Geologic Evolution of Trail Ridge Eolian Heavy-Mineral Sand and Underlying Peat, Northern Florida

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Geologic Evolution of Trail Ridge Eolian Heavy-Mineral Sand and Underlying Peat, Northern Florida

By ERIC R. FORCE *and* FREDRICK J. RICH

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The peat underlying ilmenite ore sand is a synchronous facies and records the approach of the eolian dune

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GEOLOGIC EVOLUTION OF TRAIL RIDGE EOLIAN HEAVY-MINERAL SAND AND UNDERLYING PEAT, NORTHERN FLORIDA

By Eric R. FORCE and Fredrick J. RICH

ABSTRACT

The southern portion of Trail Ridge in Clay County, Fla., has been an important domestic source of altered ilmenite, zircon, and other minerals since 1949. The ridge as a physiographic feature extends in a north-south direction over 160 km and is 1 to 2 km wide. The ore is a fine- to medium-grained sand body that extends down from the crest of the ridge about 20 m. Average heavy-mineral content is about 4 percent. Over half of the ilmenite and zircon is contained in thin, dark laminae dipping 26° to 41° southwest; these laminae extend deep within the ore and outline the slip faces of a great eolian dune complex. The subordinate dark laminae differ in heavy mineralogy and grain size from the encasing light-colored sand. The dark laminae have a modal grain size of 0.2 mm and average about 6 percent heavy minerals, among which altered ilmenite, zircon, and rutile predominate. The light-colored laminae have a coarser modal grain size of 0.3 mm and average only 1 percent heavy minerals, among which the lighter heavy minerals staurolite, sillimanite, and tourmaline form half. Grain size variables and grain surfaces are appropriate for eolian sand. Overprinted on these original features of the dune are a surficial weathering zone over 3 m thick, where tan leucoxene takes the place of black altered ilmenite, and several underlying humate-cemented zones that probably represent water-table stillstands.

The immediately underlying unit is a lignitic peaty layer 1.5 m thick, here referred to as peat. The organic fraction is derived entirely from freshwater plants. In-place tree stumps have been noted, but the predominant component of the peat is fragments of wood and other transported plant debris. The peat and its constituents indicate deposition in a swamp environment, and local horizons enriched with charcoal and fungal remains indicate periodic subaerial exposure. Vegetation varied from open shrub swamp to cypress forest.

The age of the peat has been determined palynologically as post-Miocene. Its carbon-14 age is greater than 4.5×10^4 years; that is, pre-latest Pleistocene.

The upper portion of the peat layer contains admixtures of sand. This sand is present as isolated grains embedded in laminated organic matrix and is dominantly well rounded and frosted. As a grain population, the sand in the peat matches the overlying Trail Ridge ore sand in mineralogy and grain morphology but is slightly finer in grain size. This sand we regard as an important clue to the history of the area. The sand was apparently deposited from aerial suspension, and its characteristics were acquired in the adjacent high-energy eolian environment. Upward increase of sand in peat records the approach of the dune that eventually prograded the swamp. The peat and the overlying sand are essentially the same age. Fine sand found in peat represents the sand fraction remaining suspended in flow separation at the top of the slip face of the dune. Ore represents the traction-load fraction. The Trail Ridge dune itself is probably the drainage dam that impounded the swamp it later overrode.

The sand embedded in peat is also an important clue to the weathering history of Trail Ridge heavy minerals, as entombment in peat probably arrested oxidation. The presence of leucoxene, and other features of the mineral assemblage, shows that the minerals were already weathered at deposition. This evidence is in accord with grain-surface features and grain-size–density relations. Thus, mineral alteration at Trail Ridge occurred in two stages, one before and one after deposition.

Trail Ridge apparently represents a coast-parallel transgressive dune complex, analogous to younger dunes elsewhere that have become completely decoupled from parental shorelines. The Trail Ridge body was probably composite, made up of individual parabolic dunes, each migrating southwestward. The base of the Trail Ridge body was probably originally higher at the southern end than at the northern end.

INTRODUCTION

Trail Ridge is a linear north-south-trending ridge about 1 to 2 km wide, which extends at least 160 km from northeastern Florida to southeastern Georgia. It is about 65 km inland from the coast, and its crest increases in elevation from about 46 m (150 ft) in the north to as much as 77 m (252 ft) in the south. Because the ridge typically stands tens of meters above adjacent areas and impounds the Okefenokee Swamp, it is one of the most conspicuous linear landforms in the coastal plain of the Southeastern States (fig. 1). A profile is shown in figure 2.

The ridge is composed of a sorted fine-grained to medium-grained quartzose sand body up to 20 m thick. In a 29-km portion of its length in Florida, the sand throughout its thickness averages about 4 percent heavy minerals,[1] predominantly altered ilmenite, and lesser zircon, rutile, and aluminosilicates. This sand is, or was

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[1] All listed mineral percentages are by weight, unless otherwise specified.

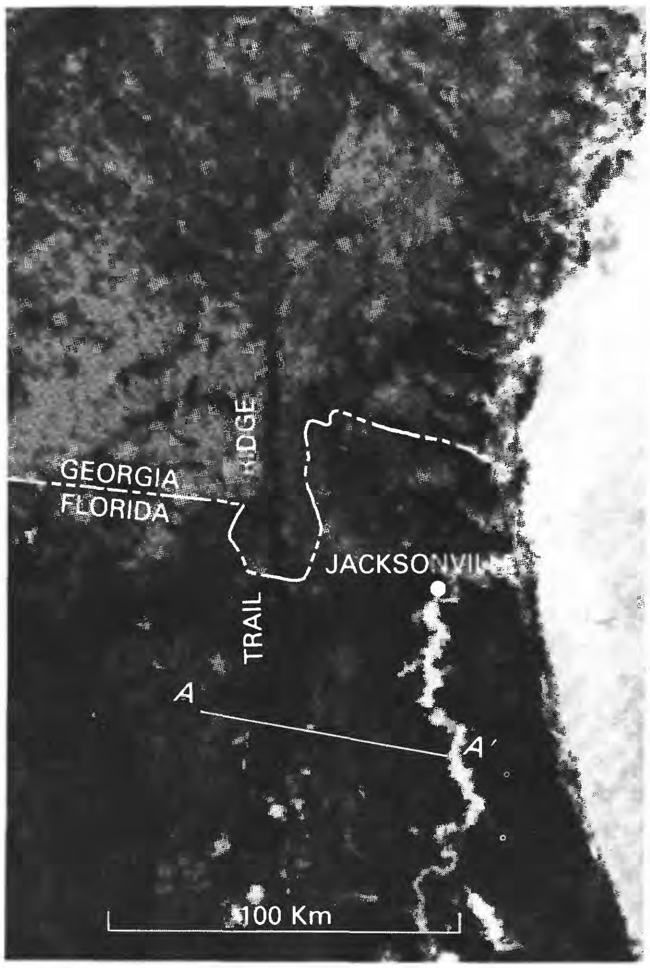

FIGURE 1.—Location of Trail Ridge shown on a satellite thermal image.

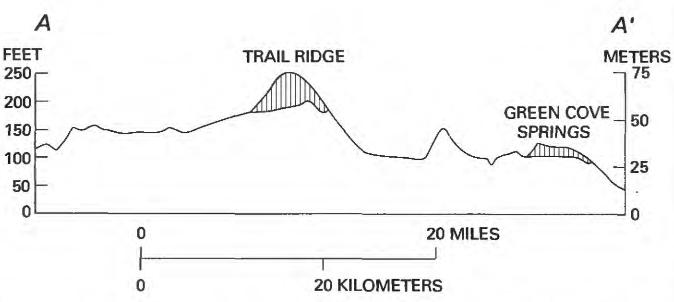

FIGURE 2.—Approximate cross-sectional profile of Trail Ridge, with vertical exaggeration of 200. Shaded bodies are heavy-mineral sands. Line of section *A–A′* is shown in figure 1.

before mining, probably the most valuable single resource of titanium minerals in the United States.

Since 1949, E.I. Du Pont de Nemours and Company has mined this body in Clay County, Fla. Exploration holes and cores in this area have shown that the central to western portions of the south end of the Trail Ridge sand body rest on about 1.5 m of lignitic peat that typically contains large wood fragments. In this paper we examine the relation between the lignitic peat and the overlying sand body (henceforth referred to as ilmenite ore sand) to clarify their original paleogeographic relation and their origin.

PREVIOUS WORK

The earliest geologic descriptions of Trail Ridge were entirely geomorphic. Cooke (1925, 1939) envisioned the ridge as a large Pleistocene marine sand spit that was attached to a mainland near Jesup, Ga. (Cooke, 1925, plate Xb). Cooke believed that the sand body possibly was tilted northward after deposition and that the sand was partly eolian in origin. MacNeil (1950) extended this view to include the Okefenokee Swamp as a former lagoon behind a Trail Ridge marine shoreline and bar.

By the mid 1940's, Florida was the site of several small heavy-mineral mining operations. Discovery of economic heavy minerals at Trail Ridge coincided with the first descriptions of its sands. Spencer (1948) reported on a U.S. Bureau of Mines drilling program on Trail Ridge that encountered valuable deposits of altered ilmenite, zircon, and rutile in sand containing 3 to 10 percent heavy minerals to depths of over 10 m. A heavy-mineral assemblage of altered ilmenite, zircon, rutile, staurolite, tourmaline, sillimanite, kyanite, corundum, monazite, and spinel was described, as was the nature of ilmenite alteration. Credit for the discovery is shared by Spencer's team and the Du Pont company, under J.L. Gillson. Thoenen and Warne (1949) extended the drilling investigations along and adjacent to Trail Ridge by using the newly developed jet drill.

The Trail Ridge mine was opened by Du Pont near the southern end of the ridge in 1949. At first the plant was operated by Humphrey Gold Corporation. The operation was described in several mining journals in the early 1950's. The most thorough such description, by Carpenter and others (1953), was the first to describe the humate-cemented "hardpan" in the ilmenite ore sand and the woody peat layer underlying it. They found wood fragments, up to 5 cm in diameter, and pinecones in this peat layer. They reported the thickness of the peat to be about 1.5 m and that of the overlying ilmenite ore sand to be up to 20 m. Average heavy-mineral grade was listed as 4 percent.

Recognition by Creitz and McVay (1948) that Trail Ridge ilmenite is altered to an iron-deficient, less-dense compound containing microcrystalline rutile, and by Cannon (1950) that the heaviest ilmenite alteration at Trail Ridge occurs above the present water table, spawned many worldwide comparative studies from 1954

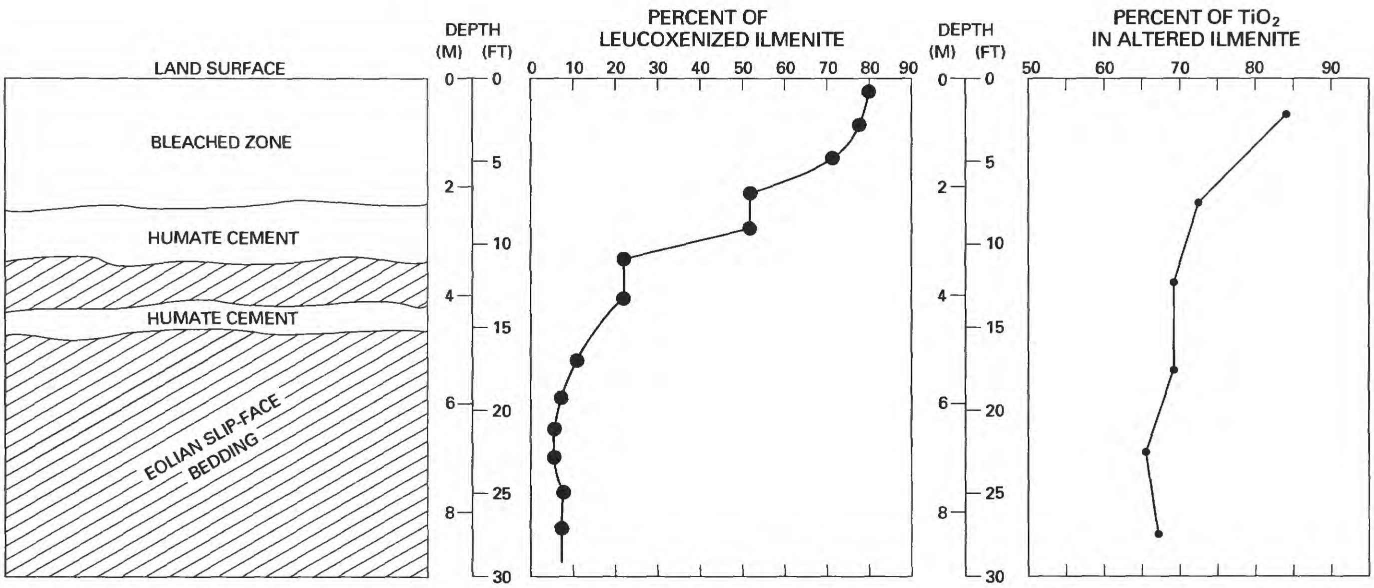

FIGURE 3.—Leucoxene zonation in the Trail Ridge ore body. Percent leucoxenized ilmenite is calculated as a moving average from E.C. Pirkle and Yoho (1970, cores TR 1 and 2); TiO_2 in altered ilmenite is from Temple (1966).

to 1966 of ilmenite alteration in sand matrix. Of these studies, the one by Temple (1966) is most concerned with Trail Ridge per se. Garnar (1972) showed the chemical alteration path for Trail Ridge ilmenite.

The papers by E.C. Pirkle and Yoho (1970) and E.C. Pirkle and others (1970) constitute the first thorough descriptions of the deposit and emphasize the vertical sequence shown in two cores. They present the first records of (1) the remarkably consistent grain size of the deposit, the median value being about 0.3 mm, (2) sedimentary structures and other original depositional features in the ore sand, and (3) configuration of the base of the ore body and the relation of ore sand to peats and other underlying lithologies. The "Trail Ridge Sequence" of these authors consists of the ore sand and underlying peat. Figure 3 shows their data on leucoxene zonation within the ore body. They hypothesized that the ore sand was deposited in a complex of beach ridges and associated eolian dunes.

Subsequent geologic publications on Trail Ridge have continued to be almost entirely by the Pirkle family and their colleagues. E.C. Pirkle and others (1971) described an additional core through Trail Ridge, adjacent to the Florida-Georgia line. F.L. Pirkle (1975) compared grain sizes, heavy-mineral suites, and grain shapes among Trail Ridge sands and proposed possible source regions. E.C. Pirkle and others (1977) described the portion of the Trail Ridge deposit northwest of Highway 301 in Florida. F.L. Pirkle and Czel (1983) reported marine fossils of probable Pleistocene age at elevations of 39 to 49 m (130 to 160 feet) in sands just west of and stratigraphically above a Georgia segment of the ridge. W.A. Pirkle and E.C. Pirkle (1984) and F.L. Pirkle (1984) summarized the evidence for a beach-ridge origin of Trail Ridge, the latter paper concluding that some grain-size characteristics of the deposit are consistent only with an eolian origin.

The most recent published work is by the authors. Rich (1985) described the palynology of the peat bed, and Force and Garnar (1985) described eolian crossbedding of the ilmenite ore sand.

NATURE OF THE TRAIL RIDGE ILMENITE ORE SAND

AREAL DISTRIBUTION AND GEOLOGIC RELATIONS

The nature of the sand composing Trail Ridge is well documented only in the portion having high heavy-mineral contents, which is at the southern end of the body, in Clay and Bradford Counties, Fla. Even there the areal distribution and geologic relations of the sand body are not adequately reported in the literature. Most of our knowledge comes from descriptions of the ilmenite ore sand in profile, in substantial part from four cored drill holes. The mining operations only rarely expose the main part of the ore body. Unpublished company reports, to which we have limited access, constitute the largest body of information that can be used to define the geometry of this sand body.

At the southern end of the ridge near Starke, Fla., the central and perhaps western parts of the sand body are underlain by lignitic peat. The nature of the contact is a

FIGURE 4.—Humate pseudobedding in Trail Ridge sand, photographed in wall of dredge pond, in interval 1.6 to 2.6 m below land surface.

major focus of this paper. The contact surface apparently dips about 3 m/km (15 feet per mile) to the west-southwest (E.C. Pirkle and Yoho, 1970, fig. 3). Underlying the peat are the "post-Hawthorn clastics" of E.C. Pirkle and others (1970), consisting in part of marine clay. North of this area, the sand body is underlain by fine-grained sands and (or) clays that locally contain wood (root?) fragments and show mineralogical indications of subaerial weathering (E.C. Pirkle and others, 1977).

The ilmenite ore sand extends from this subhorizontal base to the ground surface. Thus the ore is thickest where the elevation of the ridge is greatest (fig. 2). Maximum thickness is about 20 m.

SEQUENCE AND STRUCTURE

The ore is more or less homogeneous except for a rootlet-mottled leached zone extending down 2 to 3 m from the ground surface and grading downward into a variably indurated humate-cemented zone. Humate induration increases irregularly downward to a hardpan that can make a hammer ring. Several humate-indurated horizons occur in some localities, to as much as 6.5 m below the land surface, forming pseudobedding (figs. 4, 5) overprinted on weathered sand. This humate cement must represent precipitation at the present and former water tables. Below 6.5 m, humate cementation is weak.

The surficial leached zone and the upper part of the humate-cemented zone coincide approximately with the interval in which leucoxene is enriched at the expense of less-altered ilmenite (fig. 3).

Force and Garnar (1985) reported that the weakly cemented ilmenite ore sand underlying the humate-cemented zone shows high-angle eolian crossbedding outlined by heavy-mineral laminae dipping southwest at 26° to 41° (fig. 6). This underlying zone was exposed during a 1984 lowering of the dredge pond level at the Trail Ridge mine (figs. 5,7). A 1968 lowering had also exposed such crossbeds (E.C. Pirkle and Yoho, 1970, fig. 6; Force and Garnar, 1985, fig. 2), and a core shows the crossbeds from a deeper interval (E.C. Pirkle and others, 1970, p. 39, PTR1). These three localities represent a relatively small area (fig. 7), so it is not yet possible to define the areal extent of eolian deposits. All three localities are in the area where the sand body is underlain by peat.

FIGURE 5.—Trail Ridge ilmenite ore sand exposed in 1984. The basal interval (about 0.9 m thick) is eolian sand with southwest-dipping crossbeds, overprinted by thin humate-cemented zones. Overlying lithologies are weakly cemented sand with crossbedding still visible (0.6 m thick), massive resistant humate-cemented sand (1.2 m thick), and at the top a rootlet-mottled bleached zone (the remainder). Location is shown on map in figure 7.

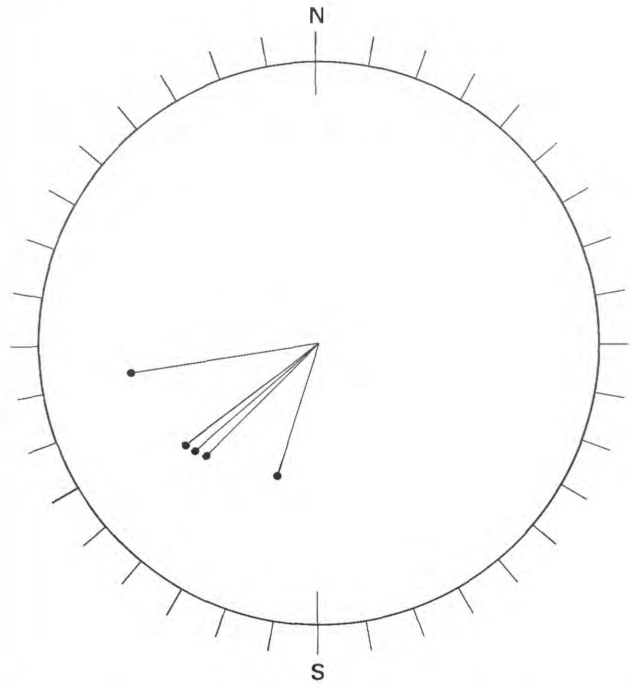

FIGURE 6.—Stereographic projection of azimuths and magnitude of crossbed dip in Trail Ridge ilmenite ore sand.

SAND MORPHOLOGY AND GRAIN SIZE

The ilmenite ore sand is remarkably homogeneous in the four profiles that have been described from cores (E.C. Pirkle and Yoho, 1970; E.C. Pirkle and others, 1970, 1977). This homogeneity is understandable in the context of an eolian origin and deposition on steep slip faces. Median grain size of the sand ranges only from 0.24 to 0.38 mm, and the distribution of median grain size values within the sand body appears random.

Skewness values for grain-size distribution of the sands have never been published. Our calculations (based on samples of E.C. Pirkle and Yoho, 1970; E.C. Pirkle and others 1970,1977) show the sands that are low in postdepositional clay give positive values, consistent with Friedman's (1961) conclusions for eolian sand. These positive values persist to the base of the ilmenite ore sand.

Grain sorting by size is good. Sorting coefficients listed by E.C. Pirkle and Yoho (1970) for the ilmenite ore sand in the two southern drill holes range only from 1.16 to 1.32, again with irregular vertical distribution.[2] There is no apparent relation to median grain size. These sorting coefficients indicate the sands to be well sorted, in the terminology of Trask (1932).

The sands are well rounded also, though this description has never been rigorously quantified. However, F.L. Pirkle (1975) presents average axial ratios of intermediate and maximum axes of zircon and aluminosilicates from one size fraction of sands from three of the drill holes. This measure of sphericity ranges from 0.64 to 0.68.

Quartz sand grains from the Trail Ridge ilmenite ore sand are somewhat frosted, and grains of altered ilmenite show a polish. Figure 8 shows scanning electron microscope photographs of quartz and ilmenite, collected in 1984 from a crossbedded sand exposed below the lowest humate hardpan layer. The surfaces are analogous to those described elsewhere for eolian sands (for example, Krinsley and Margolis, 1971).

[2] Our calculations from E.C.Pirkle and Yoho (1970) data give a range of 1.23 to 1.35. Apparently their values are for sand fractions, free of postdepositional matrix.

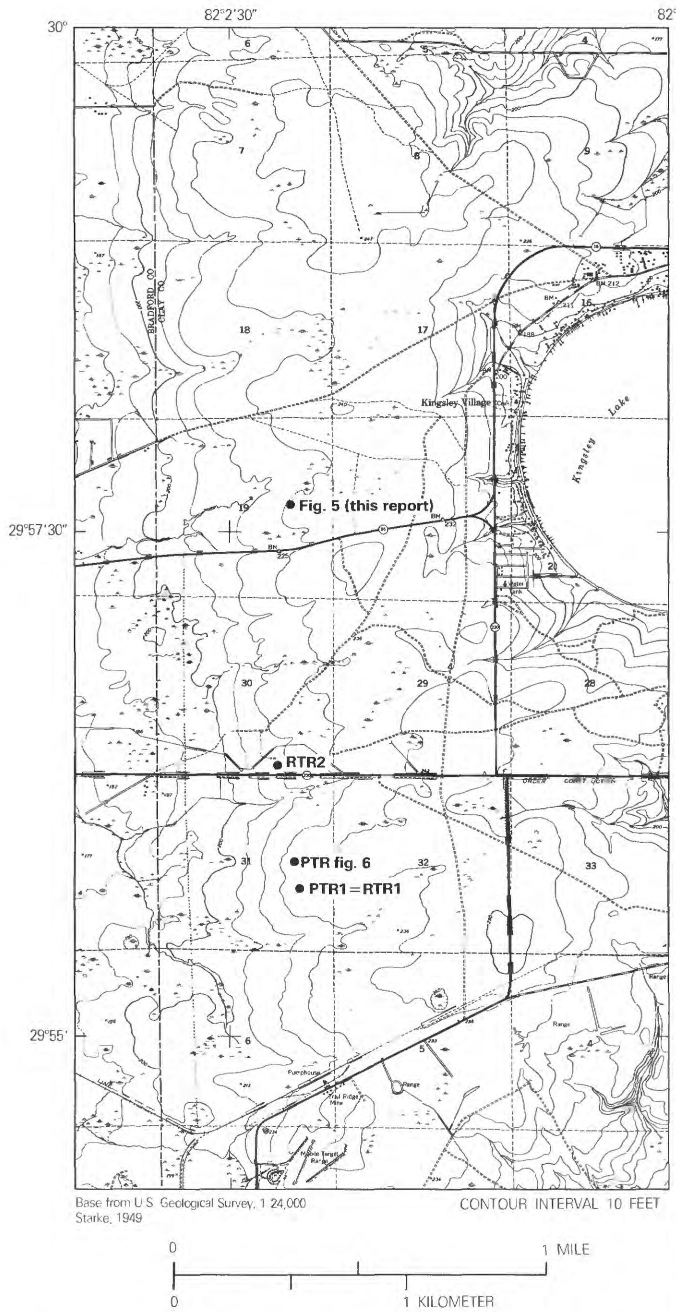

FIGURE 7.—Part of the Starke quadrangle map (1949 edition) illustrating Trail Ridge localities discussed in the text. PTR localities refer to E.C. Pirkle and Yoho (1970); RTR localities refer to Rich (1985).

HEAVY MINERALS

The heavy-mineral content of the ilmenite ore sand varies widely even in the interval samples analyzed by E.C. Pirkle and Yoho (1970) and E.C. Pirkle and others (1970, 1977). The reported heavy-mineral content ranges from less than 1 percent to 16.29 percent (in tetrabromoethane). Variation is high even within a single core. Among the drill holes, average heavy-mineral content of the body varies from 6 percent toward the south to 3 percent to the north.

Average percentages of the altered ilmenite and leucoxene in the heavy-mineral assemblage have been published by E.C. Pirkle and Yoho (1970) and E.C. Pirkle and others (1970, 1977). These minerals together range from 47 to 64 percent in the northern part of the body and from 16 to 67 percent toward the south. Values below about 50 percent are mostly restricted to the uppermost parts of the ilmenite ore sand; that is, the same zone in which leucoxene has formed at the expense of less-altered ilmenite.[3]

The remainder of the heavy (ρ>2.85) suite at Trail Ridge consists on the average of about 15 percent zircon, 2 to 3 percent rutile, 15 percent staurolite, 3 percent kyanite, 5 to 6 percent sillimanite, 5 percent tourmaline, and minor amounts of spinel, corundum, and monazite (from Spencer, 1948). The grain sizes of various heavy-mineral species from commercial concentrates are given by Garnar (1980). The median size for altered ilmenite is about 0.15 mm and for zircon about 0.10 mm. Staurolite is coarser than either (Garnar, 1980, fig. 8).

HEAVY-MINERAL VARIATION WITH SEDIMENTARY STRUCTURE

Force and Garnar (1985) found that high-angle eolian crossbeds are outlined by laminae up to 1 cm in thickness that are enriched in heavy minerals (and preferentially cemented by iron-organic compounds; see fig. 9). Intervening light-colored sands are coarser (about 0.3 mm) than the dark layers (about 0.2 mm). The light-colored sands in one layer contained 1.0 percent heavy minerals, of which only 36 percent was titanium minerals and 15 percent was zircon. This light-colored layer has high proportions of the lighter heavy minerals staurolite (24 percent), tourmaline (13 percent), and aluminosilicates (13 percent). As can be seen in figure 9, these are present as relatively coarse grains.

An adjacent layer of dark-colored sand contained 6.3 percent heavy minerals. The light mineral quartz, as well as the heavy minerals, is finer in these layers, although some coarser quartz is present (fig. 9). The heavy-mineral assemblage in the dark layer is dominated by titanium minerals (54 percent) and zircon (28 percent); staurolite, tourmaline, and aluminosilicates are each less than 10 percent of the heavy-mineral assemblage.

[3] The nature of altered ilmenite at Trail Ridge needs some explanation here. Below the surficial leucoxene zone, altered ilmenite consists of a microcrystalline aggregate of pseudorutile and other less-abundant phases (Temple, 1966) with little ilmenite detectable to X-ray diffraction. The TiO_2 contents of these aggregates average about 65 percent. Magnetic and density properties and color are still enough like ilmenite that the name ilmenite has customarily been retained.

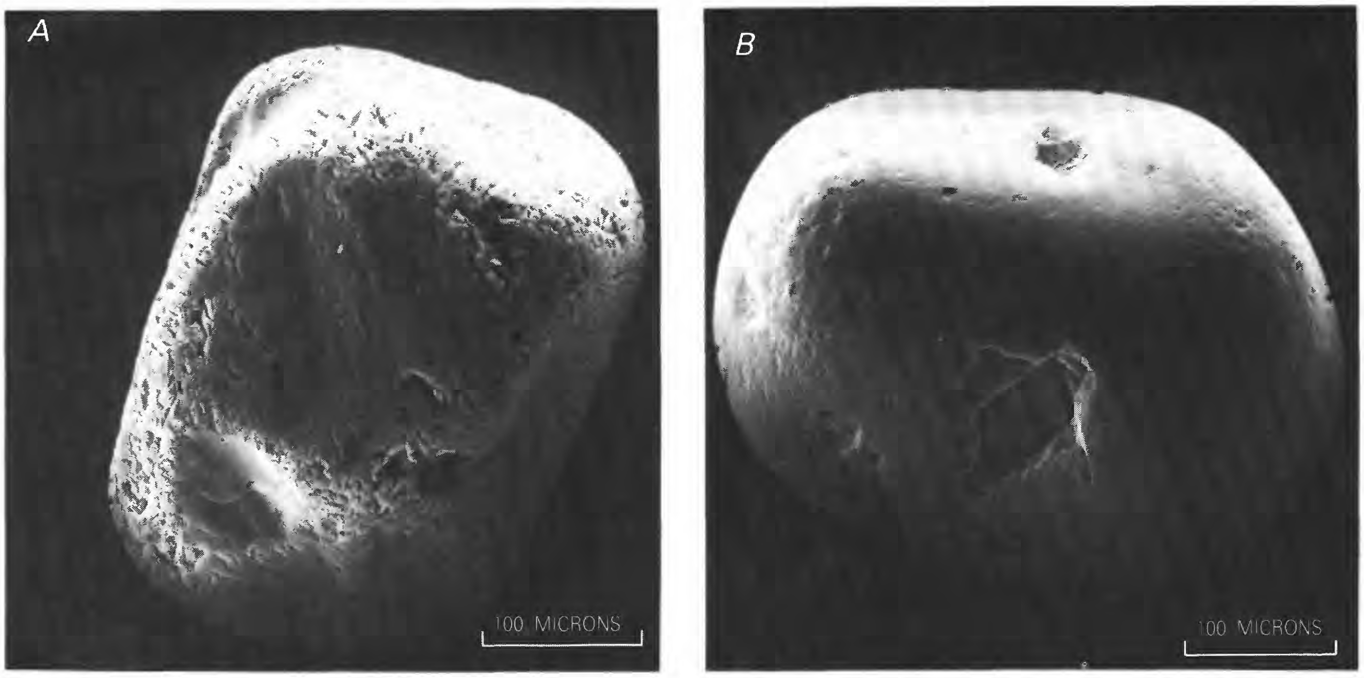

FIGURE 8.—Scanning electron microscope photographs of grains from the Trail Ridge ore sand. *A*, Quartz. *B*, Ilmenite. The structure of this grain suggests a concentric weathering zonation developed prior to deposition.

For this study, the grain-size distributions of mineral fractions in adjacent light-colored and dark-colored laminae were determined for us by Jeanette (Hilbish) Thomas. The sampled laminae are shown in figure 10, and the results in figure 11. The light-colored lamina contained 0.6 percent heavy ($\rho>2.85$) minerals, whereas the dark-colored one contained 12.3 percent. The modal grain sizes of each are similar to those analyzed by Force and Garnar (1985). In the dark-colored layer the modal grain size of both light-mineral and heavy-mineral fractions are 0.5 to 0.75 ϕ finer than in the adjacent light-colored layer. In each layer, the heavy minerals are 0.5 to 0.75 ϕ finer than the light minerals. The dark lamina contains a heavy-mineral assemblage having a much higher percentage of the densest heavy minerals, ilmenite and zircon (78 percent); the light-colored layer contains an assemblage dominated by sillimanite, staurolite, and tourmaline (55 percent). In the dark-colored bands, the size distribution of individual heavy-mineral species is a sensitive function of mineral density, with the median size of sillimanite (ρ =3.25) almost 1 ϕ coarser than that of zircon (ρ=4.6). Figure 11 suggests that ilmenite (ρ=4.7 if fresh) behaved during deposition like a mineral having specific gravity of 4.0 to 4.6 and hence must have already lost density by leaching. Leucoxene apparently had its present specific gravity of about 4.0 at deposition.

Our calculations, assuming that these layers are typical and that dark layers constitute 10 percent of the deposit, indicate that 50 to 75 percent of the titanium minerals of the deposit, and 55 to 90 percent of its zircon, are contained in these thin, dark laminae. The dark layers contain only 10 percent of the tourmaline of the deposit, however, and comparably low percentages of other minerals of intermediate density.

ORIGIN

The Trail Ridge ilmenite ore sand in the area where it is best known is clearly eolian. Steep slip faces dip southwest; dune migration must therefore have been in this direction.

The separation of grains by size into laminae richer and poorer in heavy minerals suggests that the grains are entrainment equivalents (in the sense of Slingerland, 1977). However, this equivalence probably was not established on the slip face, where the laminae formed, but on the windward side of the dune, where sorting power is great. Heavy-mineral-enriched material may have been supplied from the windward side in daily pulses (as in Hunter and Richmond, 1986).

NATURE OF TRAIL RIDGE LIGNITIC PEAT

GENERAL DESCRIPTION

The lower stratigraphic unit of the Trail Ridge sequence is referred to as peaty or sapropelic sediment

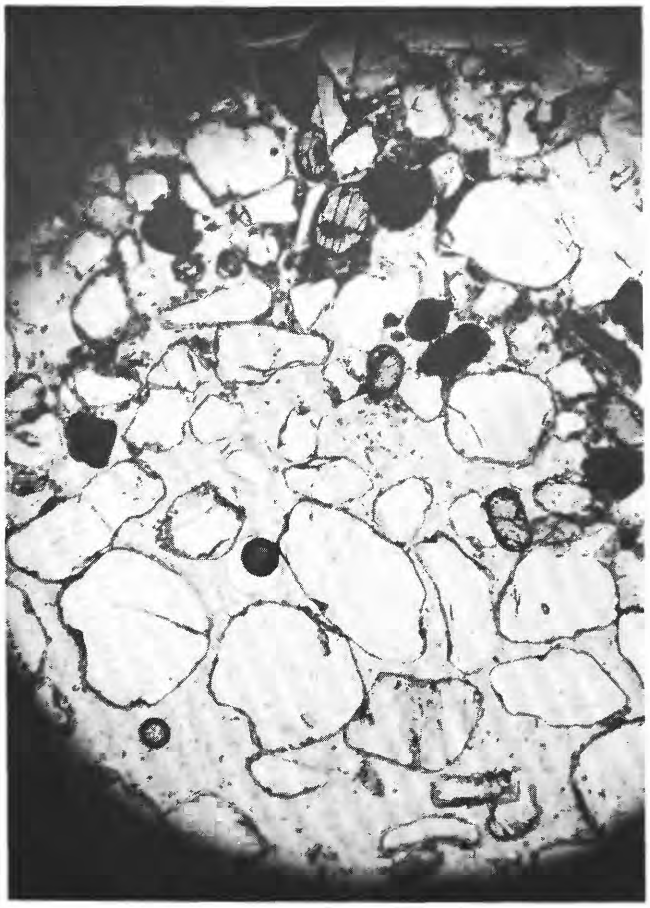

FIGURE 9.—Photomicrograph of thin section of Trail Ridge ilmenite ore sand, from impregnated box core taken toward base of the sequence shown in figure 5. Orientation is right-side-up. Field of view is 6 mm; plane light. Note dark iron-organic cement in heavy-mineral lamina.

FIGURE 10.—Laminae alternately rich and poor in heavy minerals, below humate-cemented material (at top of photograph) at locality of figure 5. (See fig. 7 for location.) Sample of heavy-mineral-rich laminae analyzed for figure 11 is shown by arrow. The heavy-mineral-poor laminae of figure 11 immediately overlie it. Field of view is 0.8 m.

by E.C. Pirkle and Yoho (1970) and is described as containing over 92 percent woody substances in a mat 1.5 m thick. We find that Trail Ridge peat when dried is medium brown in color and has recognizable woody fragments in an amorphous organic matrix, which was deformed by compaction into a fissile to blocky-fracturing mat. A laminated appearance is imparted by flattened and reoriented woody fragments. The considerable variation in peat structure includes unconsolidated peaty sand and solid plugs of wood.

The peat layer marks the lower limit of the ilmenite ore sand, and the buried stumps and branches in it are a mining nuisance. E.C. Pirkle and others (1977) note in passing that some of these stumps are in growth position. Pine cones were noted by Carpenter and others (1953).

Our samples of this organic layer, which we shall refer to as Trail Ridge peat, come from two cores of sediment. They were acquired through a joint drilling project managed by E.I. Du Pont de Nemours and Company and the Florida Bureau of Geology. The cores are referred to as RTR1 and RTR2 and come from the area of the Trail Ridge ore body in Clay County, Fla. (fig. 7).

PETROGRAPHY

Rich and others (1978) showed that Trail Ridge peat is actually intermediate between peat and lignite in character. The light color of palynomorphs, pronounced solubility of the sediment in alkali, and certain ultraviolet-emission spectral characteristics support its designation as a peat. On the other hand, the morphology of petrographic constituents (for example, the fact that samples can be polished), the huminite reflectance, and other ultraviolet-emission spectral properties indicate that the sediment is a lignite.

Microscopic analysis of 22 polished pellets of Trail Ridge peat is summarized in table 1 and shown with

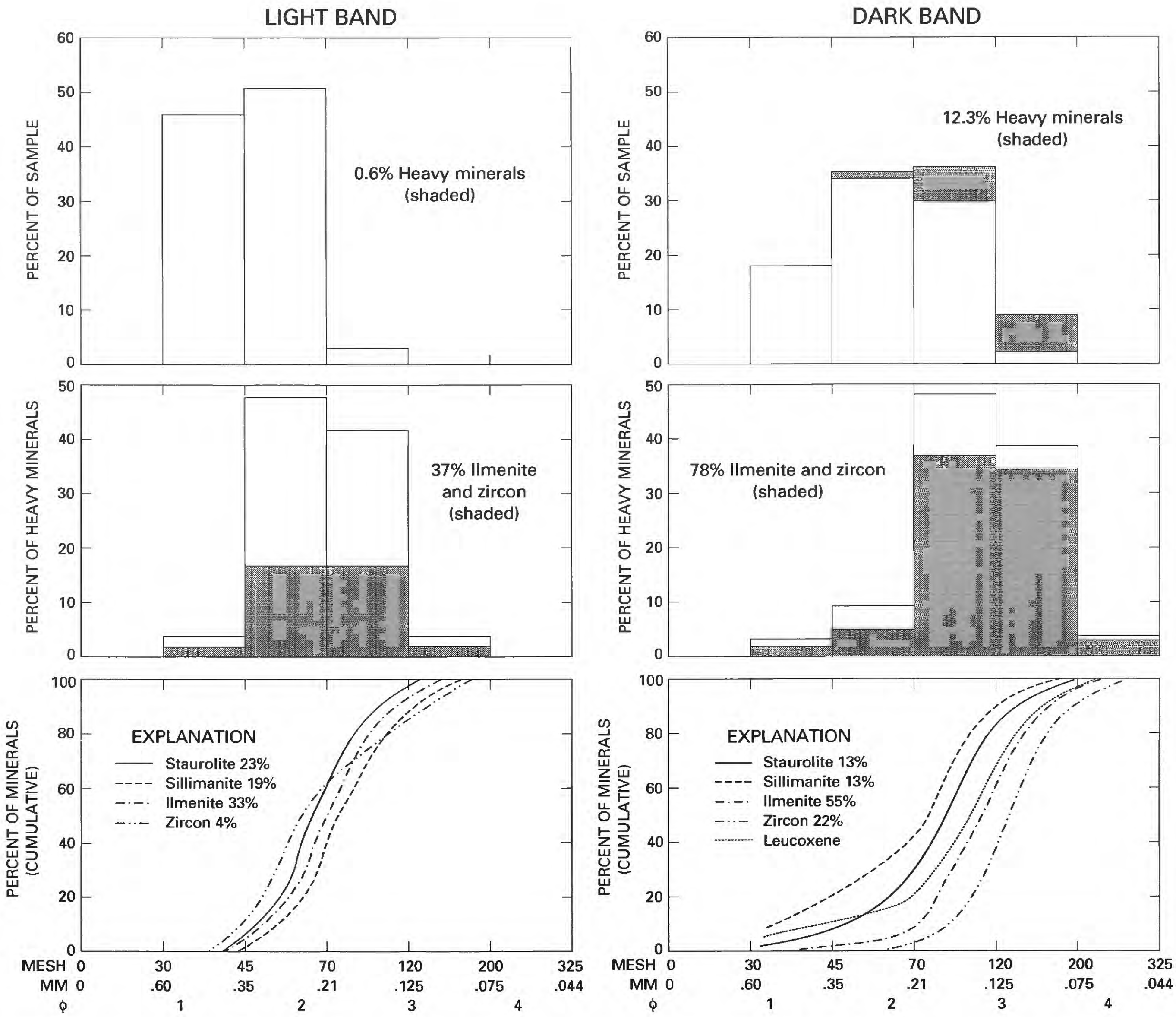

FIGURE 11.—Comparison of adjacent laminae rich and poor in heavy minerals. The upper graphs show histograms of the whole sample, the middle graphs show histograms of the heavy-mineral fraction, and the bottom graph shows cumulative curves for individual heavy-mineral species. Analyses by Jeanette (Hilbish) Thomas.

palynologic information in figure 12. The dominant constituent in all samples is detrital particles of various degraded humic materials (humodetrinite). Other constituents (defined in table 1) are textinite, ulminite, and gelinite. Local horizons of charcoal (fusinite) and fungal remains are present. Dominance by humodetrinite (fig. 13) suggests an analogy with highly degraded shrub peats of the modern Okefenokee Swamp (Rich, 1979; Cohen and others, 1984).

PALYNOLOGY

Pollen and spores in the Trail Ridge peat were studied by Rich (1985). Stratigraphic trends in microflora for core RTR2 are shown in figure 12 for comparison with petrographic constituents. In most samples, the dominant microflora is of the shrubs and small trees, especially holly (*Ilex*), wax myrtle/bayberry (*Myrica*), ti-ti (*Cyrilla*), hazel (*Corylus*) and loblolly bay (*Gordonia*), and herbaceous forms such as sedges (*Cyperaceae*), ferns (*Osmunda*), and moss (*Sphagnum*). All of these forms are consistent with or diagnostic of a freshwater origin, and some suggest standing water.

A stratigraphically lower zone of peat in RTR1 contains more abundant cypress (*Taxodium*) pollen and pollen of shrubby forms consistent with a bald cypress swamp community. Ti-ti (*Cyrilla*) shows a peak in the

TABLE 1.—*Organic and sand constituents of core samples from Trail Ridge peat*

[n.d. = no data; locations of cores are shown in figure 7]

Ulminite. Biochemically and (or) geochemically gelified tissues having little cell structure remaining.
Humodetrinite. Detrital plant fragments and bits of gelified plant tissue.
Gelinites. A broad range of structureless organic materials derived exclusively by precipitation of colloidal humic suspensions within cell cavities and interparticulate spaces.
Other huminites. A variety of morphologically dissimilar organic substances, generally derived from colloidal humic suspensions (for example, corpohuminite). Includes textinite (coalified cell walls).
Fusinite. Charred tissues, usually having well-preserved cell structure.
Other inertinites. Highly oxidized byproducts of biochemical and geochemical alteration, as well as fungal remains and minute fragments of charcoal.
Liptinites. Resins, waxes, spores and pollen, algae, and plant cuticles.
Textinite. *See* Other huminites.

Sampled interval (m depth)	Macerals, expressed as volume percent of organic matter[1]							Sand, expressed as approximate volume percent of peat[2]	Ash, expressed as weight percent dry basis
	Ulminite	Humodetrinite	Gelinites	Other huminites	Fusinite	Other inertinites	Liptinites		
Core RTR1									
15.6	30.4	54.3	1.6	4.5	2.8	4.0	2.4	n.d.	30.7
15.7	63.3	16.3	2.1	2.5	4.8	6.8	4.2	n.d.	4.3
15.8	22.0	64.2	.8	4.0	1.2	3.3	4.5	n.d.	4.7
16.0	13.0	74.5	1.3	2.0	1.3	5.8	2.1	n.d.	4.9
16.2	19.7	58.8	2.0	2.6	8.2	6.7	2.0	4 percent	36.3
16.3	15.5	71.1	2.5	5.1	1.8	2.8	1.2	.1 percent	14.0
16.5	8.7	83.7	1.0	2.8	.0	2.2	1.6	.1 percent	4.5
16.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<.1 percent	39.0
16.7–17.4	13.8	77.8	.7	4.5	.4	1.5	1.3	2 percent	65–89
17.4–17.5	44.9	44.0	.5	5.2	.5	2.5	2.4	n.d.	33.0
Core RTR2									
16.7–16.9	38.6	52.1	1.9	3.4	0.1	2.0	1.9	4 percent	47.8
16.9	19.8	69.8	1.4	2.5	.9	2.6	3.0	n.d.	57.2
17.1	27.1	62.6	.9	3.8	.3	3.0	2.3	7 percent	78.2
17.3	14.5	66.0	3.0	4.2	4.6	5.6	2.1	n.d.	32.1
17.4–17.6	11.0	75.1	2.6	6.5	1.4	2.9	.5	n.d.	7.1
17.6–17.8	17.3	69.9	1.7	6.3	1.3	2.1	1.4	<.1	4.8
17.8–18.0	4.6	79.8	2.7	2.2	3.6	5.9	1.2	n.d.	8.8
18.0–18.3	10.0	77.6	4.2	1.9	3.0	2.6	.7	n.d.	6.1
18.4	12.4	76.0	3.0	1.3	3.2	3.2	.9	<.1	8.4
18.5	n.d	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<.1	8.6
18.7	16.6	74.6	1.8	2.4	2.0	1.2	1.4	<.1	4.9
18.8	27.4	65.9	1.0	2.7	.1	2.0	.9	<.1	5.0

[1] Maceral abundance was determined by 1,000-point counts of polished pellets in reflected white light.
[2] Sand abundance was determined in thin section by use of visual comparison charts.

uppermost part of both cores. Oak (*Quercus*) and pine (*Pinus*), although common constituents, are less abundant than in modern swamps of the same region.

Palynology of many samples is closely related to petrography (fig. 12). The pollen was apparently produced by a local flora, as some of these pollen are known to have restricted dispersal patterns (Rich and Spackman, 1977). Analogous correlations have been found elsewhere by Teichmuller (1958), Corvinus and Cohen (1979), and others.

AGE

Palynology by Rich (1985) established only a post-Miocene age for the peat. Some relative-abundance evidence suggested a Pliocene rather than a Pleistocene age, but control by environmental change could not be ruled out for this evidence.

Two samples of lignitic peat from core RTR2 were analyzed for ^{14}C. Both samples, taken from the upper peat between 16.76 to 17.09 m of depth, proved to be "dead," indicating an age greater than 45,000 years B.P. (Meyer Rubin, USGS, written commun., 1985). Thus the peat is not of latest Pleistocene or Holocene age. The stratigraphic relations described below suggest that the overlying ilmenite ore sands, likewise, are of post-Miocene, pre-latest Pleistocene age.

THE SAND COMPONENT OF TRAIL RIDGE PEAT

Toward the top of the peat body, several narrow intervals of Trail Ridge PTR cores (fig. 7) have been aptly described as sandy peat (E.C. Pirkle and others, 1970, p. 50). We studied this sandy peat in thin section, as a separated bulk sample, and via analysis for ash content and chemistry. The 12 thin sections, representing most of the peat thickness in the two RTR cores (fig. 7), show that the uppermost peat layers characteristically contain about 1 percent or more of sand (table 1) that is dominantly well rounded, especially the coarser grains (fig. 13). The entire heavy-mineral suite of the overlying Trail Ridge ore body is present. Underlying peats most commonly contain little sand or more angular sand poor in heavy minerals. Ash values (table 1) partly

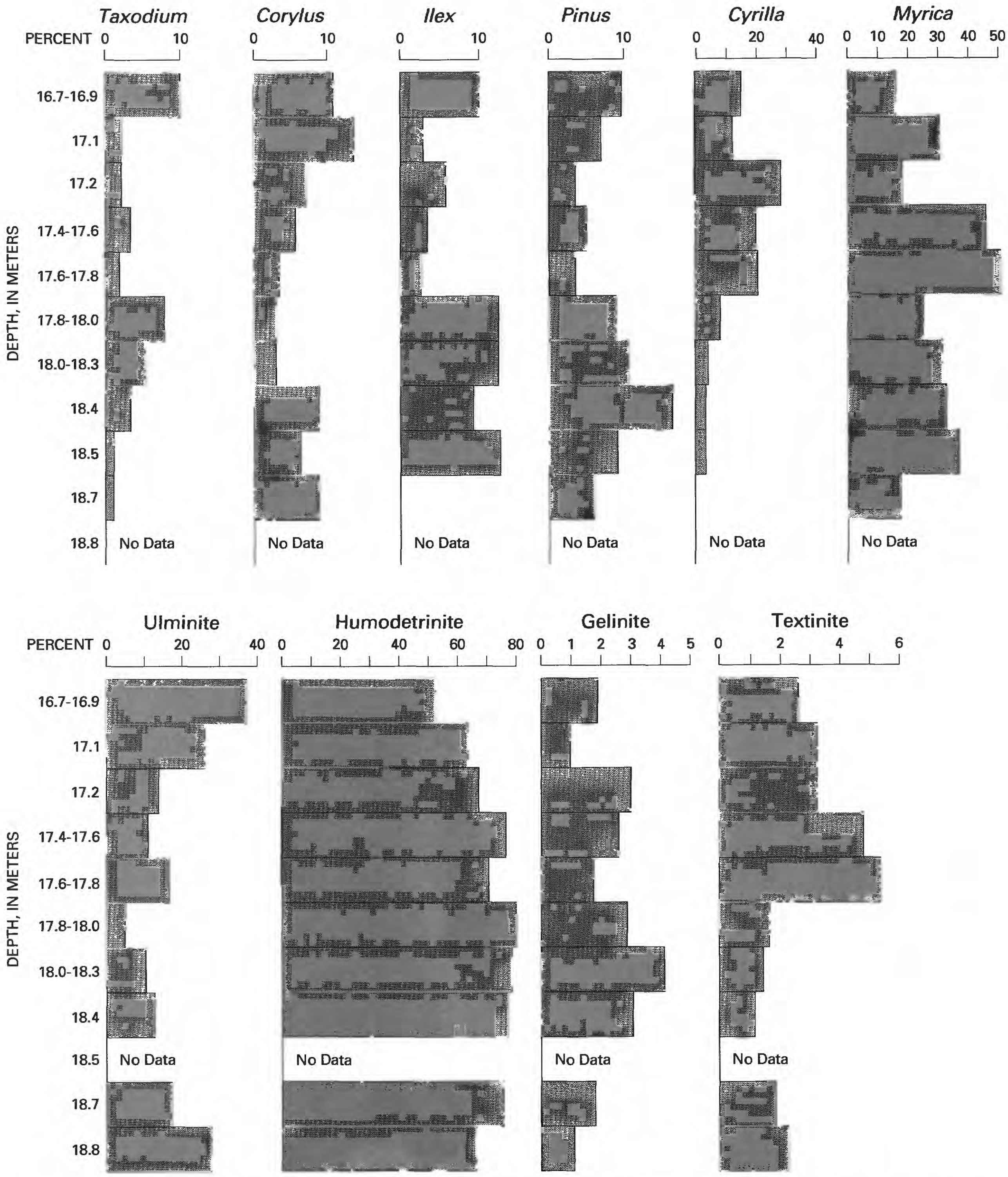

FIGURE 12.—Palynological (top) and maceral (bottom) constituents of peat in core RTR2. Palynofloral constituents are expressed as a percentage of total microflora (from Rich, 1985). Maceral constituents are expressed as a percentage of total macerals.

reflect the distribution of sand; ash from this peat commonly contains 1 to 2 percent TiO_2 and 0.1 to 0.4 percent zirconium (Jesse Yeakel, written commun., 1980).

Figures 13 and 14 show that rounded sand grains in the upper peat are isolated and disseminated and embedded in laminated organic matrix, with deformed organic material draped around the grains. The organic matrix of

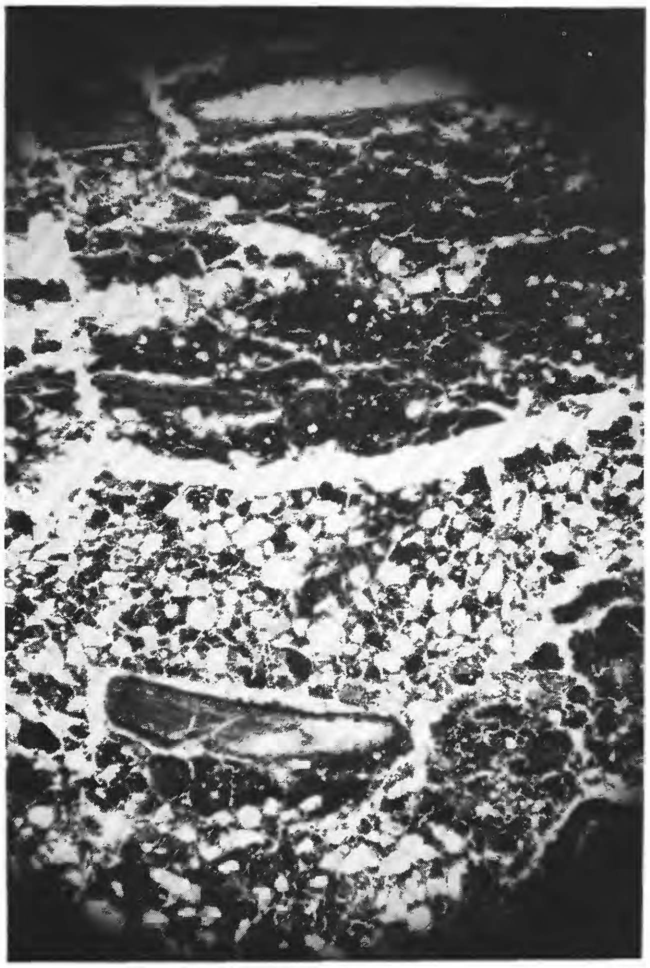

FIGURE 13.—Thin-section photomicrograph of exceptionally sandy lignitic peat from core RTR2, 17.09-m depth. Field of view is 6 mm; plane light. Sand is imbedded in an organic matrix of humodetrinite.

FIGURE 14.—Scanning electron microscope photograph of sand-bearing lignitic peat sample from core RTR2, 16.76 to 16.99 m. Note the isolation of sand grains in an organic matrix of plant fragments.

this upper sandy peat and peaty sand is dominated by humodetrinite (table 1) with admixed charcoal and (or) fungal remains, suggesting subaerial exposure of the peat during sand accumulation. It appears unlikely that the sand represents either traction-load detritus or material reworked from the overlying sand mass after deposition; in the former case the sand would be bedded, and in the latter case the sand would occupy veins. In either case, the sand grains would be in contact.

We were able to separate 1.1 g of sand from the RTR2 sample and subjected it to one of the most rigorous textural and mineralogic analyses possible for a sample of this size. Figure 15*A* shows the grain-size distribution of the sand. The modal grain size is about 0.2 mm, sorting is rather poor, and a fine tail is present in the grain-size population. Skewness is probably slightly positive. Compared to the overlying Trail Ridge ilmenite ore sand(fig. 11), there is a great deal of overlap in grain-size distribution, but modal grain size of sand in peat is finer and sorting is poorer.

Heavy-mineral content of this sand is 6.7 percent, slightly higher than in the overlying ilmenite ore sand. Heavy minerals show a modal grain size slightly finer than that of light minerals (fig. 15*B*).

The mineralogy of the sand in peat compares closely with that of overlying ilmenite ore sand. The light fraction of the sand is over 99 percent quartz. No feldspar was identified. The heavy minerals are dominated by ilmenite (46.5 percent by volume), zircon (16 percent), staurolite (8.5 percent), and sillimanite+kyanite (7.5 percent) (fig. 15). Minor but characteristic constituents are tan or gray leucoxene (5 percent), rutile (4 percent), tourmaline (2 percent), and monazite, spinel, corundum, and garnet (all less than 1 percent). Size distributions of the heavy minerals (fig. 15*C*) are apparently a function of mineral density and are related to each other much as in the overlying ilmenite ore sand.

Grain shapes and surface characteristics of the sand grains are also similar to those of the ilmenite ore sand (fig. 16). Rounding and sphericity are moderate to superb. The sand grains are frosted and show microscopic impact and abrasion features suggestive of an eolian origin. (See Krinsley and Margolis, 1971.)

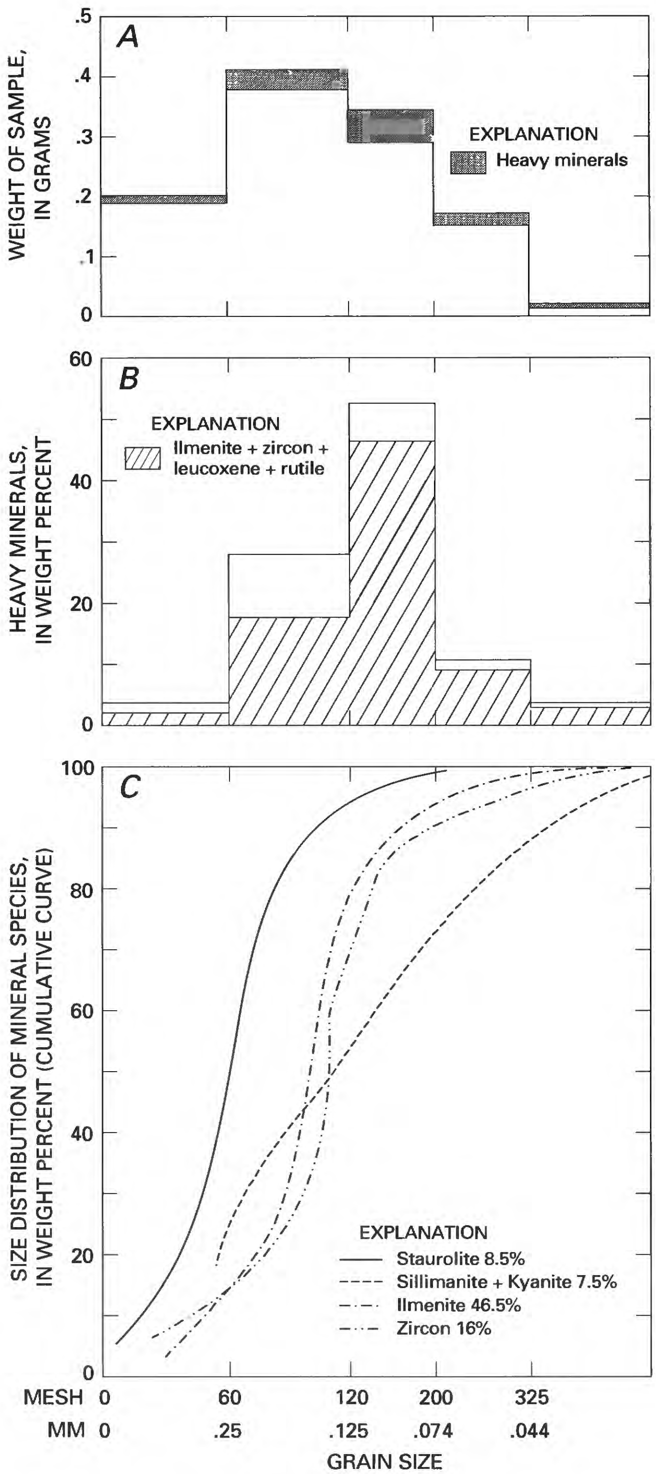

FIGURE 15.—Grain-size distributions of inorganic fraction of sandy Trail Ridge peat from core RTR2, 16.76- to 16.99-m depth. *A*, Grain-size histogram of inorganic fraction, with heavy minerals (ρ>2.85) shaded. *B*, Grain-size histogram of heavy minerals. *C*, Cumulative distributions of staurolite, ilmenite, zircon, and sillimanite.

FIGURE 16.—Scanning electron microscope photographs of sand grains in Trail Ridge peat from RTR2, 16.76- to 16.99-m depth. *A*, Quartz. *B*, Ilmenite. *C*, Zircon. ▶

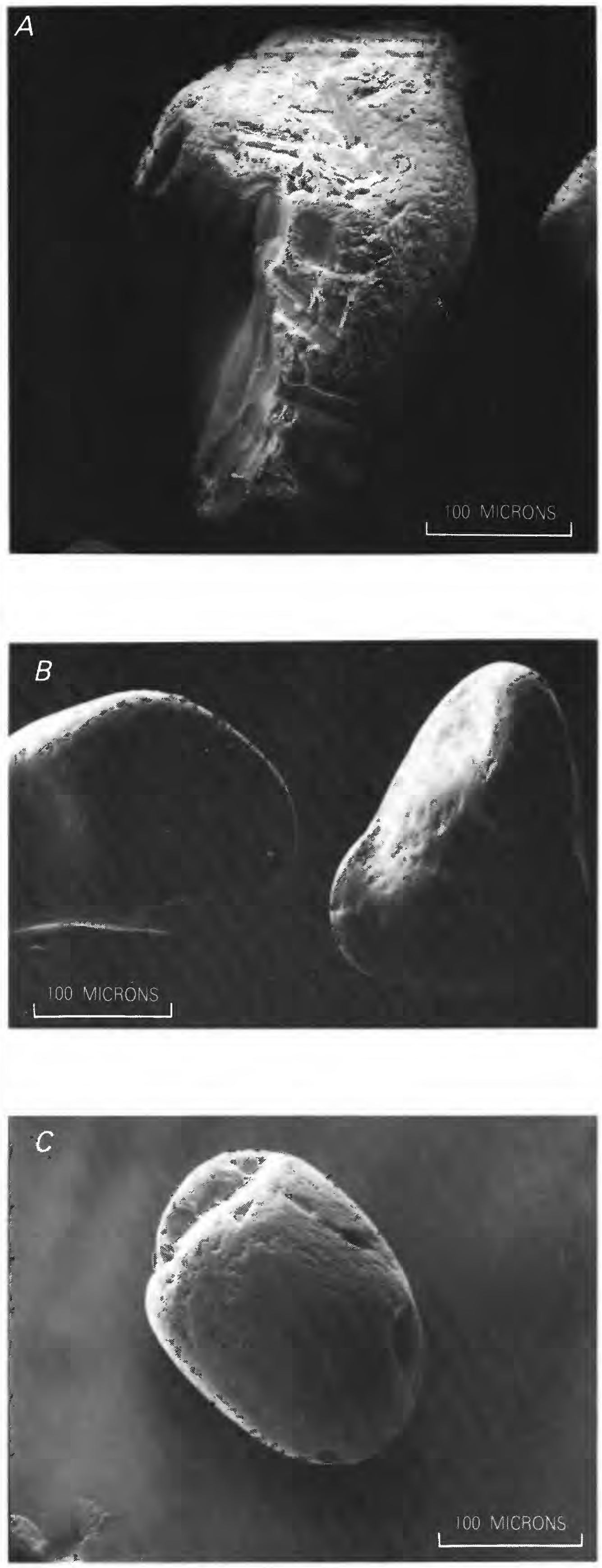

FIGURE 17.—Holocene coastal transgressive longwall dune near Newcastle, New South Wales, Australia, taken from the landward side. This dune, an economic heavy-mineral deposit, has migrated away from the coast but remains parallel to it and now rests in part on Holocene peats (Thom and others, 1981).

Certainly the sand did not acquire these features in the depositional environment, a swamp. The distribution of sand suggests that the transport agent that moved it there apparently did so in some form of suspension, not as bed load. In a swamp, the appropriate form of suspension transport is eolian. An eolian origin for the sand component of peat is an additional tie to the overlying ilmenite ore sand, which is independently known to be eolian.

DEPOSITIONAL RELATION OF TRAIL RIDGE PEAT AND SANDS

The Trail Ridge ilmenite ore sand represents a large southwest-migrating eolian dune complex. Trail Ridge peat represents a freshwater swamp, originally formed west of the dune but later overridden by it. The sand component of the upper peat was deposited from aerial suspension and acquired its characteristics in the adjacent eolian environment. The sand serves as a sensitive recorder of the approach of the dune; it represents the finer fraction that remained in suspension during eolian flow separation at the top of the slip face of the dune. The ilmenite ore sand represents the fraction that moved down the slip face as traction load. Thus the peat and the ilmenite ore sand are essentially the same age.

The existence of a large active dune, probably little-vegetated, upwind of the swamp explains the scarcity of pine and oak pollen in the peat. The portions of the swamp nearest the dune were largely subaerially exposed and vegetated partly by ti-ti. Some other portions of the swamp were subaqueous, as indicated by some of the palynoflora of the peat.

Oxidation is the first stage of ilmenite alteration (Temple, 1966) and is important in the weathering alteration of other minerals also. Thus the sand entombed in reducing peat should serve also as a recorder of the original composition of ilmenite and other minerals supplied to the dune before postdepositional weathering. The presence of leucoxene and the absence or trace amounts of labile constituents such as feldspar show that the dune was supplied by a sand already highly weathered. This observation is consistent with the previously discussed surface polish and grain-size-density characteristics in the ore sand. Since postdepositional weathering at Trail Ridge is already well established, a two-stage weathering history is implied.

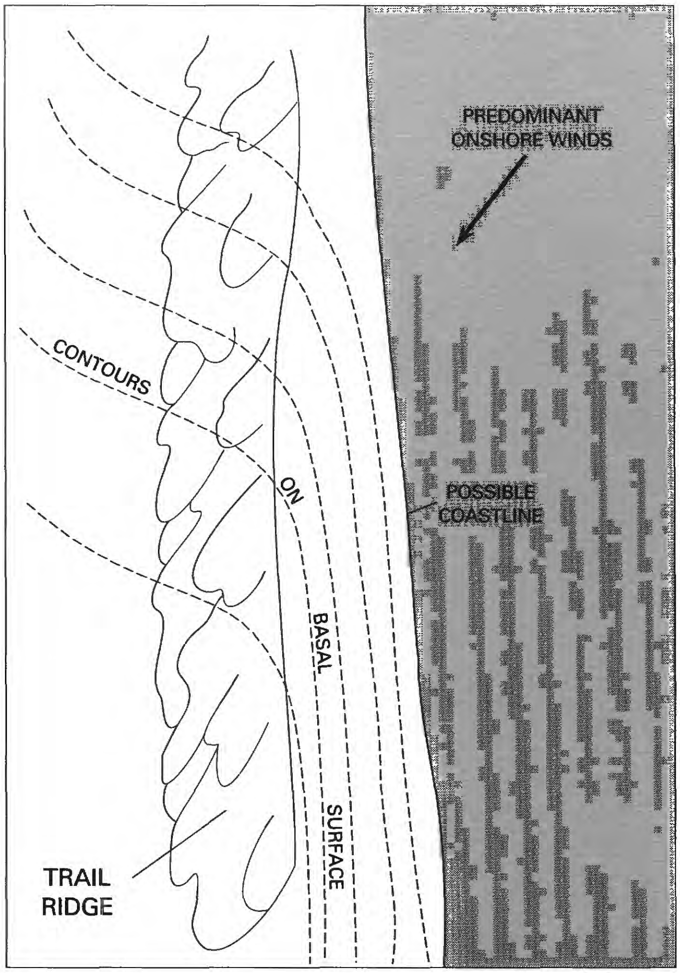

FIGURE 18.—Schematic paleogeography of Trail Ridge at the time of dune formation.

Eolian dunes very commonly block natural drainage channels, and it seems likely that the active Trail Ridge dune thus impounded the swamp represented by Trail Ridge peat. In the same way, the inactive Trail Ridge landform now impounds the modern Okefenokee Swamp.

No evidence of marine influence in deposition of the Trail Ridge sequence has ever been encountered. All observed sands are eolian, and all observed sheltered deposits were deposited in fresh water. Marine fossils collected by F.L. Pirkle and Czel (1983) were thought by them to postdate Trail Ridge deposition.

PALEOGEOGRAPHIC RECONSTRUCTION

The lack of marine facies coeval with Trail Ridge deposition suggests that the Trail Ridge dune had become decoupled from parent shoreline facies and moved inland while remaining roughly parallel to shore, similar to the formation of transgressive longwall dunes of eastern Australia (Thom and others, 1981). These bodies, of both Pleistocene and Holocene age, are similarly decoupled from parallel coeval shorelines and rest in part on marsh and swamp deposits (fig. 17). An eolian body as large as Trail Ridge would probably have been composite, composed of individual transgressive parabolic dunes oriented according to prevailing wind direction (fig. 18), analogous to Pleistocene dunes of the southern Queensland coast (Ward, 1977, 1978; Thompson and Ward, 1975) that are even larger than Trail Ridge. Many of the Australian transgressive dunes are also heavy-mineral ore bodies (McKellar, 1975).

Transgressive dunes may move inland considerable distances and climb onto irregular surfaces well above coeval sea levels (Australia—Hesp, 1986; Short, 1987; Brazil—Bigarella, 1972). Our conception of paleogeography at the time of formation of the Trail Ridge dune is shown in figure 18. The transgressive dune moved west, roughly parallel to the coast, but migrated by successive accretions of parabolic dunes moving upslope toward the southwest, thus forming slip facies oriented as shown in figure 6.

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