon (0–5 cm depth), a unit of dark-gray (10YR4/1) sand (5–15 cm depth), a unit of gray (10YR6/1) sand (15–25 cm depth), and a unit of yellowish brown (10YR5/6) sand (25–60 cm depth) underlain by a unit brownish yellow (10YR6/6) sand (60–100 cm depth) containing several quartz pebbles 2–5 cm in diameter. Sands from 100 to 130 cm depth were yellow (10YR7/6) and contained few modern roots. Sampled sands were medium-grained, moderately sorted and quartz-rich (99.9%). The profile was similar to the Evesboro soil series showing some degree of eluviation. The sample (MN-02) from the dune returned an age of 19.1 ± 1.3 ka (Table 2).

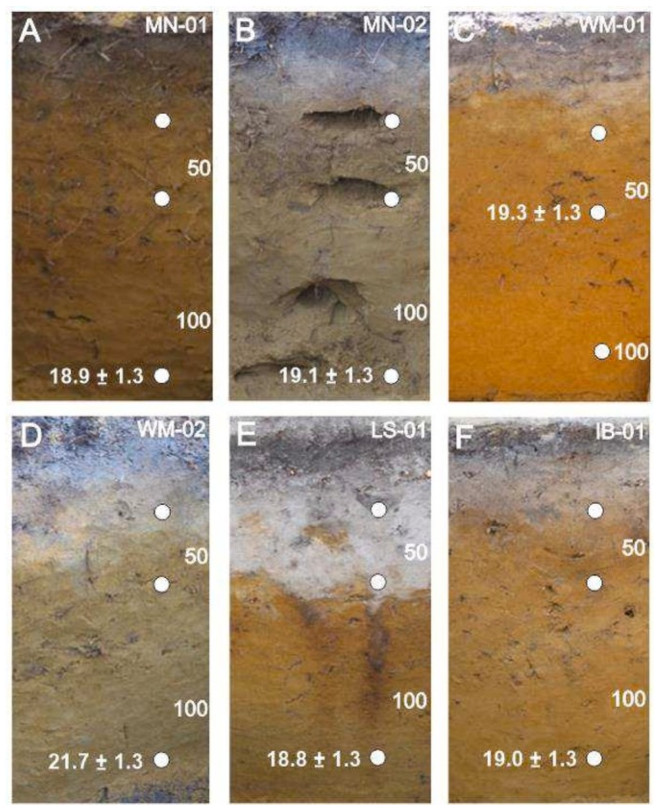


Fig. 4. Sample profiles with depths in cm, depicting variations in soil color and development and showing sample depths for grain analysis (white dots) and OSL ages with associated uncertainties.

West Mills dune field

Eolian sediment transport for the West Mills dune field is interpreted to have been generally towards the east-southeast, with net sediment transport direction of ~125°, based on the orientation of parabolic dune heads and arms. In interdune areas throughout the West Mills dune field, ~1 m thick fine-to-medium quartz-rich sand (interpreted as eolian) overlies a unit of medium sand (interpreted as fluvial; Newell et al., 2000). A continuous lag of pebbles (2–5 cm diameter), including ventifacts, occurs locally at the base of the fine-to-medium eolian sand. Auguring of a spung adjacent to the sampled lunette (Fig. 3C) encountered a gravel lag at 25 cm depth, immediately below sandy organic sediments. Auguring of the sampled lunette (WM-01 in Fig. 3C) encountered a gravel lag with ventifacts at ~1.5 m depth.

The sampled lunette section (Fig. 4C) revealed a unit of gray (10YR6/1) sand (0–10 cm depth) underlain by a unit of light-gray (10YR7/1) sand (10–25 cm depth) grading into a unit of brownish yellow (10YR6/6) sands (25–60 cm depth), which, in turn, is underlain by a unit of yellow (10YR7/6) sand (60–100 cm depth). This profile was indicative of the Lakehurst soil series. The dune sample section (Fig. 4D) revealed thicker and deeper extent of gray sand (10YR6/1; 0–15 cm depth) and light-gray sand (10YR7/1; 15–30 cm depth), with underlying yellowish brown (10YR5/6; 30–60 cm depth) and brownish yellow sands (10YR6/6; 60–130 cm depth). All sands encountered were quartz-rich (99.9%), medium-grained, and moderately sorted, and the section profiles correlate well with the Evesboro soil series (see Supplementary Section S3). The dune sample at West Mills (WM-02) returned an optical age of 21.7 ± 1.3 ka, whereas the lunette sample at West Mills (WM-01) returned an age of 19.3 ± 1.3 ka (Table 2).

Lochs-of-the-Swamp dune field

Dune morphology indicates sediment transporting winds from the west-northwest (Fig. 2C), with net sediment transport direction between 110 and 120° (Table 1). In the interdune areas throughout the Lochs-of-the-Swamp dune field, ~1 m thick moderately sorted, quartz-rich medium sand, interpreted as eolian, overlies a unit of moderately to poorly sorted medium-to-coarse sand, interpreted as fluvial. The contact is transitional, with a discontinuous lag of 2–5 cm diameter pebbles locally underlying interdune sediments at a depth of ~1.0 m—except in some localities where localized ventifact pebble lags occur.

The dune sample profile (Fig. 4E) revealed a surface unit of light-gray (10YR7/1) sand (0–3 cm depth) over a unit of dark-gray (10YR 5/1) sand (3–15 cm depth) underlain by a unit of light-gray (10YR7/1) sand (15–45 cm depth), which in turn was underlain by a unit of yellowish brown (10YR5/6) sands (45–100 cm depth) grading into a unit of yellow (10YR7/6) sands (100–140 cm depth). Sands in this profile were moderately sorted and quartz-rich (99.8% quartz at 130 cm depth) and ranged from medium sand at 30 and 60 cm depth to coarse sand at 130 cm depth. This profile showed the strongest indication of an eluviated horizon and strong iron-oxide staining, interpreted to have formed via preferential infiltration of groundwater along roots, animal burrows, microtopographic variability, or soil textural variability. This profile was indicative of the Lakewood soil series (see Supplementary Section S3). The optical dating sample (LS-01) returned an age of 18.8 ± 1.3 ka (Table 2).

Indian Branch dune field

Parabolic dune orientations at Indian Brach dune field are indicative of dune-forming winds from the northwest (Fig. 2D) and net sediment transport towards southeast at ~125° (Table 1). Sampling of a 3-m-relief dune head at the terminal position of an elongate parabolic dune revealed a 3-cm thick organic layer with an underlying sand section that was similar to what was observed in other profiles (Fig. 4F). It included a 10-cm thick gray (10YR6/1) sand, underlain by 10 cm of light-gray (10YR7/1) eluviated sand horizon with underlying yellowish brown (10YR4/6) sand with dark yellowish brown (10YR5/6) staining, which graded into a yellow (10YR7/6) sand at 80 cm depth. Sands were medium-grained and moderately to moderately well sorted throughout. The profile was characteristic of the Lakehurst soil series (see Supplementary section S3 for further details). The optical dating sample (IB-01) returned an age of 19.0 ± 1.3 ka (Table 2).

Mineralogy and grain size

Mineralogical X-ray diffraction (XRD) analysis consistently showed the samples collected for optical dating to be almost entirely composed of quartz. The Manumuskin eastern dune sample (MN01-130) was 99.7 wt% quartz, whereas the Lochs-of-the-Swamp dune sample (LS01-130) was 99.8 wt% quartz. The remaining dune and lunette samples were 99.9 wt% quartz. No other minerals were identified within the analytical detection limit of 1–3% (see Supplementary Section S3). This finding is consistent with earlier soils analysis within the Pine Barrens that noted few minerals present other than quartz, with feldspar content less that 1–2% (Martino, 1981), and observations that sand of the Bridgeton Formation commonly contains >99% quartz (Tedrow, 1986).

Grain size and distribution of all samples collected within soil C horizons at 100 and 130 cm depth (using Camsizer and Beckman Coulter Counter image analyzers), were similar and closely matched results from Mastersizer analysis using a pre-treatment without sonification and, in most cases, with low (20 s at 40%) sonification (see Supplementary Section S4, Table S1). These sands were medium-grained, ranging from a mean of 390–460 μm with one exception—the Lochs-of-the-Swamp dune sample was coarse-grained (arithmetic mean 540 μm). The West Mills lunette sample at 100 cm depth was similarly medium grained with an arithmetic mean grain size of 475 μm. In addition, all samples were moderately well sorted, symmetrically skewed, and mesokurtic. Silt and clay contents were low, typically being <0.5% in samples from the Manumuskin, Lochs-of-the-Swamp, and Indian Branch dune fields. Dune and lunette samples from West Mills were slightly higher in silt and clay content, ranging from 0.7 to 3.0% (see Supplementary Section S4, Table S1).

Despite these consistencies, sediments obtained higher in the soil profiles contained significantly more silt- and clay-sized particles, the proportion of which also increased with the degree of sonification (see Supplementary Section S4, Table S1). Unsonified dune samples from 30 to 60 cm depth typically contained between 2 and 7% silt, with the West Mills lunette containing 8.5–13.5% silt at 60 and 30 cm depth, respectively. Sonified samples typically contained 1.5–2.0 times more silt than unsonified samples.

Grain morphoscopy and microtextures

Grain analysis using the methods of Cailleux (1942) as modified by Mycielska-Dowgiałło and Woronko (1998) revealed similar sediment characteristics within the Manumuskin, Lochs-of-the Swamp, and Indian Branch dune fields (Table 5). The sediments were dominated by grains with an intermediate degree of roundness, typically expressed on grain edges and corners (type EM/RM). Their proportion included 85% in sample MN02-30 and 86% in sample LS01-60, and >92% in all remaining (9) samples (Table 5). Grains with a very good degree of roundness and matt overall surface (type RM) did not exceed 5% in the 0.5–0.8 mm fraction and 24% in the 0.8–1.0 mm fraction. The sediments characteristically presented a similar degree of roundness and matt on grain surfaces, with grains of the 0.8–1.0 mm fraction being better rounded than the 0.5–0.8 mm fraction. The grains of other categories as determined by the modified Cailleux analysis (i.e., EM/EL, C, EL, NU, Other) did not exceed 6% and were typically 0–2%, with EM/EL grains usually much less rounded than EM/RM grains. No feldspar grains were observed in the 0.5–0.8 mm fraction, but a few (<1%) were noted in the 0.8–1.0 mm fraction. The feldspar grains were sub-rounded or sub-angular whereas the quartz grains were sub-rounded.

The proportion of cracked grains (C) did not exceed 3% in any of the samples, and such grains were not present in most of the dune samples. At Indian Branch, sample IB01-30, derived from a depth of 30 cm, showed evidence of dissolution as an indicator of chemical weathering.

Table 5
Summary of modified by Mycielska-Dowgiałło and Woronko (1998) Cailleux grain-type analysis results presented as percent (%) contribution. Samples sorted by depth at each dune sample site and by generalized abundance of grain type. See Table 3 for characteristics associated with Cailleux category abbreviations.

Sample	EM/RM	EM/EL	RM	C	EL	NU	Other	EM/RM	EM/EL	RM	C	EL	NU	Other
	0.5–0.8 mm							0.8–1.0 mm						
MN01-30	85	5	3	0	0	0	6	85	2	10	0	0	0	3
MN01-60	94	2	2	0	0	0	2	81	1	17	1	0	0	1
MN01-130	94	2	3	2	0	0	0	86	2	11	0	0	0	1
MN02-30	94	1	4	0	1	0	0	73	2	24	1	0	0	0
MN02-60	96	1	1	0	0	0	1	75	0	23	1	0	0	1
WM01-30	73	17	1	2	1	0	7	62	19	9	1	0	0	10
WM01-60	48	42	1	2	2	0	5	78	9	8	1	0	0	4
WM01-100	55	33	2	3	0	0	7	86	9	2	0	0	0	2
WM02-30	66	24	0	0	1	0	9	60	24	6	1	0	0	10
WM02-60	59	31	0	0	3	0	7	56	25	13	3	0	0	4
WM02-130	60	30	0	2	0	0	8	61	21	6	3	0	0	10
LS01-30	92	2	4	2	0	0	0	78	5	16	0	0	0	1
LS01-60	86	8	2	0	2	0	4	84	3	10	0	0	0	2
LS01-130	92	3	5	0	0	0	0	–	–	–	–	–	–	
IB01-30	92	5	2	0	0	0	2	87	3	8	0	1	0	2
IB01-60	95	4	1	0	0	0	1	77	6	15	0	0	0	2
IB01-130	95	2	2	0	0	0	1	85	3	11	0	0	0	1

Evidence of dissolution was also observed with grains at Lochs-of-the-Swamp from sample LS01-30 at a depth of 30 cm. All grains from this sample were characterized by the presence of breakage-block microtextures on the surface. The proportion of this microtexture on the surface of a single grain was very large. In addition, it was the only sample to display a white grain-surface color.

In contrast to the above observations, quartz grains from the West Mills dune and lunette were characterized by a dominance of EM/RM grains that was lower than at other sites. The proportion of EM/RM grains in the 0.5–0.8 mm fraction was 48–66%, and only in the WM01-30 sample was the proportion as high as 73%. The 0.8–1.0 mm fraction was similar, but with a slightly higher proportion ranging from 55 to 86%. In the 0.5–0.8 mm fraction, grains with a high degree of roundness and completely matt surface were very rare, whereas in the coarser fraction the proportion ranges from 2 to 13%. These EM/RM grains (interpreted as being of eolian origin as per Table 3) were characterized by a low degree of roundness, with eolian processing visible only to a small extent on the grain edges. Compared to other dune field samples, the West Mills grains were poorly rounded. However, sediments from this site were distinguished by a high proportion of grains with EM/EL characteristics, which typically represent a high-energy fluvial environment (Table 3). In addition, EL grains, which are typically characteristic of longer durations of fluvial transport, also occurred in high proportion overall, ranging from 17 to 42% in the 0.5–0.8 mm fraction and from 9 to 25% in the 0.8–1.0 mm fraction. The EM/EL grains have a low degree of roundness and a completely shiny surface. In addition, Other grain types, which are characteristically marked by precipitated surfaces that result from intense chemical weathering, were particularly visible within grain micro-depressions. Overall, compared to sediments from the other study sites, the sediments of the West Mills area were characterized by a slightly higher proportion of cracked grains (C) and chemical weathering characteristics (Other).

Particle shape

The APIA indicated two groups of grains distinguished by particle shape. The first group included the dune field sites of Manumuskin (samples MN02-130 & MN02-60), Indian Branch (sample IB01-60), and Lochs-of-the-Swamp (sample LS01-130). The second group included samples from the dune field of West Mills and one sample from Lochs-of-the-Swamp (LOS01-30; Supplementary Section S2, Figs. S1 & S2).

In the first group of the three dune fields, the HS circularity parameter values ranged from the highest mean value of 0.925 and median value of 0.933 (sample MN02-130), to a low mean value of 0.913 and median of 0.918 (sample MN02-60) and of 0.911 and median of 0.920 (sample IB01-60; Supplementary Section S2, Fig. S1). This group was characterized by a slight variability in the HS circularity value (Supplementary Section S2, Figs. S1 & S2). The highest average value of aspect ratio of 0.846 was noted in two samples (MN02-130 & MN02-60) with a median of 0.852 and 0.849, respectively. Graphical relations of the aspect ratio and HS circularity showed an upward trend in parameter values, with a high concentration of grains with HS circularity values > 0.900 and $0.75 <$ aspect ratio < 0.95 (Supplementary Section S2, Fig. S2). Grains were well rounded, with smoothed corners and edges, but with small amounts of denivelation around the edges (Fig. 5A). Nevertheless, the degree of sphericity was low. A high proportion of grains had rectangular, square-like, or triangular shapes ($0.800 <$ AR < 0.980), where the a-axis was slightly longer than the b-axis and very elongate rectangular grains (AR < 0.800), and where the a-axis was much longer than the b-axis (Fig. 5A and Supplementary Section S2, Figs. S3–S18). Only a few grains had spherical or isometric (equant) shapes (AR > 0.98; HSC > 0.98). Overall, the grains within this group retained their original shape, but the degree of smoothing of the edges and corners as well as a small amount of denivelation within edges made these parameters relatively high (Fig. 5A).

In the second group, which included the West Mills samples and sample (LS01-30) from Lochs-of-the Swamp, the aspect ratio and HS circularity parameter values were lower. The mean value of HS circularity ranged from 0.896 with a median of 0.866 (sample WM02-130) to a mean value of 0.781 with a median of 0.799 (sample WM02-60). The highest mean aspect ratio value was 0.837 with a median of 0.851 (sample WM02-30), through a mean value of 0.812 and a median of 0.815 (sample LS01-30), to the lowest value of 0.800 and a median of 0.813 (sample WM03-60; Supplementary Section S2, Figs. S1–S2).

Graphs of the relation between aspect ratio and HS circularity showed dispersion of grains. Most of the grains from samples WM02-60, WM02-130, and LS01-30 were below the value 0.900 for HS circularity parameter, with varied values of aspect ratio (Supplementary Section S2, Fig. S2). Moreover, in sample WM02-60, the highest dispersion of grains within HS circularity parameter was observed, ranging from 0.600 to 0.900, and in aspect ratio ranging, from 0.700 to 0.900 (Supplementary Section S2, Fig. S2).

Grains within this second group were well rounded but with low sphericity. Their original grain shape was clearly visible, with only slightly rounded edges and corners, and with numerous denivelation within the edges (Fig. 5B). A large proportion of grains had irregular edges and rectangular (elongated), triangular, or polygonal shapes. Among these, most were rectangular grains (AR < 0.8 very elongated). Unlike the first group, very few grains were highly spherical or square

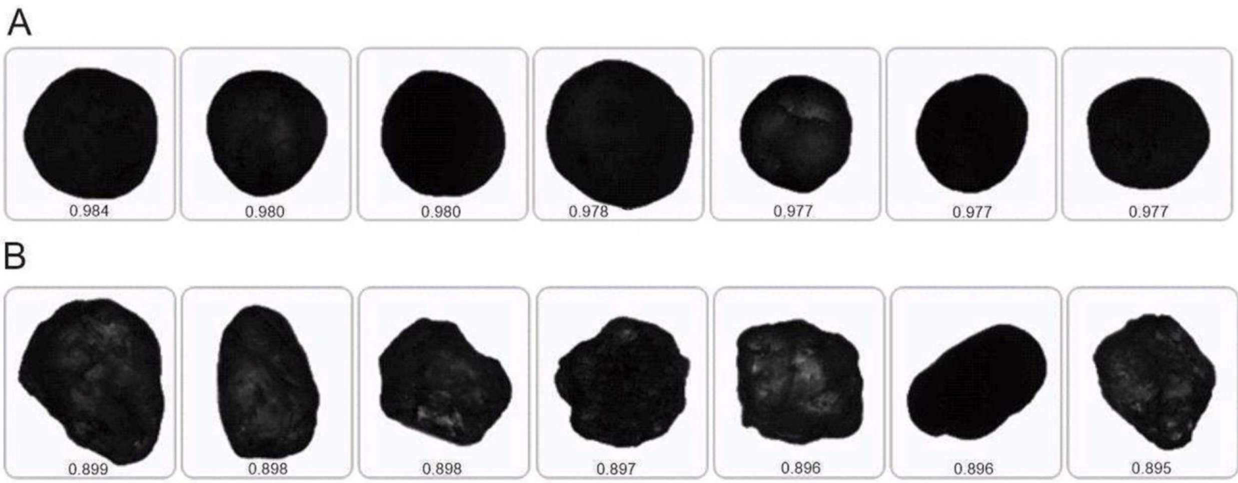


Fig. 5. Images and HS circularity of grains from: A) Manumuskin dune field showing highly circular grains with regular edges and small degree of micro-denivelation; and B) West Mills dune field showing isometric square-like grain with only rounded edges and corners and a greater degree of micro-denivelation.

(Fig. 5B) (sample WM02-30; Supplementary Section S2, Fig. S9).

Discussion

Dune morphology and stratigraphy in relation to sediment availability

All dune fields studies in the New Jersey Pine Barrens include morphologies indicative of parabolic dunes, with dune crests that are convex in the downwind direction and arms extending upwind. These dunes have morphological characteristic of open and unfilled parabolic dunes, with narrow dune heads and backslopes that are typically characteristic of an adequate, but limited sediment supply (Wolfe and David, 1997; Lemmen et al., 1998). Arms are elongate and point upwind within a narrow range of orientations of about 15° (from 290 to 305°), indicative of a predominantly unimodal wind direction. Other studies of parabolic eolian dunes have indicated that parabolic dunes commonly form under unidirectional wind regimes with adequate sand supplies and moderate vegetation cover (McKee, 1979; Lancaster, 1995; Hugenholtz et al., 2008; Swezey et al., 2013). Furthermore, the well-preserved nature of these dunes suggests that they likely stabilized due to increased vegetation cover and have not been subsequently remobilized.

In addition to parabolic dunes, morphological variations are apparent between the dune fields, including the preservation of sub-parallel dune ridges, interpreted as transverse dunes, at Manumuskin and Lochs-of-the-Swamp (Fig. 2A, C; Table 1). Transverse dunes are typically associated with a higher sediment supply than parabolic or barchan dunes (Lancaster, 1995). At each of these dune fields, transverse dunes are most well developed on the western edges of fields, proximal to sand sources as derived from the Maurice and Great Egg Harbor Rivers. At each dune field, sandy sediments were also encountered at depth with only rare pebbles or a discontinuous gravel lag. This is interpreted as permitting a local source of underlying sand supply for eolian transport. Thus, the dunes appear to have been constructed from sand that originated from adjacent river valleys, with additional sands derived from underlying sediments. The transverse dunes are indicative of locally greater sand availability for eolian mobilization in these areas, and parabolic dune morphologies are more apparent towards to the eastern edges of the dune fields where sediment supply appears reduced.

At the West Mills and Indian Branch dune fields, elongate parabolic dunes occur with extended arms and without well-developed transverse dunes (Fig. 2B, D and Table 1). The relief of dunes in the West Mills (1.5–3 m) and Indian Branch dune fields (1.5–2.5 m) is less than that of dunes in the Manumuskin (1.5–4 m) and Lochs-of-the-Swamp dune fields 2.5–5 m. At West Mills, a continuous pebble lag beneath the dunes is interpreted as a bounding surface, and at Indian Branch the dunes locally overly poorly sorted gravels of the Bridgeton Formation. These substrate conditions may limit the contribution of underlying sediments as source materials to the dunes. In addition, whereas the Manumuskin and Lochs-of-the Swamp dune fields are located downwind from major river valleys (Manumuskin and Great Egg Harbor Rivers, respectively) with higher fluvial sediment supplies, the West Mills and Indian Branch dune fields are located oblique to smaller distributary channels (Alberston Brook, and White Oak and Hospitality Branches, respectively), where sediment supply was more limited. Combined, the observations of dune morphology, relief, coarse substrates, and proximity to fluvial sediment supplies suggest that West Mills and Indian Branch dune fields were, comparatively, more supply limited.

None of the dunes appear to have migrated far from their potential source areas, with the dune corridors typically extending about 1–2.5 km from their north-westernmost boundaries (Fig. 3; Table 1). The exception is the Indian Branch dune field, which is about 4.5–6 km long, and is characterized by unfilled, elongate (i.e., hairpin) parabolic sand dunes residing over Bridgeton Formation sands and gravels (Newell et al., 2000). It is interpreted that a comparatively low sediment supply, coupled with a hard bounding surface, has resulted in greater transport distances for these dunes than for other local dune fields.

In summary, the study sites represent source-bordering dune fields composed of eolian sand derived from local sediments supplies. These include adjacent fluvial sediment sources and, to varying extents, sediment supplied from underlying and older fluvial substrates. The dune morphologies, implying high-to-low sand availability (from transverse-to-parabolic dunes), reflect the relative availability of these localized sediment supplies (Tsoar and Blumberg 2002; Hesp, 2013; Yan and Baas, 2015).

In addition to being found in arid and semi-arid environments, active transverse dunes are common in bare, moderate-to-high sediment supply areas of dune fields in contemporary sub-arctic settings in North America (Carson and MacLean 1986; Dijkmans and Koster 1990; Baughman et al. 2018), typically without localized permafrost. However, transverse dunes have also formed within permafrost settings in the western Arctic, Canada, during MIS 3 in association with large alluvial braidplains (Dallimore et al., 1997) that provided high sediment supplies for dune formation. Both active and stabilized parabolic dunes, commonly occurring within moderate-to-low sediment supply conditions, are also noted throughout arctic and sub-arctic settings, including within zones of continuous permafrost (David, 1981; Carter, 1981; Lea and Waythomas, 1990; Wolfe et al., 2020).

Eolian sand dunes that resided beyond the margins of the last major ice sheets commonly include transverse and parabolic morphologies. In southern Poland, close to the former ice front of the Scandinavian Ice Sheet, eolian dunes that were mobilized during the LGM have transverse shapes, some of which have been transformed partially or completely into parabolic dunes (Łopuch et al., 2023), and in the southern Czech Republic (Holuša et al., 2022). In South Carolina, vegetated eolian dunes that were mobilized during the Last Glacial Maximum have transverse shapes in the Carolina Sandhills region (Swezey et al., 2016) and parabolic shapes in the river valleys (Swezey et al., 2013). In the New Jersey Pine Barrens, the presence of transverse and parabolic dunes appears to be closely related to the availability of sand for dune construction, with the formation of parabolic dunes facilitated by: 1) a decrease in sediment supply away from fluvial sources; and 2) an increase in vegetation cover with climate amelioration (Yan and Baas 2015; Łopuch et al., 2023). The presence of transverse and parabolic dunes in the Pine Barrens area does not imply that permafrost or periglacial conditions occurred at that time. Nevertheless, these morphologies are not inconsistent with such environmental conditions.

Mechanisms and relative durations of transport and post-depositional weathering

Grain morphoscopy and microtexture analyses provided additional insights regarding dune-sand history and origins. Sand grains from the Manumuskin, Lochs-of-the-Swamp, and Indian Branch dune fields were well characterized by eolian processes. The high proportion (85–95%) of EM/RM grains showing intermediate degree of roundness, which develops better on grains of 0.8–1.0 mm fractions than 0.5–0.8 mm fractions, is interpreted as indicative of high-energy collisions in an eolian environment. However, only a small percentage (≤5%) showed well-rounded and matt surfaces (RM grains) characteristic of long-term high-energy collisions in an eolian environment (Tables 3, 5). Overall, this suggests a short-lived period of eolian transport and dune building, where much of the grain shape remained inherited from older (i.e., source) deposits. This conclusion is further supported by the sub-rounded to sub-angular feldspars (noted in the 0.8 to 1.0 mm size fraction), whereas the quartz grains were sub-rounded. Feldspar grains are less resistant to eolian abrasion than quartz, which suggest that these grains have likely be derived locally and not intensely worked by eolian processes. In contrast to the grains from these dune fields, those from West Mills showed a high proportion (17–42%) of EM/EL grains, characteristic of transport processes in fluvial or beach environments, in addition to a lower proportion (48–73%) of EM/EL grains characteristic of eolian environments. In this regard, the dune sands from West Mills show the highest degree of inheritance from other local sources, with the least amount of working by eolian processes (Tables 3, 5).

Morphoscopy by APIA analysis supports the interpretation that a high degree of grain morphological inheritance derives from local sediment sources with two distinctive groups of grains within the dune fields. The first group, comprised of sands from Manumuskin, Lochs-of-the-Swamp, and Indian Branch, includes grains that—although well rounded and with high degree of sphericity—have primarily retained their original shape (Supplementary Section S2, Figs. S2–S6; S17–S18). The second group, comprised of sands from West Mills and one sample at 30 cm depth from Lochs-of-the-Swamp, were well rounded but with low sphericity, and with the original grain shape clearly visible (Supplementary Section S2, Figs. S2; S7–S15). Overall, although the grains had undergone eolian transport and erosion through grain impacts, much of the original grain shape was retained in both groups, indicating that eolian modification was low or very low overall. In particular, sands from the West Mills dune field retained much of their shape inherited from source sediments. Quartz grains that have been subjected to eolian transport for a long time typically obtain highly isometric spherical shapes (Chmielowska et al., 2021). This shape is obtained through chipping and spalling from grain-to-grain collisions during transport by saltation (Kuenen, 1960; Lindé and Mycielska-Dowgiałło, 1980; Bullard et al., 2004; Blott and Pye, 2008; Chmielowska et al., 2021). However, it is a long process, requiring at least a thousand years of sustained transport (Cailleux 1942; Mycielska-Dowgiałło, 2001; Mycielska-Dowgiałło and Woronko, 2004). From these results, it can be concluded that the dune sands from these dune fields underwent short to moderate transport distances and durations under eolian processes.

All the dune sands contained very high quartz mineral contents (>99%). This indicates that it is unlikely that these deposits include sediments from either distal or glacially derived sources, which would have introduced greater mineralogical diversity. Rather, the high quartz content suggests that the eolian sediments are derived primarily from local sources, with the high quartz contents being consistent with the sands of the Cohansey and Bridgeton Formations, which are comprised primarily of quartz (Tedrow, 1986). Sediments underlying the dune fields include these formations (e.g., Lochs-of-the-Swamp and Indian Branch), as well as Quaternary-age fluvial and colluvial deposits that are, in turn, derived from these older deposits (Newell et al., 2000). Sediments adjacent and upwind of the dune fields are primarily Quaternary-age fluvial terrace and braid-plain deposits, which reside at elevations above the modern- and Holocene-age meandering rivers and tributaries.

Grain-size analysis from the dune fields typically revealed sediments to be moderately sorted medium sized sand. From an eolian transport perspective, this sand dominance implies that the primary eolian transport mechanism was by saltation (Pye and Tsoar, 1990; Seppälä, 2004; Supplementary Section S4, Fig. S1), and this is supported by the results of our morphoscopic analysis (Table 5). For all samples from 100 to 130 cm depth, clay contents were negligible and silts contents were low (0.5–3.0% in total). However, a higher proportion of silt-sized particles was noted in samples at depths of 30–60 cm. In addition, pre-treatments of samples for grain size revealed that sonified samples typically contained 1.5–2.0 times more silt than unsonified samples (see Supplementary Section S4). The higher silt contents in the near surface samples may be attributed to two possible causes. First, that silt-sized particles originated from coatings on source sediments. In a study of New Jersey soils, Tedrow (1986) found that soil particles commonly contained iron coatings that originated from the source sediments, and that silt was commonly bound to the sand grains.

A second source of the silt-sized particles could have been deposited from dust (i.e., loess). Dust particles may come from short or long suspension eolian transport (Pye 1987; Pye and Tsoar, 1990; Lancaster 2009). It seems likely that any loess, if deposited, was derived from adjacent fluvial sources. Loess deposition may have been related to reduced effectiveness of abrasion through saltation transport and greater capturing of suspended fine-grained sediment from localized fluvial sources, and as the dune fields became stabilized by colonizing vegetation (Hugenholtz and Wolfe, 2010).

Most of the observed soil profiles in this study were well drained and contained a leached upper E horizon. Consequently, fine-sized particles within this upper horizon likely migrated downward in the profile to accumulate within soil B horizons at 30–60 cm depth, resulting in higher fine-sized fractions at these depths. In addition to this eluviation, a number of samples also show evidence of post-depositional chemical weathering in the form of dissolution and breakage-block features on quartz grains. These observations generally confirm the long post-depositional stability of these dunes, as adequate time has elapsed for weathering and soil development at these sites.

Age of eolian deposition and stabilization

Optical ages from eolian sands of the New Jersey Pine Barrens range between 23 and 17.5 ka, accounting for analytical uncertainties at $\pm 1\sigma$ (Table 2). Fig. 6 compares the ages in this study to other luminescence ages derived from eolian dune sand and silt loess deposits south of the study area on the northern Atlantic Coastal Plain and adjacent Appalachian Piedmont (Feldman et al., 2000; Markewich et al., 2009; Lowery et al., 2010), as summarized by Swezey (2020). Loess deposition on the Delmarva Peninsula, Maryland, occurred mainly prior to or during the

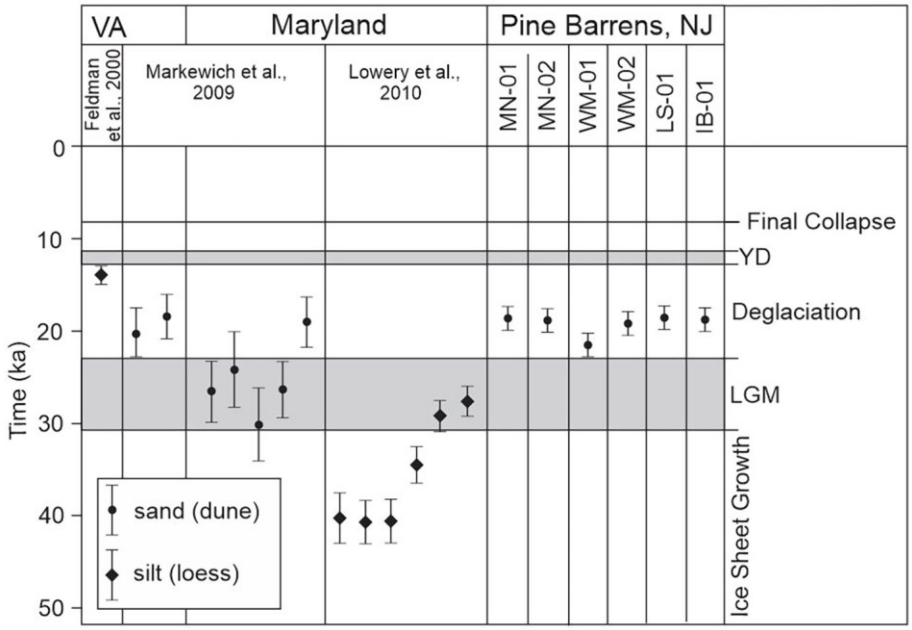


Fig. 6. Luminescence ages from eolian dune and loess deposits in the northern Atlantic Coastal Plain as summarized by Swezey (2020) and for this study. Error bars show analytical uncertainties at 1σ. LGM = Last Glacial Maximum, YD = Younger Dryas event, Final Collapse = collapse of the Laurentide Ice Sheet.

LGM, ranges in age from 44 to 27 ka (Lowery et al., 2010). In northern Virginia, local loess deposition was noted as late as 13.8 ± 1.0, sourced by glacial outwash and non-glacial alluvium from major river systems (Feldman et al., 2000). In contrast, most eolian sand dune deposition in this region occurred from pre-LGM to deglaciation, spanning an age range from 35 to 15 ka (Markewich et al., 2009). Optical ages from eolian sand dune deposition from this study are narrowly constrained within the period of deglaciation, with a weighted mean of OSL ages of 19.5 ± 0.5 ka. The close clustering of ages is interpreted as being indicative of a time of regional dune stabilization within the New Jersey Pine Barrens.

The ages of dunes stabilization in the Pine Barrens, ranging between 23 and 17.5 ka, are significant with respect to the southerly position of the LIS following the terminal LGM limit ~100 km north of these dune fields. Between 22 and 19 ka, the Hackensack Lobe of the LIS migrated ~80–105 km north of its terminal position (Fig. 1B; Stanford et al., 2021). By 17.5 ka much of the ice sheet along the eastern U.S. had migrated a further 65–90 km north to about 170 km north of its terminal position (Dalton et al., 2020). Thus, by 19 ka the ice sheet was a minimum of ~200 km north of the dune field study area and by 17.5 ka it was ~300 km north.

Dune orientations and paleo-wind regimes

The New Jersey Pine Barrens dune fields are situated within the most northerly extent of unglaciated terrain on the northern Atlantic Coastal Plain of the eastern United States, with the southeastern limit of the LIS extending to within only 100 km of the study area during the Late Wisconsinan (MIS 2). In this unique setting, understanding the process of dune mobilization and stabilization in this area is significant for interpreting environmental conditions that occurred at that time, and for providing additional insight into conditions and processes that occurred immediately adjacent to the southeastern limit of the LIS.

The Pine Barrens dunes are presently stabilized by vegetation under modern climate conditions. The modern wind regimes along the northern Atlantic Coastal Plain have also been shown to be insufficient for sustained eolian mobilization of fine-to-medium sand (Swezey, 2020). However, the preserved dune morphologies provide information about the wind conditions that mobilized dune sands south of the LGM ice margin. Specifically, the Pine Barrens dune morphologies indicate that dominant dune-forming winds originated from the WNW, with eolian sediment transport directions between 110 and 125° (Table 1) signifying transporting winds originating from between 290 and 305°. These formative wind directions are consistent with others interpreted from sand dunes on the northern Atlantic Coastal Plain, including along Delaware–Maryland border, ~100 km to the south (Markewich et al., 2015; Swezey, 2020) and from stabilized parabolic dunes, ~230 km the northwest in central Pennsylvania (Chase, 1977; Fig. 1B). The similarity in northwesterly orientation of the parabolic dune arms over a large geographic area suggests that these dunes were potentially influenced by similar winds. The ages of the dunes in this study further suggest that these winds may have been influenced by the proximity to the LIS. Indeed, Markewich et al. (2015) note that dune morphologies along the middle Atlantic Coastal Plain are consistently from the west-northwest south of the LGM and have suggested that these dunes were potentially influenced by katabatic winds emanating from the LIS. In addition, Swezey et al. (2016) suggest that vegetated eolian dunes that were activated during the LGM in the Carolina Sandhills of the southeastern Atlantic Coastal Plain were mobilized by wind velocities that were at least twice as high as the modern wind velocities.

Model-derived outputs have depicted a glacial anticyclone near the southern margins of the LIS in summer (COHMAP Members, 1988) with surface wind directions that are inconsistent with field-derived data from eolian deposits. In general, dune morphologies indicate that sediment transporting winds were consistently from the west-northwest south of the LIS at the LGM (Markewich et al., 2009, Markewich et al., 2015), being oblique to the simulated anticyclonic winds for that period. Despite several hypotheses for the divergence between modelled and ground-data-derived wind patterns, no conclusive explanation exists. Muhs and Bettis (2000) suggested that these sediment transporting winds from the northwest may have been high-velocity, low-frequency events related to incursions of the southward-displaced jet-stream, rather than to the glacial anticyclone. Furthermore, Markewich et al. (2009) suggested that in the eastern US eolian features may have been related to a period when a partial breakdown or northward displacement of the glacial anticyclone kept the region dry and cold, but still allowed late-summer sediment-transporting westerly winds to dominate.

Fluvio-eolian interactions in a periglacial environment

Morphological observations indicative of short dune-transport distances, and grain morphoscopy, and APIA results indicative of short eolian transport duration, indicate that Pine Barrens dunes have not migrated far from their primary sources of sediment (Table 5, Supplementary Section S2). Transverse dunes along the eastern margins of the two larger dune fields (Manumuskin and Lochs-of-the-Swamp) are indicative of comparatively higher sediment supplies associated with proximal alluvial sources, whereas their absence along the downwind dune-field margins indicate a lowering of the supply source. Quartz-rich mineralogy of sand grains—which have undergone eolian transport—indicate no direct external sources of sediment other than local formations (e.g., sands of the Bridgeton and Cohansey Formations) and the colluvial/alluvial deposits derived thereof.

These observations raise the question as to why dune-field lengths and associated sediment-transport pathways are relatively short, being typically 1–2.5 km in total length? Similar sediment-transport pathways of only 2–3 km are also inferred for parabolic eolian dunes that were mobilized during the LGM in most of the river valleys of the U.S. Atlantic Coastal Plain in South Carolina and Georgia (see summary in Swezey, 2020). For the New Jersey Pine Barrens, if off-ice katabatic winds were operating from the time of the LGM (~27 ka) until the time of regional stabilization (~19.5 ka), then ample time would have existed for long-distance eolian sediment transport pathways to form. A lack of sediment supply, however, could have inhibited dune formation during the LGM. Cold, dry permafrost conditions in the New Jersey Pine Barrens during the time of the LGM may have largely inhibited alluvial processes and eolian dune sand mobilization during that time. Indeed, the Pine Barrens region is considered to have been within the discontinuous permafrost zone during the LGM, with the southern limit of permafrost (i.e., sporadic) believed to have extended at least 230–320 km south of the LGM ice limit (French et al., 2009. French and Millar, 2014). French et al. (2007) and Merritts and Rahnis (2022) report OSL-dated MIS 2 primary infill wedge structures in New Jersey and Pennsylvania, respectively, indicative of past permafrost and/or deep seasonal frost. Whereas braided channels would have predominated under frozen ground conditions, sediment availability for alluvial processes would have remained relatively low due to reduced precipitation regime. Such conditions would not have been conducive to eolian dune formation due to the lack of sediment supply, with few alluvial sources and with surficial sediments mantled by eolian sediment lags due to continued winnowing by wind erosion. Such winnowing would have likely occurred when wind velocities were even stronger due to the proximity of ice front, further hampering eolian dune-construction.

The gravel lags and ventifacts that underlie several of the dune fields may have acted as bounding surfaces and further inhibited supply of underlying sand for eolian dune formation during a time of sand deflation. Climatic amelioration accompanying early glacial retreat would have resulted in increased local precipitation and runoff under warmer conditions, which would have increased alluvial sediment mobilization along braided river systems. The presence of permafrost during that time would have resulted in the impeding groundwater flow, resulting in braided-river systems that carried the majority of surface runoff in late spring and summer (e.g., Vandenberghe and Woo, 2002; French and Demitroff, 2012; Vandenberghe, 2008). Alluvial sediments deposited during runoff periods would have supplied sediment for the initiation of eolian transport across relatively barren, gravel-mantled surfaces. The addition of sand from alluvial sources, coupled with strong windy conditions, would have created conditions amenable for eolian transport and dune formation along source-bordering sediment transport pathways. Consequently, conditions favorable for dune formation would have lasted, at most, for a few thousand years during retreat of the LIS. These conditions would have ended with decreased wind velocities and increased vegetation cover, as the ice sheet retreated northward. In locations where alluvial sand and underlying sediment supplies were less abundant, dune stabilization may have occurred earlier (by ~22 ka). By then, local thawing of permafrost would also have resulted in the transition of river morphologies from braided systems with an inhibited groundwater flow to entrenched meandering streams with a confined flow that is more characteristic of Holocene river systems.

Conclusions

Relict stabilized dune fields are abundant within the New Jersey Pine Barrens of the northern Atlantic Coastal Plain, USA. These dune fields attest to ice-marginal, cold-climate eolian conditions during the Late Pleistocene with sediment transport driven by katabatic winds originating from the LIS when the terminal ice margin was in close proximity (100–200 km) to the dune fields. Spatial associations between dune fields and Quaternary alluvial deposits, including braided river terraces and incised meander channels, indicate a climate-change-driven fluvio-eolian relation of predominantly locally derived sediments. The occurrence of transverse and parabolic dunes, in association with underlying pebble lag with ventifacts, is indicative of intensive eolian transport conditions, which ceased by ~19.5 ± 0.5 ka. Although the duration of dune field mobilization remains unknown, it appears to have been relatively short-lived based on the short (1–2.5 km) dune-field width and moderate degree of rounding and grain surface modification by eolian transport processes. For the New Jersey Pine Barrens, it is thought that increased fluvial activity following the LGM provided renewed sediment input for eolian dune construction, which continued until the climate ameliorated with the northward retreat of the LIS. This study provides insightful information on the environmental conditions in the New Jersey Pine Barrens at the time of the LGM and the subsequent period of transition to postglacial conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We wish to thank the following organizations who provided help with field access and site mobilization, with extended gratitude to the following contacts: The Nature Conservancy of New Jersey—Damon Noe, Wayne Russell, and Joseph Smith (now Forsythe National Wildlife Refuge); New Jersey Fish & Wildlife—Sandy Cowan and Nathan Figley; and New Jersey Division of Parks & Forestry—Stephanie Fox, Terry Schmidt, and Robert Auermuller. In addition, Kathleen Galarza and Serge Brunner provided access to private lands. Ilya Buynevich (Temple University) shared perspectives on dunes in the field, Wayne Newell (USGS, retired) provided constructive comments on land-surface processes, Andrew Ivester (University of Sheffield) provided commentary on weathering of Pleistocene dunes, and Joseph Arsenault (Senior Ecologist) and Jessica Hallagan (Stockton University) provided commentary on soils.

Dune reconnaissance was greatly aided using New Jersey Pine Barrens imagery provided by Boyd Ostroff (Boyds Maps https://boydsmaps.com). Nicola Ferguson and Vanessa Brewer carefully prepared the optical dating samples. Attila Stopic (ANSTO) provided valuable advice on measurement of radioisotope concentrations. Christina Neudorf was supported by the NSF Laboratory Technician Support grant 1914566 and Olav Lian acknowledges support from Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery and Research Tools and Instruments grants. This paper was internally reviewed by Dr.

Peter Morse as a contribution to the GSC Climate Change Geoscience Program and is NRCan Contribution Number 20220350. It has further benefited from comments provided by several anonymous reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeolia.2023.100877.

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