An Overview of Pleistocene and Holocene Inland Dunes in Georgia and the Carolinas—Morphology, Distribution, Age, and Paleoclimate

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An Overview of Pleistocene and Holocene Inland Dunes in Georgia and the Carolinas—Morphology, Distribution, Age, and Paleoclimate

By H.W. Markewich and William Markewich

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Inland dunes in the Southeastern United States represent periods of low precipitation and (or) monsoon conditions with persistent and (or) recurrent west and southwest winds. Geomorphic position, stratigraphic position, and carbon-14 ages suggest that the most recent period of dune formation began some time after 15 ka and ended between 5 ka and 3 ka

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1994

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

GORDON P. EATON, Director

For sale by U.S. Geological Survey, Map Distribution
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Published in the Eastern Region, Reston, Va.
Manuscript approved for publication August 25, 1993.

Library of Congress Cataloging in Publication Data

Markewich, H.W. (Helaine W.)
An overview of Pleistocene and Holocene inland dunes in Georgia and the Carolinas : morphology, distribution, age, and Paleoclimate / H.W. Markewich and William Markewich.
p. cm. — (U.S. Geological Survey bulletin ; 2069)
"Inland dunes in the Southeastern United States represent periods of low precipitation and (or) monsoon conditions with persistent and (or) recurrent west and southwest winds. Geomorphic position, stratigraphic position, and C-14 ages suggest that the most recent period of dune formation began some time after 15 ka and ended between 5 ka and 3 ka."
Includes bibliographical references.
Supt. of Docs. no.: I19.3:2069
1. Sand dunes—Georgia. 2. Sand dunes—North Carolina. 3. Sand dunes–South Carolina. 4. Geology, Stratigraphic—Pleistocene. 5. Geology, Stratigraphic—Holocene. I. Markewich, William. II. Title. III. Series.
QE75.B9 no. 2069
[GB635.G4]
557.3 s—dc20
[551.3'75'09758] 93–36751
CIP

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An Overview of Pleistocene and Holocene Inland Dunes in Georgia and the Carolinas—Morphology, Distribution, Age, and Paleoclimate

By H.W. Markewich[1] and William Markewich[2]

ABSTRACT

Vegetated, inactive, quartz sand dunes, 1 to 25 m high and 7 m to 4 km long, are east and northeast of streams, rivers, and Carolina bays in parts of the Georgia, South Carolina, and North Carolina Atlantic Coastal Plain. Unstratified, symmetrical, filled-in crescent- or U-shaped dunes predominate. A few of the smaller dunes associated with Carolina bays are parabolic. Average phi size of the quartz sand ranges from 1.0 along the Neuse River in North Carolina to 1.68 along Coastal Plain rivers in southeastern Georgia.

In Georgia, 8- to 25-m-high dunes have coalesced to form 10- to 50-km-long, elongate dune fields, adjacent on the east and northeast to southeast-flowing Coastal Plain rivers such as the Ohoopee. Locally, 2- to 4-km-wide sand sheets lie leeward of the dune fields. Smaller dunes, 3 to 8 m high, lie adjacent to stream segments trending east-west, north-south, south-southwest, or southeast. Dunes that are 1 to 3 m high are most common east and northeast of Carolina bays and are the most common inland dunes in South Carolina and North Carolina. They cover large areas of the Pee Dee and Cape Fear River valleys.

Most dunes lie between 48 and 160 km of the coast, in the area that presently has the region's lowest mean annual precipitation (1,118–1,250 mm) and the lowest precipitation-to-evaporation ratio (1.1:1.0). Dune axes indicate formation by west winds in south-central and southwestern Georgia, west and southwest winds in southeastern Georgia, and southwest winds in the Carolinas.

At least two sets of dunes are present. Each set represents several dune-forming episodes. Older dunes are generally larger than younger dunes and, except where reactivated, are characterized by relatively smooth, whaleback upper surfaces. Reactivated surfaces of older dunes have irregular surface topographies that are similar in appearance to the knob-and-kettle topography of younger dunes. Relief on the upper surfaces of younger dunes is commonly 1 to 5 m.

Stratigraphic position suggests that all dunes are younger than 500 ka, that dune-forming episodes occurred during and (or) subsequent to each major glaciation, and that the most recent episode was initiated sometime after 15 ka and ended sometime before 3 ka.

Dunes were forming in parts of the Western, Central, and Northeastern United States during this same 12,000-year interval (15 ka–3 ka). The presence of dunes of similar age in so many areas of the United States suggests that severe and protracted droughts, with persistent or recurrent unidirectional winds, were common to glacial and to transitional glacial-interglacial climates in the late Quaternary. Their presence in the Southeastern United States suggests that the magnitude of climate change in the continental United States was greater than previously believed.

INTRODUCTION

Inland dunes and associated sand sheets cover thousands of square kilometers in the Coastal Plain physiographic province of Georgia, South Carolina, and North Carolina in the Southeastern United States (fig. 1). Most studies of inland dunes have been in areas where the climate is semiarid to arid, where vegetation is sparse, and where dunes are commonly 30 to 100 m high, morphologically distinct (parabolic, barchan, star, and so on), and stratified. In contrast, the Southeastern United States is characterized by a humid to wet, warm-temperate to subtropical climate, dense oak-hickory and (or) pine forests, and relatively small apparently unstratified inland dunes. Although some inland dunes in Georgia are 8 to 25 m high, 2 to 4 km long, and easily identifiable, most inland dunes in Georgia and the Carolinas are 1 to 7 m high and less than 1.0 km long and

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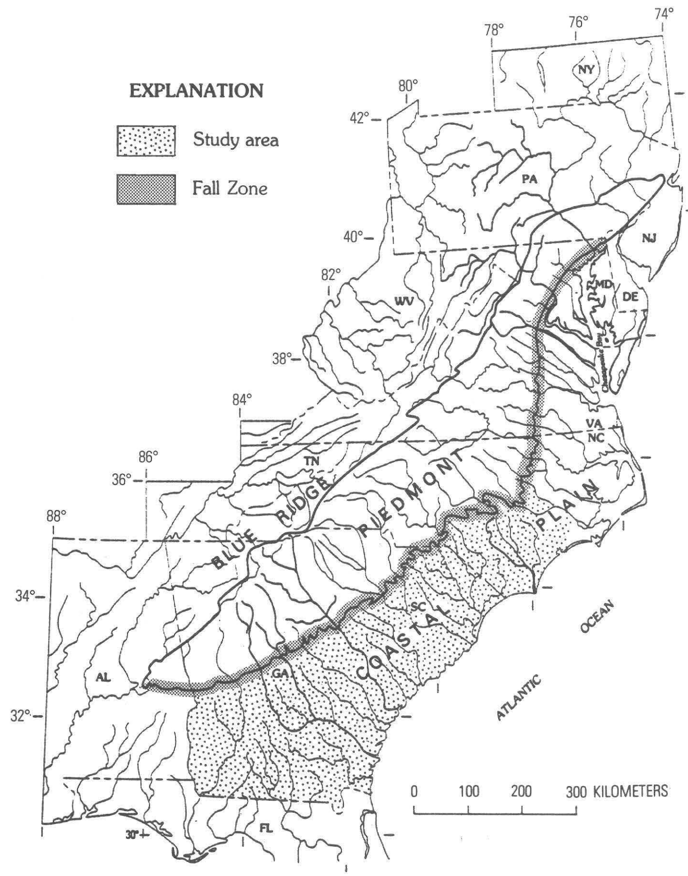


Figure 1. Boundaries of the Blue Ridge, Piedmont, and Coastal Plain physiographic provinces from Georgia through Pennsylvania. The Fall Zone marks the area where crystalline rocks of the Piedmont and the overlying sediments of the Coastal Plain are exposed in stream valleys.

do not have morphologically distinct form. The most common dune shape is a filled-in crescent or U. Dune composition is simple, generally more than 95 percent medium and fine quartz sand. The sand is unstratified, structureless, nutrient poor, and drought susceptible, with negligible water-holding capacity.

None of these dunes are active. Most are adjacent on the east and northeast to south-southeast-trending segments of the region's rivers and streams (fig. 2). Some are adjacent to shallow depressions known as Carolina bays (fig. 3). The height and areal extent of individual dunes and dune fields vary greatly. Locally, sand sheets extend from a few hundred meters to several kilometers leeward of large dunes, thinning to a feather edge from a maximum thickness of 6 to 7 m at the dune face.

The presence of inland dunes in the Southeastern United States indicates that this region has been affected by surficial processes that are not presently active. The number and height of dunes, the size of the dune fields, and the thickness and width of adjacent sand sheets suggest that drought[3] conditions prevailed for extended periods of time and were accompanied by persistent or recurring unidirectional winds. The dunes are in the part of the Southeastern United States that presently has the lowest mean annual precipitation and the highest lake and pan evaporation. This coincidence of dunes with the driest part of the region suggests that the present precipitation pattern was established sometime during the Quaternary and that a large area or subregion of the Southeastern United States has been more affected by Quaternary climate changes than the region as a whole has been.

PURPOSE, SCOPE, AND METHODS

This paper gives an overview of inland dunes in the Southeastern United States. Included are descriptions of dunes and dune fields and of the environment in which they occur. One small dune field is located in the eastern Gulf Coastal Plain in southwestern Georgia; others are in the southeastern Atlantic Coastal Plain of Georgia, South Carolina, and North Carolina (fig. 2*A*). Descriptions in the text are generalized from 50 field observations.

Cross sectional views of the dunes were afforded by 1- to 16-m-high exposures in numerous borrow pits, in cutbanks along streams and rivers, and along railroad and highway rights-of-way. Dunes were hand augered where there were no exposures. Geomorphic position and surface morphology were interpreted from aerial photographs and (or) topographic maps and checked by field observation. Geographic distribution was determined by analyses of available topographic maps (1:24,000, 1:100,000, and 1:250,000 scales), aerial photographs (1:15,000 and 1:20,000 scales), and site visits. Field descriptions included observations on mineralogy, grain size, internal structure, pedogenic development, color, thickness, and surface morphology. Except for a few samples, there were no detailed grain-size analyses. Grain-size data from these localities and from other published and unpublished sources are included. Mineralogical analysis of the clay fraction was by X-ray diffraction. The sand fraction was split for heavy and light minerals, and minerals were petrographically identified. Because of the low heavy-mineral content, consistently less than 1 percent and commonly less than 0.5 percent, we did not attempt grain counts. Local vegetation was described by using common names. Age determinations were based on analyses of geomorphic and stratigraphic position, as well as carbon-14 analyses of datable material.

[3]The reader is referred to Thomas (1962) for a literature review and a discussion of drought, specifically of drought in a region having a humid to wet-temperate climate. For the purposes of this study, drought relates to soil moisture and, therefore, to the relations among evaporation, transpiration, and precipitation.

Inland dunes in the Southeastern United States are inactive. Modern climatic data suggest that, at present, winds are not sufficient in duration or velocity to form dunes and that precipitation is too great to allow dune formation. Therefore, these data define a set of conditions in which dunes neither form nor reactivate when disturbed. The climatic data are summarized herein.

Geomorphic, sedimentologic, pedologic, and palynologic data from published and unpublished studies were integrated with available carbon-14 data to identify periods in the Pleistocene and Holocene during which there was active dune formation in the Southeastern United States. The times of dune formation were then compared with published data on periods of dune formation in other parts of the United States.

ACKNOWLEDGMENTS

We would like to thank the many people who gave of their time and knowledge in discussing inland dunes of the Southeastern United States. These include R.E. Carver, University of Georgia, Athens; M.P. Schale, North Carolina Natural Heritage Program, Raleigh; B.J. Thames, Georgia Geologic Survey, Atlanta; Mack Thomas, R.L. Wilkes, Herschell Paulk, Allen Rigdon, and Steve Lawrence, U.S. Department of Agriculture (USDA), Soil Conservation Service (SCS), Ga.; B.N. Stuckey, USDA, SCS, Columbia, S.C.; and R.F. Carter, U.S. Geological Survey, Atlanta, Ga. J.S. Olson, Lenoir City, Tenn.; P.A. Delcourt, University of Tennessee, Knoxville; and D.R. Muhs, U.S. Geological Survey, Denver, Colo., contributed many thoughtful discussions on the nature of paleoclimates during periods of dune formation and on the timing of nationwide dune-forming episodes. We also thank C.A. Bush of the U.S. Geological Survey, Denver, for providing the software for generating the sand rose diagrams.

DUNE ENVIRONMENTS

CLIMATE

The Atlantic Coastal Plain of the Southeastern United States, excluding Florida, borders the Atlantic Ocean between 30°30′ and 35°00′ N. lat and 75°30′ and 85°30′ W. long (fig. 1). The climate of the region is humid to wet, warm-temperate to subtropical (Kohler and others, 1959). Sea breezes moderate the climate along the coast, but generally the climate is warm and humid. Summers are long and hot; winters are short and mild.

Budel (1977) and Hardy and others (1982) included the Southeastern United States in the areas of temperate monsoons that occur on the eastern margins of major landmasses such as central China and eastern Australia. Unlike monsoonal areas having distinct seasons of rain and drought, areas of temperate monsoons have total mean annual precipitation (MAP) between 1,000 and 2,000 mm, experience rainfall throughout the year, and have a distinct summer precipitation maximum. The weather is dominated by tropical maritime air masses, hot and humid summers, with occasional tropical cyclones, and mild winters. In North America and Asia, occasional incursions of polar continental air bring unseasonably cold conditions during the winter months.

Inland dunes in the Southeastern United States are coincident with the area having the region's lowest MAP (1,118–1,250 mm) (figs. 2*A*, 4). In addition, mean monthly precipitation (MMP) is less than mean monthly evapotranspiration (MME) for 5 to 7 months of the year (van Bavel and Carreker, 1957). Because the area has no active dunes, its present climate can be considered a datum for conditions in which dunes do not form.

In the following sections, climatic data for this region, particularly Georgia, are summarized. Data on MAE (mean annual evaporation), MAP and MMP, temperature, and prevailing winds are shown graphically in figures 4–7. The figures summarize published and unpublished data collected by the National Oceanic and Atmospheric Administration, National Weather Service. Some of these data have been published in county soil survey reports (Aydelott and others, 1965; Paulk, 1968, 1986; Barnhill, 1977; Dudley, 1978). Other sources of climate data include Plummer (1983), Carter and Stiles (1983), Kohler and others (1959), Visher (1954), and van Bavel and Carreker (1957).

TEMPERATURE AND PRECIPITATION

The northeast-trending, 80- to 120-km-wide, elliptically shaped area in which the dunes occur extends from central Georgia through southeastern North Carolina (fig. 2*A*). Specific temperature data for the area are spotty. Temperatures range from 40 °C average annual high, to −6 °C average annual low, with mean annual temperatures from 10 to 20 °C.

In east-central Georgia, where the largest dunes occur along Coastal Plain rivers, the highest and lowest recorded temperatures in this century are 42.5 °C (in July 1952) and −15.6 °C (in January 1966), respectively. Average daily maximum and minimum temperatures for coastal and south-central Georgia are shown in figure 5.

None of the air temperatures shown in figure 5 accurately reflect the summertime air temperatures atop the inland dunes. Jerry McCollum (*in* Justus, 1976) indicated that air temperatures atop the dunes are 8–11 °C hotter than air temperatures of the surrounding terrain. The effects of the higher temperatures have resulted in floral and faunal

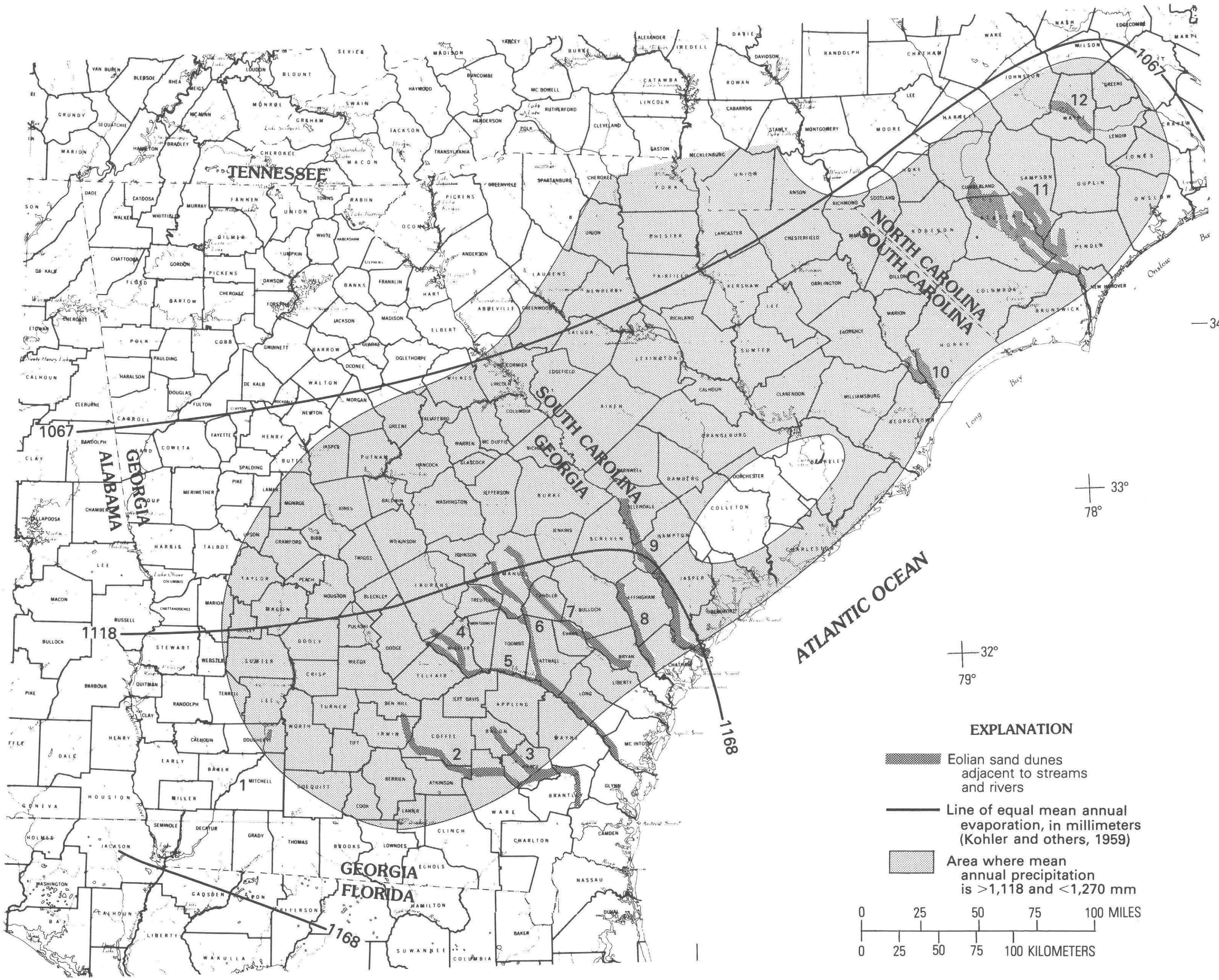


Figure 2*A*. Counties, location of dune fields, and climate data for Georgia, South Carolina, and southeastern North Carolina. Drainages are 1, Flint River; 2, Satilla River; 3, Alabaha River; 4, Little Ocmulgee River; 5, Altamaha River; 6, Ohoopee and Little Ohoopee Rivers and Pendleton Creek; 7, Canoochee River; 8, Ogeechee River; 9, Savannah River; 10, Great Pee Dee River; 11, combined valleys of the Cape Fear and Black Rivers; and 12, Neuse River. Dunes and dune fields present along smaller rivers and streams and adjacent to Carolina bays cannot be shown at this scale.

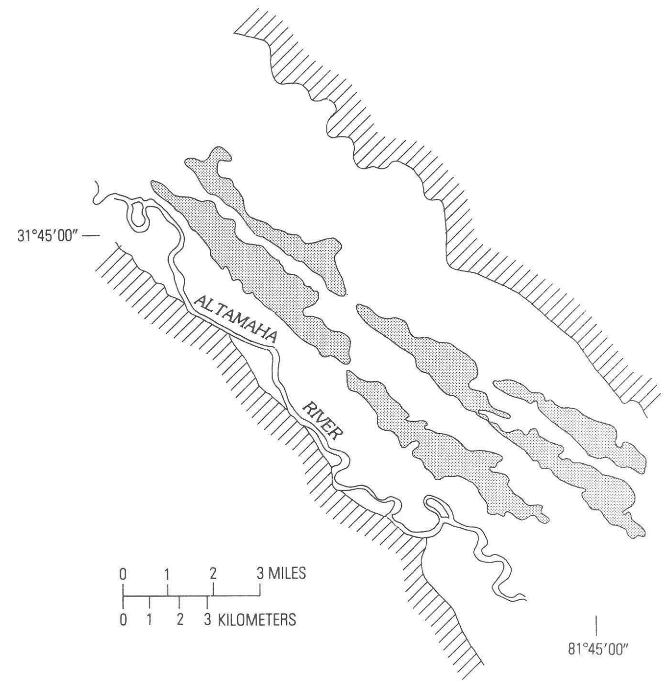


Figure 2*B*. Late Pleistocene and (or) Holocene dune fields (shaded areas) on midchannel islands and low terraces of the Altamaha River valley near Jesup, Ga. (Jesup, Ga., 1:100,000 quadrangle). Topography of some of these dunes shown in figure 10.

communities unique to the dunes, as discussed in the sections titled "Vegetation" and "Faunal Data."

The area in which most inland dunes are located has the region's lowest MAP (>1,118 and <1,250 mm) (figs. 2*A*, 4); central Georgia's MAP ranges from 1,118 to 1,168 mm (fig. 4). This area of Georgia has an average annual runoff of 225 to 325 mm and the lowest streamflow in the State (Thomson and Carter, 1955, 1963). In drought years such as 1954, central Georgia receives 550 to 700 mm precipitation, which is 40 to 50 percent less rainfall than normal. In these years, surface runoff is minimal, and the near-surface water table drops below the bottom of the stream channels. The result is negligible to no streamflow.

EVAPORATION AND EVAPOTRANSPIRATION

Kohler and others (1959) showed that lake evaporation in the central Georgia Coastal Plain is about 1,100 mm/yr (figs. 2*A*, 4). Visher (1954) indicated that annual pan evaporation in south Georgia was about 1,375 mm. Van Bavel and Carreker (1957) calculated evapotranspiration in

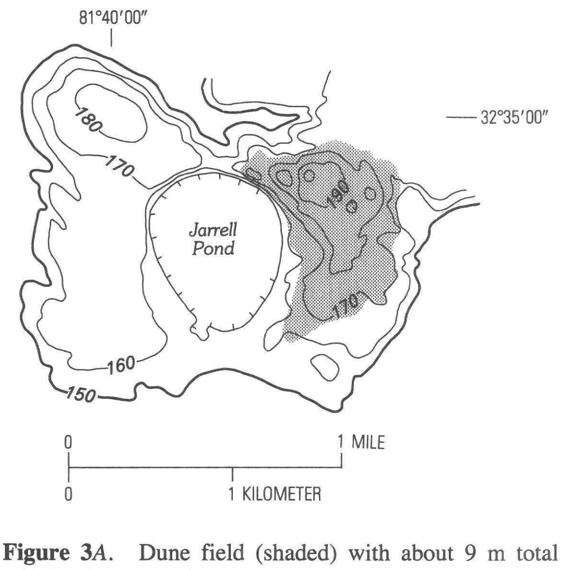


Figure 3*A*. Dune field (shaded) with about 9 m total relief adjacent to freshwater-filled Carolina bay (Jarrell Pond) in southeastern Georgia (Dover, Ga., 1:24,000 quadrangle; 10-ft contour interval). The bay has formed in terrace deposits of the Ogeechee River.

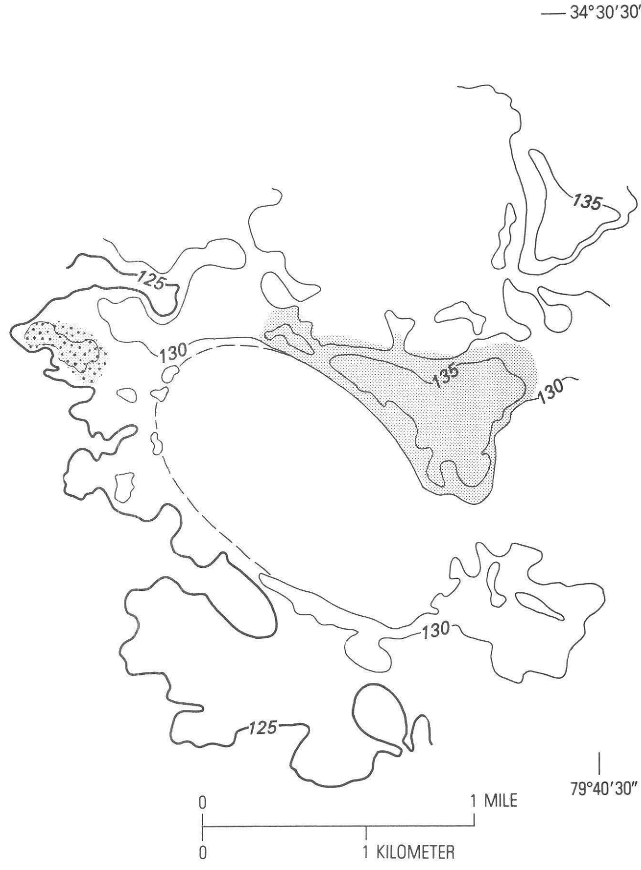


Figure 3*B*. Dune field (shaded), 2 to 3 m high, associated with a drained Carolina bay in northeastern South Carolina (Bennettsville South, S.C., 1:24,000 quadrangle; 5-ft contour interval). The bay has formed in terrace deposits of the Pee Dee River whose present channel is located about 3.2 km to the southwest. The source area for sand in the small dune field (stippled) northwest of the bay is the Pee Dee River modern flood plain. Dashed line indicates the drained bay boundary.

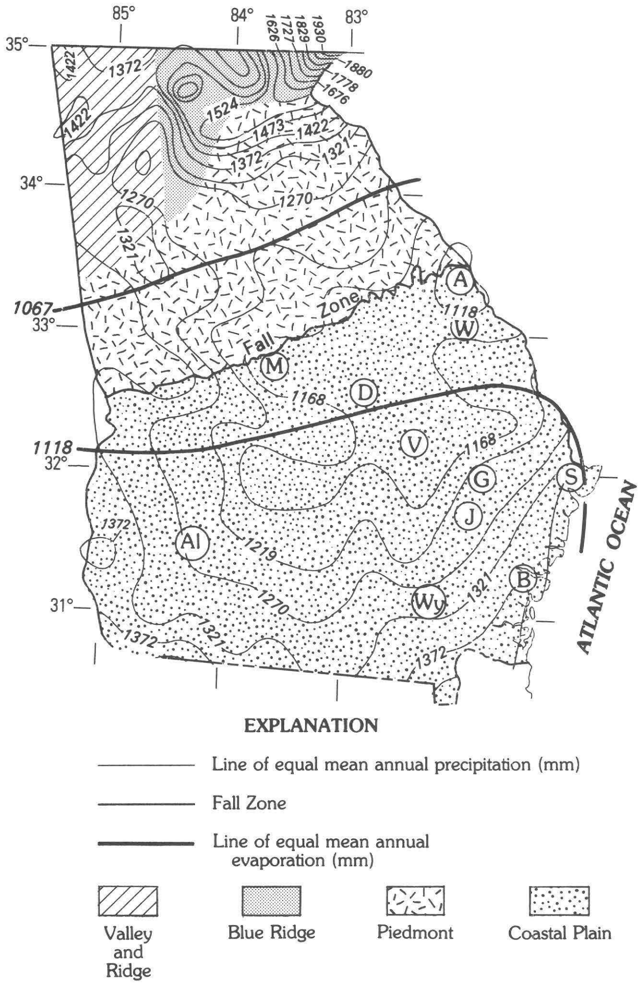


Figure 4. Mean annual precipitation (modified from Carter and Stiles, 1983) and mean annual evaporation (Kohler and others, 1959) for the Blue Ridge, Valley and Ridge, Piedmont, and Coastal Plain physiographic provinces of Georgia. Letters designate cities and towns referred to in the text or in figures 5 and 6: A, Augusta; Al, Albany; B, Brunswick; D, Dublin; G, Glennville; J, Jesup; M, Macon; S, Savannah; V, Vidalia; W, Waynesboro; Wy, Waycross. The Fall Zone marks the area where crystalline rocks of the Piedmont and the overlying sediments of the Coastal Plain are exposed in stream valleys.

the east-central Georgia Coastal Plain to be about 986 mm/yr.

Other data (van Bavel and Verlinden, 1956) suggest that evapotranspiration in the coastal area of North Carolina is about 900 mm and that pan evaporation in the Hofmann Forest (about midway along the North Carolina coast) is about 1,250 mm (Daniels and others, 1978).

Van Bavel and Carreker (1957) compared precipitation to calculated evapotranspiration in east-central Georgia and found that they were nearly equivalent, but that for 6 months of the year evapotranspiration exceeded precipitation. In drought years, the precipitation deficit is magnified; the 550 to 700 mm annual precipitation is significantly less than the 1,000 to 1,300 mm average MAE. In drought

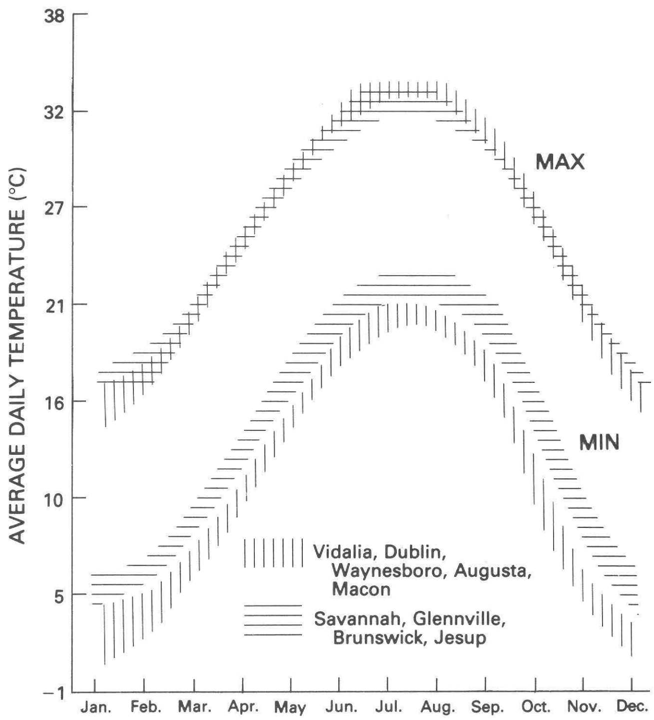


Figure 5. Average daily maximum and minimum temperature summarized by month for localities in the Georgia Coastal Plain. In the summer months, cities within 56 km of the coast (Savannah, Glennville, Brunswick, and Jesup) have lower maximum and higher minimum temperatures than do those cities farther inland (Vidalia, Dublin, Waynesboro, Augusta, and Macon). In winter months, coastal cities have both higher maximum and higher minimum temperatures than do cities farther inland.

years, the MAP:MAE (0.6:1.0 and 0.5:1.0) more nearly approximate those of semiarid and arid terrains.

WINDS

Data on the region's winds are spotty. Historical data from the turn of the century indicate that, in specific months and (or) on a yearly basis, prevailing winds in the central Georgia Coastal Plain are from the west (for example, U.S. Department of Agriculture, 1898, 1909–17 (particularly 1912)). Hodler and Schretter (1986) suggest that strong west winds in southern Georgia are possible during the winter months, depending on the locations of regional lows centered over the central Mississippi Valley. Figure 7*A* summarizes much of the available wind data for the Coastal Plain in Georgia and the Carolinas. Data show that the strongest winds are predominantly from the west and that they occur in the winter months.

Figure 7*B* shows sand rose diagrams (for winds greater than 11 knots (about 5.5 m/s)), drift potentials, and resultant drift directions of several localities in Georgia and South Carolina. The data show that a significant percentage of all winds are from the western quadrants, primarily during the

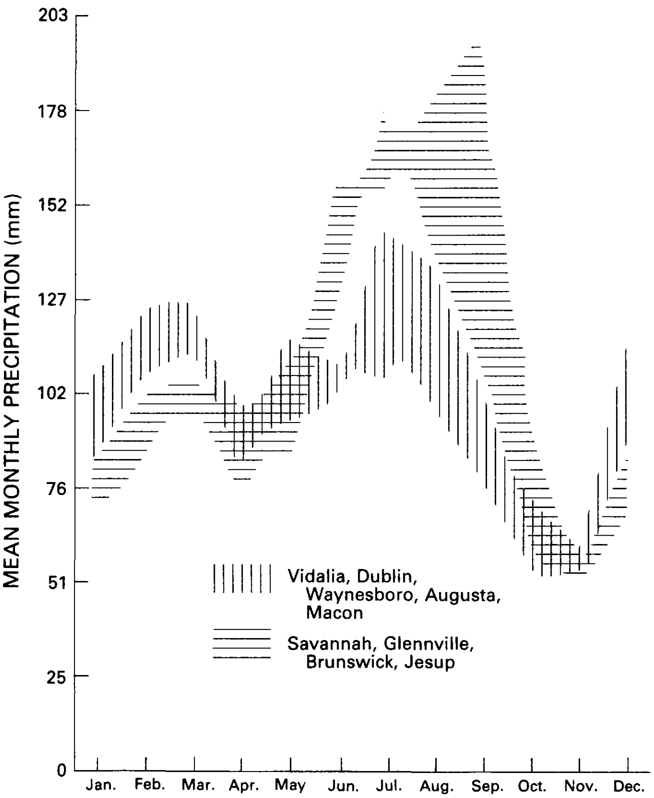


Figure 6. Mean monthly precipitation for localities in the Georgia Coastal Plain. Cities within 56 km of the coast (Savannah, Glennville, Brunswick, and Jesup) have higher total precipitation, higher summer precipitation, and a longer summer period of high precipitation than do cities farther inland (Vidalia, Dublin, Waynesboro, Augusta, and Macon).

winter months. The data do not suggest the presence of persistent strong winds necessary for dune formation.

Data for coastal areas, such as Brunswick, Ga., show a variable wind pattern except for a pronounced reversal of direction from the west in the winter months to the northeast in the late fall. (This reversal is due primarily to the effect of barometric lows in the North Atlantic Ocean in the autumn months, resulting in strong northeastern winds along the coast.) Data indicating predominantly west or southwest wind direction are from the area of the largest dunes in southeastern Georgia in a zone 50 to 150 km inland of the Atlantic coast (see data for Alma, Ga., in fig. 7*B*). A small dune field on the eastern side of the Flint River at Albany, Ga. (fig. 4), is the westernmost limit of identified dune fields in Georgia. Wind data for Albany show a dominant southwest wind.

Of all the annual drift potentials given in figure 7*B*, only one, Hunter Army Airfield (AAF), Ga. (drift potential=84), falls within the range of annual drift potentials given by Fryberger and Dean (1979, table 16, p. 150). The annual drift potential for Hunter AAF, Ga., barely makes the lowest wind energy environment category for desert regions. In addition, the weighting factors used for calculating relative rates of sand transport will certainly be different for humid vegetated terrains than those for semiarid or arid terrain. Intuitively, the result will be less drift for the same wind speed in wetter, more vegetated terrain. The proximity of the dunes to the source area of the sand, the filled-in U shape of the dunes, and the extremely steep frontal toe or slip face of the dunes, as well as the lack of evidence for significant dune migration, all suggest that Pleistocene and Holocene dunes in the Southeastern United States formed in geographically and climatically restricted areas where drift was minimal.

Available wind data for the region are from large upland flats generally used for aviation. No data are available for wind conditions in the river valleys where more than 90 percent of the area's dunes are located. To determine true drift potentials for the region, the following specific data are needed: (1) the relative increase and subsequent decrease in wind velocity as the wind moves across the valley (descent, transversal, and ascent); (2) the effect(s) of wind zonation or funneling along valleys parallel to the dominant wind direction; and (3) the effect(s) of vegetation type (tree, grass, shrub) on wind velocity. A weighting factor for drift potentials in humid to wet, vegetated terrain also has to be calculated.

VEGETATION

Thick deposits of quartz sand in Georgia, South Carolina, and North Carolina generally have floral communities that are distinctive from those on adjacent, less sand-rich substrata. The thickest and most areally extensive sand deposits are present along the Fall Zone (fig. 1) and are alluvial, marine, colluvial, or eolian in origin. These deposits range in age from the Late Cretaceous to Holocene but were not part of this study. Deposits having the highest quartz sand content (generally >95 percent) are on the eastern and northeastern sides of streams and rivers at altitudes below 80 m. Generally, these deposits have dunal morphology and consist of nutrient-poor, highly permeable, fine and medium quartz sand that has extremely low water-holding capacities. These are the deposits discussed in this report.

The combination of the relatively higher air and soil temperatures, the near equivalency of the MAP and MAE, and the high permeability and very low water-holding capacity of the sand permits the growth of unique floral and faunal communities on the dunes and dune fields. The uniqueness of the floral communities was recognized early in the settlement of Georgia (Hawkins, 1799), but these communities were not described until the early part of this century (Harper, 1906). Some years later, Wells and Shunk (1931) described similar vegetation on thick sand deposits in the Coastal Plain of North Carolina.

Because some work on dunal chronosequences has been based on sequential variation in vegetative communi-

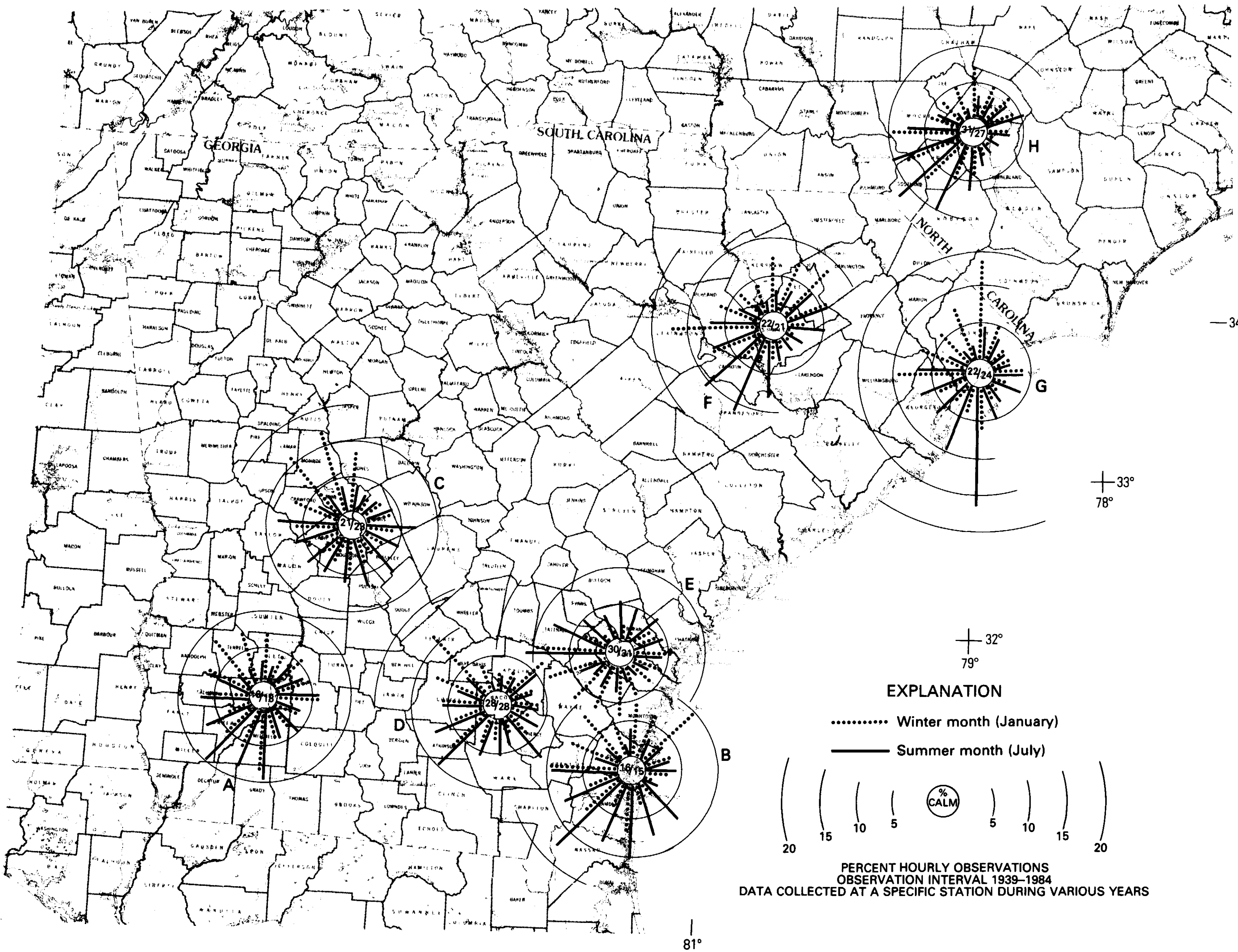


Figure 7*A*. Rose diagrams summarizing hourly wind observation data from 1939 to 1984 from eight Coastal Plain cities in Georgia, South Carolina, and North Carolina. Diagrams show percent of time wind blew from a given direction in January (dotted line) and July (solid line) and percent time during those months that winds were calm (January, upper number in center of rose; July, lower number in center of rose). Meteorological stations: (A) Albany, Ga. (31°35′ N. lat, 84°07′ W. long); (B) Brunswick, Ga. (31°15′ N. lat, 81°28′ W. long); (C) Robins Air Force Base (AFB), Ga. (32°38′ N. lat, 83°36′ W. long, about 45 km south of Macon); (D) Alma, Ga. (about 45 km west-southwest of Jesup), (E) Fort Stewart, Ga. (31°53′ N. lat, 81°34′ W. long, about 50 km west of Savannah); (F) Shaw AFB, S.C. (33°58′ N. lat, 80°28′ W. long); (G) Myrtle Beach AFB, S.C. (33°41′ N. lat, 78°56′ W. long); (H) Pope AFB, N.C. (35°10′ N. lat, 79°01′ W. long). Unpub. data from National Oceanic and Atmospheric Administration, Asheville, N.C.

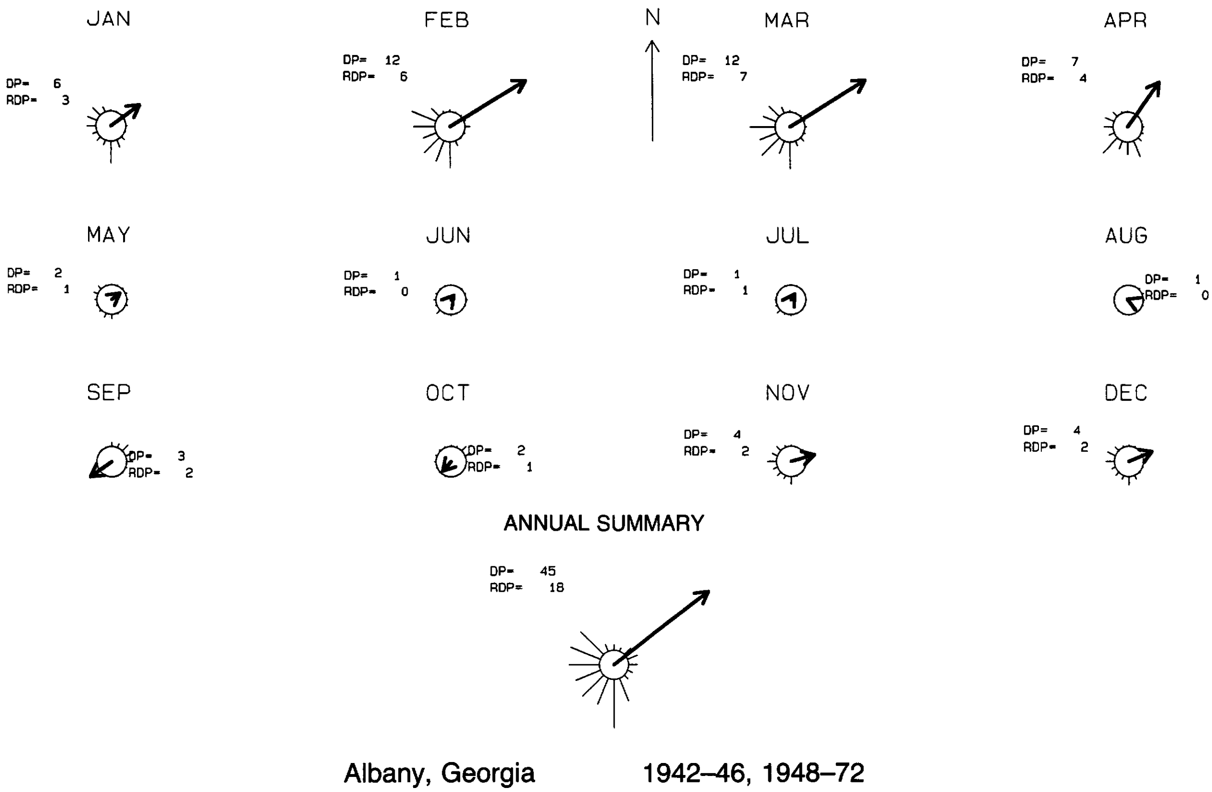


Figure 7*B*. Sand rose diagrams showing drift potential (DP), resultant drift potential (RDP), and resultant drift direction (arrows) for winds greater than 11 knots (about 5.5 m/s) (monthly and annual data). Thin lines are drift potential vectors (mm) that are proportional in length to potential amount of sand drift from a given direction toward the center of the circle. Arrows are resultant drift potential vectors (mm), a measure of relative sand-moving capability of wind, derived from reduction of surface wind data through a weighting equation. Directions of arrows indicate resultant drift directions, or the net trend of sand drift. Meteorological stations: Albany, Ga. (31°35′ N. lat, 84°07′ W. long); Fort Stewart, Ga. (31°53′ N. lat, 81°34′ W. long, about 50 km west of Savannah); Hunter Army Airfield (AAF), Ga. (32°01′ N. lat, 81°08′ W. long, at Savannah); Brunswick, Ga. (31°15′ N. lat, 81°28′ W. long); Robins Air Force Base (AFB), Ga. (32°38′ N. lat, 83°36′ W. long, about 45 km south of Macon); Alma, Ga. (about 45 km west-southwest of Jesup); Shaw AFB, S.C. (33°58′ N. lat, 80°28′ W. long); Myrtle Beach AFB, S.C. (33°41′ N. lat, 78°56′ W. long); Pope AFB, N.C. (35°10′ N. lat, 79°01′ W. long). Unpub. data from National Oceanic and Atmospheric Administration, Asheville, N.C.; equations from Fryberger and Dean, 1979. Station locations shown on figure 4 or 7*A*.

ties (Olson, 1958b,d; Walker and others, 1981), we have included a summary of published descriptions of vegetation on inland dunes in Georgia and North Carolina. Our field observations, however, suggest that vegetation differences are more probably related to sand thickness, and possibly grain size, and not to age of deposit.

Much of Georgia's dune sand is covered with what Wharton (1977, p. 180–185) called the "Dwarf Oak Forest" (Longleaf Pine-Turkey Oak).

> ...an open canopy forest usually on conspicuous sandhills and deep sands on ridge tops...an extremely dry forest of small deciduous oaks seldom over 15 ft (4.6 m) high, with or without longleaf pine overstory...much open sand, litter absent, often with conspicuous ground lichens, cactus, yucca, and other xeric plants...forests occur on deep sand ridges parallel to and east of major streams in the Coastal Plain....Turkey oak, bluejack oak, dwarf post oak, and longleaf pine are dominant trees....

Wharton's "Dwarf Oak-Evergreen Shrub Forest" has a smaller areal extent and is present in areas where the sand is exceptionally deep and somewhat coarser than in areas of the "Dwarf Oak Forest."

> ...This habitat is particularly evident on the dunes along the Ohoopee River....environment occurs on deep coarse sands...a striking habitat with rare evergreens, such as rosemary...and evergreen woody mints...as dominant ground cover....Trees can be quite old at small diameters. One oak (4 inch [10.2 cm] diameter) was about 60 yrs old, another (6 inch [15.2 cm] diameter) approximately 138 yrs. Trees are turkey oak and longleaf pine. Shrubs included rosemary (*Ceratiola ericoides*), red basil (a woody mint) (*Calamintha coccinea*), blue flowering woody mint (*Calamintha ashei*), shrub goldenrod (*Chrysoma pauciflosculosa*), jointweed (*Polygonella polygama*)....Herbs include sand spikemoss (*Selaginella arenicola*), nailwort (*Paronychia* sp.), a lichen (commonly called British soldier)....

The vegetative community on inland dunes in North Carolina differs somewhat from that in Georgia. The following description of the "Xeric Sandhill Scrub" community was provided by M.P. Schale (North Carolina

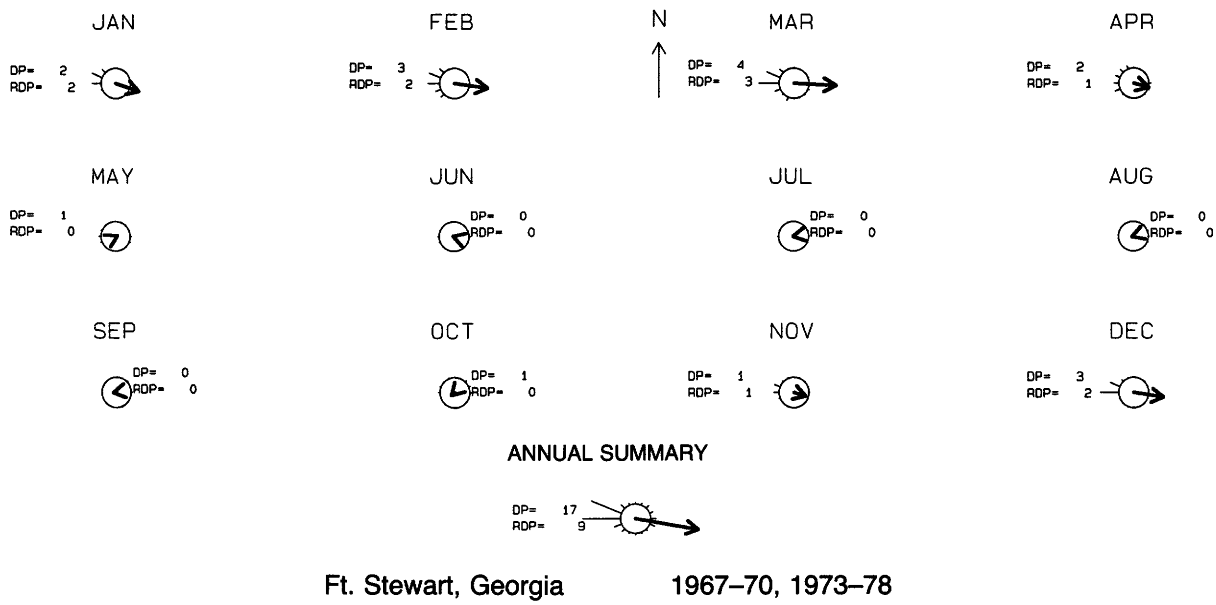


Figure 7*B*. Continued.

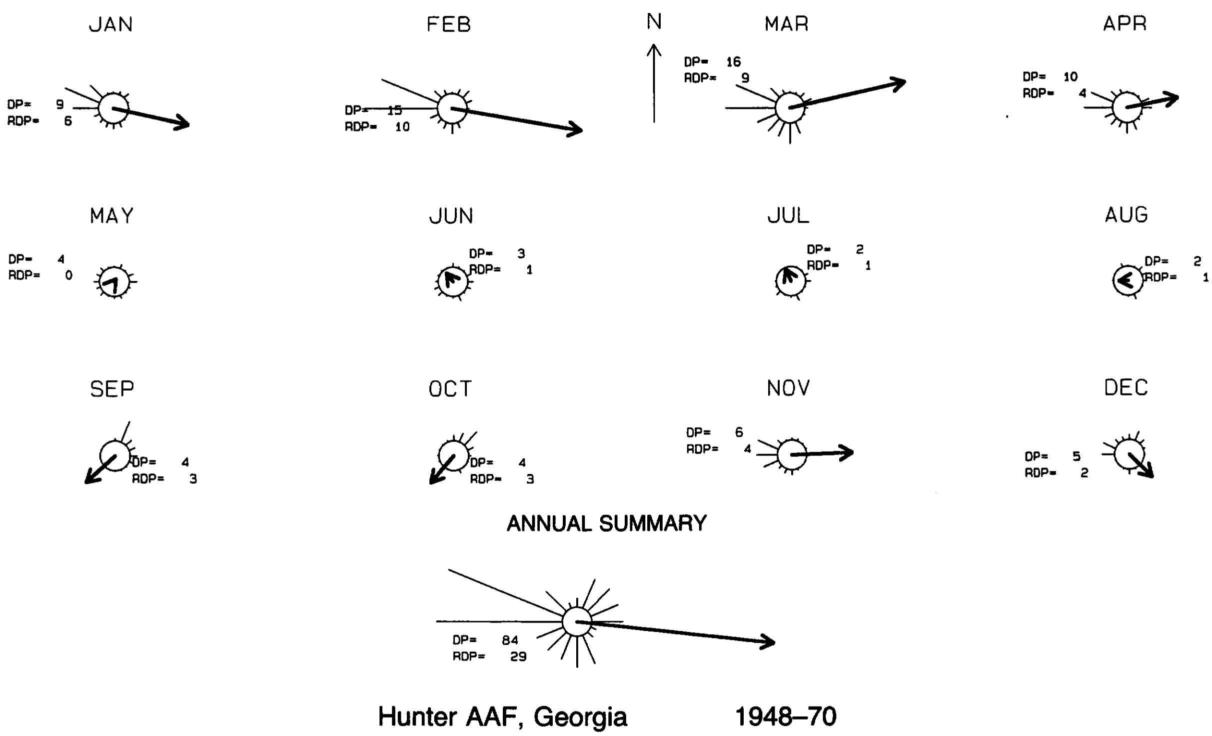
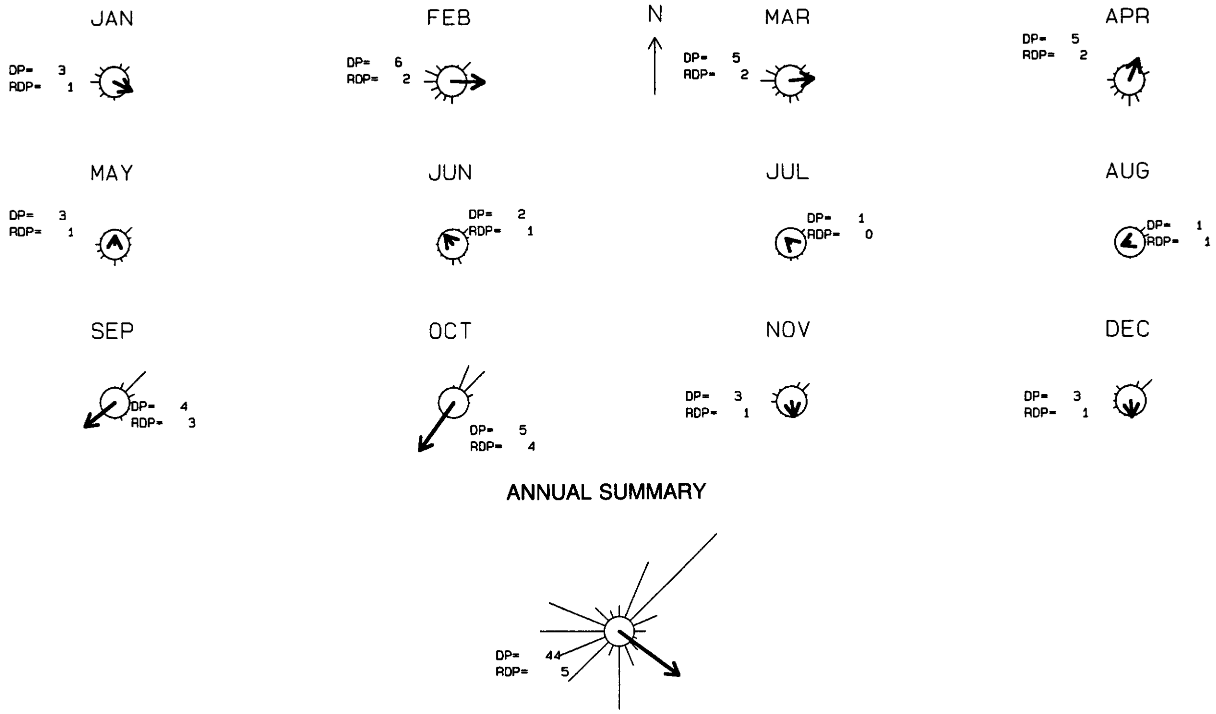
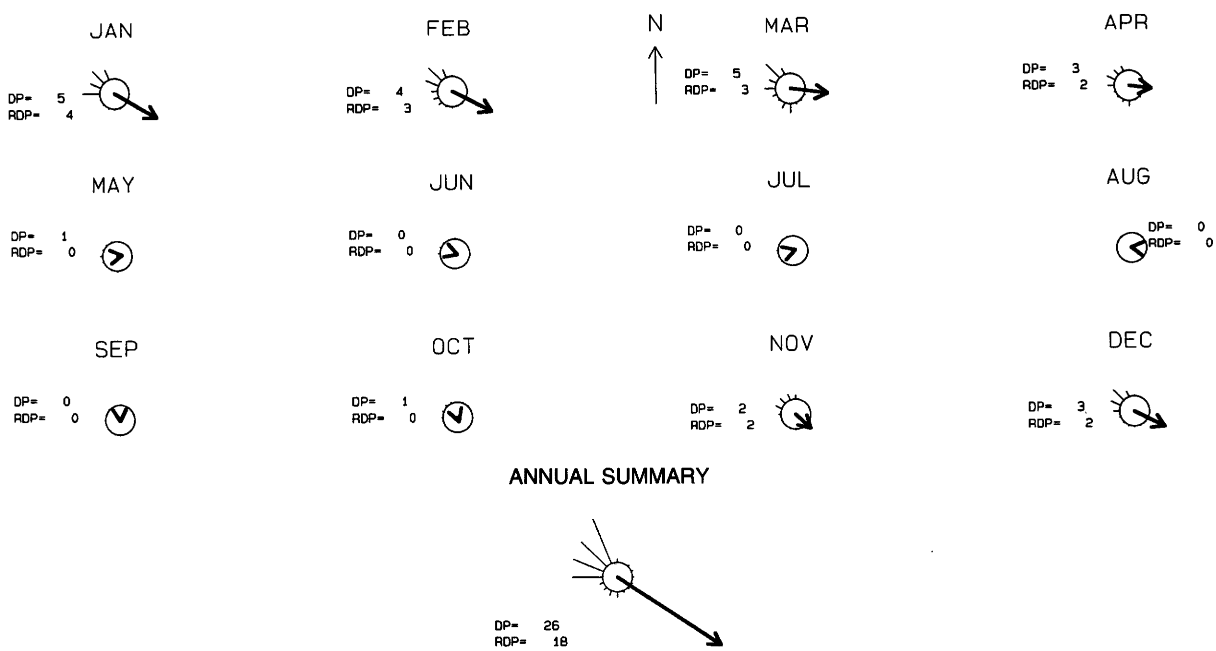


Figure 7*B*. Continued.



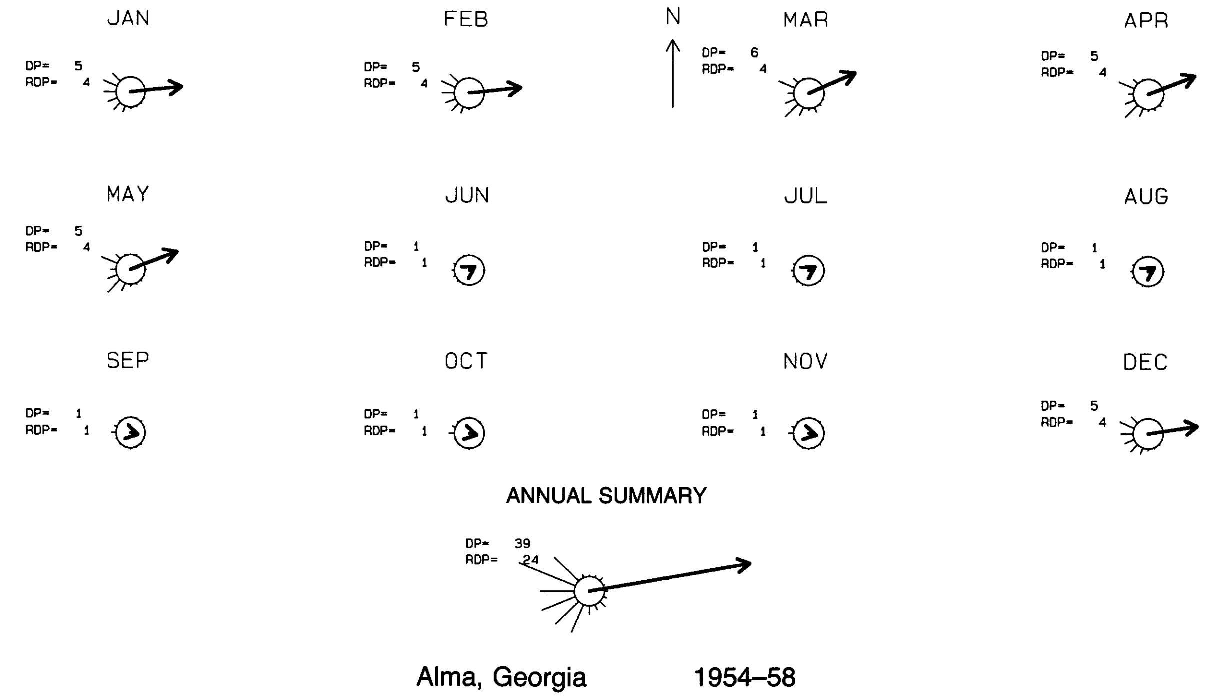
Brunswick, Georgia 1945–46, 1951–70

Figure 7*B*. Continued.



Robins AFB, Georgia 1967–70, 1973–79

Figure 7*B*. Continued.



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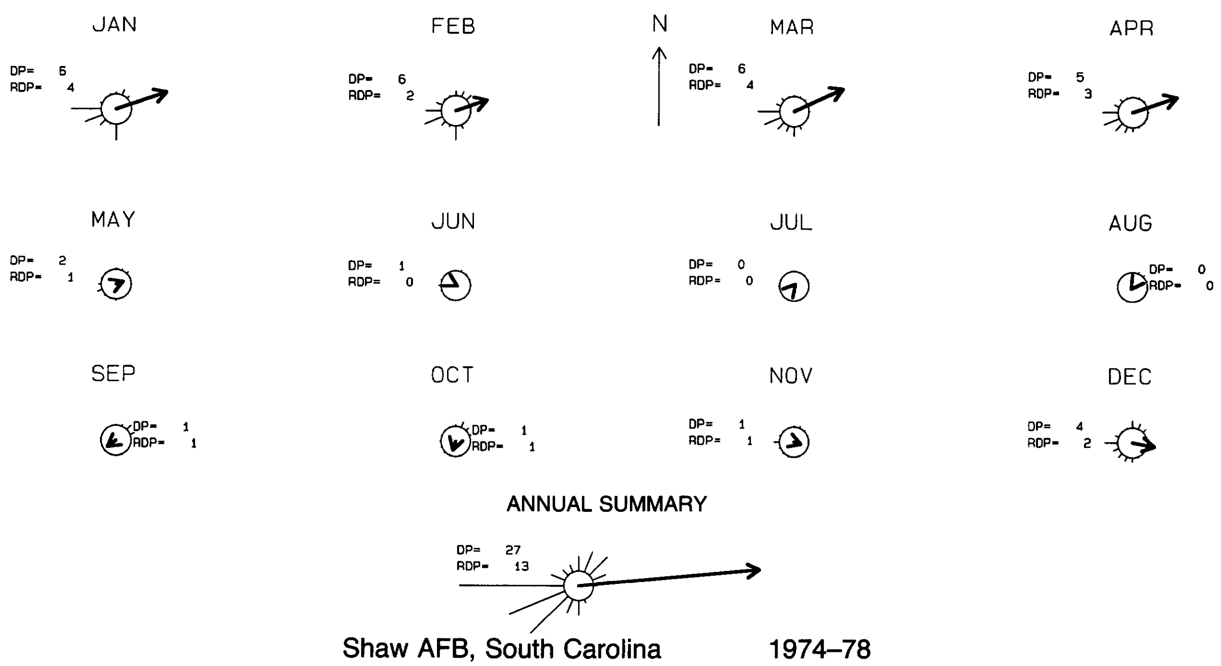

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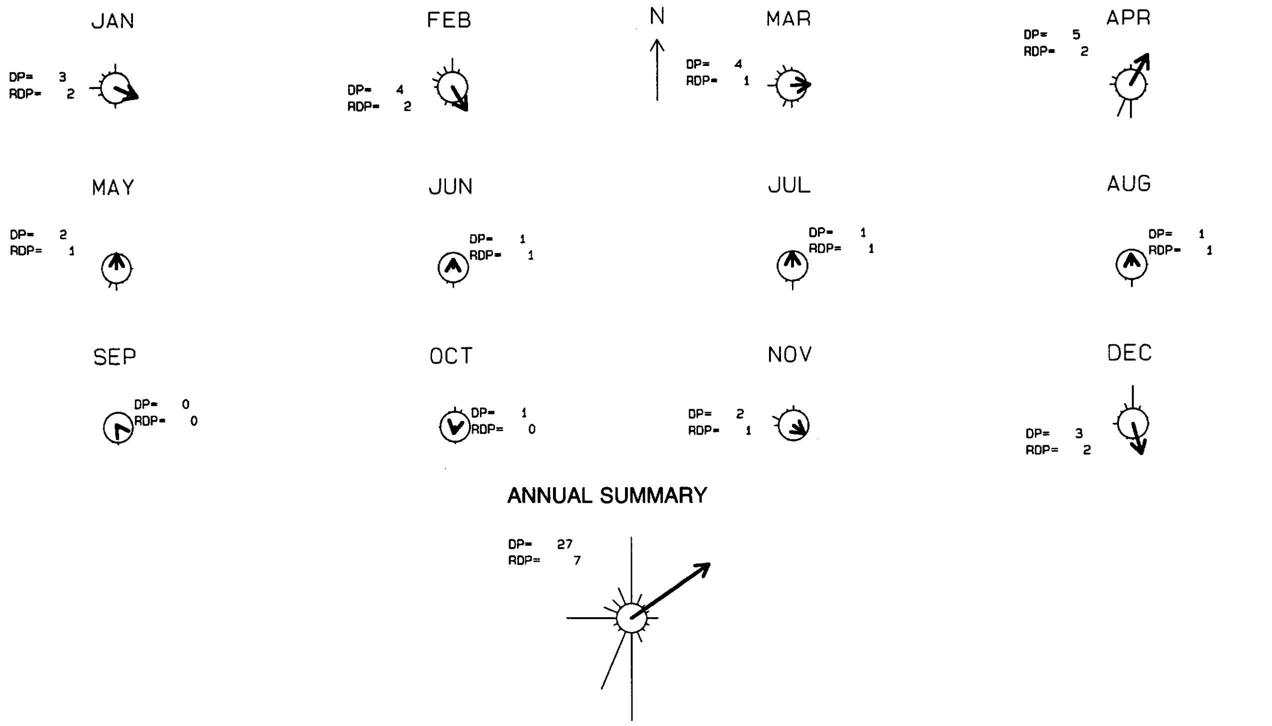
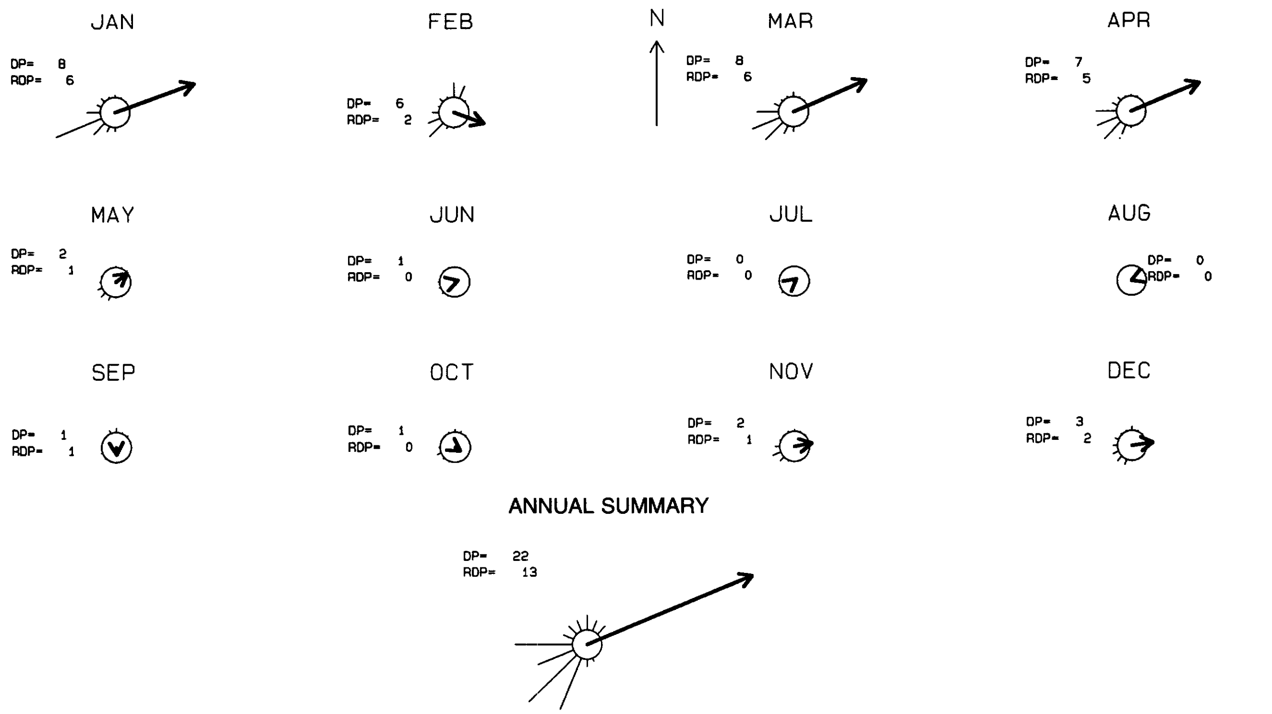


Myrtle Beach AFB, South Carolina 1969–70, 1973–81

Figure 7*B*. Continued.



Pope AFB, North Carolina 1970–80

Figure 7*B*. Continued.

Natural Heritage Program, Raleigh, NC 27611, written commun., 1990).

...open canopy of *Pinus palustris* with an open to dense understory of *Quercus laevis*. Occasional *Quercus margaretta*, *Sassafras albidum* ...*Diospyros virginiana* may occur...sparse low shrub layer...of *Guylussacia dumosa* and *Toxicodendron toxicarium* is sometimes present....Sand barren variant, on the most excessively drained sands which support only sparse woody and herbaceous vegetation...occur primarily on aeolian sand deposits and Carolina bay rims.

STREAM CHARACTERISTICS

BLACK-WATER STREAMS

Although small dunes are present along larger clear-water streams and rivers, the largest dunes and most extensive inland dune fields are located at altitudes of less than 80 m along whiskey-colored, black-water streams whose drainage basins lie wholly within the Coastal Plain physiographic province. These streams have wide, tree-choked, meandering channels with slow-moving water; wide, swampy, tree-covered flood plains; and interfluve swamps at the head of many small tributaries. The chemistry, sediment load, and discharge pattern of these streams greatly influenced and (or) controlled the availability of sand during dune-forming episodes.

Maximum average discharge values of the three black-water streams associated with the most extensive dune fields are 27.3 m^3/s for the Ohoopee River at Reidsville, Ga., 26.7 m^3/s for the Satilla River at Waycross, Ga., and 12.6 m^3/s for the Canoochee River at Claxton, Ga. (Inman, 1971; data from gaging stations nearest the dune fields). During droughts, these large Coastal Plain streams, as well as most smaller streams, have negligible flow, due in large part to the ground-water table dropping below the level of the streambed.

Cherry (1961) described the black water of Lower Coastal Plain streams in Georgia as having high color (commonly >300 platinum cobalt units), pH values commonly less than 6.0 (in many streams <5.0), a greater quantity of organic than inorganic materials in suspension, and high iron contents. Beck and others (1974) formulated similar conclusions and characterized the waters as having low suspended load, low ionic strength, low pH values, a predominance of organic over inorganic constituents, and relatively high concentrations of iron and aluminum.

The effects of the organic-rich, low-pH, black water on the sediment through which it flows has not been adequately studied, but as pH lowers and organic matter increases, the suspended sediment load decreases and the percent quartz sand in the alluvium increases (Cherry, 1961; Stokes and others, 1984; Perlman, 1985; H.W. Markewich, unpub. data). Chelation, adsorption, and dissolution are the processes apparently responsible for the decrease in clay content of the alluvium (R.L. Malcolm, U.S. Geological Survey, Denver, Colo., oral commun., 1991). The result is stream alluvium having an average quartz sand content of 95 to 98 percent that was derived from surrounding sediment having a 30 to 70 percent kaolinitic clay content (H.W. Markewich, unpub. field data, 1985–90). During periods of low water, when the flood-plain and channel sand is subaerially exposed, the alluvium is susceptible to wind erosion and becomes an available source area for windblown dune sand. Dunes associated with black-water streams are present both on alluvial terraces and on eastern valley walls, where they form long ramps extending from the valley floor to the interfluve.

CLEAR-WATER STREAMS

Some small dunes and dune fields are present on the flood plain and terraces of high-discharge, regional, clear-water rivers such as the Savannah, which drains the Coastal Plain, Piedmont, and Blue Ridge provinces, and the Altamaha, which drains the Coastal Plain and Piedmont provinces. Generally, these rivers have lower organic matter content, higher pH values (6.0–6.5), lower color (about 75 platinum cobalt units), and greater suspended sediment load than do Coastal Plain streams. The average discharge values of regional drainages, where adjacent to dunes, are an order of magnitude greater than those of Coastal Plain rivers (283–453 m^3/s, the range in average discharge for regional drainages in South Carolina and Georgia, as compared to 12 and 28 m^3/s, the maximum average discharge values for the Canoochee and Ohoopee Rivers, respectively, in Georgia) (Gunter and others, 1983; Bennet and others, 1984; Stokes and others, 1984). Dunes present on the eastern and northeastern sides of regional drainages are generally smaller than dunes associated with Coastal Plain streams and rivers. They are commonly present on channel-bar deposits, midchannel islands, and low terrace surfaces and not as sand ramps on the eastern valley walls.

REGIONAL SYNTHESIS

GENERAL DESCRIPTION AND DISTRIBUTION OF INLAND DUNES

Most inland dunes in Georgia and the Carolinas occur in an area between 48 and 160 km from the coast that has a MAP of less than 1,250 mm, a MAE of about 1,100 mm, and black-water streams with average discharge values less than 28 m^3/s.

GEORGIA

Veatch and Stephenson (1911) first discerned the geographic distribution and essential character of dunes in

Georgia. They noted that the sand hills slope toward the streams that they border; that the sand is gray, yellow, or light brown, unconsolidated, and structureless; that the sand belts may reach a width of as much as 3–5 km; that they lie parallel to the streams, generally on the eastern or left sides of the streams; and that the sand deposits appear to be at higher elevations than the accumulations of loose sand on nearby river or stream terraces. They suggested that the sand deposits were of fluvatile origin with subsequent shifting and in part redeposition by wind.

Hurst and others (1966), in their study of part of the Coastal Plain in south-central Georgia, described the dunes as "massive drifts," commonly more than 4.5 m thick and 1.6 km wide along the eastern sides of the major streams. They noted that the drifts extend along the entire eastern banks of the larger streams and that the sand exhibits little or no stratification or crossbedding. They suggested that the sand was concentrated in drifts during Holocene time by prevailing southwesterly to westerly winds.

By using Landsat imagery, Pickering and Jones (1974) recognized the parabolic (crescent) shape of the dunes and noted that dunes having the best parabolic form occur along S. 20° E.-trending reaches of the Ohoopee, Canoochee, Altamaha, and Savannah Rivers. Dunes along some of the rivers, such as the Altamaha, extend to the river mouth and merge with Pleistocene coastal dunes.

Axes of inland dunes in Georgia indicate formation by west winds in the central Coastal Plain and by west and southwest winds nearer the coast. The main source areas of the dune sand were stream channels and flood plains (figs. 8–12). A few small dune fields are adjacent on the east to shallow depressions locally referred to as Carolina bays (fig. 3*A*). The bays served as source areas for the dune sand.

Dunes in Georgia vary greatly in size and extent (figs. 10, 12–14). Dunes along small first order streams are commonly only 1 to 3 m thick and several tens of meters across. One- to 2-m-high and 3- to 10-m-high dunes are common along regional drainages such as the Altamaha and the Savannah. The highest (8–25 m) and largest dunes are adjacent to streams in southeastern Georgia, where drainage basins lie wholly within the Coastal Plain. The largest of these dunes occur where two or more stream valleys, at least one parallel to the prevailing wind direction, intersect (fig. 13).

Commonly, the dunes and dune fields along the clear-water regional drainages are on flood plains and terraces and downstream from confluences with major black-water Coastal Plain tributaries (see the distribution of dunes along the Altamaha and Ohoopee Rivers on fig. 2*A*). None of the dunes are as large as those along Coastal Plain drainages.

Along higher order Coastal Plain streams in Georgia, such as the Ohoopee River, 10- to 25-m-thick, 2- to 4-km-long dunes coalesce to form 20- to 80-km-long linear dune fields (fig. 8). The dunes form sand ramps that climb 20 to 40 m up the eastern valley wall of the Ohoopee River valley (figs. 8, 12*A*) or large U-shaped forms on low terraces (fig. 9). Locally, dunes that form ramps on the valley sides extend beyond the crest of the interfluve (fig. 8). Wedge-shaped sheets of sand extend from a few hundred meters to 6.0 km leeward of the dunes. Thickness of the sand sheets ranges from a maximum of 7 m near the dunes to about 20 cm (minimum recognizable thickness) at leeward limit. Where dunes coalesce, short, straight, west-flowing ephemeral streams define the boundaries of individual dunes (fig. 8).

At several localities in Georgia, at least two sets of dunes are present, such as on the flood plain and valley side northeast of the Satilla River near Waycross (fig. 12*C*), or piggybacked onto older and larger dunes east of the Canoochee River near Claxton (fig. 13). Although they have been described as parabolic (Pickering and Jones, 1974), most dunes are a filled-in crescent or U shape; they generally do not have the windward-pointing arms characteristic of parabolic dunes. The whaleback upper surfaces of some of the younger dunes and (or) reactivated surfaces of older dunes are characterized by a hummocky, knob-and-kettle topography (figs. 8–10). The smooth back-slope surfaces of some older dunes suggest that they were minimally affected by the most recent dune-forming event(s).

SOUTH CAROLINA AND NORTH CAROLINA

None of the dunes adjacent to southeast-flowing streams in South Carolina and North Carolina are higher than 10 m, most are less than 8 m high, and many are less than 2 m high. Dunes less than 2 m high are not identifiable on many of the quadrangle maps of the area because their height is less than the commonly used 5-ft topographic contour. They are identifiable on most aerial photographs and on satellite imagery.

Most dunes are adjacent to streams, but at several localities dunes extend from Carolina bay to Carolina bay and cover large areas of the flood plains and low terraces (fig. 14). In the Carolinas, dune axes indicate formation by southwest winds (Thom, 1967; Carver and Brook, 1989) (fig. 14). In the valleys of the Cape Fear and Pee Dee Rivers, dune morphology indicates that there was some cross-valley migration. However, most inland dunes in the Carolinas have the filled-in U shape and are directly adjacent to the channel and (or) terrace sand source. These characteristics suggest that the dunes did not migrate far, if at all, from the original site of deposition.

As in Georgia, at least two sets of dunes have been identified in the Carolinas. Thom (1967) recognized two sets associated with the Great Pee Dee River and a few of its

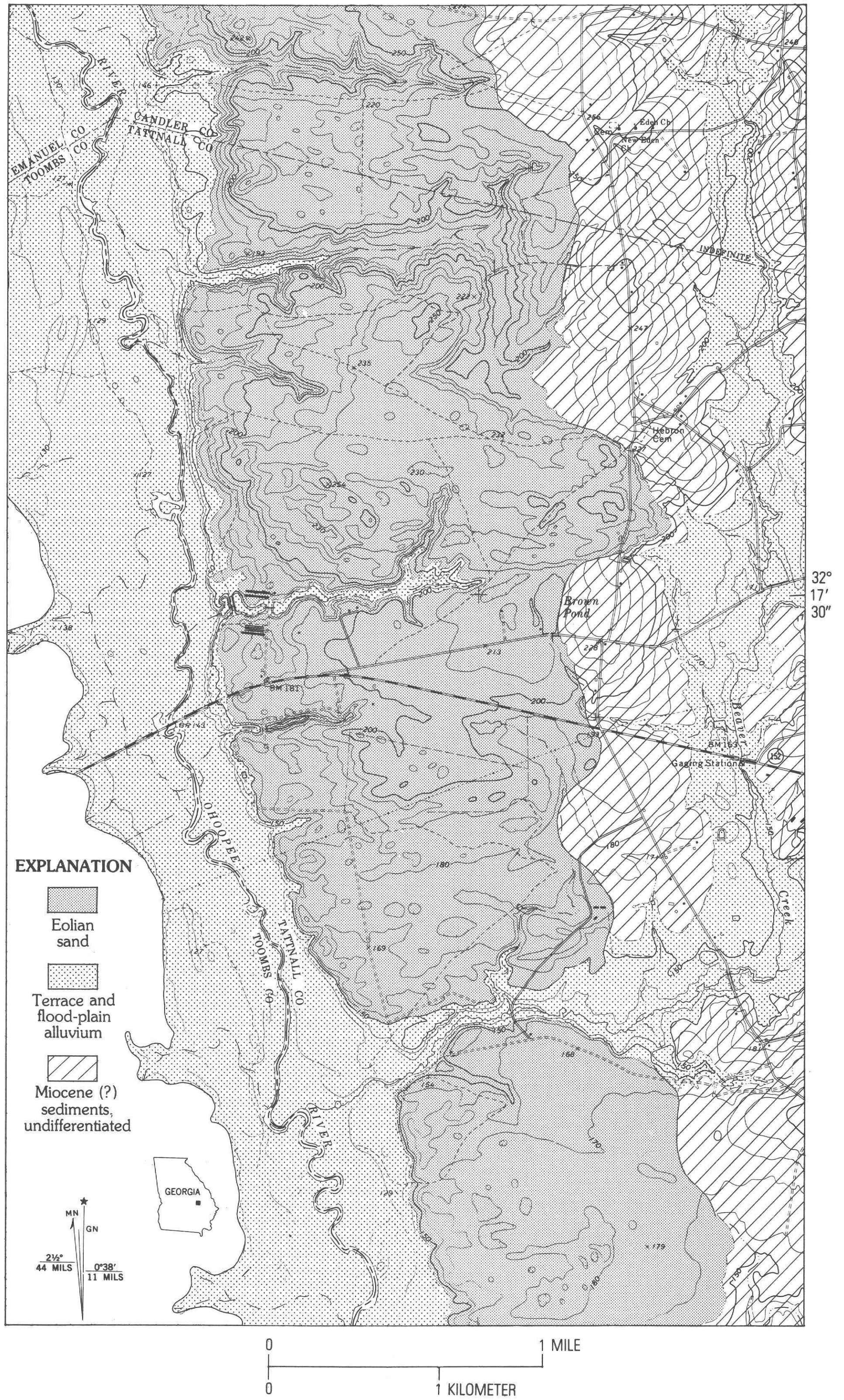


Figure 8. Topographic expression of large, 20- to 25-m-high, coalescing dunes adjacent on the east to the Ohoopee River flood plain in the south-central Georgia Coastal Plain (Cobbtown, Ga., 1:24,000 topographic quadrangle; 10-ft contour interval). Locally, intermittent or ephemeral drainages mark dune-to-dune boundaries and the contact between dune slip faces and the ridge-forming Miocene(?) substrata. Differences in topographic expression between dunes, and (or) between the windward and leeward part of an individual dune, suggest that, at the surface, a few meters of sand were reactivated during the most recent dune-forming event. Line weight of dune boundary is heavier where boundary departs from topographic contour.

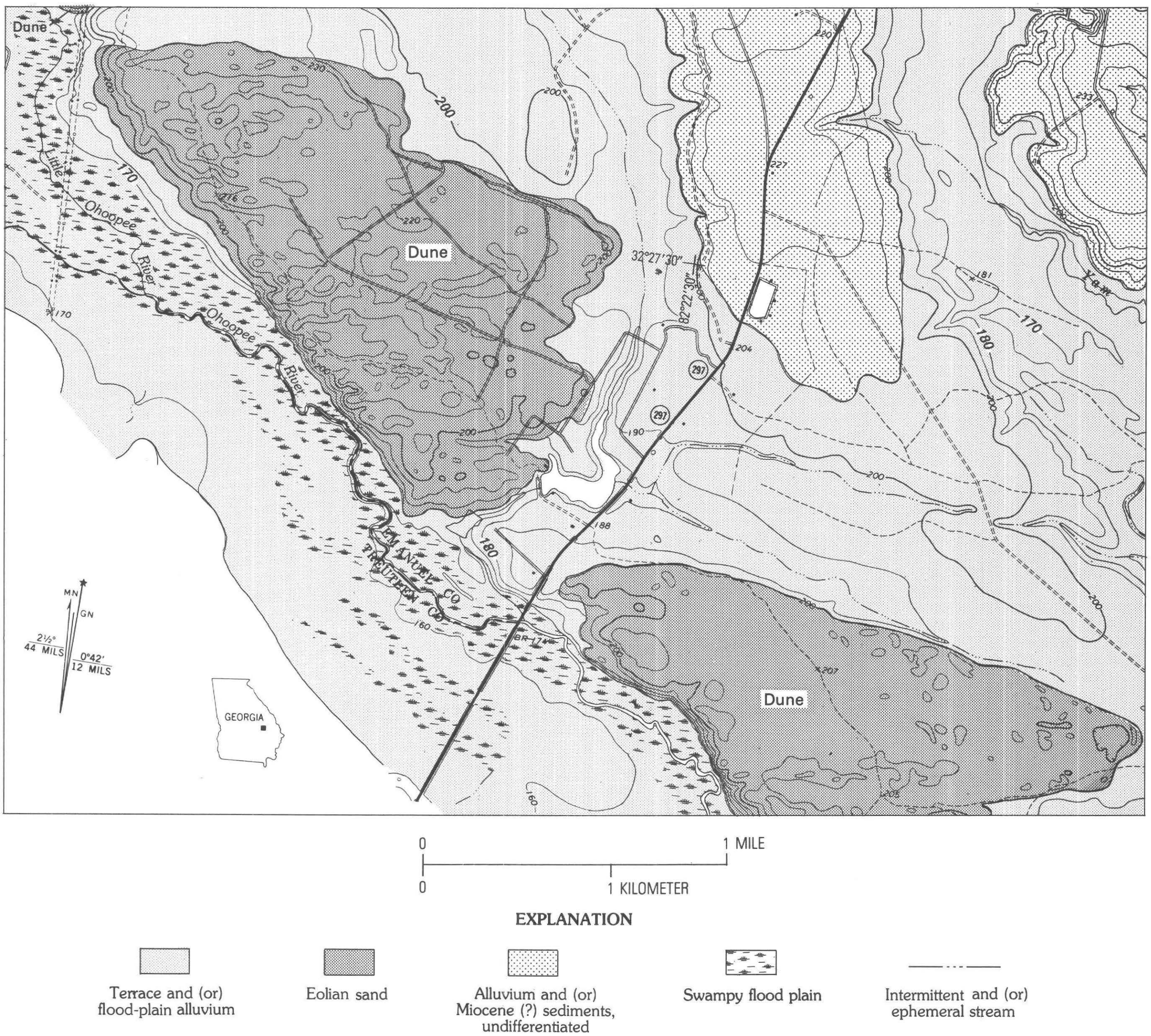


Figure 9. Eolian sand dunes, 5 to 15 m high, on low terraces to the east of the Little Ohoopee River and Ohoopee River flood plains (Covena and Nunez, Ga., 1:24,000 quadrangles;10-ft contour interval). Representative contours show the contrasting morphologies of the eolian dune sand and the stream-deposited or stream-modified alluvial sand. Substratum is a middle to upper Miocene(?), highly weathered, red-orange to purple, locally pebbly (quartz), fluvial, clayey (kaolinitic) sand or sandy clay.

tributaries in northeastern South Carolina. He suggested that one set of low (<3 m high) dunes blocked the mouths of remnant channels on the lowest terrace and that another older set blanketed the surface of the next higher terrace.

Soller (1988) discriminated two dunal assemblages by using mineralogy and geomorphology in the lower Cape Fear River valley in southeastern North Carolina. He noted that the mineralogical differences were not sufficient for field mapping but that geomorphic differences were pronounced, with the best developed dunes adjacent to the Cape Fear and Black Rivers.

Daniels and others (1969) studied small, structureless bodies of eolian sand adjacent on the east to the Neuse River and one of its tributaries in the Coastal Plain of North Carolina. They observed that (1) individual dunes along the Neuse River are between 2 and 5 m high, (2) dunes are present from the highest interfluves to just above the flood plains, and (3) individual dunes are generally less than 1.5 km long but the coalesced dunes form linear fields that extend up to 8 km along the river. They suggested that the morphologies and geomorphic positions of the dunes indicate several periods of formation.

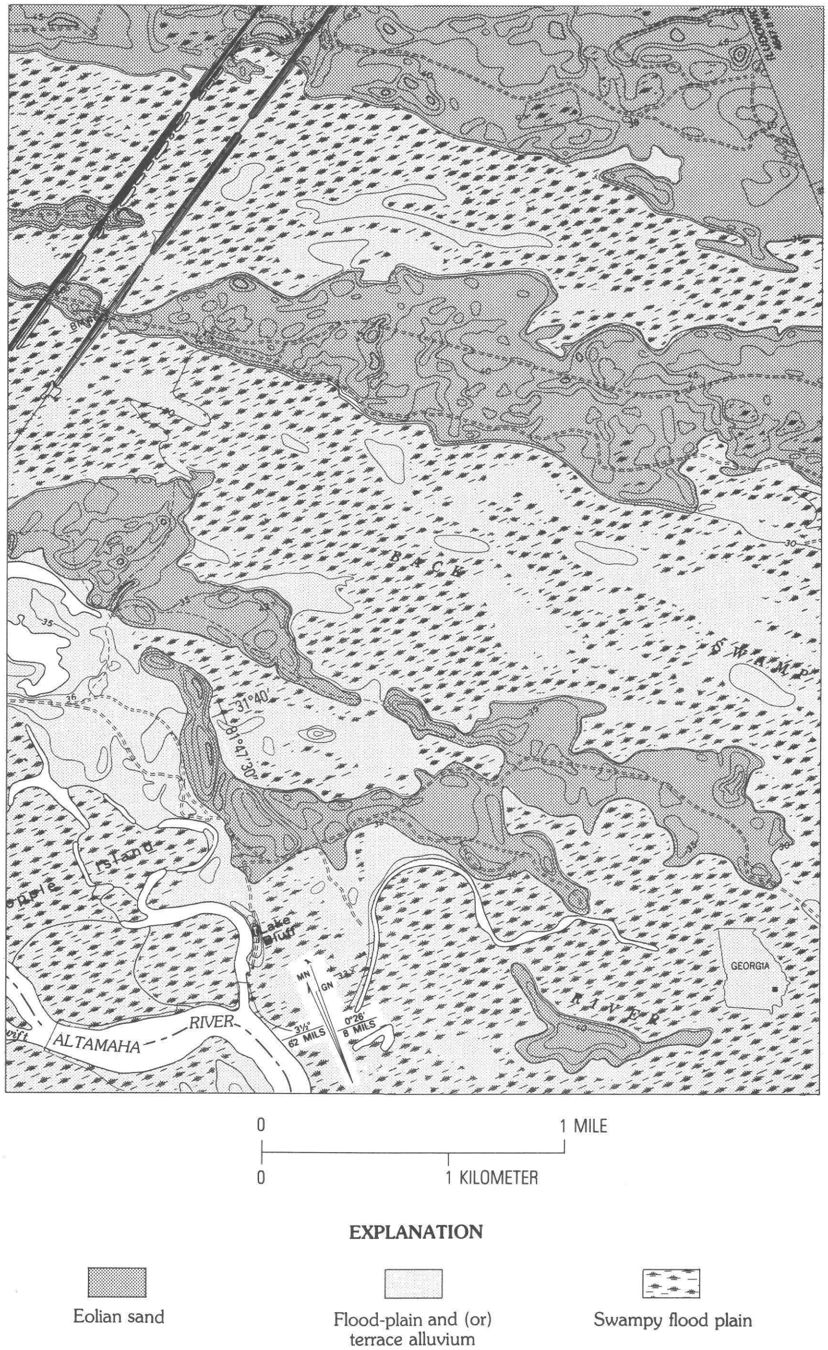


Figure 10. Eolian sand dunes, 3 to 15 m high, on Altamaha River midchannel islands and low terraces about 32 km downstream from the confluence of the Ohoopee and Altamaha Rivers near Jesup, Ga. (Doctortown, Ga., 1:24,000 topographic quadrangle; 5-ft contour interval). Representative contours show the dunal morphology. The truncated southwestern boundaries of the dunes suggest postdepositional erosion by floodwaters.

PARTICLE-SIZE DISTRIBUTION, MINERALOGY, AND GRAIN MICROMORPHOLOGY

Most inland dunes on the southeastern Atlantic Coastal Plain are unstratified and structureless. Bedding, if apparent at all, is thin and near the base of the dune. Neither our observations nor previously published data suggest any recognizable trends in particle-size distribution, either vertically within a dune or with increasing distance from source area (Daniels and others, 1969; Hails and Hoyt, 1969;

Thames, 1982). Table 1 gives particle-size distribution data for the upper meter of sand in late Pleistocene and (or) Holocene dunes along the Savannah River (Jasper County, S.C.; 32°33′ N. lat, 81°15′ W. long).

Generally, the dune sand in Georgia is (1) medium to fine with a mean grain size of 1.68 phi (0.31 mm) (Hails and Hoyt, 1969; Thames, 1982), (2) moderately to moderately well sorted, and (3) symmetrical to fine skewed and mesokurtic to leptokurtic (Thames, 1982). Daniels and others (1969) showed that most dune sands along the Neuse River in North Carolina are in the 1-phi size range and that there is little vertical variation in sand size. Soller (1988) showed that all dunes in the lower Cape Fear River valley have a mean between 1.2 and 1.6 phi and are better sorted than the river sands. This size range for inland dune sand in the Southeastern United States agrees with the 1- to 2-phi size range (0.5–0.25 mm) for inland dunes as reported in Ahlbrandt (1979).

Sand in Georgia's inland dunes is predominantly (commonly >98 to 99.8 percent) medium and fine, subangular to subrounded quartz. Thames (1982) showed that potassium feldspar ranged from 0 to 2.1 percent, but the average potassium feldspar content was less than 0.6 percent. We found less than 1 percent potassium feldspar in all dune sand, even where superjacent to alluvium of regional drainages. No plagioclase feldspar has been identified. Medium and coarse quartz sand grains are commonly pitted and (or) frosted and conchoidally fractured. Thames (1982) considered the conchoidal fracturing, the distinctive "rolling" topography of the grain surfaces, and a high degree of occurrence of upturned plates over much of the surface area of the grains as evidence for an eolian origin of the sand.

Heavy minerals everywhere constitute less than 1.0 percent of the dune sand. Our observations and those of Thames (1982) suggest that, at most localities, heavy minerals constitute less than 0.5 percent. No variation in heavy-mineral content with depth has been observed; however, neither has there been a detailed study of the effects of weathering. Preliminary background gamma radiation measurements (taken for potential dating by optically stimulated luminescence) suggest that heavy-mineral content may decrease with increasing distance from the sand source (H.T. Millard, U.S. Geological Survey, Denver, Colo., oral commun., 1992). This decrease may indicate sorting with distance from source area or it may indicate more than one age of dunes.

Opaque minerals compose about half of the heavy-mineral suite. Of these, we identified ilmenite, leucoxene, limonite, hematite, and magnetite. Non-opaque minerals

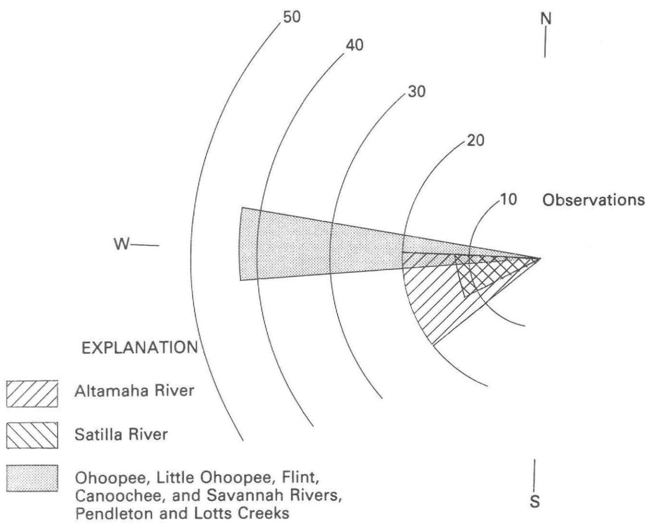


Figure 11. Rose diagram showing paleowind directions for dunes in the Atlantic Coastal Plain of south Georgia as indicated by dune axes. Number of observations indicated by distance outward from center.

Table 1. Particle-size distribution data (in weight percent) for dunes along the Savannah River, Jasper County, S.C.

[Two sites; both at 32°33′ N. lat, 81°15′ W. long]

Horizon designation	Horizon thickness (inches)	Sand						Silt	Clay	Texture
		Very coarse	Coarse	Medium	Fine	Very fine	Total sand			
Site 1										
A11	0–3	0.27	20.33	64.02	14.08	1.29	95.25	1.37	3.38	Sand
A12	3–7	.22	23.17	60.26	14.94	1.41	95.83	.71	3.45	Sand
C1	7–23	.21	20.47	66.17	11.93	1.22	96.68	.25	3.07	Sand
C2	23–80	.16	18.37	68.22	11.80	1.45	98.91	.22	.87	Sand
C3	80–90	.20	32.69	60.54	5.09	1.48	99.22	.16	.62	Sand
Site 2										
AP	0–10	0.32	29.14	59.86	10.15	0.53	95.67	3.89	0.44	Sand
A2	10–88	.21	24.07	64.13	11.06	.52	96.07	3.57	.36	Sand
C	88–106	0.0	21.26	64.14	14.19	.41	98.15	1.64	.21	Sand

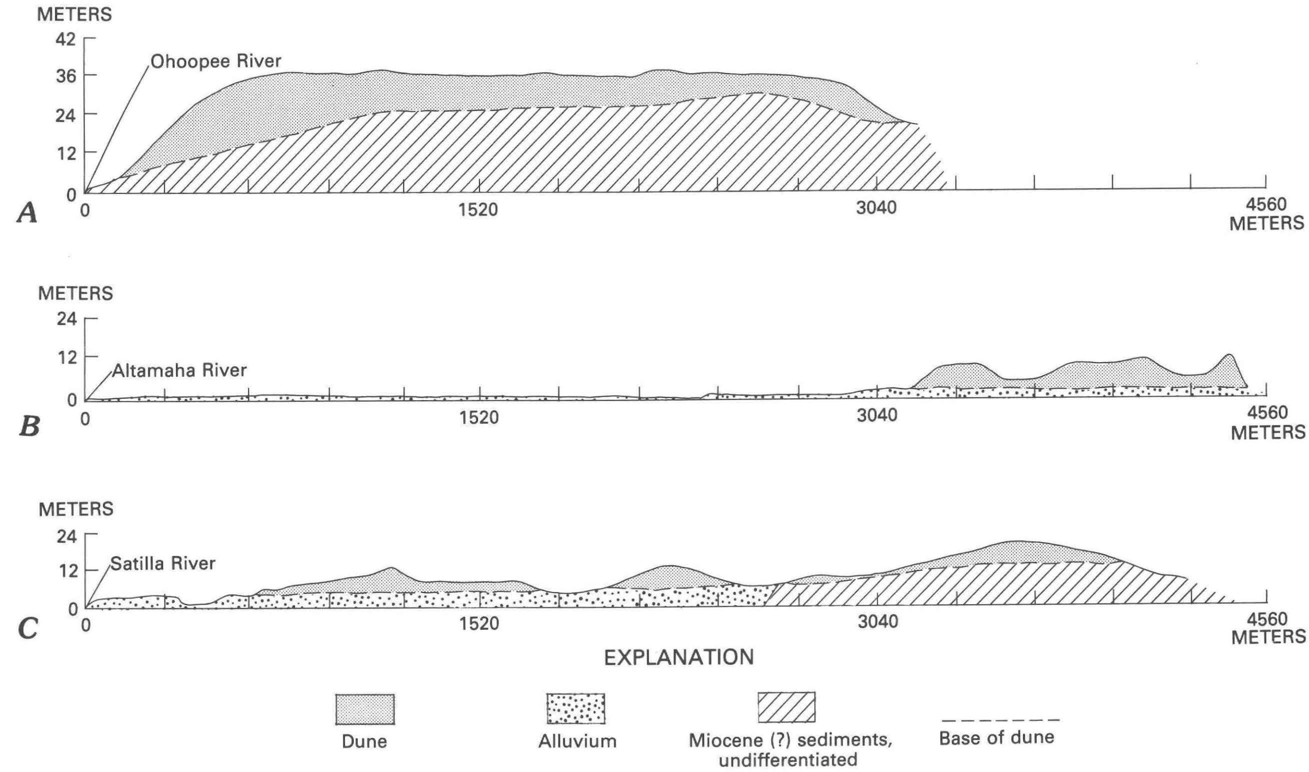


Figure 12. Cross sections showing relations of dunes to river valleys and of dune sand to substrata of, *A*, the west-facing valley side of the Ohoopee River (Cobbtown, Ga., 1:24,000 quadrangle); *B*, the "second bottom" or first terrace on the eastern side of the Altamaha River (Altamaha SE., Ga., 1:24,000 quadrangle); and *C*, the flood plain and west-facing valley side of the Satilla River (Blackshear, Ga., 1:24,000 quadrangle). Vertical exaggeration approximately 10×.

include, but are not restricted to, sillimanite, tourmaline, epidote, hornblende, and staurolite.

Although the percent fines in the inland dune sands of Georgia is always less than 10, generally less than 5, and commonly less than 2, the relative percent does vary with depth. The upper meter of dune sand commonly has between 2 and 5 percent silt and clay derived from very minor additions of eolian material and (or) by weathering. From about 1 m depth to the base of the sand dune, the percent silt and clay in the dunes is also variable but is always less than 2 percent; the variability is attributed to differences in source material composition.

The <2-μm fraction of dune sediments in Georgia is primarily quartz and kaolinite with minor vermiculite, illite, halloysite, microcline, and lepidicrosite or goethite (figs. 15, 16). The kaolinite is the result of weathering of the small percentage of labile minerals in the dune sands and (or) represents addition of airborne material from the surrounding terrain. The <2-μm quartz may represent an original size fraction and (or) a subsequent airborne addition. The <2-μm fraction is primarily present as coatings on sand grains but does constitute a measurable size fraction in the upper meter of the dune sand and at irregular intervals throughout the deposit. Clay minerals are mixed, but kaolinite is dominant. The crystallinity of clay-sized minerals in the surface few meters is less than at depth in the older dunes—possibly the result of dissolution by low-pH, high-organic surface water moving downward through the litter layer into the sand.

Data from Georgia suggest that younger dunes have a more complex mineral assemblage than do older dunes (figs. 15, 16). In the Cape Fear River valley of North Carolina, Soller (1988) noted a similar mineralogic difference between older and younger dunes. He showed that the clay fraction in the younger dunes was mixed but in the older dunes was kaolinitic. He suggested that there has been greater alteration of the fine fraction in the older dunes and that the source area of fines in the younger dunes was nearby upland surfaces on weathered Coastal Plain sediments.

EROSION, OXIDATION, AND PEDOGENESIS

EROSION

Generally, inland dunes in the Georgia and the Carolinas have retained their initial U shape (figs. 8–10, 13, 14) and exhibit only minor evidence of erosion. Although field observations confirm that there is some channel flow across the surface of the dunes during extremely high precipitation

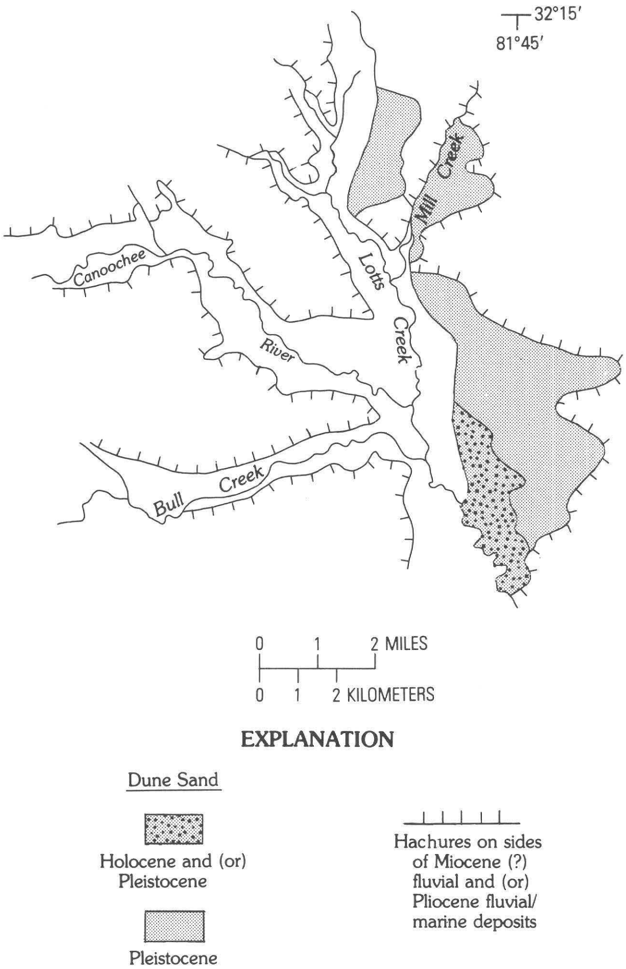


Figure 13. Location of 3- to 20-m-high dunes across the valley from the junction of east-west-trending valleys of Bull Creek and the Canoochee River and north-south-trending valleys of Lotts Creek and Mill Creek in Georgia. Younger piggyback dunes are stippled; larger, older dunes are shaded. Maximum altitude of dunes is 48 m; flood-plain altitude is between 10 and 13 m.

events, gullying is not a major erosional process. Overland flow and gullying are minimized due to high permeability (>50 cm/h) of the sands, but water moving as overland flow can be seen in the first hour or so of a major storm, particularly where there is abundant vegetation and surface litter. As a storm continues, water begins to move rapidly through the highly permeable sand.

We made no attempt to study the reasons for the initial water repellency of dunes in the Southeastern United States. Studies have been conducted on the role of microflora in the water repellency of sandy soils in Australia (Bond, 1964; Bond and Harris, 1964; Roberts and Carbon, 1972) and on the role of humidity in inducing the repellency of sandy soils (Jex and others, 1985). Amundson and Tremback (1989) recently commented on overland flow on, and water repellency of, vegetated coastal dunes near San Francisco, Calif. They state that the origin of the repellency is unknown, "but appears to be a consequence of hydrophobic organics derived from the litter" (p. 1802). They suggest that the reader refer to Ma'Shum and others (1988) for a more complete discussion of hydrophobic substances in soils.

OXIDATION

Oxidation of dune sand is minimal. In younger dunes having pronounced hummocky topography, oxidation depths are between 2.5 and 3 m. Older dunes are generally oxidized to depths between 5 and 6 m. Oxidation colors in the dune sand are pale and only locally differ significantly between older and younger dunes. The unweathered color of the dune sand is very pale brown with a hue of 10*YR* or 2.5*Y*, a value of 4 to 8, and chroma of 3 to 8. Dune sand along regional drainages such as the Savannah River can have a slightly redder color due to oxidation of the slightly higher percentage of labile minerals (still generally <2 percent).

PEDOGENESIS

Most dune sands in Georgia and the Carolinas lack significant soil development. Argillic horizons are rare. Cambic horizons are common in dune sand along regional drainages such as the Savannah but not in dune sand along Coastal Plain streams. Where present, cambic horizons have a maximum of 5 percent clay.

In a few localized areas, where dune thickness is less than 3 m, lamellae have developed in the dune sand. Lamellae composition is primarily iron oxide and minor clay content. Where present, lamellae are 5–25 mm thick and occur near the base of the dune.

Most dune soils are mapped as Typic Quartzipsamments, extremely droughty, highly permeable (>50 cm/h), and excessively drained, with very low available water-holding capacity. Depth to seasonal water table is everywhere greater than 2 m, at most localities greater than 3 m, and at many localities greater than 7 m.

Buried A horizons are not common but do occur in both older and younger dunes. Limited field data suggest that they are more common in the older dunes. Where observed, the buried A horizons are thin and discontinuous and have a low content of disseminated organics.

DUNE AGE

In Georgia, there is a dearth of datable material from dunes, interdunes, and terrace alluvium. Geomorphic position, surface morphology, depth of oxidation, and degree of soil development suggest that, below 10 m altitude, all inland dunes in southeastern Georgia are younger than the marine Pamlico sequence (considered to be between 500 ka

Figure 14. Aerial photograph of Carolina bays and dunes in the Cape Fear River valley near Elizabethtown, N.C. Singletary (A) and White (B) Lakes are perennial water-filled depressions. Other bays are swamps, or were swamps, and have been drained for agricultural use. Small fields of low U-shaped and parabolic dunes extend northeastward from the bays, cover much of the valley floor between the bays, and locally have migrated into adjacent bays. No bays or dunes are present on the most recent valley fill directly adjacent to the Cape Fear River or its tributaries. Arrow indicates flow direction.

and 200 ka) and that many are younger than the Princess Anne (250 ka to 100 ka) and (or) Silver Bluff (120 ka to 40 ka) sequences (*see* Markewich and others, 1992, for review of recent literature on Pliocene and Pleistocene marine deposits). Reconnaissance mapping suggests that dune-forming episodes were associated with periods of low or rising sea level (H.W. Markewich, unpub. field data).

A carbon-14 age of 14,690±250 yr B.P. (Laboratory No. W–5790, U.S. Geological Survey, Reston, Va.) has been determined for wood taken from point-bar sediments associated with a low terrace or "second bottom" of the Altamaha River near its junction with Ten Mile Creek (31°51′50″ N. lat, 82°07′ W. long; Altamaha SE., Ga., 1:24,000 quadrangle). Numerous morphologically distinct sand dunes are present on a matched terrace about 1 km downstream and across the river from this sample locality. The position of the dunes on this low terrace suggests that they are younger than 15 ka.

A carbon-14 age of 3090±100 yr B.P. (Laboratory No. W–6369, U.S. Geological Survey, Reston, Va.) is available for wood from flood deposits on a low terrace of the Ogeechee River, just southwest of Savannah (32°00′31″ N. lat, 81°18′08″ W. long). These deposits are associated with a low terrace that is geomorphically younger and

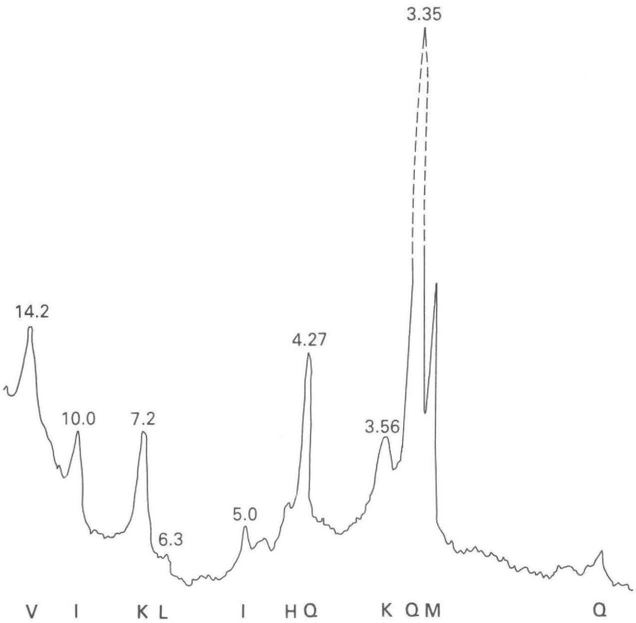


Figure 15. X-ray diffraction pattern of <2-µm fraction (primarily extremely thin coatings on quartz grains) from 1.2-m depth in small, 2-m-high dune on eastern side of Ohoopee River about 3 km west-southwest of Reidsville, Ga. (Reidsville West, Ga., 1:24,000 quadrangle). The dune is located about 7 m above the modern flood plain. H, halloysite; I, illite; K, kaolinite; L, lepidicrosite; M, microcline; Q, quartz; V, vermiculite. Diffraction measured in angstroms.

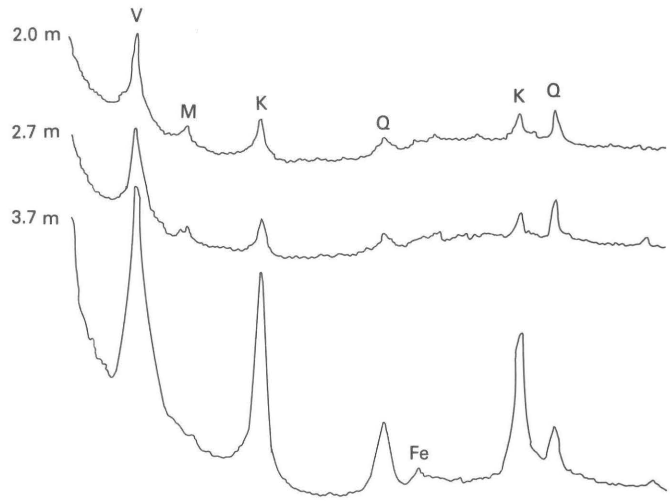


Figure 16. X-ray diffraction patterns of <2-µm fraction (primarily extremely thin coatings on quartz grains) from a large 15-m-high dune on eastern side of the Little Ohoopee River (Covena, Ga., 1:24,000 quadrangle). Depth shown in meters. Fe, goethite; K, kaolinite; M, mica; Q, quartz, V, vermiculite. Diffraction measured in angstroms.

topographically lower than the adjacent dunes; this association suggests that dune formation ceased prior to 3 ka.

Soller (1988) suggested that at least two sets of dunes are present in the lower Cape Fear River valley of southeastern North Carolina and that the most recent dune-forming interval was from about 8 ka to 6 ka. He also suggested that the older dunes were greater than 30 ka and were possibly the same age as the Carolina bays (200 ka to 60 ka). Soller's work agrees with that of Daniels and others (1969), who identified at least two different deposits of eolian sands along the Neuse River in North Carolina and suggested that the older dunes were greater than 30 ka and that the younger dunes were less than 11 ka.

DISCUSSION

ARE INLAND DUNES IN THE SOUTHEASTERN UNITED STATES EOLIAN?

Since originally described, most inland dunes in the Southeastern United States have been ascribed an eolian origin (Veatch and Stephenson, 1911; Hurst and others, 1966; Daniels and others, 1969; Pickering and Jones, 1974; Carver and Brook, 1989). The structureless, unstratified nature of the sand is difficult to explain by eolian processes, but the crescent shape, the geographic distribution, grain size, and sorting suggest deposition by wind. The lack of internal structure and the low content of fines suggest that the dunes formed in vegetated terrain directly adjacent to sand source areas—flood plains, low terraces, and (or) Carolina bays—or that the dune sand is so well sorted that bedding cannot be distinguished.

Several publications address dune formation in vegetated terrain, but only a few discuss dune formation in humid to wet climates. Hack (1941) suggested that the nearly symmetrical parabolic dunes in northern New Mexico resulted from the accumulation of great quantities of sand in areas where plants have been aggressive enough to survive being covered. He stressed the importance of "bare space" as source areas for dune sand in vegetated regions and suggested streambeds as a common source. He suggested that bare space was extended by inhibition of vegetative growth in downwind areas as sand was picked up, transported, and redeposited.

Olson (1958b–d), from his work on the shore dunes of Lake Michigan, did not feel as strongly about the role of vegetation-free areas in dune formation. He suggested that vegetation can actually cause dunes to form and postulated that vegetation dissipates the energy of wind burdened with sand, which in turn forces the wind to drop part of its load.

Daniels and others (1969) suggested that the lack of internal structure and the abrupt thinning at their eastern edge indicated that the dunes along the Neuse River in North Carolina were formed by sand blown into standing vegetation. They felt that Cooper's (1958, 1967) precipitation ridge explanation for the encroachment of Oregon's and California's coastal dunes into vegetated terrain could be applied to dunes along the Neuse.

Many of the processes identified in these studies probably were involved in the formation of inland dunes in the Southeastern United States. The unstratified character of dune sand in this region is probably due in part to the interference of vegetation (tree canopies, trunks, and roots, as well as understory trees and shrubs) with airfall layering and grain transport. It is also probable that some layering or bedding has simply not been recognized due to the uniform grain size and monomineralogy of the sand, both of which inhibit recognition of internal layering or structure. Bioturbation also may have contributed to the destruction of any recognizable bedding.

We hypothesize that the dunes formed as the result of wind erosion of great quantities of sand from exposed flood plains, terraces, and Carolina bays and the accumulation of that sand on adjacent vegetated terraces and (or) valley sides. The low content of <63-μm material in the dune sand also suggests that the surrounding upland surfaces on weathered Coastal Plain fluvial and marine sediments were vegetated during periods of dune formation.

The interrelations among valley shape (topography), sand availability, wind strength, and duration of dune-forming conditions determined dune size and dune field size and distribution.

HOW ARE INLAND DUNES IN THE SOUTHEASTERN UNITED STATES DISTRIBUTED?

Although almost all inland dunes in the Southeastern United States occur in an area having average MAP less than 1,250 and MAP:MAE about 1.1:1.0, dunes vary greatly in size and shape depending on local topography, wind direction, and availability of sand. Only small and intermediate dunes (1–8 m high, <1 km long) are present on the wide flood plains and low terraces of regional drainages such as the Altamaha and Savannah Rivers in Georgia, the Great Pee Dee River in South Carolina, and the Cape Fear and Black Rivers in North Carolina. These dunes commonly have hummocky surfaces and steep frontal toes. We hypothesize that the relatively small size is due to (1) a higher content of fines in the source sand, which would reduce its susceptibility to wind erosion; (2) the lesser effect of drought on streams having significantly greater discharge (less flood-plain and channel sand subaerially exposed); and (3) continual modification and (or) attenuation of the dunes by shifting stream channels and floodwaters (fig. 10), in the manner suggested by Mader (1983) in his study of Mesozoic paleodune sand in central Europe. Consistent shifting of fluvial channels and flooding of overbank areas inhibit development of large eolian sand accumulations in flood plains.

Large dunes in the Southeastern United States are associated with rivers like the Ohoopee and Ogeechee in southeastern Georgia that have average discharge values an order of magnitude less than the regional drainages and relatively narrow, steep-walled valleys. These large whaleback dunes form sand ramps up the eastern wall of the stream valleys; locally the ramps extend onto or beyond the interfluves. Because of their valleyside positions, these dunes are not as affected by flooding as are dunes along the larger rivers. As sand is blown onto the valley wall, both dune height (between 10 and 25 m) and length (up to 4 km) increase. The largest dunes occur where two or more southeast- and (or) east-trending stream segments join, such as at the confluence of Bull Creek, the Canoochee River, Lotts Creek, and Mills Creek just east of Claxton, Ga. (fig. 13). In geomorphic positions such as this, the combined factors of a large sand source and a topographic alley for the wind form exceptionally large dunes.

Small dune fields that extend from and (or) have migrated into Carolina bays are more like those formed on flood plains and terraces of the area's regional drainages than the ramp-forming dunes in the narrower Coastal Plain valleys. Dune height is generally less than 3 m. Total width of an individual dune field is generally less than 2 km. Some fields have coalesced to cover valley floors and choke small drainages. Some larger fields extend from the edge of one bay into the bowl of another (see features described on fig. 14). These smaller dunes and broad, low dune fields are characteristic of river valleys in northeastern South Carolina and southeastern North Carolina, such as the Great Pee Dee and the Cape Fear-Black River valleys, respectively. We hypothesize that the low relief of the region, and the limited number of black-water Coastal Plain streams oriented perpendicular or parallel to prevailing wind, has resulted in few to no large ramplike dunes so characteristic of Georgia's Coastal Plain streams.

WHAT ARE THE AGES OF INLAND DUNES IN THE SOUTHEASTERN UNITED STATES?

Geomorphic and stratigraphic positions suggest that dunes in the southeastern Georgia Coastal Plain formed during the late Pleistocene glacial and (or) immediate postglacial period. Carbon-14 analyses indicate that the most recent dune-forming episode began some time after 15 ka and ended some time before 3 ka.

Thom (1967, 1970), Thames (1982), Soller (1988), and Carver and Brook (1989) have written on the spatial and the temporal relations between dunes and Carolina bays in the Southeastern United States. Thames (1982) did not comment on the absolute age of dunes or bays but considered Carolina bays in southeastern Georgia to be younger than the area's dunes. Thom (1967, 1970), from his work in northeastern South Carolina, thought that the relations

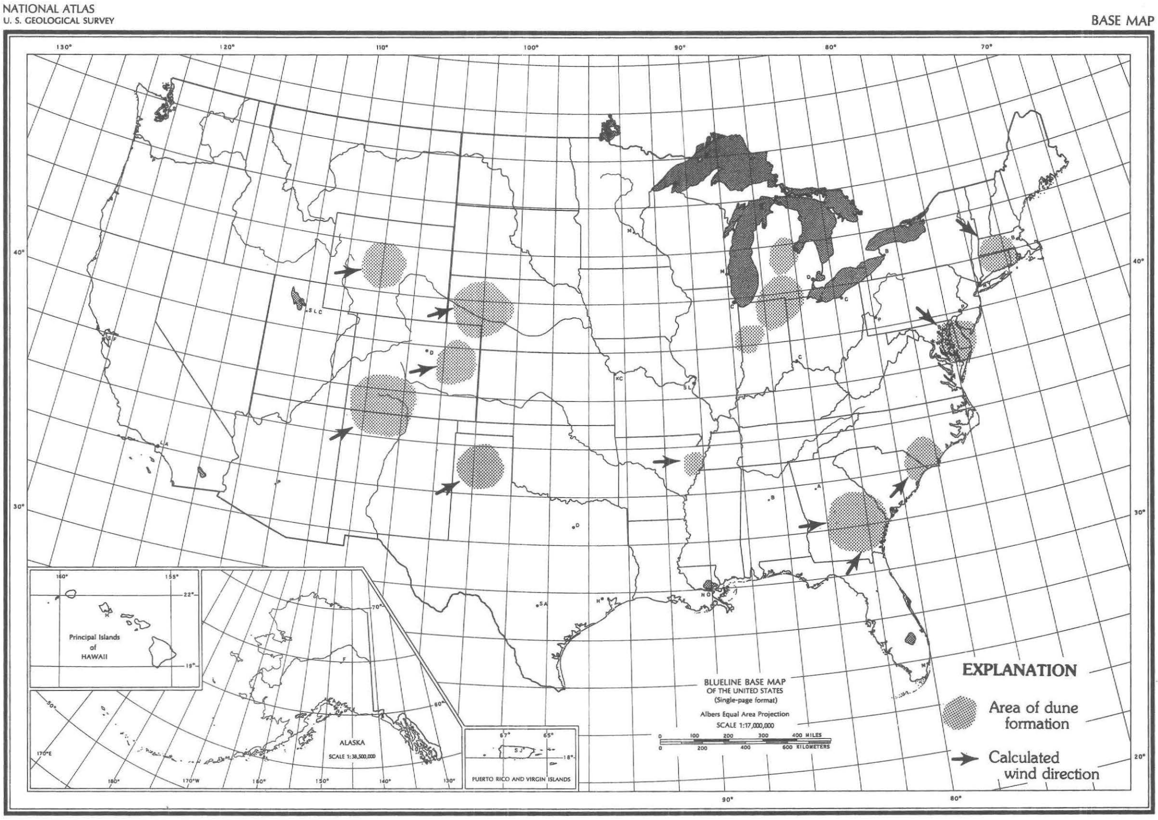


Figure 17. Areas of dune formation in the United States and calculated wind direction during the latest Pleistocene and early Holocene (between about 15 ka and 3 ka). Data from Hack, 1941; Olson 1958a; Schafer and Hartshorn, 1965; Daniels and others, 1969; Thom, 1970; Ahlbrandt, 1973; Saucier, 1978; Denny and Owens, 1979; Ahlbrandt and Fryberger, 1980; Gile, 1981, 1988; McFadden and others, 1983; Schultz, 1983; Wells and others, 1983, 1990; Gaylord, 1984; Keen and Shane, 1985; Price and others, 1988; Soller, 1988; Carver and Brook,1989; Stone and others, 1991; and this study.

between dunes and bays indicated formation of dunes and bays by west-southwest and southwest winds, that locally dunes had modified some of the bays, and conversely that some bays had formed on dunal topography. He considered both dunes and bays to be less than 30 ka. Carver and Brook (1989) discussed paleowind directions in the Atlantic Coastal Plain during the late Pleistocene and reviewed the literature on the origin(s) and age(s) of Carolina bays. They accepted the interpretation of Thom (1967, 1970) that Carolina bays and dunes were coeval and formed by southwest winds around 30 ka.

While studying the Pleistocene fluvial and marine stratigraphy of the Cape Fear River valley, Markewich and Soller (1983) and Soller (1988) suggested that Carolina bays formed between 60 ka and 200 ka, thus supporting Frey's (1951) estimate of 100 ka for Singletary Lake, a large bay in the Cape Fear River valley. Soller (1988) considered it probable that some of the older dunes were formed contemporaneously with Carolina bays, that the younger dunes greatly postdated the bays, and that some dunes were as young as 5 ka.

Data from Georgia and the Carolinas suggest that all dunes are younger than 500 ka and that the most recent dune-forming episodes occurred in the 12,000-year interval between 15 ka and 3 ka.

HOW DO THE AGES COMPARE WITH THE AGES OF INLAND DUNES IN OTHER PARTS OF THE UNITED STATES?

Evidence suggests that, during the late Pleistocene and early Holocene, dunes formed in many different regions of the United States. Areas of the United States having dunes younger than 15 ka are shown in figure 17. A short summary of data from a few of these areas is given in the following paragraphs.

ARIZONA AND NORTHWESTERN NEW MEXICO

Hack (1941) suggested that the youngest dunes in the western Navajo Country of Arizona were middle Holocene in age and formed by west winds. He recognized that older, Pleistocene age dunes also were present and that, in many places, they were overlain by younger dunes or mass gravity deposits. Recently Schultz (1983), McFadden and others (1983), and Wells and others (1983, 1990), on the basis of previous work and their own investigations, suggested a late Pleistocene age for the major dune-building event in the San Juan basin of New Mexico and showed that the younger dunes in northwestern New Mexico date from about 13 ka and are as young as 1.5 ka.

COLORADO

Price and others (1988) analyzed samples from pedons along two southwest-northeast transects in eolian deposits of southwestern Colorado. On the basis of argillic horizon development and a carbon-14 age determination of a musk ox vertebrae in the upper eolian deposit, they suggested a late Pleistocene age (about 15 ka) for these deposits. They implied that most eolian deposition in southwestern Colorado had ended prior to the beginning of the Holocene.

TEXAS AND NEW MEXICO

Gile (1981, 1988) reported on dunes ranging in age from less than 0.1 ka to middle Pleistocene in western Texas and eastern New Mexico (Bailey County Sandhills on the southern High Plains). The dunes were formed by west and southwest winds. He concluded that alluvium deposited by an ancestral Pecos River was the source of the eolian sediments. He interpreted the sandy C horizons, which separate sets of pedogenetic horizons, as evidence of multiple episodes of sedimentation and soil burial. He correlated his oldest dune sands with the Peoria loess and an age between 25 ka and 15 ka; the next oldest with the Monahans Interval, from 13 ka to 11 ka (Haynes, 1975; Oldfield and Schoenwetter, 1975); and the youngest with the arid time between 11.5 ka and 7 ka (Haynes, 1968, 1975).

WYOMING

The Ferris-Lost Soldier dune field of south-central Wyoming lies in what Gaylord (1984, p. 1) described as a "topographically-regulated 'corridor' of high wind." He concluded that (1) eolian activity in the area began between 13.36 ka and 10.94 ka; (2) the most active periods of Holocene dune building were between 7.66 ka and 5.94 ka, and for about 1,500 years sometime after 5.94 ka; (3) dunes began to stabilize after 4.54 ka due to rising local water tables and revegetation; and (4) a short period of dune reactivation occurred about 0.3 ka.

Ahlbrandt (1973) suggested that dune-forming intervals in the Killpecker dune field in south-central Wyoming were between 11.25 ka and 10.65 ka, and 7 ka and 3 ka, and that the dune fields not only continued to be active into the latest Holocene but also have never completely stabilized.

KANSAS AND NEBRASKA

The dunes of northwestern Nebraska have always been controversial in the number of events represented, in postulated source areas, and in time(s) of formation. After considering the work of Ahlbrandt and Fryberger (1980), Ahlbrandt and others (1983), and previous investigators, as well as conducting their own palynological investigations, Wright and others (1985) concluded (1) that the massive dunes of the Nebraska Sandhills are predominantly pre-Holocene, 12 ka to 9 ka, in age and (2) that the younger, smaller dune fields located along the Dismal and Middle Loupe Rivers are probably Holocene in age, 5 ka to 3 ka and 8.5 ka to 7 ka, respectively. Ongoing studies suggest that the Nebraska dune fields as well as others in the High Plains formed in the Holocene and that the youngest dunes may be as young as 1.5 ka to 0.3 ka (D.R. Muhs, U.S. Geological Survey, Denver, Colo., oral commun., 1992).

MIDDLE CONTINENT

Keen and Shane (1985) reported middle Holocene sand dunes in east-central Michigan. Fields of Pleistocene to Holocene dunes along the Indiana shore of Lake Michigan were studied by Olson (1958a–d). Late Pleistocene and (or) Holocene dunes also are present in the White River valley and the Kankakee Plain of western Indiana (*see* Miles and Franzmeier, 1981). Cooper (1938) suggested that dunes of the upper Mississippi Valley were possible late Pleistocene climatic indicators. Saucier (1978) suggested that sand dunes in the Western Lowlands of eastern Arkansas were paleoclimatic indicators that were probably deposited between 22 ka and 18 ka, at least in part during Peoria time, 30 ka to 12 ka. Recent work suggests that sand dunes in the Western Lowlands of the Mississippi River valley may be post-Peoria, nearer 9 ka.

MIDDLE ATLANTIC AND NORTHEASTERN UNITED STATES

Dunes on the Delmarva Peninsula have been included in the Pleistocene Parsonsburg Sand by Denny and Owens (1979) and Denny and others (1979). The dunes are similar in morphology, particle-size distribution, internal structure, and origin to dunes in Georgia and the Carolinas. Denny and others (1979) and Denny and Owens (1979) thought that dunal morphology suggested at least two periods of dune development by northwest winds. Peat beds at or near the base of the upland dunes range in age from about 30 ka to 13 ka. Younger dunes, on the southeastern and eastern sides of some of the larger rivers, were not dated but were considered Holocene (Denny and Owens, 1979). Microfloral assemblages from peat beds in the older dunes suggest that dune-forming events were synchronous with glacial maxima.

Schafer and Hartshorn (1965) called the dunes in glacial Lake Hitchcock the most extensive in New England. The dunes lie on the eastern side of the Connecticut River on lake bottom, delta, and terrace sediments. The position of the dunes adjacent to and on lake sediments suggests that the dunes formed during the most recent early postglacial interval. Stone and others (1991) reported a 14.33±0.43 ka age for wood in eolian sand associated with a paleoperiglacial feature in Lake Hitchcock sediments. This date also suggests an early postglacial time for eolian activity in New England.

DO INLAND DUNES IN THE SOUTHEASTERN UNITED STATES FIT GLOBAL MODELS AND PALEOCLIMATIC DATA?

GLOBAL CLIMATE MODELS

Street and Grove (1979) provided a bibliography (through 1978) of the available literature on late Pleistocene and Holocene paleoclimates. In their summary article, they noted that (1) from 21 ka through the remainder of the Pleistocene, aridity intensified in the tropics of Africa, South America, and the Caribbean and that lake levels were low in Florida and the Yucatan; (2) a decrease in sea-surface temperatures resulted in suppression of monsoons and diminished global moisture transport; and (3) during the glacial period, both the tradewinds and the middle latitude westerlies strengthened and the westerlies were probably displaced equatorward.

Kutzbach and Wright (1985) suggested that, at about 18 ka, during full glaciation, the jet stream was split around the North American ice sheet and that the southern branch of the stream was much stronger than at present over the southern part of the United States. Berger and others (1985) supported the idea that the last deglaciation occurred in pulses and suggested that (1) the initiation of deglaciation occurred some time after 14 ka, (2) there was a pause in deglaciation from about 11 ka to 10 ka, and (3) after this pause, deglaciation continued into the Holocene. Kutzbach and Street-Perrott (1985) suggested a global pattern of aridity in the Northern Hemisphere during the early Holocene. They concluded that the Northern Hemisphere had an enhanced seasonal or monsoonal climate during the early Holocene and that the monsoonal climate was at its extreme at 9 ka and 6 ka, during the postglacial maxima. All these data are in agreement with the postulated time of the most recent dune-forming episodes in the Southeastern United States—beginning sometime after 15 ka and ending between 5 ka and 3 ka.

PALEOCLIMATE DATA

The occurrence of latest Pleistocene to middle Holocene dunes in the Western, Central, Northeastern, and Southeastern United States suggests that, during the transition from glacial to interglacial periods, the climate of the United States included periods of drought characterized by persistent and (or) recurrent strong unidirectional winds. In the Southeastern United States, the effects of drought conditions included a lowering of the regional water table and subsequent reduction in flow or the drying up of many streams and rivers. Paleoclimate data corroborate the occurrence of drier climates in the Southeastern United States during the latest Pleistocene and the early Holocene and suggest that these climate conditions were established during the most recent full-glacial interval. Evidence for periods of aridity in the late Pleistocene and early Holocene in the Southeastern United States is seen in the pollen, faunal, and archeological records.

POLLEN DATA

Whitehead (1965, 1973), Watts (1975, 1983), and Delcourt and Delcourt (1985) reviewed the pollen record for the Southeastern United States for the past 20,000 years. Pollen data from Georgia and adjacent parts of Alabama indicate at least two periods of relatively xeric conditions—from some undetermined time to about 30 ka and between 14 ka and 5 ka. The latter period corresponds to the time given for abrupt surface temperature warming in the Caribbean and increasing aridity in the Northern Hemisphere (Kutzbach and Street-Perrott, 1985).

Published literature on pollen stratigraphy in Georgia and the Carolinas contains few data on Pleistocene climates before 30 ka and only some from around 30 ka. Watts (1973) established the G-4 Pinus-Quercus-Herb zone in 29,630±1,400 yr B.P. bog sediments in Bartow County, northwest Georgia, and suggested that this zone indicates a prairielike herb-rich grassland, locally treeless, with some pine and oak. Markewich and Christopher (1982) reported on the relative frequencies of spores and pollen from late Pleistocene carbonaceous clays (27,740±520 yr B.P.) incorporated in the valley fill of Uphapee Creek, a tributary of the Tallapoosa River in east-central Alabama. They suggested that the relatively high content (27 percent) of herbaceous composites in an oak-pine and minor hickory pollen assemblage indicated a floral assemblage having many more herbaceous plants than was common in the middle or late Holocene.

Palynological data from Goshen Springs in southeastern Alabama also suggest a climate drier than that of the late Pleistocene. Delcourt (1980) showed that forest canopy dominance shifted from southern pines to oaks at about 26 ka and that, from 26 ka to about 8.5 ka, Goshen pond was seasonal and had large annual water-table fluctuations. Delcourt (1980, p. 382) commented on late Pleistocene climate change in this part of the Southeastern United States, "During the Altonian and early Farmdalian Substages of the Wisconsinan, a climatic trend toward increased droughtiness or pronounced seasonality of precipitation is consistent with the paleohydrologic evidence provided by the aquatic pollen types and the plant macrofossils."

At about 8.5 ka, the palynologic and plant macrofossil records indicate a reestablishment of a permanent pond at Goshen Springs, which Delcourt interpreted as indicating a decreasing trend in the severity of summer drought. His data indicate that, at Goshen Springs, southern pines were fully reestablished by 4.7 ka.

Pollen data suggest that, from 8.5 ka to 5 ka, the climate of the extreme south-central Georgia and north-central Florida Coastal Plain was drier than at present and was characterized by dry oak forests and intervening savanna or prairie (Watts, 1969, 1971). The increasing wetness of eastern Alabama during this time period suggests that there was a more rapid transition from drier to wetter conditions in eastern Alabama than in southern Georgia. The present pattern of precipitation (fig. 4), with east-central Alabama wetter than south- and east-central Georgia, probably was established or reestablished during this time period.

FAUNAL DATA

Paleofaunal evidence for latest Pleistocene and Holocene climates that were drier than present is not as direct as the paleofloral data. Late Pleistocene faunal assemblages suggest that species living on the Georgia Coastal Plain during the Wisconsinan glacial maximum immigrated into the Valley and Ridge province of northwest Georgia during the postglacial maximum warming trend (Holman, 1985a,b) in the latest Pleistocene and (or) early Holocene. We suggest that this immigration may have been driven by the lack of water, as well as by increasing temperatures.

Tenuous but corroborating evidence for dry periods in the latest Pleistocene and early Holocene may be the presence of *Gopherus polyphemus* in the Coastal Plain sandhill regions of Georgia and the Carolinas. This tortoise, more common to Texas, probably migrated eastward during the late Pleistocene and (or) early Holocene when climatic conditions were favorable and now exists as an isolated remnant faunal population.

ARCHEOLOGICAL DATA

Although relatively few archeological data are available from dunes in the Southeastern United States, available data from terrace deposits indicate significant climate change, from drier to wetter conditions, during the middle Holocene in Georgia. Brooks and others (1986) suggested that the shifts in fluvial depositional regimes in the lower Savannah River valley, and in the Indian subsistence-settlement patterning in the same region, followed a change from drier to wetter conditions sometime between 5 ka and 3 ka. A similar change in river pattern, from braided to meandering, also has been suggested for older (middle Wisconsinan) terraces along the Little Pee Dee River (Thom, 1967, 1970), thus implying that many such changes in climate occurred during the late Pleistocene in the Southeastern United States.

SUMMARY

The central and eastern parts of the Coastal Plain of Georgia, South Carolina, and southeastern North Carolina are characterized by extensive fields of unstratified quartz sand dunes adjacent on the east and northeast to streams, rivers, and Carolina bays. The dunes appear to have accumulated by sand blown from flood plains into adjacent vegetated terrain. There is little to no evidence of dune migration. Filled-in, U-shaped (crescent) dunes predominate. Locally, 2- to 4-km-wide sand sheets lie leeward of large dunes. The dunes occur in that part of the region having the lowest MAP (<1,250 mm) and lowest MAP:MAE (about 1.1:1.0). The largest and highest dunes and the longest dune fields are associated with narrow Coastal Plain river valleys. Smaller, lower dunes, many of which form areally extensive dune fields, are associated with the broad valleys of major regional drainages and with shallow depressions known as Carolina bays.

Dune formation occurred when the region's paleoclimate was characterized by (1) low local and regional water tables, which resulted in low stream discharge values for regional drainages and extremely low- to no-discharge low-order tributaries; (2) low MAP and MAP-to-MAE ratios (probable MAP, <700 mm, and MAP:MAE, 0.5:1.0) and a more monsoonal climate; and (3) strong, persistent or recurring west and southwest winds. Under the present climate of the Southeastern United States, inland dunes are neither reactivating nor forming. Therefore, the present climate serves as a datum for conditions not favorable to dune formation.

The inland dunes formed where several climatic, topographic, and geochemical conditions were met. If any one of the conditions was not met, then dunes did not form. Conditions included the following:

(1) A specific range in orientation of stream segments and (or) Carolina bays: (a) primarily stream segments or

Carolina bays oriented about S. 20° E. in Georgia and about S. 40° E. in southeastern North Carolina and (b) some short stream segments oriented east-west, north-south, and southwest-northeast.

(2) An adequate sand source, either sandy channel and flood-plain deposits, Carolina bay rims, or the bays themselves. The largest dunes formed along low-pH, organic-rich, black-water drainages that have average discharge values of less than 28 m^3/s and relatively narrow stream valleys, such as the Ohoopee and Canoochee River valleys in Georgia.

(3) Strong, recurrent or persistent winds—from the west in the central Georgia Coastal Plain, from the west and southwest in the southeastern Georgia Coastal Plain, and from the southwest in the Coastal Plain of the Carolinas.

(4) MAP of less than 1,250 mm (probably <700 mm, or >700 mm but a strongly monsoonal climate).

(5) MAE of about 1,100 mm.

In Coastal Plain stream valleys, dunes are most common across from or just downstream from a confluence of two or more streams. Along regional drainages, the first appearance of dunes is just across from or downstream from the confluence of a regional drainage with a major Coastal Plain tributary, such as the first occurrence of dunes along the Altamaha River immediately downstream from its confluence with the Ohoopee River.

Geomorphic relations and weathering and pedologic data indicate that there are at least two sets of dunes in the study area, each of which represents at least two dune-forming episodes. In Georgia, the two sets can best be seen along the Satilla and the Canoochee Rivers. Two sets of dunes also are present along the Great Pee Dee River in South Carolina and along the Cape Fear and Neuse Rivers in North Carolina.

Field evidence from recent work in southeastern Georgia indicates that (1) the oldest deposits of quartz sand having recognizable dunal morphology are younger than the Pamlico sequence of marine sediments (younger than 500 ka and possibly younger than 250 ka); (2) numerous deposits are less than 50 ka; (3) dunes on the flood plains and low terraces are between 15 ka and 5 ka; and (4) the younger the dune, the greater the relief on the dune surface.

Geomorphic, floral, faunal, and archeological evidence suggests that, by some time between 5 ka and 3 ka, the climate of the Southeastern United States had become less monsoonal and (or) MAP had increased and that dune formation had ceased.

Although paleowind directions, as determined from dune axes, compare favorably with modern wind directions, sand rose plots generated from historical wind data suggest that modern winds are incapable of significant dune formation. To verify this conclusion, more data are needed from stream valleys where dunes are located.

The coincidence in time of formation (between 15 ka and 5 ka) of latest Pleistocene and early Holocene dunes in parts of the Southeastern, Western, Central, and Northeastern United States suggests that drought and high winds were common throughout the country during this 10,000- to 12,000-year interval.

CONCLUSIONS

As Saucier stated in his paper on the sand dunes of the Western Lowlands of the Mississippi River alluvial valley (1978, p. 23):

> The real significance of the eolian features is thought to be their witness to the types of climatic/ecologic changes that occurred in the region and which have gone largely unrecognized by physical and social scientists. More attention must be given to evaluating the significance of even seemingly minor ecological changes on both man and the shaping of this physical environment.

The legacy of dune-forming episodes in the Southeastern United States is tens of thousands of square kilometers of land (in an area 100 km wide and 400 km long) mantled by excessively drained, droughty, low-nutrient sand. These areas have marginal agronomic economies and are more susceptible to climatic deterioration than is the region as a whole. The presence of the dunes in such a large part or subregion of the Southeastern United States suggests that the degree of climate change associated with glaciation and (or) with glacial-interglacial transitions in the continental United States may have been greater than previously recognized. Even in the Southeastern United States, climatic conditions were probably not acceptable for sustainable agriculture. An evaluation of the effects that such a climate would have on the area today seems like a logical avenue for future investigation.

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*U.S. G.P.O.:1994-301-077:80092

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