Geology of the Charleston Phosphate Area, South Carolina

GEOLOGICAL SURVEY BULLETIN 1079

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By HAROLD E. MALDE

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A detailed study of the area from which phosphate rock was first produced in this country

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GEOLOGY OF THE CHARLESTON PHOSPHATE AREA, SOUTH CAROLINA

By Harold E. Malde

ABSTRACT

The Charleston phosphate area, part of a district from which phosphate was produced from 1867 to 1938, lies northwest of Charleston, S. C., between the Ashley and Cooper Rivers. The exposed rocks are marine and range in age from Oligocene to Pleistocene. Soils and swamp debris obscure much of the area.

The Oligocene Cooper marl, a soft, very fine grained, impure carbonate deposit, is the oldest formation exposed, cropping out in the river bluffs. The Cooper marl dips southward from 8 to 14 feet per mile and overlies beds of Eocene age upturned on the north. From a thickness of 200 feet near Charleston the Cooper marl thins and pinches out 20 miles north. It thickens southwestward to at least 280 feet. Carbonates in the Cooper are mainly calcite, but dolomite locally replaces calcite in the upper part. Other constituents are sand, clay, phosphate, and water. The marl is massive and smooth textured. Fossils suggest deposition in relatively cool water, 100 to 200 fathoms deep. Mollusks from outcrops high in the Cooper near the coast indicate a late Oligocene age, but other fossils farther inland, closer to the base, are early Oligocene.

Miocene formations in the region are thin and discontinuous. The lower Miocene is absent, except possibly for a limestone bed, 1 foot thick, 30 miles northwest of Charleston. The middle Miocene Hawthorn formation, limy or marly phosphatic sand and clay, crops out along the Savannah River, but thins northeastward and apparently is missing at Charleston. The Hawthorn dips south about 4 feet per mile. A bed of coquina as much as 10 feet thick and a mile broad, part of the upper Miocene Duplin marl, is buried by younger deposits in the eastern part of the area, and crops out on the Cooper River and Goose Creek. The Duplin thickens northeastward to a maximum of 41 feet and rises inland to a height of 170 feet. It dips southeast about 2 feet per mile. Fossils in the Duplin marl near Charleston resemble Pliocene species, but those farther inland are upper Miocene.

The Pliocene Waccamaw formation is not exposed, but ditch spoil southwest of the Charleston Military Airport contains Pliocene fossils apparently dredged from a shell bed about 8 feet above sea level. Outcrops of the Waccamaw formation northeastward along the coast are at comparable altitude.

Pronounced changes in relative sea level during late Pliocene or early Pleistocene time are suggested by fossils from well cuttings found 83 feet beneath Charleston and from an outcrop farther inland 65 feet above sea level.

Pleistocene marine deposits cover nearly all the Charleston area. The Ladson formation, first named in this report, is the oldest and most widespread. It consists of a layered sequence of sand and clay, conglomeratic at the base, divisible into four members. From bottom to top the members are characterized respectively by phosphate, fine sand, medium-grained sand, and coarse sand.

The Ladson formation dips seaward (southeast) about 2 feet per mile. It rests on eroded Tertiary deposits and is as much as 35 feet thick. Locally, at least 10 feet of beds have been removed by erosion. Differential erosion along bedding planes has formed flat benches, and weathering profiles on these benches are buried locally by surficial deposits.

Relative ages of the surficial deposits younger than the Ladson are inferred from their topographic relations. The oldest, a sand deposit on Tenmile Hill, forms ridges parallel to the coast from 35 to 45 feet above sea level. Surficial deposits of intermediate age correlate with the Pamlico formation and form a sandy terrace rarely higher than 25 feet above sea level. The youngest deposits are on terrace benches along the estuary of Goose Creek and range from 20 to 25 feet above sea level.

The phosphate rock is phosphatized Cooper marl reworked into the lower part of the Ladson formation. Mineralogically, the phosphatic material is carbonate-fluorapatite, a common marine phosphate whose composition can be expressed by the formula $Ca_{10}(PO_4, CO_3)_6F_{2-3}$. Amounts of calcium phosphate in the phosphate rock are proportional to amounts of calcium carbonate in the Cooper marl and average 61 percent "bone phosphate of lime". Presumably the phosphate rock could have formed by replacement of calcium carbonate with carbonate-fluorapatite.

Soils in the area differ according to the geologic age of the deposits on which they are formed. Those with red mottling and brown hardpan are developed on the Ladson formation. Younger deposits are little weathered, but are weakly oxidized or contain organic accumulations of plants that grew in poorly drained terrain. Progressively older soils have profiles that suggest polygenetic development.

INTRODUCTION

The Charleston phosphate area lies northwest of Charleston, S. C., between the Ashley and Cooper Rivers. The area of detailed study in this report is the Ladson 7½-minute quadrangle, shown in figure 1. Reconnaissance regional studies also were made and the results are included in this report.

The investigation of the Charleston phosphate area is one of several studies undertaken by the Geological Survey on behalf of the Division of Raw Materials of the Atomic Energy Commission to examine phosphate deposits in the southeastern Coastal Plain, chiefly in Florida. The Charleston area was selected for study because it has been the most productive in South Carolina. No mining has been done since 1938 and little since 1920.

The area studied in detail includes a major part of the former mine workings, which are mostly along the Ashley River. (See pl. 1.) These workings, broken into rows of low ridges and overgrown with tangled vegetation, are little used today except for selective lumbering.

South Carolina was the second State to begin a Geological Survey. (See Bouvé, 1849.) Results of work begun by Lardner Vanuxem were published in 1826. Edmund Ruffin (1843) continued the survey which culminated in 1848 with the first State geologic map, prepared by Michael Tuomey. A later map was made by Earle Sloan (1907,

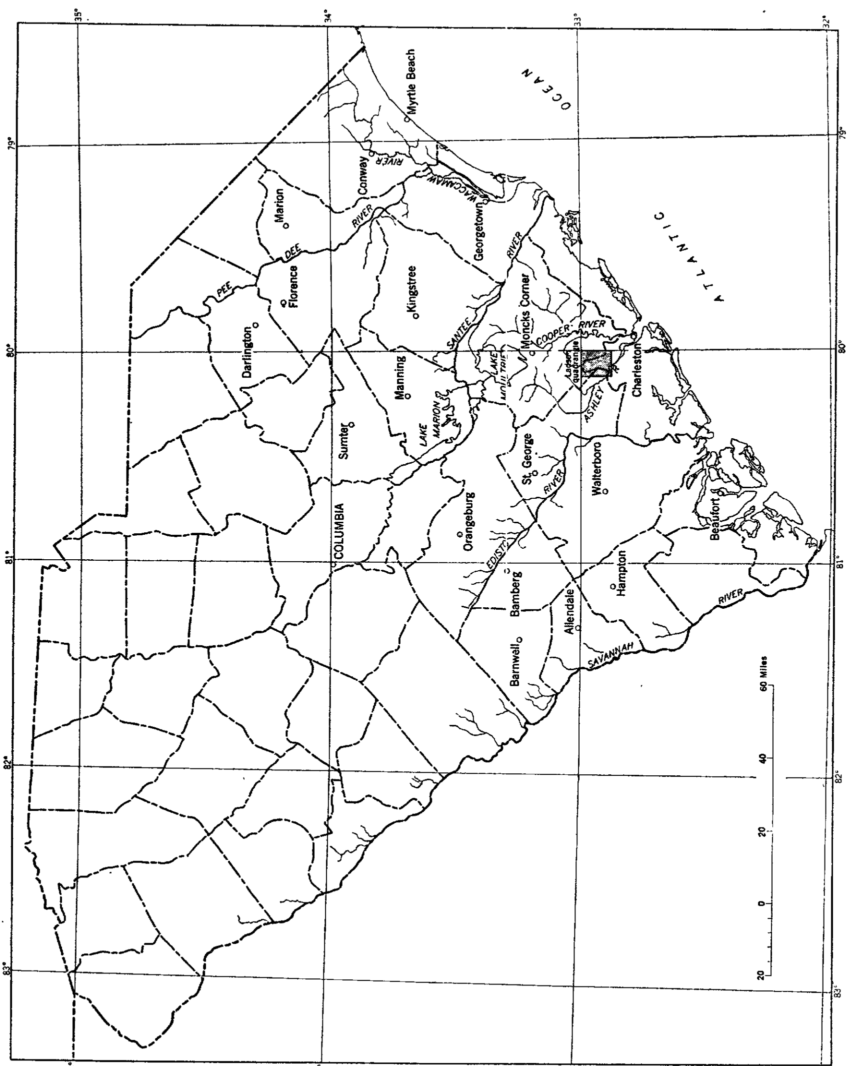

FIGURE 1.—Index map showing location of the Ladson quadrangle.

1908) who gave an extensive list of mineral and fossil localities. C. W. Cooke (1936) made a reconnaissance geologic map of the South Carolina coastal plain and gave data on many newly discovered outcrops. No detailed surveys have been made, but additional stratigraphic information is available in several reports describing formations and their fossils. (See Petty, 1950.)

Publication of reports on the phosphate rock began soon after production started in 1867. Among the authors who described the phosphate rock were N. A. Pratt (1868), F. S. Holmes (1870), N. S. Shaler (1870), C. U. Shepard, Jr. (1881), O. A. Moses (1872, 1883), A. R. Guerard (1884), R. A. F. Penrose (1888), D. T. Day (1893), Francis Wyatt (1894), P. E. Chazal (1904), F. B. Van Horn (1909), W. H. Waggaman (1913), G. S. Rogers (1914).[1]

Despite the number of earlier reports and the length of time during which the coastal plain of South Carolina has been studied its geology is not well known, largely because rock exposures are poor and it is covered by thick weathered residues. Results of this survey suggest that details found in a small area are applicable to much wider areas. Detailed local surveys could therefore furnish a better understanding of the geologic development and resources of the whole coastal plain of South Carolina.

Fieldwork, totaling 5 months, was done at intervals during 1953 and 1954. About half the time was spent making a geologic map. Because vegetation, soil, and swampy ground obscure lithologic contrast discernible at shallow depth, the map was constructed by tracing geologic boundaries with a soil auger. Mapping of boundaries by distinguishing the texture 2 feet below the ground surface proved feasible, and nearly a thousand auger holes were bored. Concurrently, the kind of soil was identified and related to the mapped deposits. About three weeks were spent in reconnaissance, but most of the remaining time was spent in boring to a rock unit that underlies the whole area. These holes were bored by hand with a 1¼-inch auger closely fitted in 1¼-inch pipe as casing. In most places the auger could bring up samples in advance of the casing, but the casing had to be driven through some beds in advance of the auger (because of water), resulting in disturbed samples. Ordinarily, the auger was advanced 3 to 6 inches to obtain a sample. Sedimentary structures were, of course, deformed by the auger; but the gross lithology and some bedding features could be observed. The diameter of the auger limited the size of the material that could be brought up, so that large fossils and phosphate-rock conglomerate were broken. Small fossils

[1] Additional information is available in theses by H. F. Mappus, University of South Carolina, 1935, and J. H. Watkins, University of North Carolina, 1937 and 1942.

and phosphate pebbles came up undamaged. Logs of these auger holes are given on pages 84–95.

Friendly cooperation from residents of the region made the work enjoyable and hastened its completion. To enumerate all who helped would be impractical, but their services are appreciated no less than those whose individual contributions are here acknowledged. Logs of drill holes at the Charleston Military Airport and in the Cooper River channel were made available by Colonel C. L. Landaker, Colonel C. C. Zeigler, and Major J. W. Blair, Corps of Engineers, U. S. Army. Drilling information obtained during construction of water-supply tunnels for the city of Charleston was made available by F. B. McDowell, Jr., manager and engineer, Commissioners of Public Works, and by C. B. Hallock, resident engineer, M. M. Moorer, superintendent of tunnel construction, and C. G. Shipley, plant superintendent, Charleston Water Works. Charles Black gave information on drilling at the Charleston Naval Base. An unpublished reconnaissance geologic map of the region nearby prepared by Willard Cornack was loaned by L. W. Bishop, director, South Carolina Research, Planning, and Development Board. Useful chemical data was made available by B. K. Garner, chief chemist, Carolina Giant Cement & Lime Company, Harleyville, and by the Parker Laboratories, Charleston. J. A. Zeigler, secretary and treasurer, South Carolina Public Service Authority, gave information obtained during construction of the Pinopolis Dam power house. Two collections of fossils were given by Stephen Taber, Professor Emeritus of Geology, University of South Carolina.

The following colleagues gave help or advice during the preparation of the report: J. T. Hack and F. S. MacNeil gave advice in the field; Z. S. Altschuler and E. J. Young helped in problems related to the phosphate rock; F. C. Lee assisted in the boring of auger holes; F. S. MacNeil, Ruth Todd, Estella B. Leopold, I. G. Sohn, C. W. Cooke, Druid Wilson, and Remington Kellogg (U. S. National Museum) identified the fossils; and A. J. Gude III, made X-ray determinations of minerals.

STRATIGRAPHY

GENERAL FEATURES

Exposed rocks in the Charleston area range in age from Oligocene to Pleistocene. Drilling has reached Eocene and Cretaceous rocks that crop out farther north, toward the Cape Fear upwarp.

Correlation of the Tertiary marine formations in South Carolina with those in neighboring states is shown in figure 2. The Eocene

			Georgia [1]	South Carolina [2]	North Carolina and Virginia [2]
Pliocene			Charlton formation	Waccamaw formation	Croatan sand
Miocene	Upper		Duplin marl	Duplin marl	Yorktown formation
Miocene	Middle		Hawthorn formation	Hawthorn formation	St. Marys formation
					Choptank formation
			Chipola formation		Calvert formation
Miocene	Lower		Tampa limestone	?	Trent marl
Oligocene			Suwannee limestone	Cooper marl	?
			?		
Eocene	Jackson group		Ocala limestone	Barnwell formation	?
Eocene	Claiborne group	Upper	Gosport sand	Castle Hayne limestone	Castle Hayne limestone
		Middle	McBean formation	McBean formation / Santee limestone	Santee limestone
			Lisbon formation	?	
				Warley Hill marl	
		Lower	Tallahata formation	.Congaree formation	
	Wilcox group		Hatchetigbee formation		
			Tuscahoma sand	?	?
			Nanafalia formation	Black Mingo formation [3]	?

[1] MacNeil (1947) [2] Cooke and MacNeil (1952); Richards (1950) [3] May include some Paleocene

FIGURE 2.—Correlation of the Tertiary formations in South Carolina with those in neighboring States.

rocks change from shale in the lower part to limestone in the middle part and then to sand. Massive olive-green marl makes up the Oligocene, the oldest rocks exposed in the Charleston area. Miocene rocks are distributed unevenly. A limy, clastic wedge of middle Miocene age thickens southward from the vicinity of Charleston, and patches of upper Miocene limestone are scattered in a 50-mile belt paralleling the coast. Pliocene shells in poorly consolidated sand are found near the present coast as high as about 10 feet above sea level.

Pleistocene deposits, largely a layered sequence of sand and clay that is conglomeratic at the base, conceal nearly all the Tertiary rocks in the Charleston area. The conglomerate contains the phosphate rock that was formerly exploited commercially. Overlying the eroded, weathered surface of these beds are deposits of surficial sand whose morphology suggest marine origin. Mollusks in some of these deposits are identical with those now living offshore, but for geomorphic reasons the deposits are regarded as Pleistocene.

OLIGOCENE SERIES

COOPER MARL

NAME

Calcareous deposits along the Cooper and Ashley Rivers now known as the Cooper marl were described first by Ruffin (1843, p. 7–11) under the heading "Marl of the Ashley and Cooper Rivers and their branches." The marl was discussed subsequently by Lyell (1845a), Tuomey (1848, p. 162–169, 190, 211), Holmes (1870, p. 18), Clark (1891, p. 52–54, 81), Dall (1898, p. 330, 341), Sloan (1907, p. 90–91; 1908, p. 462–464), Vaughan (1912, p. 739), Stephenson (1914, p. 85), and Rogers (1914, p. 186–187). These writers variously assigned the Cooper marl to the Eocene or to the Oligocene. Cooke (1936, p. 72–75, 82–89) summarized the knowledge of the Cooper marl and assigned it to the Jackson group (upper Eocene), although paleontological evidence of age was scanty. Paleontological information obtained later (Cooke and MacNeil, 1952, p. 27–28) indicated early Oligocene age for the Cooper marl exposed near Harleyville, S. C., 40 miles northwest of Charleston. Fossil collections made in the vicinity of the type area during the present survey contain several new species that indicate late Oligocene age. In this report, the Cooper marl is assigned to the Oligocene, recognizing that the beds exposed near the present shore are younger than those exposed farther inland.

DISTRIBUTION

A list of Cooper marl outcrops is given by Cooke (1936, p. 82–89). All are in river bluffs nowhere higher than 15 feet above water level. Along the Edisto River the outcrops are 25–50 miles inland; along the Ashley River they extend inland 20 miles from the vicinity of Charleston; most along the Cooper River are on the West Branch near Moncks Corner. Outcrops away from the principal streams are rare, but northwest of Charleston Cooper marl was found along Goose Creek, a tributary of the Cooper River, concealed beneath a foot or or more of swamp debris (pl. 1). Comparable occurrences probably exist elsewhere, but the detailed work needed to find them has not been done.

Excavations and wells yield other data (pl. 2). The lower contact has no reported surface exposure, but the marl lies on the Castle Hayne limestone (upper part of the Claiborne group, of Eocene age) at an altitude of 57 feet in an excavation of the Carolina Giant Cement & Lime Company 2 miles north of Harleyville (Cooke and MacNeil, 1952, p. 25–26; B. K. Garner, oral communication). Measurements on a photograph, made during construction of the power house for the Pinopolis Dam, show Cooper marl on limestone (probably Castle

Hayne) 49 feet below sea level (Zeigler, [1944?], p. 21). A well at the inlet of the F. B. McDowell, Jr., Tunnel at Foster Creek, 13 miles north of Charleston, was drilled through the contact between Cooper marl and underlying limestone 200 feet below sea level (F. B. McDowell, Jr., oral communication). The Cooper marl rests on Eocene limestone beneath Charleston at a depth of 260 feet, that is, 255 feet below sea level (Stephenson, 1914, p. 72). The log of a well at Fechtig in Hampton County (Cooke, 1936, p. 110) is interpreted to record the lower contact of the Cooper marl at 293 feet below sea level. An outcrop at 100 feet altitude at Baldock, formerly thought to be Cooper marl (Cooke, 1936, p. 88–89) has been reidentified (Cooke and MacNeil, 1952, p. 26–27) as Barnwell formation (Jackson group—Eocene); it is here assumed to approximate the base of the Cooper marl. These data form the basis of structure contours shown on plate 2.

STRUCTURAL ATTITUDE

Structure contours drawn at the base of Cooper marl show a southward dip of 8 feet per mile between Pinopolis and Charleston and 14 feet per mile near Fechtig. Beds 200 feet above the base near Charleston are late Oligocene, whereas those at Harleyville are early Oligocene. Perhaps beds as young as those at Charleston once covered Harleyville, but this is improbable. More likely, the formation thickened toward the sea causing the upper beds to lie flatter than the base.

THICKNESS

The present thickness of the Cooper marl is influenced by unconformities at the top and bottom. The Cooper is covered by Tertiary and Quaternary deposits. Where overlain by Miocene rocks at Fechtig, the Cooper is 275 feet thick, but northward, where overlain by younger rocks, it thins and disappears. Northward thinning appears partly related to an arch formed in underlying rocks. Near the Savannah River the Cooper rests on Jackson rocks; farther northeast on Claiborne rocks; and, still farther, where the Cooper thins out near the Santee River, Wilcox rocks reach the surface.

The zero-thickness line shown in plate 2 corresponds approximately with the basal Cooper marl contact drawn by Willard Cornack on an unpublished map prepared for the South Carolina Research, Planning and Development Board.

OUTCROP

Outcrops of Cooper marl are massive, smooth, vertical, featureless bluffs. At river level the bluffs flatten and become planed benches. Above river level the marl commonly is slightly case-hardened and yellow, but at river level it is usually soft and veiled with a dark-green or black film. Fresh exposures made by digging with a spade reveal a uniform olive color, tinged with brown or yellow. Irregular thin zones of lighter colored limestone are found locally. When freshly exposed the marl appears smooth textured and slightly granular, resembling a massive, slightly sandy mud.

Solution of lime carbonate in the zone of fluctuating river level has formed basins a few inches wide that resemble potholes. Because the river waters are slightly acid, solution must be effective in cutting back the marl bluffs.

The Cooper marl is little weathered and lacks a persistent overburden of residuum. Ordinarily, the top of the marl is unaltered, but locally the upper few inches are very soft and sandy, suggesting leaching. Leaching, decreasing downward for several feet, is shown in drill samples, but is not commonly discernible at outcrops. Cooper marl in some bluffs along the south side of the Ashley River is yellowish and possibly oxidized.

LITHOLOGIC CHARACTER

The Cooper marl consists dominantly of carbonates (25–75 percent), sand (10–45 percent), clay (2–5 percent), and phosphate (5–20 percent). Mixed with these constituents is 15–25 percent water to make a smooth, compact, homogeneous mass. When dry the marl is hard and white, or pale gray, but when fresh (moist) it is soft and olive (5 *Y* 5/3)[2] or olive gray (5 *Y* 6/2). The softness of the fresh marl and its impermeability and massiveness were exploited to construct the Edisto River–Goose Creek Tunnel (Gibson, 1942) and the F. B. McDowell, Jr., Tunnel. The entire lengths of these tunnels are in the Cooper marl. They are unlined and have a bore of 7 feet. Although lacking reinforcement, the tunnels in places support 70 feet of overburden. During the water year October 1950–September 1951, about 51 million gallons a day passed through the Edisto River–Goose Creek Tunnel for the Charleston water supply (U.S. Geological Survey, 1953, p. 229). During construction of the McDowell tunnel, 1½ miles of the tunnel bore in Cooper marl was examined. The marl is uniform in color and texture without trace of bedding, but faint laminae of sorted grains can be seen on close inspection. Mollusk shells are distributed at random, several in each cubic yard of material. Pieces of fresh Cooper marl can be broken in the hands and have a silty feel.

Carbonates in the Cooper marl have been shown by X-ray study to be mostly calcite, but dolomite partly replaces calcite in the upper part of the marl in some samples obtained by drilling, and occurs sporadically at depth, mixed with calcite. Ankerite is associated with

[2] Symbol is the Munsell color notation.

the dolomite. In thin section, the carbonates are seen in minute grains, rarely as large as 0.002 mm, although some clusters of grains five times larger are sparsely scattered throughout. Foraminiferal shells, many intact, contribute significant amounts of carbonate.

The sand consists of quartz and some feldspar in subangular and angular grains 0.05–0.03 mm in diameter, well sorted to an average size of 0.1 mm (very fine sand).

The clay-size material is probably not all mineral clay but includes siliceous mud. The insoluble residue of a minus 200-mesh sample of marl contained abundant quartz, some oligoclase, and minor amounts of illite, as shown by X-ray study. Traces of clay in some samples of untreated marl were detected by X-ray study. Chemical analyses of the marl show 1.6 to 3.6 percent Al_2O_3. (Analyses 7–21, table 4, p. 64.)

The phosphate occurs as well-rounded, brown grains 0.1–0.5 mm in diameter, and rarely as fragments of teeth and bone. Some phosphate can be seen in thin section as having formed within foraminiferal shells, and to have replaced the shell wall. Possibly some of the phosphate is too fine grained to be seen, but the amount visible seems sufficient to account for the P_2O_5 determined by chemical analysis.

Quartz pebbles and rock fragments are scattered through the marl but are very scarce. Phosphatized internal molds of pelecypods are more common. The molds ordinarily are black and have dense, shiny surfaces. An exceptional number of such molds can be seen in Cooper marl exposed on the west bank of Four Hole Swamp in the road cut of U.S. Highway 78 (colln. D195–T, fig. 3). Locally, the Cooper marl is glauconitic.

The term "marl" was applied indiscriminately by early geologists working in the Coastal Plain to any limy material accessible for agricultural use, including limestone, greensand, and loose shells. Ruffin (1843) and Sloan (1908) assayed the lime carbonate content of rocks found during their surveys and described many as marl. As used today, "marls are semifriable mixtures of clay materials and lime carbonate . . . [and] contain 25 to 75 percent clay." (Pettijohn, 1949, p. 286.) The Cooper marl contains little clay, but some sand, and is not properly a marl as defined above. More precisely, it is a consolidated (although not indurated), impure, very fine grained carbonate deposit. No rock names in current use seem to apply; nonetheless, the term marl describes the carbonate content, consistence, and "muddy" appearance of the Cooper.

STRATIGRAPHIC RELATIONS

The Cooper marl rests on unweathered Eocene limestone wherever the base has been exposed by excavating or was reached by drilling.

At the cement plant north of Harleyville the contact is sharp, flat, and regular, although slightly wavy. The contact is similar at the power house of the Pinopolis Dam (Zeigler, [1944?], photograph, p. 15). Northward overlap of the marl on successively older rocks (p. 8), demonstrates an unconformity at the base formed by erosion of a large-scale upwarp, expressed today in Cretaceous rocks of the "Carolina Ridge" at Cape Fear (Richards, 1945).

Exposures of the upper contact of the Cooper marl are common along the Ashley and Cooper Rivers where unconsolidated Quaternary sand, clay, and gravel overlie the marl. The contact is easily distinguished by change in texture, sorting, and color. Because the upper part of the marl is locally leached, the content of lime carbonate is not a reliable criterion for choosing the contact. Beneath Charleston the marl is overlain by sand containing Pliocene shells (Stephenson, 1914, p. 71, 85). At the Foster Creek inlet of the McDowell tunnel, Duplin marl (upper Miocene) consisting of a cemented shell aggregate overlies the marl. At other places along the tunnel, as much as 2 feet of sand and clay (possibly Miocene), separates the Cooper and the Duplin (see pl. 4). Miocene(?) sand overlies the marl at Harleyville (Cooke and MacNeil, 1952, p. 26) and at Fechtig (Cooke, 1936, p. 110). At Givhans Ferry the marl is overlain by lower Miocene(?) sandy limestone with abrupt contact (pl. 3). The excavations for the power house at Pinopolis exposed a pale-colored rock unit (perhaps Tertiary limestone), which quarried out in blocks bounded by bedding planes and vertical joints, overlying the marl with sharp, regular contact.

Between Harleyville and the coast the upper contact slopes seaward about parallel with the present surface, except that it drops abruptly 85 feet beneath the surface at Charleston. Near Fechtig the slope is steeper.

Earlier authors had access to exposures made during the mining of phosphate rock, and have described stratigraphic relations at the top of the Cooper marl that differ from those found during the present survey. Sloan (1908, p. 287–289) described 28 feet of "dark-green drab marl" beneath 6 feet of loam, phosphate rock, and clay at the Ashley Marl Works. The dark-green drab marl was phosphatic in the upper part and was separated from light-gray marl below (Cooper marl) by a "broken layer of rounded quartz pebbles." Cooke (1936, p. 114) interpreted the dark-green drab marl as probably Hawthorn formation (middle Miocene), but its description resembles Cooper marl that crops out across the Ashley River at Runnymede and that found beneath phosphate rock by auger boring nearby. At Lambs, Cooke (1936, p. 87–88) identified 2½ feet of "fine gray sandy marl containing inclusions of harder white marl and many irregular phosphatic nodules and shark teeth" as Hawthorn formation, resting on Cooper marl. No formation that resembles the description of this layer was found during the present survey, and I am at a loss to explain its relation to the beds described in this report. If the term "marl" has been misapplied, the layer is possibly correlative with the phosphate member of the Ladson formation (p. 39) of Pleistocene age.

Sections representative of the stratigraphic relations of the Cooper marl are shown graphically on plate 2. The section at Fechtig is interpreted from a description by Cooke (1936, p. 110); that at Charleston from a description by Stephenson (1914, p. 71–73); and that at Harleyville from a description by Cooke and MacNeill (1952, p. 25–26). Descriptions of the other sections on plate 2 follow.

Log of well at Foster Creek inlet, F. B. McDowell, Jr., Tunnel

[Commissioners of Public Works of the city of Charleston, S.C., serial no. 2417, April 1953; altitude 7 feet]

	Thickness (feet)
Pleistocene:	
1. Sand and clay; coarse at base	9
Unconformity.	
Miocene:	
2. Duplin marl. Coquina, indurated. (colln. 27; cf. colln. D203–T)	3
Oligocene:	
3. Cooper marl. (cf. colln. 12, 21)	195
Eocene:	
4. Limestone, hard, white; 33 ft penetrated.	

Section exposed during excavations for the power house of the Pinopolis Dam

[Interpreted from photograph by Zeigler (1944?, p. 21). Altitude, 10 feet]

	Thickness (feet)
Quaternary:	
1. Sand and clay	11
Tertiary(?)	
2. Limestone(?), pale-colored, bedded; blocky jointing	14
Oligocene:	
3. Cooper marl	34
Unconformity?	
Eocene:	
4. Castle Hayne(?) limestone; 6 ft exposed.	

MODE OF DEPOSITION

The Cooper marl is entirely marine. Its fauna is rich in Foraminifera (table 2) and much of the fine-grained carbonate of which it is largely composed probably was derived from the shells of these animals. Because the Cooper is massive and uniform, and appears to lack sedimentary features associated with processes near shore, it may have accumulated in water relatively deep. The Foraminifera, according to J. A. Cushman (*in* Stephenson, 1914, p. 81), are "an assemblage as may have occurred in water ranging in depth from 100 to 200 fathoms". According to E. B. Leopold (p. 25), hystrichosphaerids in the Cooper suggest that it was deposited in moderately deep water.

Lithologically and chemically the Cooper marl is rather uniform (analyses 7–21, table 4, p. 64), except for differing amounts of silica; but foraminiferal assemblages at Harleyville and Charleston are dissimilar and suggest a facies change (p. 21).

Compared with the limestone formations above and below, the Cooper marl is less calcareous and contains far fewer mollusks. These lithologic and faunal contrasts suggest reversals in the conditions of deposition, the limestone beds indicating shallow water, the marl deeper water.

The mollusks in the Cooper resemble forms that lived farther north (p. 19), suggesting a cool-water environment. Although the mollusks include some bottom-living forms, most were free swimmers.

FAUNA

CHARACTER OF THE FAUNA

Except for abundant Foraminifera, the fauna of the Cooper marl has been poorly known. The invertebrate megafauna of the Cooper, as known when Cooke wrote his report on the South Carolina coastal plain, consisted mostly of a few pelecypods and gastropods. The present collections add considerably to the list of Cooke, totaling 23 genera of which 5 are gastropods and 15 are pelecypods. Some genera are represented by several species. In addition to the Foraminifera, pelecypods, and gastropods, the Cooper marl contains corals, barnacles, hystrichosphaerids, and several genera of ostracodes. The Cooper is also noted for skeletons of primitive toothed whales and teeth of sharks and skates.

As shown by study of a well at Charleston (Stephenson, 1914), the Cooper marl is fossiliferous throughout its depth. At outcrops, fossils with calcitic shells—like pectens and oysters—are preserved intact, but fossils with aragonitic shells are preserved as molds.

Nodular phosphate rock near Charleston is highly fossiliferous and is believed to be phosphatized Cooper marl (p. 42). Therefore, the phosphate rock fauna is discussed here. The original shells are gone from the phosphate rock, but their external and internal walls are shown as molds. According to F. S. MacNeil, many of the megafossils are the same as those that have been found in the Cooper marl. Microfossils in the phosphate rock are less well preserved and have not been identified, but include a large number of Foraminifera.

FOSSILS FROM THE COOPER MARL AND NODULAR PHOSPHATE ROCK

Megafossils from the Cooper marl and nodular phosphate rock identified by F. S. MacNeil are listed in table 1. The localities from which the fossils were collected are shown on figure 3.

TABLE 1.—*Invertebrate megafossils from the Cooper marl and phosphate rock nodules*

[Identified by F. S. MacNeil]

	Cooper marl									Phosphate rock				Remarks
	D280–T	D194–T	D195–T D204–T D281–T	D285–T	D286–T	D287–T	D288–T	D289–T	D294a–T	D197–T	D198–T D199–T D200–T D201–T	D284–T	D295–T	
Gastropoda:														
Busycon? sp.												×		
Dolium (*Malea*) n. sp.? aff. *D. camura* (Guppy).				×	×									*D. camura* occurs in the Miocene of the Dominican Republic.
Epitonium cf. *E. charlestonensis* Johnson.	×													
Ficus sp.				×										
Modulus? sp.				×										
Murex sp. aff. *M. mississippiensis* Conrad and *M. trophoniformis* Heilprin.												×		Related forms are found in the Byram formation (middle Oligocene) of Alabama and Mississippi and the Tampa limestone (lower Miocene) of Florida.
Naticoid, undet.											×			
Turritella n. sp. aff. *T. bowenae* Mansfield.												×		Probably identical with a form in the Chickasawhay limestone (upper Oligocene) of Mississippi.
Pelecypoda:														
Amusium sp. aff. *A. cerinus* (Conrad).									×		×		×	The type of *A. cerinus* is from the Calvert formation (middle Miocene) of Maryland.
n. sp.?					×			×						Reported in the literature as *Pecten* (*Pseudamusium*) *calvatus* (Morton).
Anomia jugosa Conrad	×		×											Unique in the Cooper marl, but related to *A. taylorensis* Mansfield and *A. onslowensis* Richards.
sp. (smooth individual)					×									Possibly *A. jugosa*.
Antigona (*Artena*) n. sp. aff. *A. lamellacea* Kellum.				×				×		×	×	×	×	*A. lamellacea* Kellum was described from the Trent marl (lower Miocene) of North Carolina; reported in the literature as *A. undulata* (Conrad).
Astarte n. sp.? aff. *A. thomasii* Conrad and *A. vicina* Say.											×	×	×	Related forms are found in the Calvert formation; most *Astarte* are cool- to cold-water species.
Brachydontes mississippiensis (Conrad).				×			×	×						
Cardita (*Cyclocardia*) n. sp.? aff. *C. castrana* (Glenn).				×						×	×	×	×	Nearest to a form in the Trent marl; *C. castrana* was described from the Calvert formation.
Cardium n. sp. aff. *C. anclotensis* Mansfield and *C. muricoides* Hubbard.												×		Related forms are found in the Tampa limestone of Florida and the upper Oligocene of Puerto Rico.
n. sp. aff. *C.* (*Trachycardium*) *hernandoensis* Mansfield.											×			Juvenile; has 10 more ribs thau *C. hernandoensis*.
Chlamys n. sp. aff. *C. coccymelus* Dall.									×					*C. coccymelus* was described from the Calvert formation; close to *C. permistus* Beyrich from the Oligocene of Holland.
cocoana (Dall)		×												Occurs in the Red Bluff clay (lower Oligocene) of Alabama.

sp. aff. *C. duplex* Cooke and *C. suwanneensis* (Dall).							×		×					Both *C. duplex* and *C. suwanneensis* are of Oligocene age.
n. sp.? aff. *C. madisonius* (Say)									×					*C. madisonius* is a Miocene form in Virginia.
sp								×						
Crenella sp								×						
Gryphaeostrea sp. aff. *G. plicatella* (Morton).							×		×				×	The highest record for the genus *Gryphaeostrea* is the Marianna limestone (middle Oligocene) of eastern Mississippi. All other records are Eocene.
Lucina sp	×		×				×							Internal molds.
Nemocardium? sp				×										
Ostrea n. sp. aff. *O. queteleti* Nyst					×	×								*O. queteleti* occurs in the Oligocene of Germany, Belgium, and Holland.
sp. aff. *O. thomasii* (Conrad) Glenn.									×			×		The type of *O. thomasii* is from the Calvert formation.
sp								×						Juvenile.
"*Ostrea*" n. sp									×					
Panope sp			×											
Pecten n. sp. aff. *P. humphreysi* Conrad.									×			×		Has 3-4 more ribs than the Calvert form.
Phacoides sp. aff. *P. contractus* (Say)												×	×	*P. contractus* ranges throughout the middle and upper Miocene in Maryland.
Plicatula? sp												×		The ribs have large, spinelike flarings.
Pododesmus philippi Gardner									×					Occurs in the St. Marys formation (middle Miocene) of Virginia.
Pteria cf. *P. argentea* (Conrad)				×										
Thracia? sp								×						
Venus sp												×		Fragments only.
Coelenterata:														
Balanophyllia sp				×			×	×		×	×	×	×	
Flabellum sp								×						
Cirripedia:														
Balanus? sp	×						×	×						A unique form with broad, well rounded folds on the fixed plates.

NOTE.—Description of localities from which collections were taken are as follows:

Cooper marl

Collection No.	*Description*
D280–T	Utsey Bluff, north bank of Edisto River, about 5 miles southwest of Reevesville; from ledges about 35 feet below top of bluff and 5 feet above river level.
D194–T	Carolina Giant Cement & Lime Company, 2 miles north of Harleyville; from unit 3 of section measured by Cooke and MacNeil (1952, p. 26).
D195–T, D204–T, D281–T	Four Hole Swamp, west bank where crossed by U. S. Highway 78, 2.7 miles east of Dorchester; from semi-indurated marl bed about 27 feet below top of bluff opposite bridge abutment and about 2 feet below road grade.
D285–T	Runnymede, alongside boat landing steps of old plantation house, south bank of Ashley River.
D286–T	Shaft 20, Edisto River-Goose Creek Tunnel; from spoil.
D287–T	Shaft 19, Edisto River-Goose Creek Tunnel; from spoil.
D288–T	Magnolia Gardens, south bank of Ashley River near tool shed; from phosphatic, very firm, pale-yellow marl about 6 feet above river level.

Cooper marl

Collection No.	*Description*
D289–T	F. B. McDowell, Jr., Tunnel, inlet shaft on Foster Creek; from spoil.
D294a–T	Charleston Military Airport, drainage ditch leading from southwest corner; spoil believed to be from Cooper marl.

Phosphate rock

Collection No.	*Description*
D197–T	Borrow pit on Goose Creek, 1.2 miles southeast of the Charleston Water Works; nodule of phosphate rock in spoil.
D198–T, D199–T, D200–T, D201–T	Mine spoil southeast of The Farms and south of the Charleston Military Airport; four localities.
D284–T	Griggs Landing, south side of Ashley River; loose nodules of phosphate rock.
D295–T	Charleston Military Airport, drainage ditch leading from the southwest corner; nodule of phosphate rock in spoil.

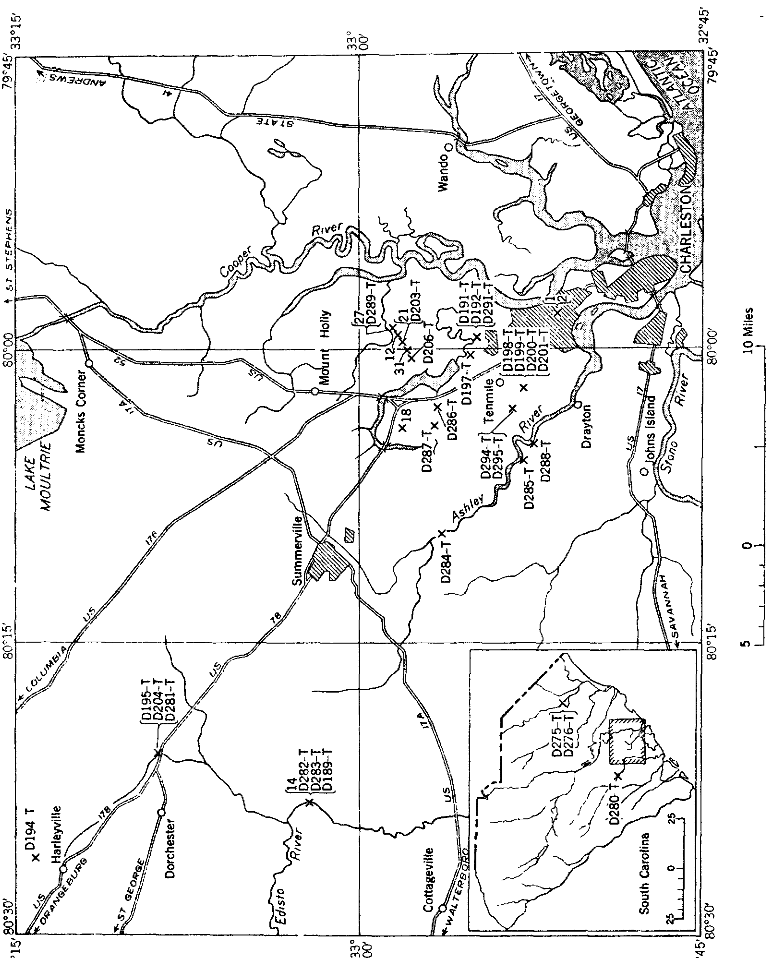

FIGURE 3.—Index map of fossil localities.

Fossils from the Cooper not listed in table 1, but mentioned by Cooke (1936, p. 82–89), include a brachiopod, *Terebratulina*, collected at Four Hole Swamp, and two gastropods, *Cassidaria* and *Lyria*, collected at Ingleside. Johnson (1931) described from the Cooper two gastropod species, *Epitonium chamberlaini* and *E. charlestonensis*, that have never been found elsewhere.

Additional fossils reported from the phosphate rock (identified by W. C. Mansfield in Cooke, 1936, p. 103–104), but not listed in table 1, are:

Gastropoda:
- *Ecphora quadricostata* Say [3]
- *Turitella* cf. *T. tampae* Heilprin

Pelecypoda:
- *Anomalocardia*? sp.
- *Cardium* sp. aff. *C. taphrium* Dall
- *Glycymeris* sp.
- *Leda* sp. aff. *L. flexuosa* Heilprin
- *Marginella* sp.

Foraminifera from the Cooper marl identified by Ruth Todd are listed in table 2.

TABLE 2.—*Foraminifera from the Cooper marl*
[Identified by Ruth Todd]

	Collection 12	Collection 21
Textulariidae:		
Spiroplectammina mississippiensis (Cushman)	×	×
mississippiensis alabamensis (Cushman)	×	×
Textularia adalta Cushman?	×	×
Verneuilinidae:		
Gaudryina jacksonensis Cushman	×	×
Pseudoclavulina cocoaensis Cushman	×	-----
Valvulinidae:		
Dorothia cf. *D. cylindrica* (Nuttall)	×	×
Karreriella cubensis Cushman and Bermudez	×	-----
mexicana Nuttall	×	×
cf. *K. siphonella* (Reuss)	×	-----
Schenckiella gracillima (Cushman and Bermudez)?	×	-----
Liebusella byramensis (Cushman)	×	-----
byramensis extans (Cushman)	×	-----
Miliolidae:		
Massilina decorata Cushman	×	×
Lagenidae:		
Robulus alato-limbatus (Gümbel)	×	×
arcuato-striatus (Hantken) *carolinianus* Cushman	×	×
limbosus (Reuss)	×	×
limbosus (Reuss) *hockleyensis* (Cushman and Applin)	×	-----
Planularia cooperensis Cushman	×	×
Marginulina cooperi Cushman	×	-----
cooperi Cushman (smooth)	×	×
cooperi Cushman (costate)	-----	×
karreriana Cushman	×	×
nuttalli Todd and Kniker	×	-----

[3] The specimen so identified may be a species of *Rapana* (F. S. MacNeil, oral communication).

TABLE 2.—*Foraminifera from the Cooper marl*—Continued

	Collection 12	Collection 21
Lagenidae—Continued		
Dentalina cf. *D. cooperensis* Cushman	×	×
cooperensis Cushman	-----	×
halkyardi Cushman	×	-----
cf. *D. vertebralis* (Batsch)	×	-----
Nodosaria affinis Reuss	×	×
Saracenaria cf. *S. arcuata* (d'Orbigny)	×	-----
hantkeni Cushman	×	×
Lagena acuticosta Reuss	-----	×
costata (Williamson)	×	-----
Polymorphinidae:		
Guttulina spicaeformis (Roemer)	×	-----
Globulina gibba punctata d'Orbigny	×	-----
münsteri (Reuss)	×	-----
rotundata (Bornemann)	×	×
Glandulina laevigata d'Orbigny *ovata* Cushman and Applin	×	×
Sigmomorphina vaughani Cushman and Ozawa	×	×
Nonionidae:		
Nonionella hantkeni (Cushman and Applin) *spissa* Cushman	×	×
jacksonensis Cushman	×	-----
Heterohelicidae:		
Spiroplectoides curta Cushman	-----	×
Gumbelina cubensis Palmer	×	-----
Plectofrondicularia cookei Cushman	×	×
cf. *P. vaughani* Cushman	×	×
Nodogenerina cooperensis Cushman	×	×
Buliminidae:		
Buliminella sp	×	-----
Bulimina ovata d'Orbigny	×	×
Oolina hexagona (Williamson)	×	-----
Virgulina recta Cushman	×	-----
Bolivina costifera Cushman	×	×
quadricosta Cushman and McGlamery	×	-----
spiralis Cushman	×	×
Uvigerina cookei Cushman	×	×
Angulogerina cf. *A. byramensis* (Cushman)	×	-----
cooperensis Cushman	×	×
Rotaliidae:		
Discorbis assulata Cushman	×	×
Gyroidina orbicularis d'Orbigny *planata* Cushman	×	×
Eponides cf. *E. campester* Palmer and Bermudez	×	×
umbonatus (Reuss)	×	-----
Siphonina jacksonensis Cushman and Applin	×	×
Cancris cocoaensis Cushman	×	×
Cassidulinidae:		
Cassidulina globosa Hantken	×	×
Chilostomellidae:		
Sphaeroidina variabilis Reuss	×	×
Globigerinidae:		
Globigerina sp. (similar to *G. bulloides*, but probably not identical)	×	×
Anomalinidae:		
Anomalina cf. *A. bilateralis* Cushman	×	×
jacksonensis dibollensis (Cushman and Applin)	×	×
Cibicides lobatulus (Walker and Jacob)	×	-----
pseudoungerianus (Cushman)	×	×

NOTE.—Localities from which collections were made are shown on plate 4.
Description of localities 12 and 21 are as follows:
12. Cooper marl in F. B. McDowell, Jr., Tunnel, 3,760 feet from inlet shaft, 40 feet below sea level.
21. Cooper marl in F. B. McDowell, Jr., Tunnel, 4,890 feet from inlet shaft, 40 feet below sea level.

Ostracodes from the Cooper marl identified by I. G. Sohn are listed below. Collection 12 is the same as that examined by Ruth Todd. Collection 18 is from 26½ feet below the surface in a well 1.3 miles N. 73° E. of Otranto.

Ostracoda from the Cooper marl

[Identified by I. G. Sohn]

	Collection 12	Collection 18
Alatacythere aff. *A. ivani* Howe, 1951	×	-----
A.? (fragment)		×
Buntonia? sp.	×	-----
Bythocypris? *gibsonensis*? Howe and Chambers, 1935		×
Cytherella spp.	×	×
Cytheretta sp. indet.		×
Cytheromorpha? sp.		×
Cytheropteron sp.	×	-----
C.? sp.	×	-----
Paracypris? sp.	×	-----
Trachyleberis davidwhitei (Stadnichenko), 1927	×	×
T.? *jacksonensis* (Howe and Pyeatt), 1935	×	×

From Cooper marl in the F. B. McDowell, Jr., Tunnel, about 7,000 feet from the inlet shaft and 40 feet below sea level (colln. 31, fig. 3), Remington Kellogg of the U. S. National Museum identified a bone as the "zygomatic process and adjoining otic region" of a seacow (sirenian).

CORRELATION OF THE FAUNA

Pelecypods are the best fossils for dating the Cooper marl. Foraminifera and ostracodes are more numerous but less helpful for dating. Gastropods and the vertebrate fossils give supporting evidence of age.

The pecten *Chlamys cocoana* (Dall) in collection D194–T from Harleyville is an early Oligocene form found in the Red Bluff clay of Alabama (Cooke and MacNeil, 1952, p. 27). Collections from Utsey Bluff and Four Hole Swamp contain *Anomia jugosa* Conrad, a form unique to the Cooper, but not good for dating. Collections nearer the coast, and higher in the Cooper, contain several new species that suggest to MacNeil approximate equivalence with the upper Oligocene Chickasawhay limestone of the Gulf Coast (Alabama and Mississippi) and with the middle Miocene Calvert formation (Virginia and Maryland). From this evidence the Cooper marl is considered to have been deposited throughout the Oligocene. Faunal affinity with northern forms suggests a cool-water environment, although perhaps this affinity implies no more than a facies similarity with the north. F. S. MacNeil (written communication, Nov. 19, 1954) has discussed the age significance of the new species as follows:

Collections D285–T and D289–T contain a new species of *Antigona* (*Artena*) most nearly related to *A. lamellacea* Kellum described from the Trent marl (lower Miocene) of North Carolina. This species has been reported (Cooke, 1936, p. 103) as *A. undulata* (Conrad) but I can find no record of such a species having been described. This species differs from that in the Trent by the presence of conspicuous ventrally undercut shelves on the central disk.

The nearest relative of a new species of *Chlamys* in collection D294–T is *C. coccymelus* Dall, a Calvert (middle Miocene) form in Maryland. The species is close to *C. permistus* Beyrich from the Oligocene of Holland. Another *Chlamys* in this collection is most nearly related to *C. madisonius* (Say), a Miocene form in Virginia. A third *Chlamys* in collections D288–T and D294a–T resembles *C. duplex* Cooke and *C. suwanneensis* (Dall), both Oligocene.

A probably new species of *Cardita* (*Cyclocardia*) in collection D285–T resembles a form in the Trent marl which H. G. Richards identified as *Venericardia granulata*, but both the Cooper form and the one identified by Richards are closer to *C. castrana* (Glenn) from the Calvert than to *V. granulata*. The Cooper species is the oldest known member of this group, and apparently the only Oligocene member, in the southeastern United States.

The highest record for the genus *Gryphaeostrea* outside the Cooper marl (collections D288–T and D294a–T) is the Marianna limestone (middle Oligocene) of eastern Mississippi. [The Marianna specimens are in collections made by MacNeil, but their descriptions are unpublished.] All other records are Eocene. *Gryphaeostrea* is abundant at the Charleston Military Airport as a loose shell.

Collections D286–T and D287–T contain a new species of *Ostrea* unlike any known oyster in the Tertiary of the southeastern United States, but closely related to *O. queteleti* Nyst, a form in the Oligocene of Germany, Belgium, and Holland. This relationship with the European Oligocene is interesting in view of the fact that the fauna of the Cooper indicates cooler water than the Gulf Coast Oligocene, and that the Cooper is the northernmost Oligocene known on the Atlantic Seaboard. [Richards (1950, p. 18) reports Oligocene deposits in the subsurface in Onslow County, N. C.] This is probably the species reported by Cooke (1936, p. 85) from Ingleside as *O. carolinensis* Conrad which is a member of the *O. compressirostra* group occurring in the Santee limestone (middle Eocene). Another *Ostrea* in collection D294a–T is related to *O. thomasii* (Conrad) Glenn, a Calvert form.

The nearest relative of a new species of *Pecten* in collection D294a–T is *P. humphreysi* Conrad, a Calvert form. The *Amusium* in this collection is nearest to *A. cerinus* (Conrad), also a Calvert form. The species of *Amusium* in collections D286–T and D289–T is new, but probably the form reported (Cooke, 1952, p. 83–88) as *Pecten* (*Pseudamusium*) *calvatus* (Morton) from this area.

Pododesmus philippi Gardner in collection D294a–T is found in the St. Marys formation (middle Miocene) of Virginia.

The gastropod *Dolium* (*Malea*) in collections D285–T and D286–T is probably a new species, possibly related to *D. camura* (Guppy) in the Miocene of the Dominican Republic.

The barnacle *Balanus* in collections D288–T and D289–T is a unique form with broad, well-rounded folds on the fixed plates.

Some megafossils in the phosphate rock have not been found in the Cooper marl. These have been discussed by F. S. MacNeil (written communication, Apr. 2 and Nov. 19, 1954) as follows:

The probably new species of *Astarte*, which is a common fossil in the phosphate rock, is most closely related to two species occurring in the Calvert formation (middle Miocene) of Virginia, but is not at all related to species in the Trent marl (lower Miocene) of North Carolina. Most *Astarte* are cool- to cold-water species. There are no *Astarte* in the Tampa, Suwannee, or Chichasawhay limestones, these being warmer water deposits. The new species of *Cardium* in collection D284–T is not like any *Cardium* that has been described. It is a little like *C. anclotensis* Mansfield from the Tampa limestone of Florida, but has less than 30 ribs as opposed to 44 ribs in *C. anclotensis*. *Cardium muricoides* Hubbard from the upper Oligocene of Puerto Rico may also be related, but the published illustrations of that species are inadequate for any definite comparison. The new species of *Cardium* in the mine spoil south of the Charleston Military Airport has 61 ribs—10 more than *C.* (*Trachycardium*) *hernandoensis* Mansfield, a form in the Suwannee limestone (upper Oligocene) of Florida to which it is most closely related. The species of *Phacoides* in collections D284–T and D295–T is more like *P. contractus* (Say), which ranges throughout the middle and upper Miocene of Maryland, than it is like any known species in the lower Miocene or Oligocene to the south.

The gastropod species which are closest to the *Murex* in collection D284–T are *M. mississippiensis* Conrad from the Byram formation (middle Oligocene) of Alabama and Mississippi and *M. trophoniformis* Heilprin from the Tampa limestone (lower Miocene) in Florida. The new species of *Turritella* in collection D284–T is probably identical to a form in the Chickasawhay limestone (upper Oligocene) of Mississippi that Mansfield figured as *Turritella* aff. *T. bowenae* Mansfield, an upper Oligocene species from the Suwannee limestone.

Because pelecypods in the phosphate rock are mostly identical to forms in the Cooper marl—forms that are otherwise unique in the region—MacNeil believes there is little doubt that the phosphate rock and the Cooper marl are faunally the same. The faunal affinities of the fossils, whether found in both the phosphate rock and the Cooper marl or not, are mainly similar. Lack of similarity of the gastropod faunas is not surprising, because these animals are preserved in the Cooper marl today chiefly as molds, a manner of preservation not likely to be retained during phosphatization.

Many of the Foraminifera reported here by Ruth Todd were also identified by her in Cooper marl at Harleyville (see Cooke and MacNeil, 1952, p. 27), but there are faunal differences between Charleston and Harleyville that she attributes to a facies change, the fauna near Charleston suggesting a somewhat deeper water environment (written communication, Oct. 19, 1954, and June 3, 1955).

According to I. G. Sohn (written communication, Apr. 15, 1954), the ostracode fauna of collection 12 differs from that at Harleyville "in the presence of winged genera and in the absence of several species of *Trachyleberis* and *Cytheridea*."

Remington Kellogg (written communication, Sept. 10, 1954) compares the specimen of the seacow (colln. 31) with skulls of *Halitherium schinzi* recorded from the middle Oligocene of Germany, Belgium, and France, and with *Halitherium antillense* from the Oligocene of Puerto Rico, Italy, and Egypt, although "positive identification cannot be made without reference to molar teeth."

POLLEN, SPORES, AND MARINE MICROFOSSILS

By Estella B. Leopold

Five samples of the Cooper marl from auger hole 245 (USGS paleobotany loc. D1101; p. 92) were prepared for microspore analysis. The position of the samples in the hole was as follows: Sample L, depth 17–18 feet; sample M, 19–20 feet; N, 22–23 feet; O, 26–27 feet; P, 29–30 feet.

To prepare the samples, 3 to 5 grams of each were placed in polyethylene beakers and demineralized at room temperature for 3 to 7 days in a mixture of three parts hydrofluoric acid (52 percent stock) and one part concentrated hydrochloric acid. The samples were then washed with warm dilute hydrochloric acid to prevent precipitation of the dissolved silicates and bleached in an acidified 10 percent aqueous solution of sodium chlorite. After dehydration in glacial acetic acid, the samples were acetylated for 10 minutes at 100° C with a mixture of nine parts acetic anhydride and one part concentrated sulfuric acid. A final wash with glacial acetic acid removed soluble carbohydrates. The residues were then washed several times with water and mounted in glycerine jelly matrix on slides. Percentages of pollen, spores, and microfossils observed in the samples are listed in the following table and shown graphically in figure 4. Because the number of microfossils and spores greatly exceeds the number of pollen grains, the percentages are based on the total counts.

Percent of pollen, spores, and microfossils in samples of Cooper marl from auger hole 245

	Percent in samples indicated				
	L	M	N	O	P
Pollen					
Conifers:					
Pinus; entire	2.5	.5	1.8	2.5	-------
Pinus; fragments (weighted ½)	.6	.9	1.8	1.6	4.5
Total	3.1	1.4	3.6	4.1	4.5
Picea (spruce)	1.3	.5	-------	.8	.6
Total conifers	4.4	1.9	3.6	4.9	5.1
Dicots:					
Undetermined	3.2	22.9	16.5	21.3	16.1
Woody:					
Carya (hickory)	1.9	.5	.9	-------	-------
Quercus (oak)	.6	1.8	2.8	4.9	1.3
Betuloid types	2.5	.5	-------	-------	2.6
Ulmaceae (elm family)	-------	1.8	-------	.8	.6
Ericaceae (Rhododendron type)	-------	.5	-------	-------	-------
Sapotaceae	.6	.9	-------	-------	1.3
Total woody dicots	5.6	6.0	3.7	5.7	5.8

Percent of pollen, spores, and microfossils in samples of Cooper marl from auger hole 245—Continued

	Percent in samples indicated				
	L	M	N	O	P
Pollen—Continued					
Dicots—Continued					
Herbaceous:					
Compositae (daisy family)		0.5			
Chenopodiaceae and Amaranthaceae	0.6	.5			0.6
Total dicots	9.4	29.9	20.2	27.0	22.5
Monocots:					
Undetermined	17.7	1.4	4.6	4.1	3.2
Potamogeton (pond weed)		.5			
Liliaceae (lily family)		.9			
Cyperaceae (sedge family)	1.3				
Gramineae (grass family)	.6	.9	1.8		
Total monocots	19.6	3.7	6.4	4.1	3.2
Total pollen	33.4	35.5	30.2	36.0	30.8
Spores					
Schizaeaceae		0.5	0.9		1.3
Polypodiaceae	1.3				
Fern (undet.)		2.3	4.6		
Smooth spores	26.0	17.4	25.7	19.7	18.7
Fungal spores				.8	
Total spores	27.3	20.2	31.2	20.5	20.0
Microfossils					
Hystrichosphaeridae:					
Hystrichosphaera and *Hystrichosphaeridium*	24.1	32.8	31.3	41.1	48.6
Micrhystridium sp. (large)	3.2	.5	3.7	.8	
Micrhystridium sp. (small)	12.0	11.0	1.8	1.6	.6
Rhizoflagellates			1.8		
Total microfossils	39.3	44.3	38.6	43.5	49.2
Total pollen, spores, and microfossils	100.0	100.0	100.0	100.0	100.0
Number of grains counted	158	218	109	122	155

The pollen spectrum of these samples shares several characteristics with the Brandon lignite (Oligocene) of Vermont. Characteristics that differentiate the Cooper marl from Miocene or younger sediments of the southeastern coastal region are low conifer content (2–5 percent) and the absence of Compositae pollen. (The single grain of Compositae pollen found in sample M was probably introduced during sampling or by laboratory contamination. The oldest sediments known to contain Compositae pollen are Miocene.)

Among the pollen identified as *Pinus* in these samples were a few grains that resemble *Podocarpus* cf. *P. gracilior* Pilger which is similar to pollen of some closed-cone pines. Lacking certain identification, these were lumped with the genus *Pinus*.

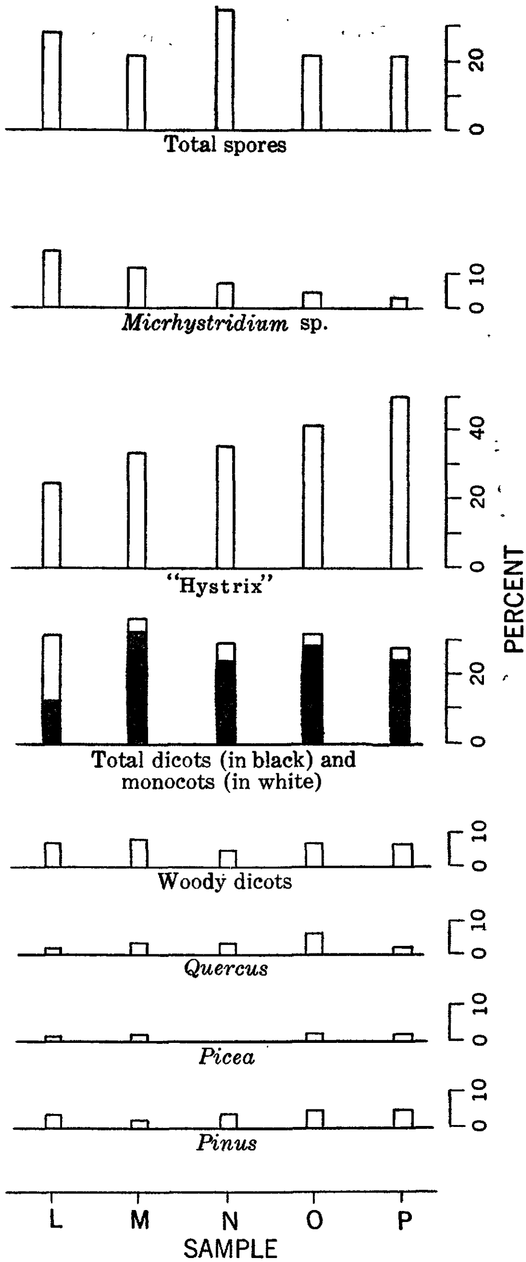

FIGURE 4.—Diagram showing percent of pollen, spores, and microfossils in a section of Cooper marl from auger hole 245.

The microorganisms of the family Hystrichosphaeridae give some clues as to the environment in which the Cooper marl was deposited. Certain living forms of hystrix (*Hystrichosphaera* and *Hystrichosphaeridium*) are marine dinoflagellate algae and, as far as is known, live at depths of 100 feet or more (Erdtman, 1954). The high percentage of this genus, particularly in the lower part of the profile, suggests that these sediments were deposited in moderately deep marine waters. However, the forms of *Micrhystridium* (affinity not known) that are prevalent in these samples are common in Pleistocene fresh and brackish water sediments. An abundance of these *Micrhystridium* forms presumably indicates shallower water and lower saline content than is suggested by an abundance of hystrix. Hence, the increasing abundance of *Micrhystridium* higher in the profile, relative to hystrix, suggests shallowing and a decreasing salinity. Pollen density in the samples supports this interpretation. It was observed that samples near the top of the profile were comparatively rich in pollen, which suggests that the water was becoming more shallow.

It is of interest that *Hystrichosphaeridium striolatum* Deflandre, from the Oligocene of Europe, is very similar to a hystrix form that is common in sample L. Other Hystrichosphaeridae identified in these samples are:

Hystrichosphaera penicillata Ehrenberg cf. *H.* forma *coronata* Wetzel
  ramosa Ehrenberg
Hystrichosphaeridium cf. *H. pseudohystrichodinium* Deflandre
Micrhystridium parvispinum Deflandre
  parvispinum forma *major* Deflandre
  cf. *M. reticulatum* Deflandre

The climate when the Cooper marl was being deposited was warm and equable, as shown by the dominance of humid mesothermal woody dicot types and the scarcity of conifers. The fact that the conifer pollen is largely *Pinus* supports this interpretation. Because the molluscan fauna indicates that the water temperature was relatively cool, suggesting the presence of a cool northern Atlantic ocean current, the land temperature was probably warmer than local sea temperature at this time.

AGE

Paleontologic evidence indicates that the Cooper marl is of Oligocene age, the basal beds exposed inland at Harleyville being early Oligocene and the higher beds nearer the coast late Oligocene. Of the molluscan species identified by MacNeil in the higher beds, seven are most nearly related to forms in the Miocene farther north, and two are close to forms in the Oligocene of Europe. Although some of the pelecypods in the phosphate rock have not been found in the Cooper, MacNeil reports that they show similar relationships, two resembling forms in nodules are reworked at the base of a section containing Pleistocene fossils and rest on the Cooper marl, it appears that the Hawthorn formation in the Charleston area has been removed by erosion, but a bed of sand and clay not more than 2 feet thick on the Cooper marl at the McDowell tunnel (see pl. 4). may be a remnant of the Hawthorn formation. No middle Miocene deposits are known farther north in South Carolina.

A study of well logs and of probable Hawthorn outcrops near Orangeburg indicates that the base of the Hawthorn formation is an unconformity dipping southward about 4 feet per mile, a trend parallel to the base of the Cooper marl, but about three times less steep.

DUPLIN MARL

NAME

The Duplin marl was named by Dall (1896, p. 40) for exposures at Natural Well near Magnolia in Duplin County, N. C. Cooke (1936, p. 117–123) summarized the subsequent use of the name for upper Miocene deposits in the Carolinas and Georgia, and described Duplin marl outcrops between the Savannah and Pee Dee Rivers in South Carolina.

A marl bed containing upper Miocene fossils was described by Cooke (1936, p. 115–117) at Raysor Bridge on the Edisto River 8 miles southwest of St. George, and named the Raysor marl; but this name is now abandoned and the bed is regarded as part of the Duplin marl, paleontologically equivalent to beds along the Pee Dee River, although older than the type Duplin in North Carolina (p. 33).

The term Duplin marl, defined as the rocks deposited in this region during late Miocene time, denotes a stage, in the time-stratigraphic sense. The Duplin has a distinctive marine fauna but little lithologic uniformity; it would be difficult to identify Duplin outcrops if adequate fossils were lacking. Many other time-stratigraphic units in the Atlantic and Gulf Coastal Plain are similarly named, but with progress in detailed mapping formations will be defined as rock units, not on the basis of age. The term Duplin marl might then be abandoned.

DISTRIBUTION

Outcrops of Duplin marl in South Carolina are most numerous in the vicinity of the Pee Dee River where, at Darlington (Cooke, 1936, p. 121), they are found as high as 170 feet above sea level. Southwest and northeast of the Pee Dee area the Duplin outcrops are scattered within a belt parallel to the coast about 50 miles wide. Places where the Duplin is known are shown on plate 3 which was compiled largely from descriptions by Cooke (1936, p. 106–107, 120–122) and Sloan (1908, p. 308, 316, 324–325). The section at the McDowell tunnel is new. An outcrop on Goose Creek, tentatively assigned by Cooke (1936, p. 129–130) to the Pliocene, is here regarded as Duplin marl (p. 34).

From plate 3, the base of the Duplin marl dips seaward (southeast) about 2 feet per mile. The strike appears to trend eastward in the north.

LITHOLOGIC CHARACTER

In the northern part of the State the Duplin varies from massively bedded, sandy limestone toward the coast to sandy or clayey coquina farther inland (Tuomey, 1848, p. 175; Sloan, 1908, p. 307–308; Cooke, 1936, p. 120–122). Similar lithologic variability occurs in the central part of the State (Tuomey, 1848, p. 178–179; Sloan, 1908, p. 281; Cooke, 1936, p. 86). Along the Savannah River the Duplin consists of shells in sand, locally indurated to impure limestone (Veatch and Stephenson, 1911, p. 372–374). In the Charleston area it varies from porous, white, indurated coquina at the McDowell tunnel to clayey, yellow, soft coquina at Goose Creek.

At several places the lower part of the Duplin contains phosphatic pebbles or sand, as at Davis Landing, Givhans Ferry, and Porters Landing. At the McDowell tunnel, granules of lustrous, black phosphate with pitted surfaces are scattered throughout. A chemical analysis showed 4.4 percent P_2O_5 (analysis 22, table 4, p. 65).

STRATIGRAPHIC RELATIONS

The base of the Duplin marl is an unconformity. Along the Pee Dee River the Duplin rests on Cretaceous rocks (Peedee formation). Farther south it lies on Eocene rocks (probably Black Mingo formation), and in the Charleston area on Oligocene rocks (Cooper marl). The Duplin along the Savannah River is on middle Miocene rocks (Hawthorn formation). Much of the erosion shown by this unconformity probably took place during the early and middle Miocene—represented by few deposits in the region—but pebbles at the base of the Duplin suggest some contemporaneous erosion.

Fossils indicate that the Duplin marl near the present coast—as at McDowell tunnel and Goose Creek—is younger than Duplin marl farther inland—as at Raysor Bridge and Davis Landing (see p. 33), showing that Duplin marl near the present coast was deposited during a regression of the sea, after the beds inland were laid down.

The Duplin marl in South Carolina is overlain by sand and clay, probably all of Quaternary age. In the Charleston area Sloan (1908, p. 291) observed that nodules of phosphate rock lie on the Duplin marl (which he called the Goose Creek marl) 0.6 mile west of Goodrich.

Sections representative of the stratigraphic relations of the Duplin marl are shown graphically on plate 3. The section at Porters Landing is from a description by Veatch and Stephenson (1911, p. 372); those at Raysor Bridge, Brick Church, Shiloh, and Davis Landing are from descriptions by Cooke (1936, p. 116, 121, 122, and 120). Altitudes of outcrops plotted on the map, but not shown graphically, are localities mentioned by Cooke (1936, p. 121–122). Descriptions of the other sections on plate 3 follow.

Section exposed in east bank of Edisto River near Givhans Ferry, about one-fourth mile upstream from old ferry road

[Altitude, 61 feet]

	Thickness (feet)
Quaternary:	
1. Surficial sand	12
Upper Miocene:	
Duplin marl:	
2. Limestone, massive, white or pale-yellow; abundant mollusks; lower 3 ft sandy; 6-in bed at base of pebbles of quartzite, phosphate rock, limestone, bone, and oyster shells. Contact with layer below abrupt and flat with one inch of relief. (colln. 14, D189–T)	12
Unconformity.	
Lower Miocene(?):	
3. Limestone, pale-yellow, sandy, fossiliferous; fine grains of phosphate; top riddled with borings of marine animals. (colln. D283–T)	1
Oligocene:	
Cooper marl:	
4. Marl, sandy, pale-yellow; friable and soft; lumps of hard marlstone; grades into layer below	8
5. Marl, olive-brown, compact; granular texture; 6 ft exposed.	

Section at shaft 1 of F. B. McDowell, Jr., Tunnel

[Commissioners of Public Works of the City of Charleston, S. C., serial no. 2248, October 1950]

[Altitude, 17 feet]

	Thickness (feet)
Pleistocene:	
1. Soil	1
2. Sand, yellow	1
3. Clay	6
4. Sand and clay	1
Unconformity.	
Upper Miocene:	
Duplin marl:	
5. Limestone, porous; made of shells cemented by calcite; granules of black, lustrous phosphate scattered throughout. (colln. D203–T)	7
Miocene(?)	
6. Sand and clay	2
Oligocene:	
Cooper marl.	

Test holes near shaft 1 of the McDowell tunnel show that the Duplin marl extends about half a mile along the line of the tunnel. The

Duplin occurs also at the inlet shaft. The stratigraphy along the tunnel, as interpreted from logs by the tunnel engineers, is shown graphically on plate 4. The sand and clay beneath the Duplin marl in several of these test holes is possibly of Miocene age.

Drab greenish clay spoil in a borrow pit, 0.4 mile south of Yeamans Hall (colln. D191–T), apparently was dredged from beneath limestone (Duplin marl) and may be stratigraphically equivalent to sand and clay beneath the limestone at the McDowell tunnel.

FAUNA

The Duplin marl has a rich molluscan fauna. About 250 species have been identified from the locality near Brick Church (Gardner and Aldrich, 1919). Almost all are pelecypods or gastropods, but collections near Charleston contain a few echinoids. The original shells are usually preserved. Fossils commonly found are *Amusium mortoni* (Ravenel), *Chlamys eboreus* (Conrad), *Chlamys jeffersonius* (Say), *Eontia incile* (Say), *Ostrea disparilis* Conrad, and *Ostrea sculpturata* Conrad.

NEW COLLECTIONS FROM SOUTH CAROLINA

Fossils from Duplin marl identified by F. S. MacNeil are listed in the following table.

Fossils from the Duplin marl

[Identified by F. S. MacNeil]

	D275–T	D276–T	D189–T 14	D191–T D192–T D291–T	27	D203–T
Gastropoda:						
Aurina cf. *A. mutabilis* (Conrad)				X		
Busycon pyrum subsp. cf. *B. excavatum* Conrad				X		
Calyptracea sp						X
Cancellaria cf. *C. rotunda* Dall	X					
Crepidula sp				X		
Crucibulum ramosum (Conrad)	X					
Cymatesyrinx lunata (H. C. Lea)				X		
Fasciolaria cf. *F. rhomboidea* Rogers	X					
Fusinus cf. *F. equalis* (Emmons)				X		
sp. aff. *F. equalis* (Emmons) and *F. dalli* Mansfield				X		
Ilyanassa sp						X
Mitra carolinensis Conrad			X			
Oliva sp						X
Petaloconchus sculpturatus H. C. Lea	X					
Polinices sp. aff. *P. heros* (Say)				X		
Terebra sp. cf. *T. unilineata* Conrad				X		
Turritella duplinensis Gardner and Aldrich				X		X
sp. aff. *T. alumensis* Mansfield						X
subannulata ochlockoneensis Mansfield			X			
n. sp. aff. *T. alaquaensis* Mansfield and "*T.* sp. aff. *T. perattenuata* Heilprin" Mansfield			X			
cf. *T. burdeni* (Tuomey and Holmes)	X					
cf. *T. cookei harveynensis* Mansfield	X					
Urosalpinx? sp				X		
Uzita consenoides (Olsson)				X		
Vermetus sculpturata H. C. Lea			X			
Xenophora sp			X			

Fossils from the Duplin marl—Continued

	D275-T	D276-T	D189-T 14	D191-T D192-T D291-T	27	D203-T
Pelecypoda:						
Amusium mortoni (Ravenel)				×	×	×
Anadara sp. cf. *A. improcera* (Conrad)			×			
sp. cf *A. propatula* (Conrad) (=*hians* Tuomey and Holmes)						×
Astarte sp. cf. *A. undulata* Say				×		
sp. cf. *A. undulata deltoidea* Gardner						×
sp. aff. *A. vaughani* Mansfield						×
Callocara cf. *C. leonensis* Mansfield	×					
Cardium sp				×		
Cerastoderma acutilaqueatum (Conrad)	×					
Chione (*Lirophora*) *athleta* Conrad	×					
Chione cortinaria Rogers and Rogers						×
sp. aff. *C. cribaria* Conrad				×		
n. sp.? aff. *C. cymaina* Gardner and *C. latilirata* Conrad				×		
Chlamys (*Plagioctenium*) *eboreus* (Conrad)						×
eboreus (Conrad)			×		×	
eboreus (Conrad) var.?			×	×		
eboreus cf. *C. darlingtonensis* Dall	×	×				
jeffersonius (Say)		×				
Dosinia? sp			×			
Eontia incile (Say)		×				
Eucrassatella gibbesii (Tuomey and Holmes)	×					×
sp. cf. *E. gibbesii* (Tuomey and Holmes)				×		
sp. aff. *E. gibbesii* (Tuomey and Holmes) and *E. undulata* (Say)			×			
Glycymeris americana (Defrance) (rugose mutant)						×
Laevicardium sp				×		
Lima carolinensis Dall				×		
Macrocallista sp	×					
Ostrea disparilis Conrad	×	×	×	×		
sp. cf. *O. disparilis* Conrad						×
sculpturata Conrad	×			×		×
sp. (juvenile)					×	
Panope sp. cf. *P. reflexa* Say	×					
Papyridea n. sp. aff. *P. spinosa* Meuschen	×					
Pecten hemicyclicus Ravenel				×		
cf. *P. ochlockoneensis* Mansfield	×					
Pecten (*Euvola*) sp						×
Phacoides densatus (Conrad)				×		
Phacoides (*Bellucina*) *tuomeyi* Dall			×			
Plicatula marginata Say	×			×		
sp. cf. *P. marginata* Say						×
Semele sp. aff. *S. alumensis* Dall						×
Thracia sp						×
Venus sp				×		×
Echinoidea:						
Echinocardium gothicum (Ravenel)				×		
Mellita sp. cf. *M. caroliniana* (Ravenel)						×
Cirripedia:						
Balanus sp			×			

NOTE.—The localities from which the fossils were collected are as follows:

Collection No.	*Description*
D275-T	Godfrey Ferry Bridge, south side of Pee Dee River at excavation for new bridge abutment on U. S. Highway 378; 7–8 feet above river level.
D276-T	Davis Landing, south bank of Pee Dee River; unit 3 of stratigraphic section given by Cooke (1936, p. 120).
D189-T 14	Givhans Ferry, east bank of Edisto River; unit 2 of stratigraphic section on page 30.
D191-T D192-T D291-T	Borrow pit 1.3 miles south-southeast of Melgrove (0.4 mile south of Yeamans Hall), near Seaboard Air Line crossing of Goose Creek, Ladson quadrangle; spoil believed to be from Duplin marl.
27	F. B. McDowell, Jr., Tunnel, inlet shaft on Foster Creek; spoil believed to be from Duplin marl.
D203-T	Shaft 1, F. B. McDowell, Jr., Tunnel; unit 5 of stratigraphic section on page 30.

In addition to the fossils listed in this table, W. C. Mansfield (*in* Cooke, 1936, p. 120) identified from locality D276-T (Davis Landing) *Cardium acutilaqueatum* Conrad?, *Venus rileyi* Conrad?, *Chama congregata* Conrad, and *Ostrea sculpturata* Conrad. From the next bed lower in the Duplin at this locality he identified *Arca* aff. *A. leonensis* Mansfield and *Panope reflexa* Say. From locality D189–T (Givhans Ferry) Mansfield (*in* Cooke, 1936, p. 86) identified in addition *Pecten raveneli* Dall and *Amusium mortoni* (Ravenel).

CHARACTER AND AGE OF THE FAUNA

F. S. MacNeil (written communication, Apr. 2 and Nov. 19, 1954) has commented on the age significance of these fossils as follows.

> Both *Chlamys jeffersonius* (Say) and *Eontia incile* (Say) occur low in the Yorktown formation of Virginia and northern North Carolina, and *Chlamys eboreus* cf. *C. darlingtonensis* Dall is close to a form in zone 1 of the Yorktown. These forms are found in the Duplin marl along the Pee Dee River. Collections near Charleston and at Givhans Ferry contain *Amusium mortoni* (Ravenel) which occurs in the highest part of the Yorktown formation and has never been found low in the upper Miocene. The type of *Pecten raveneli* Dall, identified by Mansfield at Givhans Ferry, comes from the Caloosahatchee formation (Pliocene) of Florida, and is reported from the Duplin marl in Robeson County, North Carolina. *Pecten hemicyclicus* Ravenel, a unique form in the exposures near Yeamans Hall on Goose Creek, differs from *P. raveneli* in having a much larger shell (Mansfield, 1936, p. 182). According to Abbot (1954, p. 362) *P. raveneli* is living today in the Gulf of Mexico and the Atlantic from the West Indies to North Carolina. The *Pecten* at Godfrey Ferry Bridge (colln. D275–T) is more like *P. ochlockoneensis* Mansfield than *P. hemicyclicus* Ravenel, the form at Goose Creek. The new species of *Turritella* at Givhans Ferry (colln. D189–T) was reported by Cooke (1936, p. 122) as *T.* cf. *T. etiwanensis* Tuomey and Holmes, but is more closely related to *T. alaquaensis* Mansfield and "*T.* sp. aff. *T. perattenuata* Heilprin" Mansfield. The *Eucrassatella* from the borrow pit near Yeamans Hall is longer than typical specimens of *E. gibbseii* (Tuomey and Holmes), comparing in this respect with *E. densus* (Dall). The *Fusinus* in collection D189–T at Givhans Ferry is probably the same form as the species of *Fusus* reported by Richards (1950, fig. 74–*o*) from the Waccamaw formation at Tar Heel on the Cape Fear River, North Carolina.

Druid Wilson (written communication, Dec. 4, 1953) states that the "rugose mutation" of *Glycymeris americana* (Defrance) in collection D203–T from the McDowell tunnel occurs only in the upper Miocene.

MacNeil (written communication, Nov. 19, 1954) refers the exposures at Davis Landing and Godfrey Ferry Bridge on the Pee Dee River to the lower part of the upper Miocene because they

> contain fossils characteristic of the Yorktown formation of Virginia and the *Ecphora* zone of the Choctawatchee formation of Florida . . . older than the type Duplin which is equivalent to the *Cancellaria* zone in Florida,

but he believes that the exposures near Charleston are high upper Miocene, because the fossils have affinity with Pliocene forms.

CORRELATION OF THE RAYSOR AND GOOSE CREEK MARLS OF FORMER USAGE

The marl near Raysor Bridge that Cooke called Raysor marl is correlated here, on paleontologic grounds, with the Duplin marl exposed along the Pee Dee River because, according to statements made by W. C. Mansfield (*in* Cooke, 1936, p. 115–117), the fossils suggest the same correlation as those in the Pee Dee River exposures, that is, with the Yorktown formation of Virginia and the *Ecphora* zone of the Choctawatchee formation of Florida.

Near Yeamans Hall on the southeast side of Goose Creek is a bluff of soft yellowish limestone that Sloan (1908, p. 472–473) called the Goose Creek marl, or "phase." The marl has been variously assigned to the Miocene (Ruffin, 1843, p. 28–29) and the Pliocene (Tuomey, 1848, p. 179; Tuomey and Holmes, 1857). Fossils identified by W. C. Mansfield (*in* Cooke, 1936, p. 129) include *Amusium mortoni* (Ravenel), *Ostrea scupturata* Conrad, and *Plicatula marginata* Say—forms common in the Duplin marl—and the echinoid *Encope macrophora* (Ravenel) thought to be restricted to Pliocene or younger deposits. On this basis, Cooke (1936, p. 130) tentatively referred the marl at Goose Creek to the Waccamaw formation (Pliocene), although he cautioned it "may properly belong to the Duplin." The Goose Creek outcrop is less than half a mile from the borrow pit where limestone that lithologically resembles the Goose Creek outcrop has been dated, on the basis of its fossils, upper Miocene—hence, Duplin. No doubt both these exposures are the same formation. Marl at the locality called "The Grove," east of the Cooper River and 5 miles northwest of Wando, first described by Lyell (1845a, p. 433), contains the same species as the marl on Goose Creek and appears "to occupy the same stratigraphic horizon" (Cooke, 1936, p. 129).

PLIOCENE SERIES

WACCAMAW FORMATION

DISTRIBUTION AND STRATIGRAPHIC RELATIONS

The Waccamaw formation—the marine Pliocene deposits in South Carolina—according to Cooke (1936, p. 124),

> probably occupies a broad belt that extends parallel to the coast from the North Carolina boundary through Horry County and part of Georgetown County.

Cooke also mapped Waccamaw formation along the Cooper River and Goose Creek north of Charleston, based on exposures at Yeamans Hall and The Grove that were thought to be Pliocene, but here are regarded as upper Miocene. In the northern part of the State, the Waccamaw is less than 15 feet thick and rests on Cretaceous rocks from 5 to 10 feet above sea level.

Stephenson (1914, p. 85) reported Pliocene shells overlying Cooper marl in a well at a depth of 82–83 feet at Charleston, the lowest altitude for Pliocene fossils reported in the Carolinas (see pl. 2). The highest is 65 feet above sea level along the Lake Marion-Lake Moultrie diversion canal, about 17 miles northwest of Moncks Corner, where Richards (1943, p. 3) reports *Eontia variabilis* MacNeil, a form that resembles specimens from the Waccamaw formation. None of the associated fossils are found in the Waccamaw formation; some are not known to be pre-Pleistocene; others are mainly older. Richards (1943, p. 6–7) therefore favors a late Pliocene or early Pleistocene age. Because the Waccamaw formation in North Carolina and northern South Carolina lies nearly flat, it seems improbable that the bed at the diversion canal and the fossils beneath Charleston, 150 feet different in altitude, are the same age. More likely, they are somewhat younger than the Waccamaw formation and date from an early Pleistocene fluctuation in sea level.

A NEW LOCALITY NEAR CHARLESTON

The only new Pliocene locality found during the present survey is along the drainage ditch leading from the southwest corner of the Charleston Military Airport (pl. 1) where Pliocene fossils occur in the ditch spoil. From auger borings made nearby, it is estimated that the Pliocene fossils are in a bed about 8 feet above sea level. Above this altitude in the ditch bank are nodules of phosphate rock closely packed in a clay matrix. Although this locality lies within an area shown on plate 1 as mine spoil, the bed of phosphate rock was observed where the ditch passes through an abandoned railroad grade. Apparently, the deposits beneath the railroad grade were not disturbed during mining. The fauna from this locality as identified by F. S. MacNeil is listed below.

Collection D294–T from spoil of drainage ditch leading from southwest corner of the Charleston Military Airport

[Believed to be from a bed of Pliocene age]

Gastropoda:
- *Epitonium* sp. cf. *E. pourtalesii* Verrill and Smith

Pelecypoda:
- *Arca* sp. aff. *A. subsinuata* Conrad
- *Callocardia* (*Agripoma*) *sayana* Dall
- *Cardita* cf. *C. arata* (Conrad)
- *Corbula* sp. aff. *C. inaequalis* Say
  - cf. *C. scutata* Gardner
- *Dosinia* cf. *D. elegans* Conrad
- *Erycina* cf. *E. carolinensis* Dall
- *Fossularca adamsi* Smith
- *Glaus* (*Pleuromeris*) *tridentata decemcostata* (Conrad)
- *Mulinia congesta* (Conrad)
- *Spisula* (*Hemimactra*) sp.
- *Venus* sp. cf. *V. rileyi* Conrad

The age of this fauna has been discussed by F. S. MacNeil (written communication, Nov. 19, 1954) as follows.

> The gastropod *Epitonium pourtalesii* Verill and Smith is a Recent species not previously known as a fossil, but all the other species are common Pliocene forms. Some occur, also, in the upper Miocene. *Mulinia congesta* (Conrad) has been found at a few Pliocene localities, but is a common upper Miocene species. So is *Venus rileyi* Conrad. Species of *Corbula* of the *C. scutata* type are not known earlier than Pliocene in this region. I am inclined to believe this fauna is Pliocene, most closely related to the fauna of the Croatan sand.

PLEISTOCENE SERIES

Pleistocene deposits cover nearly all the Charleston phosphate area, but were studied in detail only in the Ladson quadrangle. (See pl. 1.) Here the Pleistocene deposits are chiefly marine and can be divided into four units. In ascending order they are: the Ladson formation; sand on Tenmile Hill; the Pamlico formation; and terrace deposits along Goose Creek. Red-mottled soils (p. 74) on the eroded surface of the Ladson formation are overlain by the younger deposits. Relative ages of the younger deposits are inferred from their topographic relations.

LADSON FORMATION

NAME, SUBDIVISIONS, AND TYPE SECTION

The Ladson formation, which is here named for the town of Ladson, consists of sand and clay, coarse-grained or conglomeratic at the base, that underlies most of the ground surface in the Ladson quadrangle. Because weathering and soils alter and conceal the formation, the type section was measured from a drill hole 1 mile N. 58° W. of Ladson, but weathered parts of all units of the formation crop out in the west bank of Poppenheim Swamp west of Ladson (see pl. 1).

Outcrops in the lower part of the Ladson formation were identified by Cooke (1936, p. 148–149) as the Talbot formation, "the deposits laid down in the Talbot sea, whose abandoned shore line stands 42 feet above present sea level." He found "many exposures . . . along United States Highway 52 in the southern part of Berkeley County" (partly in the Ladson quadrangle). The upper part of the Ladson formation lies within the Penholoway terrace, as mapped by Cooke (1936, pl. 2). Deposits of the Penholoway terrace were believed by Cooke (1936, p. 130) to be older than those of the Talbot terrace, but mapping and auger boring in the Ladson quadrangle has shown that deposits of the Talbot terrace underlie those of the Penholoway terrace. No attempt was made to trace the terraces as erosional forms and search for regional clues as to their origin, but in the Ladson quadrangle they seem to correspond best with bounding planes between layers differing slightly in lithology (p. 53).

Earlier, Sloan (1908, p. 477–484) had variously identified these beds of the Ladson formation with the Lafayette Phase, the Hampton clays, the Ten-Mile sands, and the Accabee gravels—names no longer used.

The Ladson formation is divided into four mapped members (pl. 1). In ascending order these members are characterized respectively by phosphate; fine sand; medium-grained sand; and coarse sand. Representative sections are shown graphically in figure 5. Subsurface correlations (see p. 84-95) are shown in plate 5. The description of the type section follows:

Log of auger hole 242, 1 mile N. 58° W. of Ladson

[Altitude 56 feet]

	Thickness (feet)
Top eroded. An estimated 15 ft has been removed from the coarse sand member.	
Ladson formation:	
Coarse-sand member:	
1. Sand, coarse, very slightly clayey, yellow to reddish-yellow (7.5 *Y* 7/8); very dark brown humus in upper one-half foot	3
2. Sand, coarse, slightly clayey; very dark brown changing downward to light brownish gray; firm in upper part; friable below	4
Total coarse sand member	7
Medium-sand member:	
3. Sand, medium-grained; and stiff, very pale yellowish gray clay (10 *YR* 8/2)	1½
4. Clay interlaminated with medium-grained sand; stiff; pale-brown to pale-yellowish-gray; lower part more sandy	1½
Total medium-sand member	3
Unconformity?	
Fine-sand member:	
5. Sand fine and pale-yellow clay (2.5 *Y* 8/4): upper foot mostly clay	3
6. Clay, slightly fine sandy, stiff, pale-yellow	2
Total fine-sand member	5
Phosphate member:	
7. Medium-grained sand and clay, very light gray; sparse grains of phosphate	6
8. Sand, fine- and medium-grained, clayey, gray (5 *Y* 5/1); lower half mostly fine sand	7
9. Clay and fine sand, plastic, gray; abundant grains and pebbles of phosphate	5½
Total phosphate member	18½
Total Ladson formation	33½
Unconformity.	
Cooper marl:	
10. Marl, olive (5 *Y* 4/3); phosphate grains in upper part; shells; upper foot soft; 8½ ft penetrated.	

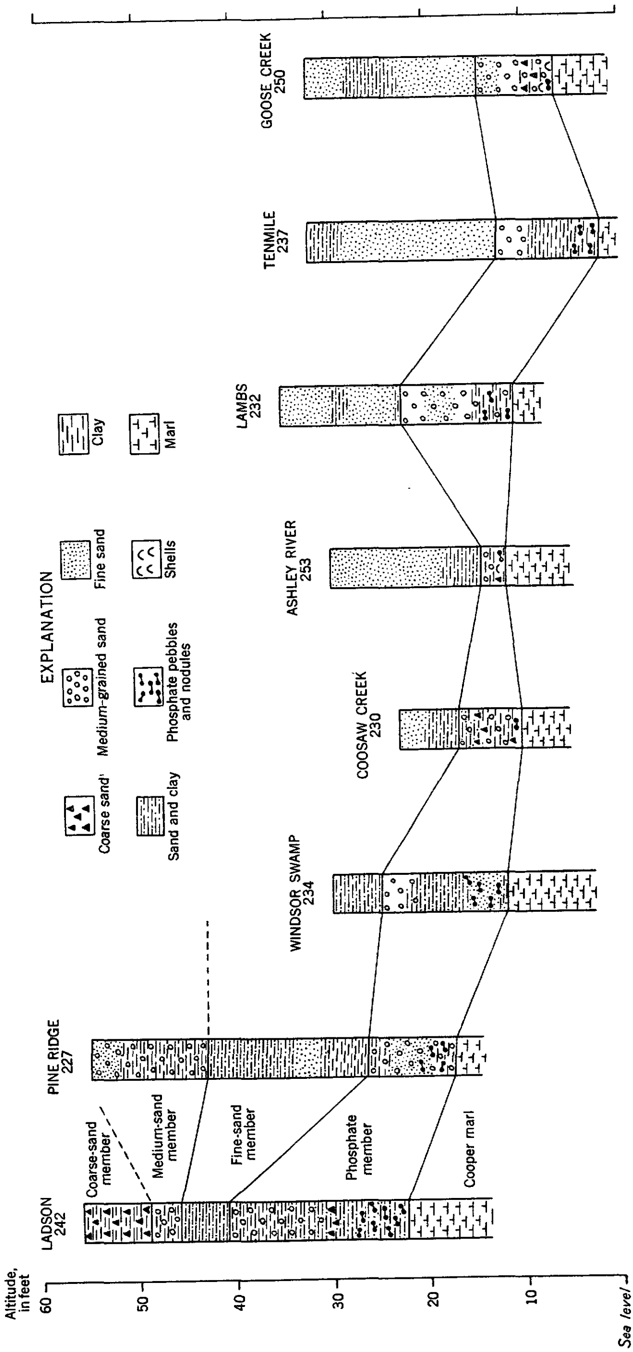

FIGURE 5.—Representative sections of the Ladson formation.

PHOSPHATE MEMBER

GENERAL FEATURES

The phosphate member of the Ladson formation includes all beds at the base that are dominantly medium or coarse grained, or conglomeratic, and contain phosphate. Commonly the phosphate is concentrated in the lower part as grains of coarse sand, or as pebbles or cobbles of phosphate rock.

Sloan (1908, p. 335) observed that

> rounded lumps of phosphate rock appear in two distinct phases; first resting on the Ashley-Cooper marls in extension of the original beds; second as transported material . . . accumulated during the Pleistocene.

The words "extension of the original beds" refer to outliers of the Edisto marl (abandoned), said to be phosphatized marl which forms a "more or less continuous sheet about one foot thick" (Sloan, 1908, p. 471) inland from the Charleston area. Thus, Sloan recognized both undisturbed and reworked phosphate rock. Fossils in the phosphate rock, identified as Miocene by Dall (1894, p. 300–301), apparently led Sloan to his conclusion that some lumps of phosphate rock are Miocene outliers on Cooper marl, but fossil collections made during the present survey show that the phosphate rock contains the fauna of the Cooper marl (p. 21). Accordingly, the phosphate rock may occur either as a phosphatized upper part of the Cooper marl (see p. 45–46) or as reworked material. Only the reworked phosphate rock is part of the Ladson formation.

The workers who followed Sloan spent little time studying the age and stratigraphy of the phosphate rock. Vaughn (1912, p. 807) and Rogers (1914, p. 188) continued to use the name Edisto marl and suggested stratigraphic equivalence with the St. Marys formation (middle Miocene) of Maryland. Cooke (1936, p. 112–115) included the phosphate rock in the Hawthorn formation.

DISTRIBUTION AND OUTCROP

The phosphate member crops out intermittantly in bluffs on the south side of the Ashley River from Griggs Landing (colln. D284–T, fig. 3) to Drayton, 3 miles downstream from Magnolia Gardens. On the north side of the Ashley River most of the former outcrops have been mined out. Weathered parts of the phosphate member, covered with soil, border Goose Creek and Windsor Swamp.

The distribution of phosphate rock in South Carolina was shown first in a map by C. U. Shepard, Jr. (*in* Penrose, 1888, pl. 1). The map was modified by Rogers (1914, pl. 2) whose map, with additions, is reproduced here as figure 6. The "river rock" shown on the map is gravel reworked in present estuaries and younger than the "land

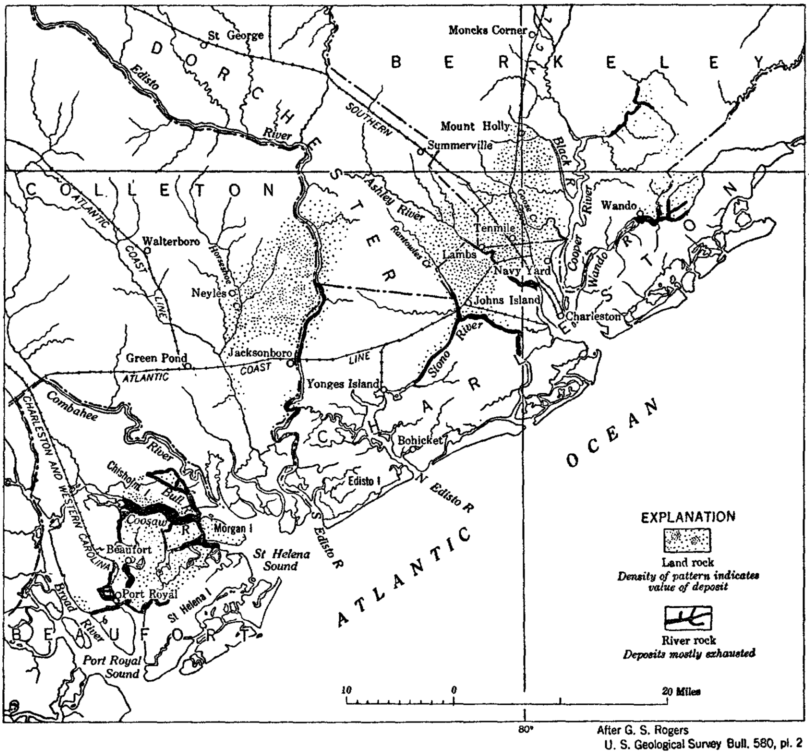

FIGURE 6.—Map showing the approximate original distribution of phosphate rock in South Carolina. (After Rogers, 1914, pl. 2.)

rock." According to various authors, the "land rock" throughout the region stratigraphically and lithologically resembles phosphate rock in the Charleston area.

In Beaufort County the phosphate rock is near the shore and about at sea level. Northward, deposits of phosphate rock lie farther inland and as high as 12 to 15 feet above sea level; toward the coast the deposits decline in altitude to about 3 feet above sea level. The base of the phosphate member of the Ladson formation lies above 20 feet altitude in the northwest part of the Ladson quadrangle, but only the beds below 15 feet altitude contain large amounts of phosphate rock. Although the base of the phosphate rock has several feet of relief locally (Rogers, 1914, p. 189–199), the beds dip seaward (southeast) about 1 foot per mile. Along the present shoreline near Charleston the phosphate rock would lie 5 to 10 feet below sea level if preserved.

Natural outcrops of the phosphate member are few, but excavations expose weathered deposits in several places in the Ladson quadrangle (see pl. 1).

Borrow pits:
- 0.4 mile northwest of Goodrich.
- 0.7 mile north of The Farms.
- 1 mile northeast of The Farms, adjacent to Goose Creek.
- 0.7 mile east of Goose Creek Reservoir where crossed by U. S. Highway 78.
- 1.5 mile northeast of Ladson along road near confluence of Ancrum Swamp and Goose Creek.

Drainage ditch leading from the southwest corner of the Charleston Military Airport. (See p. 35.)

Railroad cuts:
- 0.2 mile north of Otranto.
- On north side of Goose Creek Reservoir, adjacent to U. S. Highway 52.

LITHOLOGIC CHARACTER

The phosphate member consists of unconsolidated gravel, sand, and clay, rather poorly sorted into layers. The gravel is concentrated in the lower 2 feet and is composed of irregular pieces of phosphate rock (more or less closely packed), rounded pebbles of phosphate and quartz, mixed sizes of sand (partly phosphatic), and clay. Bones, fish teeth, and shells are common in the gravel, and shells locally occur higher. Above the gravel, the deposit is better sorted: pure sand and pure clay are found, although layers of mixed sand and clay are more common. Some of the sand is "fine sand" (0.125–0.25 mm), but most is "medium-grained sand" (0.25–0.50 mm) or coarser. Sand above the gravel is not ordinarily phosphatic. Where unweathered the phosphate member is gray, olive gray, or yellowish gray. Some layers that carry ground water are stained yellow or brown. Weathered parts are vividly mottled red, yellow, and gray.

Penrose (1888, p. 62–63) described eleven varieties of phosphate rock in South Carolina that differ as to color, surface enamel, chalkiness, contained sand, shells, concretionary laminae, and ferruginous impurities. Several are dark-colored rounded pebbles with enameled surfaces that are most abundant in the "river rock" estuary deposits. In the "land rock," the most abundant variety is light brown and chalky without enamel, constituting most of the phosphate rock in the Charleston area.

Phosphate rock in the Charleston area occurs as nodules that range in size from small pebbles to large cobbles. The term "nodule" is locally used to indicate an irregular, rounded outline and the presence of tunnellike holes, which give the rock pieces intricate shapes. Various authors have attributed these holes to solution or to boring by clams. The nodules are pale brown, faintly mottled with darker brown, and weather white. Freshly broken surfaces show fine granular texture, differing only in color from the texture of fresh surfaces of Cooper marl. The nodules are massive. Although indurated, they are easily scratched with a knife to form a chalky powder. The nodules range between 2.2 and 2.5 in specific gravity.

Molds of fossils are prominent in the nodules. Those of the megafossils are cavities showing the external and internal walls of shells; those of Foraminifera (far more abundant) are similar, but the smaller Foraminifera commonly occur only as external molds. Original shells are not preserved. Some rounded grains of pale-brown, amorphous phosphate, scattered throughout, are replacements of Foraminifera. Other fossils are fish teeth and bone fragments, but these are very scarce. The voids representing former shells constitute about one third the volume.

Phosphate in the nodules occurs chiefly in two forms. About 10 percent is in lustrous brown grains 0.1 to 0.5 mm in diameter, at least some of which are phosphatized Foraminifera. Most of the remaining phosphate makes a microcrystalline groundmass. Seen in thin section, the groundmass is brown and partly opaque. Clusters of phosphate grains about 0.002 mm in diameter are common around minute voids in the nodules, but the phosphate elsewhere is much finer grained. The pebbles are dense and have a surface enamel, but otherwise resemble the groundmass of the phosphate-rock nodules. Chemical analyses (analyses 28–33, table 4, p. 65) show about 28 percent P_2O_5. This is equivalent to 61 percent "bone phosphate of lime," a figure computed by multiplying percent P_2O_5 by 2.18.

Scattered throughout the nodules are subangular and angular grains of quartz and some feldspar, 0.05 to 0.3 mm in diameter, that make 10 to 15 percent of the volume.

X-ray study of the phosphate rock reveals no clay. Chemical analyses show 0.99 to 1.5 percent Al_2O_3, probably all of which can be accounted for in the feldspar. But opaque areas in thin sections are perhaps caused by clay too sparse to be detected by X-rays.

Lithologically, the phosphate rock nodules resemble the Cooper marl except that phosphate takes the place of carbonates. The chemical relation of the phosphate rock and Cooper marl is discussed on pages 62–70.

In sand and clay between nodules of phosphate rock are phosphatic pebbles with hard, shiny, pale-brown, dark-brown, or black surfaces. Some pebbles, although harder, resemble the phosphate rock nodules; others are dense, without shell molds, and resemble pebbles found rarely in the phosphate rock nodules and the Cooper marl. The chemical compositions of these varied pebbles (analyses 24–27, table 4, p. 65) compares with the phosphate rock. X-ray diffractometer patterns of phosphatic material in a pebble in Cooper marl and in a nodule of phosphate rock appear identical as shown in figure 7 and in table 3.

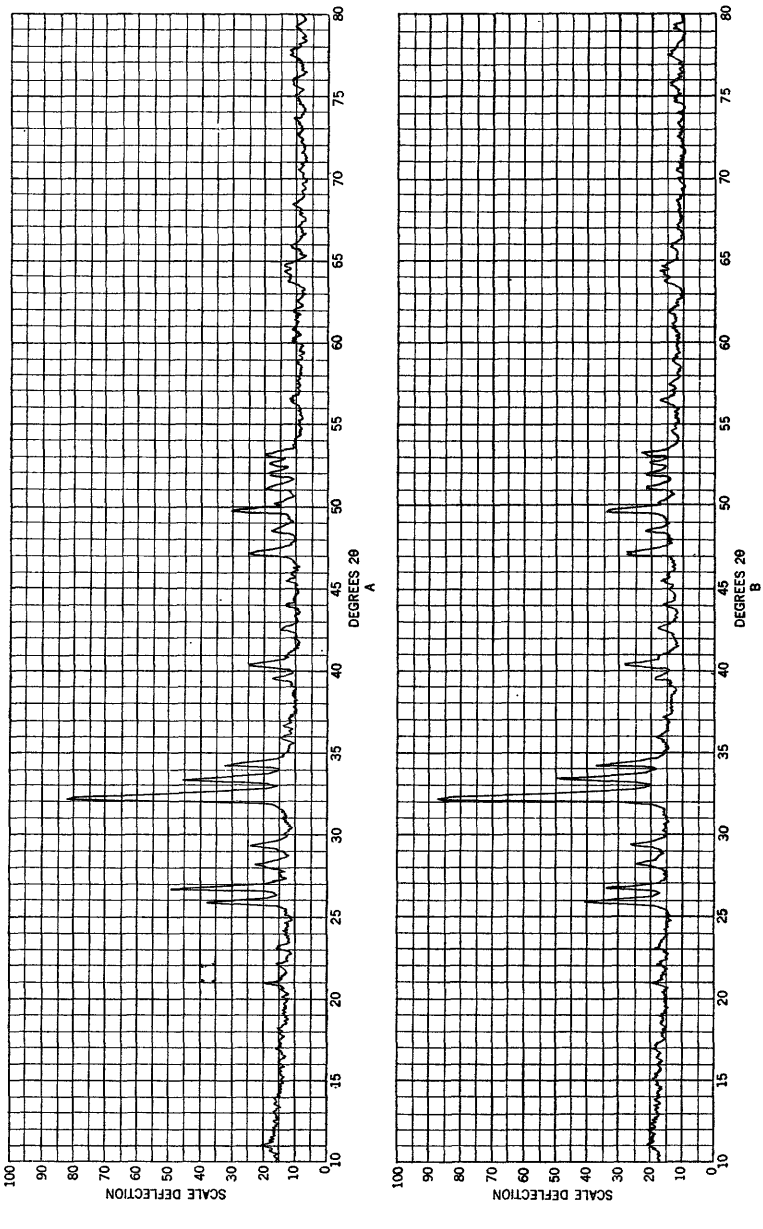

FIGURE 7.—X-ray diffractometer pattern of phosphatic material. See table 3 for location of sample.

TABLE 3.—*List of* d-*spacings of phosphatic material as measured with X-ray diffractometer*

[Copper radiation, nickel filter, λ=1.5418A]
2θ is angle of rotation on instrument used.
*d*A is *d*-spacing.
$I:I_1$ is ratio of intensity.

2θ	*d*A	A $I:I_1$	B $I:I_1$	2θ	*d*A	A $I:I_1$	B $I:I_1$
11.05	8.01	7	4	48.55	1.87	11	12
16.95	5.23	4	4	49.75	1.83	29	29
22.1	4.02	6	5	51.15	1.79	13	12
23.1	3.85	6	5	52.0	1.76	12	12
25.9	3.44	37	37	52.65	1.74	12	11
28.2	3.16	16	15	53.2	1.72	14	14
29.35	3.04	17	16	54.6	1.68	1	3
32.15	2.78	100	100	56.5	1.63	6	8
33.35	2.69	48	48	61.8	1.50	3	4
34.3	2.61	30	31	63.75	1.46	7	8
35.9	2.50	6	5	64.3	1.45	8	10
37.15	2.42	3	3	64.65	1.44	8	9
40.4	2.23	21	22	65.9	1.42	7	5
42.6	2.12	8	9	74.8	1.27	4	5
44.0	2.06	6	7	75.8	1.25	6	6
45.5	1.99	6	5	77.5	1.23	6	7
47.15	1.93	23	23	79.2	1.21	4	5

Sample A. Pebble from Cooper marl in auger hole 232, depth 24 feet.
Sample B. Nodule of phosphate rock, found 0.5 mile south-southeast of The Farms, Ladson quadrangle (analysis 29, table 4).

Pebbles and nodules closely similar in lithologic character, chemical composition, and mineral constituents may be related in origin, but not all the phosphatic materials are so similar. Sand in some phosphatic pebbles is more abundant and coarser grained than in others, indicating that not all the pebbles have the same source. Some pebbles are shaped like internal molds of pelecypods and resemble phosphatic molds in the Cooper marl (p. 10). Analysis 23 in table 4 (p. 65) shows the chemical composition of a black phosphatic pebble with conspicuous grains of coarse sand.

STRATIGRAPHIC RELATIONS

The phosphate member rests on Cooper marl along the Ashley River and at some places where the base has been reached with an auger, but appears to lie on younger formations locally. A borrow pit 0.4 mile south of Yeamans Hall (colln. D191–T) exposes limestone, believed to be Duplin marl, beneath phosphate rock. Phosphate nodules on Duplin marl were observed by Sloan (1908, p. 291) 0.6 mile west of Goodrich. A layer of nodular phosphate rock in a ditch at the southwest corner of the Charleston Military Airport lies above the level from which Pliocene fossils were apparently dredged (p. 35).

The contact on the Cooper marl ordinarily is sharp, but in places the Cooper has been partly leached and reworked into the phosphate member, obscuring the contact. As shown on plate 5, the irregular base of the phosphate member rises northwestward almost parallel to the land surface. The phosphate-bearing zone is locally 30 inches thick, but more commonly is 8 to 16 inches thick (Rogers, 1914, p. 193). Nodules of phosphate rock are not found higher than 15 feet above sea level, although phosphatic sand and pebbles extend higher.

The top of the phosphate member is chosen where the size of the sand grains changes from medium size (or coarse) to fine. However, some beds that contain fine sand lie between coarser beds and are included. As thus mapped, the phosphate member is 1 to 18 feet thick, averaging 10 feet. The top is quite regular, so the variations are due mostly to the irregular base.

Deposits younger than the Ladson formation overlie the weathered upper surface of the phosphate member at Windsor Swamp and along the upper reach of Goose Creek.

Sections of the phosphate member are given on pages 84–95.

All the phosphate-rock nodules seen during this survey were reworked, but continuous layers of similar phosphate rock have been reported apparently in place. Such layers would be older than the Ladson formation, but are mentioned here to note that the phosphatized upper surface of a marl deposit—the source of the phosphate-rock nodules—may be preserved locally.

Downward transition of phosphate nodules into unaltered marl was described first by Moses (1883, p. 506):

> At Bee's Ferry [Drayton], on the Ashley River, . . . the indurated [nodular] phosphate near the surface . . . imperceptibly goes over into the [Cooper] marl for the space of 10 feet or more.

Penrose (1888, p. 63) described similar relations:

> Occasionally large, flat . . . masses are . . . highly phosphatized on the upper side, while toward the lower side the mass grows poorer and poorer in phosphates, until it differs but little in composition from the underlying marl.

Penrose (1888, p. 63) also observed in the Bull River

> A variety [of phosphate rock] consisting of a mass of concentrically laminated nodules cemented together with a matrix of marl containing many shells.

Sloan (1908, p. 298–299) reports that at the Bolton mines, 0.3 mile south of Johns Island, a railroad station 9 miles west of Charleston, "the phosphate rock is not of concretionary structure, but consists of a bed of phosphatized marl, . . . extremely irregular and even jagged in outline, and in many instances is honeycombed with irregular spaces." At "The Dividers," a small island dividing the Edisto River at about the level of low tide, 2 miles above the Atlantic Coast Line Railway bridge at Pon Pon Station (cited by Wilmarth, 1938, pt. 1, p. 662, as the type locality of the Edisto marl of former usage) Sloan (1908, p. 285) described a hard marl, perforated by pholadae, "which, in favorable situations elsewhere, has been phosphatized to form 'phosphate rock' . . . The underlying marl conforms to the soft Ashley-Cooper type." This seems to be a description of a hardened upper surface of Cooper marl, bored by clams, but not phosphatized.

Some of the phosphate rock mined in the vicinity of Mount Holly "was in sheets, requiring blasting."[4]

Other authors have described phosphate rock nodules which seem excessively large. Leidy (1877, p. 210) reported a nodular mass of phosphate rock weighing 1,150 pounds. Penrose (1888, p. 61) observed that "the nodules . . . vary from the size of a pea to that of a mass weighing a ton or more."

FINE-SAND MEMBER

DISTRIBUTION AND OUTCROP

The fine-sand member consists of noncalcareous, evenly bedded, fairly well layered fine sand and clay overlying the phosphate member. It crops out in the central and northwest parts of the Ladson quadrangle.

Between Tenmile and Otranto the fine-sand member forms a flat surface 30 to 35 feet above sea level, dissected by tributaries of the Ashley River and Goose Creek. This surface terminates northwestward at a slope in beds of the overlying medium-sand member. Southeastward the surface is buried by the sand on Tenmile Hill (p. 54). Farther southeast, near Goodrich, the fine-sand member is less than 20 feet above sea level and mostly concealed by the Pamlico formation (p. 57).

Near Ladson and Woodstock the member is exposed in slopes bordering swamps but, except for yielding a fine sandy soil, forms no distinctive outcrops.

The Ladson quadrangle has no outcrops showing the sedimentary characteristics of the fine-sand member, but many excavations expose several feet of beds—all weathered:

Borrow pits:
- 0.2 mile northwest of Goodrich.
- 0.5 mile north of The Farms.
- 0.7 mile northeast of The Farms.
- 1 mile northeast of The Farms, next to county road.
- About a mile north of The Farms.
- At Charleston Water Works.
- 0.4 mile east of Lambs.
- About a mile north of Lambs.
- Near Peters Creek on U.S. Highway 52.

Railroad cuts:
- 0.1 mile north of Otranto.
- 0.6 mile north of Poppenheim Crossing at Ararat.

[4] Mappus, H. F., 1935, The phosphate industry of South Carolina: Thesis for M. S. degree, South Carolina Univ., Columbia, S. C., p. 11.

LITHOLOGIC CHARACTER AND STRATIGRAPHIC RELATIONS

Weathering has effaced stratification in the fine-sand member within 5 feet of the surface, but bedding can be seen in excavations. The following are typical sediments: very well sorted, massive, fine sand, in places micaceous; similar sand but with crossbedding at angles of 5° to 10°; fine sand containing thin, wavy laminae of pure clay, in places crossbedded; laminated clay, commonly with dispersed grains of fine sand. The beds range from several inches to several feet thick, and are usually sharply separated. Although the beds appear flat and can be traced several hundred feet along walls of excavations, beds cannot be matched between auger holes a mile apart. Like the phosphate member below, the unweathered fine-sand member is gray, olive gray, or yellowish gray. Staining by iron oxide is common.

The base and top of the fine-sand member are both abrupt changes to material containing medium-grained or coarse sand; the maximum thickness is 20 feet. The member thins northwestward to 5 feet at the type locality of the Ladson formation and is absent in the north-central part of the area. Exposures are inadequate to show why the member thins northwestward, but erosion is a plausible cause.

A variety of deposits younger than the Ladson formation locally lie on the weathered upper surface of the fine-sand member, as at Tenmile, near Goodrich, and along Goose Creek.

Sections of the fine-sand member are given on pages 84–95.

MEDIUM-SAND MEMBER

DISTRIBUTION AND OUTCROP

The medium-sand member forms the rather flat areas in the north-west part of the Ladson quadrangle at about 45 to 50 feet above sea level. On the southeast these flat areas are bounded by slopes in which the medium-sand member crops out, and that descend about 10 feet to the level of the fine-sand member.

LITHOLOGIC CHARACTER AND STRATIGRAPHIC RELATIONS

Unweathered beds of the medium-sand member are not exposed in the area, but a road cut 10 feet deep on U. S. Highway 52 on the north side of Goose Creek Reservoir exposes material only partly weathered. This exposure shows laminae of medium-grained sand from 3 to 5 millimeters thick that alternate with clayey laminae of comparable thickness. The laminae are wavy and crossbedded at low angles. Auger holes in the medium-sand member pass through fewer abrupt lithologic changes than are found in the underlying beds and commonly show more sand than clay. The medium-sand member contains appreciable amounts of fine sand, but can be mapped from the medium-grained sand in its soils. In addition to texture, the more massive character of the medium-sand member, as compared to underlying members of the Ladson formation, is distinctive in drill holes.

The medium-sand member rests partly on the phosphate member and partly on the fine-sand member. Local omission of the fine-sand member may indicate that the beds were originally lenticular, but more likely the medium-sand member lies on an uneven surface, once the sea floor. No special significance is inferred from the unevenness at the base; comparable irregular surfaces between less contrasting beds in the Ladson formation probably escaped notice. A change to coarse sand marks the top of the member, which is from 3 to 12 feet thick.

Sections of the medium-sand member are given on pages 84–95.

COARSE-SAND MEMBER

The coarse-sand member, the uppermost part of the Ladson formation, consists of slightly clayey, coarse sand. It crops out in the northwest corner of the Ladson quadrangle above about 50 feet altitude and extends farther northwest to form a flat area 60 to 65 feet above sea level.

Road cuts a mile northwest of Ladson, and auger holes elsewhere, show that the coarse-sand member is massive and well sorted, except for a small amount of clay.

The top of the coarse-sand member lies outside the area surveyed and was not located precisely, but finer textured deposits above the 70-foot contour indicate that the member is 15 to 20 feet thick.

MODE OF DEPOSITION

Fish teeth and mollusk shells near the base of the Ladson formation, and microfossils from the fine-sand member 15 feet above the base, show that the lower part is marine. Sedimentary features in the nonfossiliferous beds are consistent with marine origin, also. Layers of laminated clay and well-sorted sand with flat, regular contacts that can be traced hundreds of feet probably could have been laid down in this coastal area only in water relatively unagitated. On the other hand, abrupt vertical changes in lithology and some poorly sorted or crossbedded layers suggest near-shore currents. The abundant pollen and the microfauna of the fine-sand member indicate near-shore deposition in water less than 100 feet deep (p. 52).

The coarse-textured upper half of the Ladson formation contains no fossil or sedimentary clues as to its origin, but marine diatoms reported (Tabor, 1941; Richards, 1943; Flint, 1940) from 50 to 73 feet above sea level 5 miles north of Moncks Corner (fig. 1) suggest that it is marine, also.

FAUNA

Fossils from the Ladson formation are of mixed origin. Some are phosphatized mollusks, fish teeth, and bones (chiefly vertebrae), many doubtless reworked from older rocks (see Leriche, 1942, p. 98); the remainder are indigenous shells. Collections of indigenous shells were made from auger holes 225, 247, 248, 250, 251, and 253—all from the phosphate member. The fragmentary fossils in these collections are not listed here, but F. S. MacNeil (oral communication) believes they are all Pleistocene and related faunally to a better preserved collection, which he determined as follows:

Collection D206–T from shells in clay 33 feet beneath the surface at shaft 2 of F. B. McDowell, Jr., Tunnel; equivalent to unit 9 of auger hole 225, page 84.

Gastropoda:
- *Littorina* sp.

Pelecypoda:
- *Anadara* sp. cf. *A. transversa* (Say)
- *Anomia* sp.
- *Barnea* sp.
- *Corbula* cf. *C. dietziana* C. B. Adams
  - cf. *C. swiftiana* C. B. Adams
- *Gemma* sp.
- *Lunarca* sp. cf. *L. pexata* (Say)
- *Ostrea* cf. *O. virginica* Linné
- *Semele* sp.

Discussing this fauna, MacNeil says:

> All the species in collection D206–T are living forms. The best fossil for dating is *Lunarca pexata* (Say) which has never been found in deposits older than the Pleistocene. *Anadara transversa* (Say) is a common Recent species and typically Pleistocene, but there are some closely related forms in the Pliocene and upper Miocene. Both of the species of *Corbula* are closest to Recent forms. *Ostrea virginica* Linné ranges through the Pliocene into Recent. I regard this fauna as Pleistocene.

POLLEN, SPORES, AND MARINE MICROFOSSILS

By Estella B. Leopold

Ten samples of the Ladson formation from auger hole 248 (USGS paleobotany loc. D1100; p. 93) were prepared in the same way as samples of Cooper marl described on page 22. The position of the samples in the hole was as follows:

Sample	Depth (feet)	Sample	Depth (feet)
A	17½–18	F	22–23
B	18½–19½	G	23–24
C	19½–20	H	25½–27
D	20–21	I	27–27½
E	21–22	J	27½–28

Another sample from the interval 28–33 feet was prepared but proved to have too little pollen to count. Percentages of pollen, spores, and microfossils in these samples are listed in the following table and shown graphically in figure 8.

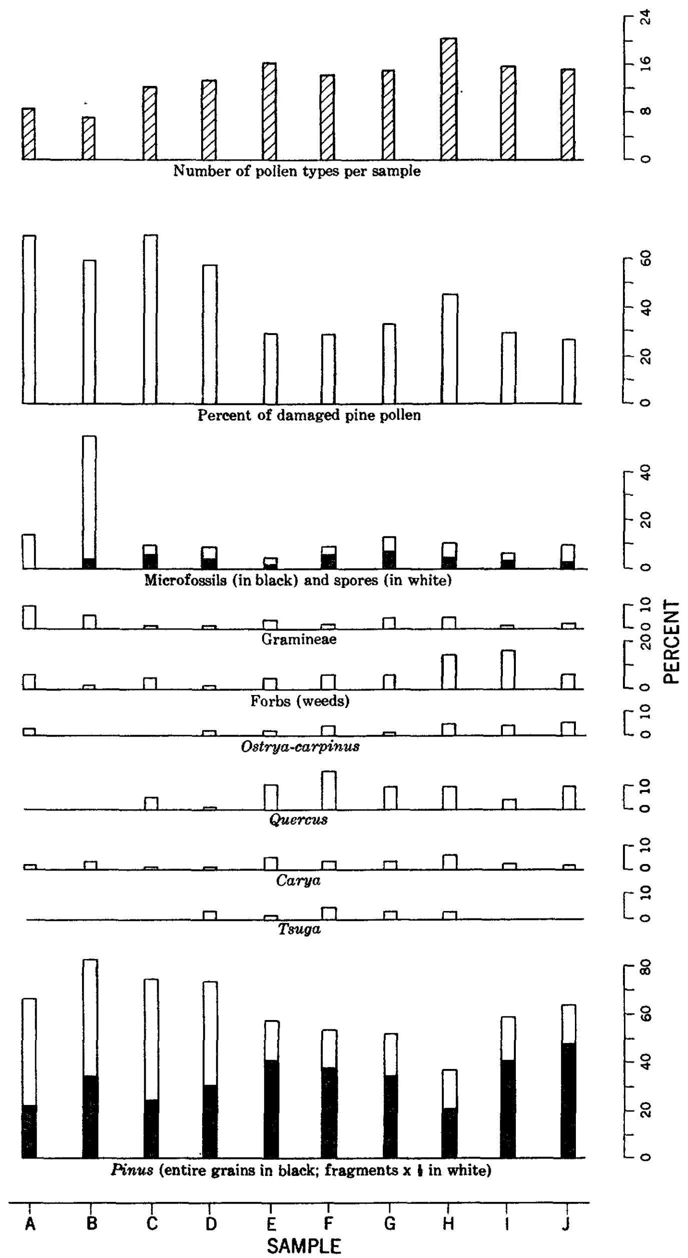

FIGURE 8.—Diagram showing percent of pollen, spores, and microfossils in a section of the Ladson formation from auger hole 248.

Percent of pollen, spores, and microfossils in samples of the Ladson formation from auger hole 248

[Percent of spores and microfossils based on amounts relative to 100 grains of pollen]

	Samples									
	A	B	C	D	E	F	G	H	I	J
Pollen										
Conifers:										
Pinus; entire	21.0	35.0	23.8	31.5	41.3	37.9	35.4	20.2	42.2	48.0
Pinus; fragments (weighted ½)	45.0	48.8	51.9	42.5	16.8	15.0	17.7	16.9	18.0	17.0
Total	66.0	83.8	75.7	74.0	58.1	52.9	53.1	37.1	60.2	65.0
Tsuga (hemlock)				1.7	.8	2.8	1.7	2.0		
Abies (fir)				.9				2.0	1.4	
Picea (spruce)							1.7	1.3		
Total conifers	66.0	83.8	75.7	76.6	58.9	55.7	56.5	42.4	61.6	65.0
Dicots:										
Undetermined	12.0	4.0	3.7	6.0	8.4	6.6	13.5	12.1	4.1	1.0
Woody:										
Fagus (beech)								.7		
Ilex (holly)								.7		
Ostrya-Carpinus (ironwood)	1.0			1.7	1.7	3.8	.8	5.4	4.1	6.0
Carya (hickory)	2.0	2.5	.7	.9	5.0	2.8	2.5	6.0	2.1	2.0
Betula (birch)					.8	1.9		1.3		2.0
Ulmus (elm)					.8	.9	.8			1.0
Quercus (oak)			5.2	.9	10.1	15.1	9.2	8.1	4.1	9.0
Acer (maple)					.8		1.7			
Alnus (alder)				.9					.7	
Corylus (hazel)			.7						.7	1.0
Ericaceae (heath family)			.7							
Theaceae (tea family)										1.0
Total woody dicots	3.0	2.5	7.3	4.4	19.2	24.5	15.0	22.2	11.7	22.0
Herbaceous:										
Compositae (daisy family)			.7	.9	1.7		.8	1.3	8.2	1.0
Chenopodiaceae (goosefoot family)	7.0	1.1	3.0		.8	1.9	1.7	6.0	2.7	2.0
Amaranthaceae (amaranth family)					1.7	4.7	2.5	6.7	5.5	3.0
Rosaceae (rose family)			1.5	.9	1.7			1.3	.7	3.0
Total dicots	22.0	7.6	16.2	12.2	33.5	37.7	33.5	49.6	32.9	32.0
Monocots:										
Undetermined	3.0	2.5	6.7	4.3	3.4	2.8	5.0	2.0	3.4	1.0
Sparganiaceae (bur-reed family)								1.3		
Cyperaceae (sedge family)	1.0	1.1		6.0	.8	1.9	.8			
Gramineae (grass family)	8.0	5.0	.7	.9	3.4	1.9	4.2	4.7	2.1	2.0
Typha latifolia (cat tail)			.7							
Total monocots	12.0	8.6	8.1	11.2	7.6	6.6	10.0	8.0	5.5	3.0
Total pollen	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Number of pollen grains counted	100	80	135	117	119	106	119	149	146	100
Spores										
Polypodiaceae		11.3	2.2			1.9		1.3	1.4	2.0
Fern (undetermined)	6.0	1.2	1.5	.9			.8	.7		
Lycopodiaceae	1.0		.7							
Smooth spores	3.0	41.2		5.1	2.5	3.8	2.5	5.4	2.7	4.0
Fungal spores			.7							
Total spores (per 100 pollen grains)	10.0	53.7	5.1	6.0	2.5	5.7	3.3	7.4	4.1	6.0

Percent of pollen, spores, and microfossils in samples of the Ladson formation from auger hole 248—Continued

	Samples									
	A	B	C	D	E	F	G	H	I	J
Microfossils										
Hystrichosphaeridae:										
Hystrichosphaera and *Hystrichosphaeridium*		1.2	1.5	.9		2.8	4.2	.7	.7	1.0
Micrhystridium sp. (small)			2.2	.9			1.7	2.7	.7	1.0
Radiolarians			.7							
Total microfossils (per 100 pollen grains)		1.2	4.4	1.8		2.8	5.9	3.4	1.4	2.0
Total spores and microfossils (per 100 pollen grains)	10.0	54.9	9.5	7.8	2.5	8.5	9.2	10.8	5.5	8.0
Number of grains counted	110	124	148	126	122	115	130	165	154	108

The dominance of pollen compared to microfossils and spores in these samples suggests a near-shore depositional environment. The presence of hystrichosphaerids and of radiolarian parts shows that these sediments are marine. Because specimens of hystrix are infrequent, however, and these forms have been collected in quantity only in marine waters more than 100 feet deep (Erdtman, 1954), the water depth was perhaps less than 100 feet while these sediments were being deposited. Variations in numbers of hystrix in the samples are regarded as too small to draw meaningful inferences as to lesser fluctuations in water depth.

The abundance throughout the profile of tree pollen characteristic of middle latitudes indicates that the climate was no cooler than today's. Comparison with the pollen spectra of modern and post-Wisconsin lake sediments from the North Carolina coastal plain (Frey, 1953) shows a considerable similarity between pollen contained in the Ladson formation and modern pollen rain in the region. However, *Nyssa* (sour gum) and *Liquidambar* (sweet gum) pollen, which constitute from 1 to 3 percent of the material examined by Frey, are absent. The amount of pine pollen at the top and bottom of the profile (65 to 80 percent), as well as the amount of oak pollen (less than 9 percent), are numerically equivalent to amounts in the modern pollen rain, suggesting a climate similar to the present. In the central part of the profile the amount of pine pollen decreases (50 to 60 percent) and the oak pollen increases (10 to 15 percent), indicating a climate warmer than the present although not as warm as during the Thermal Maximum in North Carolina (Frey, 1953). A temporary appearance of maple, holly, and beech, and an increase in hickory, grass, and Compositae pollen in these middle layers supports this interpretation.

Distribution of pollen in the profile and its state of preservation suggest that the profile is somewhat weathered. As shown at the left of figure 8, damage to pine pollen increases upward in the profile whereas, correspondingly, the variety of pollen decreases. Damage to pine pollen could have resulted from rough treatment in the laboratory, but because all the samples were prepared in the same way, the damage is presumed to reflect weathering. The decrease in variety of pollen apparently is caused partly by absence of fragile pollen types such as *Scirpus*, Rosaceae, and *Typha* that would be most easily destroyed by weathering. Because sediments at the top of the auger hole are deeply leached and weathered, the fact that the pollen spectrum far below the surface shows signs of weathering is not surprising, for pollen grains are rather susceptible to even mild oxidation.

In terms of Pleistocene stratigraphy, the similarity of the pollen assemblage to the modern pollen rain suggests that the Ladson formation is interglacial. This conclusion is of geomorphic interest because the position of these marine sediments relative to present sea level supports the view that interglacial climate caused sea level to rise.

RELATION TO COASTAL TERRACES

The Ladson quadrangle lies within a region long considered to have been terraced during successive high stands of the sea between glacial stages of the Pleistocene. According to this hypothesis, during an interglacial stage the sea rose, depositing sediment and notching the coastal plain, thus forming a terrace. Because the ocean basins were subsiding (or the continents were emerging), successively younger interglacial stages are represented by successively lower terraces. In consequence, the terrace deposits are separated by uncomformities where the coastal plain is notched.

A study of coastal terraces in South Carolina is beyond the scope of this survey, but detailed mapping in the Ladson quadrangle revealed stratigraphic relations within the Ladson formation that make identification of some of the terraces questionable. Areas heretofore considered to be underlain by younger beds are shown to be underlain by beds stratigraphically older; deposits heretofore believed to be separated by an unconformity are shown to be in stratigraphic sequence. Specifically, deposits of the "Penholoway terrace" overlie the supposedly younger deposits of the "Talbot terrace".

Relatively flat areas within the Ladson formation that have been identified with coastal terraces could have been caused by differential erosion of materials differing slightly in lithology. One of the flat areas 30 to 35 feet above sea level between Tenmile and Otranto is underlain by the fine-sand member of the Ladson formation. A smaller flat area, 45 to 50 feet above sea level between Woodstock and Ladson, is underlain by the medium-sand member. Another flat area 60 to 65 feet above sea level northwest of Ladson is underlain by the coarse-sand member. These flat areas closely approximate the bounding planes between the various lithologic units and terminate landward where the surface characteristics of the rocks change.

SAND ON TENMILE HILL

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

From Tenmile northwestward across the flat surface formed by the fine-sand member of the Ladson formation are ridges built by deposits of fine sand. These deposits are here informally termed, "sand on Tenmile Hill," after the area of high ground known locally by this name. The ridges near Tenmile are long, continuous, and slightly curved parallel to the present coast. Farther northwest the ridges are progressively less continuous and ultimately are expressed only by mounds of sand in rows. The ridges all rise from about the same altitude (35 feet) but the ridge crests decline in altitude northwestward from 46 feet at The Farms to about 40 feet near Otranto. Thus, the deposits thin northwestward. The maximum thickness is 12 feet at The Farms.

Because the sand on Tenmile Hill lies topographically high and is consequently very well drained, it is valued for agriculture. A swamp surrounded by sand on Tenmile Hill northeast of The Farms (now artificially filled) is anomalous.

The sand on Tenmile Hill may actually occupy more area than is shown on plate 1: only those deposits more than 2 feet thick are mapped because it proved impractical to distinguish the sand from the upper 1 or 2 feet of soil developed in the fine-sand member of the Ladson formation.

LITHOLOGIC CHARACTER AND STRATIGRAPHIC RELATIONS

The sand on Tenmile Hill consists of very well sorted, loose or friable fine sand or, in some places, very fine sand. The sand grains are subangular and include 1 or 2 percent of dark minerals. The sand contains no mica or clay. Fragments of woody, carbonized plant remains are common in the upper 5 feet. The top several feet of sand have weathered pale yellow, but the lower part is nearly white. Sedimentary structures are lacking, although brownish-yellow and slightly more compacted zones, 1 or 2 feet thick, are revealed in borrow pits. As these zones are not lithologically distinct and are discontinuous, they are probably not sedimentary but are due to weathering.

The base of the sand on Tenmile Hill is mapped where the loose, pale-yellow sand changes to firm, mottled sand, ordinarily somewhat clayey, or where the deposits become stratified. This criterion was used to choose the contact with the fine-sand member of the Ladson formation in auger holes 236 and 249 (p. 89 and p. 94.) Laterally from these auger holes, and throughout the area surveyed, the contact was drawn where the sand on Tenmile Hill thins so that the firm, mottled material lies within 2 feet of the surface. In the course of testing with an auger it was found that the mottled material beneath these deposits lies more or less flat. Stripping in the central area of the Charleston Military Airport exposed mottled material buried 6 feet by the sand on Tenmile Hill. Locally, as in the following section, the sand on Tenmile Hill rests directly on unweathered beds of the fine-sand member of the Ladson formation.

Section in wall of borrow pit 0.2 mile southwest of The Farms

[Altitude 45 feet]

	Thickness (feet)
Sand on Tenmile Hill:	
1. Sand, fine, very friable, very dark gray (10 *YR* 3/1); numerous fragments of carbonized wood	½
Contact gradational.	
2. Sand, fine, massive, slightly firm, brownish-yellow (10 *YR* 6/6); sparse, faint mottles of brown (7.5 *YR* 5/8) in lower part; fragments of carbonized wood decrease in abundance downward	2½
Contact indefinite, discontinuous.	
3. Sand, fine, massive, very friable, pale-yellow (2.5 *Y* 7/4); sparse fragments of carbonized wood	1½
Contact gradational, discontinuous.	
4. Sand, fine, massive, slightly firm, yellow (2.5 *Y* 6/6)	½
Contact indefinite, discontinuous.	
5. Sand, fine, massive, friable, pale-yellow (5 *Y* 7/3) with faint mottles of yellow (2.5 *Y* 7/6)	½
Contact sharp, wavy.	
6. Sand, fine, massive, moderately firm, light-yellowish-brown (2.5 *Y* 6/4)	1½
Contact indefinite.	
7. Sand, fine, massive, friable, very pale yellow (5 *Y* 8/3)	5
Total of sand on Tenmile Hill	12
Ladson formation (fine-sand member):	
8. Sand, fine, friable, very pale yellow; laminae of gray clay; flakes of mica common; 1 ft exposed.	

Sand similar to the deposit at The Farms, but lacking firm zones, is exposed south of the Ashley River. The section follows.

Section in road cut on north side of State Route 61, 0.9 mile southwest of the Ashley Marl Works (0.3 mile south of auger hole 253)

[Altitude 43 feet]

	Thickness (feet)
Sand on Tenmile Hill:	
1. Sand, fine, massive, loose, dark-grayish-brown (10 *YR* 4/2)	½
Contact gradational.	
2. Sand, fine, massive, loose, brown (10 *YR* 5/3); numerous fragments of carbonized wood	½
Contact gradational, wavy.	
3. Sand, fine, massive, friable, brownish-yellow (10 *YR* 6/6); fragments of carbonized wood	1½
Contact indefinite.	
4. Sand, fine, massive, friable, yellow (10 *YR* 7/6); fragments of carbonized wood in upper part	3
5. Covered	3
Total of sand on Tenmile Hill	8½
Ladson formation (fine-sand member) at base.	

MODE OF DEPOSITION AND AGE

Perhaps the most notable feature of the sand on Tenmile Hill is its lithologic and topographic resemblance to deposits of sand near the present shore. The lithologic resemblance was noticed by Sloan (1908, p. 481):

> The surficial part of the [Tenmile] ridge consists of a red clay-loam and clays which in places are capped with fine-grained yellow and white sands which are of much more recent origin, for they extend southerly . . . , and constitute parts of the sea island sands.

The topographic resemblance is less apparent. Topographically, the deposits of loose sand near the present shore form parallel ridges several miles long, from 5 to 10 feet high, and from 100 to 2,000 feet broad, concave toward the sea. Presumably, these deposits were constructed as beach ridges, offshore bars, or as sets of dunes—in any case, near the littoral zone. Ridges of the sand on Tenmile Hill are comparatively less uniform and continuous. No doubt their original pattern, if once more similar to deposits of sand near the present shore, has been modified by consequent drainage and by wind. Their pattern seems most of all like dunes.

Before the sand on Tenmile Hill was deposited the Ladson formation was eroded to resemble the terrain of today and then weathered to form red-mottled soils, still preserved beneath the deposits. Since then there has been no submergence because inundation during a rise in sea level would likely have destroyed the pattern of the sand on Tenmile Hill.

PAMLICO FORMATION

NAME AND DISTRIBUTION

Stephenson (1912, p. 286) named the Pamlico formation from marine deposits near Pamlico Sound in eastern North Carolina whose upper surface forms a plain nowhere higher than 25 feet above sea level. Cooke (1936, p. 149) applied the name in South Carolina to "the deposits that accumulated when the sea stood about 25 feet above its present level." As used in this report, the Pamlico formation includes sand that is mainly below 25 feet altitude, resting on weathered beds of the Ladson formation, although the mapping necessary to relate this sand to the type Pamlico formation has not been done.

The Pamlico formation is not widespread in the Ladson quadrangle, but underlies the land between the Cooper and Ashley Rivers on which Charleston is built, and the land between the Ashley and Stono Rivers. In some places the Pamlico rises 30 feet above sea level as ridges of loose sand, which resemble those of the sand on Tenmile Hill. But mostly the Pamlico formation is lower and forms a poorly drained terrain.

Inland from outcrops of the Pamlico formation is a slope—relatively steep for the region—formed partly in the Ladson formation and partly by the sand on Tenmile Hill. Because the slope trends across the regional drainage and parallels the coastline, it is perhaps a feature caused by marine erosion. Red-mottled soil is developed in the part of the slope formed in the Ladson formation and also in the flat terrain that extends seaward.

LITHOLOGIC CHARACTER AND STRATIGRAPHIC RELATIONS

Surface relief of the Pamlico formation is a guide to its lithologic character. Where the Pamlico forms well-drained ridges, 25 to 30 feet above sea level, the deposits are pale-yellow very well sorted loose or friable fine sand or very fine sand. The sand is subangular and contains from 1 to 2 percent dark grains. In the more extensive, low, poorly drained locations the sand is similar, but the deposits are dark and firm. At borrow pits where the poorly drained deposits have been exposed several years, erosion has emphasized beds from a quarter inch to more than 2 inches thick, crossbedded at angles as steep as 5°. The bedding disappears as the deposits are traced laterally into yellow friable sand at better drained locations. Evidently, expression of bedding and degree of firmness depend upon drainage and not upon the original character of the deposits. In places, the well-drained Pamlico contains slightly firm, brownish zones that resemble some zones in the sand on Tenmile Hill.

Some characteristics of the Pamlico formation are described in the sections that follow.

Section of Pamlico formation in wall of borrow pit 0.2 mile west of Goodrich

[Altitude 19 feet; land marginal to the borrow pit is poorly drained]

	Thickness (feet)
1. Sand, fine, firm, black (10 *YR* 2/1); rich in humus	½
Contact gradational, regular.	
2. Sand, fine, firm, dark-brown (7.5 *YR* 3/2); contains faint medium-sized mottles of brown; massive when freshly exposed but crossbedding is shown by sharply defined partings on the weathered face	2½
Contact indefinite.	
3. Sand, fine, friable, brown (10 *YR* 5/3); contains distinct fine mottles of dark brown; bedding as in unit 2	1½
Contact gradational.	
4. Sand, fine, friable, massive, pale-brown (10 *YR* 7/3); exposed	½
Total exposed Pamlico formation	5
Lower beds covered.	

All parts of the above section are damp. The left side of plate 6 shows the place where the section was measured.

Section of Pamlico formation in wall of borrow pit 0.2 mile west of Goodrich and 75 feet south of the preceding section

[Altitude 21 feet; land marginal to the borrow pit is well drained]

	Thickness (feet)
1. Sand, fine, loose, very dark brown; rich in humus	½
Contact sharp, irregular.	
2. Sand, fine, loose, dark-grayish-brown (10 *YR* 4/2); contains faint fine mottles of pale brown and yellow; abundant fragments of carbonized wood	½
Contact indefinite, irregular.	
3. Sand, fine, very friable, massive, light-yellowish-brown (10 *YR* 7/5); contains faint fine mottles of reddish yellow and very pale yellow	1
Contact indefinite, wavy.	
4. Sand, fine, very friable, massive, pale-yellow (2.5 *Y* 8/4); contains very faint coarse mottles of very pale brown	1
Contact indefinite, wavy.	
5. Sand, fine, very friable, massive, pale-yellow (2.5 *Y* 8/5); contains sparse distinct medium-sized and fine mottles of yellowish red (5 *YR* 5/8)	1
Contact sharp and regular on weathered face; gradational on fresh face.	
6. Sand, fine, friable, massive, pale-yellowish-gray (2.5 *Y* 8/3); contains distinct medium-sized mottles of yellowish red (5 *YR* 5/8); exposed	3
Total exposed Pamlico formation	7
Lower beds covered.	

PAMLICO FORMATION EXPOSED IN WALL OF BORROW PIT 0.2 MILE WEST OF GOODRICH

Deposits on the left are poorly drained; those on the right grade into deposits that lie 2 feet higher and are better drained. Bedding is visible in the poorly drained part, but is less distinct in the better drained part. Divisions on the pole are 1 foot long.

Beds underlying the Pamlico formation between Goodrich and Tenmile are in the fine-sand member of the Ladson formation, but the phosphate member of the Ladson formation in this vicinity is not deeply buried and may locally be in contact with the Pamlico. Extensive mine workings between the Ashley and Stono Rivers, where the land rises about 15 feet above sea level, suggest that the Pamlico in that area is underlain by the phosphate member.

Stephenson (1914, p. 71, 82) reports Pleistocene shells from 73 to 75 feet beneath Charleston. Shells at depths nearly as great in Beaufort County are assigned by Cooke (1936, p. 150) to the Pamlico formation. If the shells beneath Charleston are Pamlico, they would indicate a thickness of about 80 feet, which wedges out northwestward in about 8 miles.

FAUNA AND AGE

Between the inland edge of the Pamlico formation and the present coast are many localities of fossil shells, all lower than 25 feet, and mainly below 10 feet. According to Cooke (1936, p. 149), "most of the fossils are marine mollusks that inhabit the littoral zone along the Carolinas today." He places these fossils in the Pamlico formation and describes a number of the localities (Cooke, 1936, p. 150–154). A famous locality at Simmons Bluff, Yonges Island, on the Stono River (fig. 1) has a large fauna that lived in water either about the same temperature as now or slightly warmer.[5]

The fossils identified below by F. S. MacNeil are from light-brown sand in the outcrop area of the Pamlico.

Collection 2 from about 5 feet above sea level in light-brown sand at Pittsburgh Metallurgical Company, Charleston, 2,300 feet east of Fourmile House

[Surface altitude about 15 feet; Professor Stephen Taber, collector]

Pelecypoda:
- *Anadara* sp. (fragment)
- *Divaricella* sp. (fragment)
- *Mulinia lateralis* Say

The light-brown sand containing collection 2 is 16.5 feet thick and rests upon a compact layer of shells in sand. This layer of shells is probably part of the Pamlico formation. F. S. MacNeil identified the following fossils.

[5] Pugh, G. T., 1905, Pleistocene deposits of South Carolina, with an especial attempt to ascertain what must have been the environmental conditions under which the Pleistocene Mollusca of the State lived: Thesis, Vanderbilt Univ., Nashville, Tenn.

Collection 1 from the same locality as collection 2, but from about 2 feet below sea level in a layer of shells, closely packed in sand

[Prof. Stephen Taber, collector]

Gastropoda:
- *Acteocina canaliculata* (Say)
- *Busycon?* sp. (protoconch)
- *Terebra dislocata* (Say)

Pelecypoda:
- *Anadara transversa* (Say)
- *Anatina canaliculata* (Say)
- *Cardium robustum* Solander
- *Divaricella quadrisulcata* (d'Orbigny)
- *Lunarca pexata* (Say)
- *Mulinia lateralis* Say

MacNeil (written communication, Dec. 10, 1953) reports that

> *Anatina canaliculata* (Say) and *Lunarca pexata* (Say) are not known to have lived earlier than the Pleistocene, nor are the genera to which they are assigned known in pre-Pleistocene deposits in this part of the world. *Anadara transversa* (Say) is a common Recent species and typically Pleistocene. The other fossils occur in deposits as old as Pliocene.

Attempts have been made to date the Pamlico formation by correlating it with various Pleistocene interglacial stages when melting of ice caused sea level to rise. Flint (1940) found a scarp in Virginia, North Carolina, and Georgia, which he called the Suffolk scarp. It rises as much as 60 feet above sea level. Flint did not locate the Suffolk scarp in South Carolina, but the scarp at Suffolk, Va., superficially resembles the slope that descends seaward from Tenmile. In both places the deposits at the top of the slope (or scarp) are pale-yellow, loose sand. The beds laid down when the Suffolk scarp was formed have never been traced stratigraphically into deposits that accumulated during a retreat of Pleistocene ice, but Flint speculated that the scarp dates from the Sangamon interglacial age.

The Suffolk scarp is used by various authors to define the inland edge of the Pamlico terrace, 25 feet above sea level, which Cooke (1945, p. 248) has assigned to a "mid-Wisconsin recession" of glacial ice. The same correlation is proposed by MacNeil (1950, p. 99).

In exposures along the Intracoastal Waterway near Myrtle Beach, S. C., dark carbonaceous clay containing rooted cypress stumps at the top is overlain, apparently conformably, by 18 feet of Pamlico formation, of which the lower 6 feet are rich in marine mollusks. The clay, known as the Horry clay (Cooke, 1937), was deposited partly in fresh water and contains pollen indicative of an interglacial climate (Frey, 1952, p. 220). The radiocarbon age of the cypress stumps is greater than 20,000 years. Flint and Deevey (1951), assuming that the Horry clay and the Pamlico formation were both laid down during the same interglacial age, interpreted the radiocarbon age as dating the Pamlico formation at least as old as Sangamon, because they believed the only time since the Sangamon that the sea could have been higher than at present was during the Thermal Maximum, about 7,000 years ago. They did not discuss the possibility of a middle Wisconsin rise in sea level. Radiocarbon dates show that a rise in sea level associated with a middle Wisconsin deglaciation could not have occurred more recently than 27,500 years ago (Flint and Rubin, 1955; and Flint, 1955). Thus, the minimum radiocarbon age of the cypress stumps does not rule out a middle Wisconsin rise in sea level.

Dating the deposits here identified with the Pamlico formation will depend upon evidence not now available, but in view of weathering in early Wisconsin and older drift observed in the continental interior—apparently lacking in these deposits—they probably are not older than Wisconsin.

TERRACE DEPOSITS ALONG GOOSE CREEK

GENERAL FEATURES

In places along the valley walls bordering Goose Creek, flat areas capped by deposits of loose, yellow or brown sand define a terrace that rises upstream. The flat areas average 300 feet wide and rise from less than 20 feet altitude near the Charleston Water Works to about 25 feet at Windsor Swamp. The terrace deposits are mapped only where they are at least 2 feet thick because they are lithologically indistinguishable from a soil horizon 1 or 2 feet thick at the top of the Ladson formation. The average thickness is 4 feet.

The terrace deposits vary in lithologic character. All are dominantly fine sand, but the upstream deposits contain some medium-grained sand. This change corresponds with differences in the underlying beds. Downstream the deposits overlie the fine-sand member of the Ladson formation; upstream they overlie the phosphate member.

Weathering in the Ladson formation on which the terrace deposits rest has developed a brown hardpan on red-mottled material. Upslope from the terrace deposits, the hardpan is commonly lacking, suggesting that the weathering profiles beneath the terrace deposits were truncated by erosion.

RELATIVE AGE

The terrace deposits along Goose Creek are believed to date from a time when Goose Creek was about 15 feet above its present grade. The weathering profiles on which the terrace deposits lie are developed in beds as low as present sea level (p. 73–74), and indicate that Goose Creek would have been 15 feet above present grade after an earlier period when it stood lower.

The terrace deposits are topographically below the highest parts of the Pamlico formation and are regarded, therefore, as mainly younger.

PHOSPHATE ROCK

CHEMICAL RELATION OF PHOSPHATE ROCK AND COOPER MARL

Elsewhere in this report paleontologic, lithologic, and stratigraphic reasons were given for believing that the nodular phosphate rock was derived from the Cooper marl by chemical replacement (p. 21, 42, 45). The present discussion concerns some of the chemical similarities and contrasts. In table 4 the first twenty-one analyses are of Cooper marl; analyses 23 through 33 are of phosphatic material. On the basis of physical properties, samples of Cooper marl represented by the first six analyses are partly leached; the other Cooper marl samples are comparatively fresh. Of the phosphatic materials, those listed as analyses 28 through 33 are lithologically and paleontologically similar to Cooper marl; analyses 24 through 27 probably are also related to Cooper marl and represent the phosphatized interior molds of fossils. A black, siliceous pebble, analysis 23, has no resemblance to Cooper marl. Accordingly, only samples 24 through 33, which seem related to Cooper marl, are discussed here.

A conspicuous difference in chemical composition between the Cooper marl and the phosphate rock occurs in the proportions of SiO_2 and CaO, as shown in figure 9. The straight-line relationship shown in this graph suggests a mixture of two end members containing SiO_2 and CaO, respectively. Although the silica content of Cooper marl varies considerably, the average Cooper marl contains from two to three times as much SiO_2 as the phosphate rock. As the silica is mainly quartz, either the samples of Cooper marl have been leached of lime more than seems evident from the preservation of fossils, or

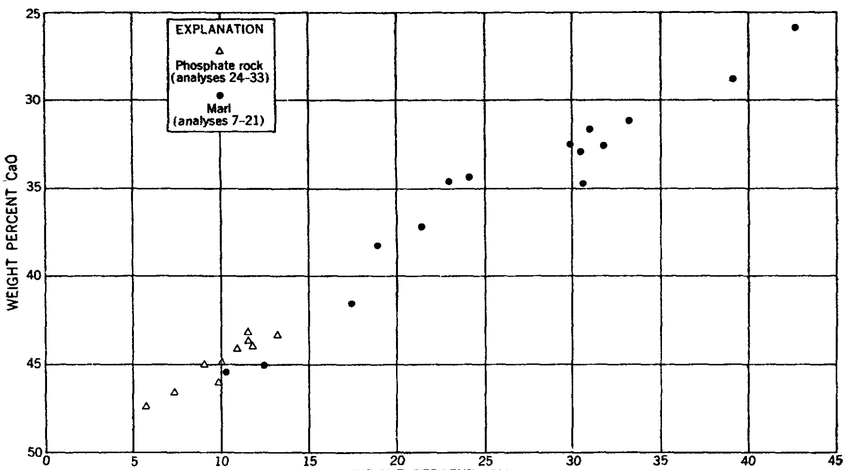

FIGURE 9.—Graph of lime and silica in Cooper marl and phosphate rock.

pore space in the marl was filled during phosphatization with a calcium compound, that is, calcium phosphate. Considering the low porosity of the Cooper, some of the siliceous minerals probably were replaced by calcium phosphate, also. Proportions of TiO_2, Al_2O_3, and some other minor constituents are different in Cooper marl and the phosphate rock, like the SiO_2, and seem to substantiate the inferred infilling and replacement. It appears that the chemical relations can be better understood if the phosphate rock and Cooper marl are considered on a silica-free basis.

If the major constituents of the phosphate rock and Cooper marl are considered on a silica-free basis, the amounts of P_2O_5 and CO_2 vary widely relative to a rather constant amount of CaO. As shown in figure 10, the amounts of these oxides in Cooper marl plot as a row of points that trend toward the amounts plotted for phosphate rock, demonstrating that the marl is partly phosphatic. A line drawn in figure 10 to connect $Ca_3(PO_4)_2$ and $CaCO_3$, representing mixtures of these compounds, would have a similar trend owing to their nearly identical content of CaO. Although the relations shown in this graph

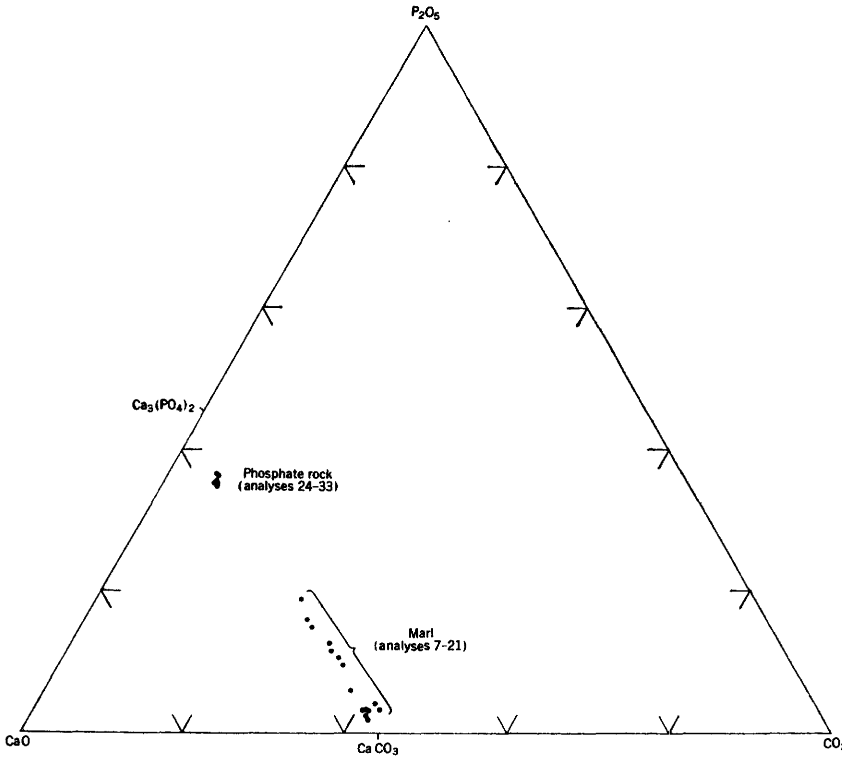

FIGURE 10.—Triangular diagram showing the relative amounts of CaO, P_2O_5, and CO_2 in Cooper marl and phosphate rock. Amounts computed from percentages listed in table 4.

TABLE 4.—*Chemical analyses of rocks*

[Samples 1-31 analyzed by Harry F. Phillips, Paul L. D. Elmore, and Katrine E. White except as follows: F, analyses 2-13, 15-20, 24, and 25 by Lillie D. Jenkins, others by Sarah Berthold; analyses of Sr by Helen Worthing and Claude L. Waring]

	Samples of Cooper marl																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	57.7	40.8	31.5	28.9	28.9	27.7	23.0	24.1	21.4	17.4	18.9	31.8	39.1	42.6	33.2	29.9	31.0
Al_2O_3	5.4	5.2	4.2	4.2	5.4	4.3	3.6	3.6	3.6	2.6	3.2	2.5	2.3	2.2	2.3	2.4	2.6
Total Fe as Fe_2O_3	1.6	2.1	1.0	1.0	1.2	.81	.61	.82	1.0	.88	1.2	.94	.85	.80	.82	.94	.86
MnO	.02	.04	.04	.04	.02	.02	.02	.02	.02	.02	.02	.02	.02	.01	.02	.01	.00
Cr_2O_3																	
MgO	1.0	6.6	9.2	10.1	7.0	4.2	3.0	2.8	2.1	1.6	2.3	1.1	1.2	1.2	1.6	1.9	2.0
CaO	15.5	18.0	21.7	21.6	24.0	29.7	34.6	34.4	37.2	41.5	38.3	32.6	28.8	25.8	31.2	32.5	31.7
Na_2O	1.0	.89	.72	.68	.65	.76	.71	.71	.58	.48	.52	.66	.59	.60	.55	.51	.54
K_2O	1.3	1.0	.83	.82	.93	.82	.69	.70	.66	.51	.58	.54	.51	.53	.48	.48	.54
TiO_2	.35	.31	.26	.23	.27	.24	.17	.20	.18	.16	.16	.18	.14	.16	.16	.14	.17
F	1.06	.64	.40	.44	.30	.28	.23	.30	.25	.30	.23	1.16	.94	1.04	.85	.87	.74
Cl																	
SrO[1]	.07	.03	.02	.01	.02	.02	.03	.05	.03	.03	.05	.1	.1	.1	.06	.06	.08
P_2O_5	9.6	5.2	3.8	3.2	2.8	2.4	2.1	2.4	2.1	1.8	2.1	8.6	8.2	8.7	7.2	5.6	6.1
CO_2	1.8	14.8	21.9	23.6	22.0	24.3	27.3	26.6	28.0	31.0	28.7	16.5	14.2	11.8	17.8	20.8	19.6
Total S as SO_3	.65	.54	.54	.43	.59	.57	.38	.52	.56	.38	1.4	.92	.98	1.0	.92	1.3	1.2
H_2O	3.8	3.8	3.3	3.3	4.7	3.1	2.5	2.5	2.5	2.3	2.9	2.6	2.2	2.4	2.3	2.4	2.6
Total	100.85	99.95	99.41	98.55	98.78	99.22	98.94	99.72	100.18	100.96	100.56	100.22	100.13	98.94	99.46	99.81	99.73
Less O for F, Cl and S	.45	.27	.17	.18	.13	.12	.10	.13	.10	.13	.10	.49	.40	.44	.36	.37	.31
Corrected total	100.40	99.68	99.24	98.37	98.65	99.10	98.84	99.59	100.08	100.83	100.46	99.73	99.73	98.50	99.10	99.44	99.42

	Samples of Cooper marl—Con.				Coquina	Samples of Phosphate member of Ladson formation										
	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
SiO_2	30.5	12.5	30.6	10.3	15.1	28.2	7.4	5.8	9.1	11.8	11.6	11.6	9.9	11.0	10.04	13.30
Al_2O_3	2.2	1.8	1.6	2.8	.70	1.5	.70	.62	1.3	.98	1.5	1.0	.84	1.0	1.06	.99
Total Fe as Fe_2O_3	.70	.72	.36	2.0	.35	2.5	2.2	1.8	2.3	1.8	2.4	1.0	1.4	1.2	1.49	1.56
MnO	.00	.02	.00	.01	.00	.00	.00	.00	.00	.01	.02	.01	.01	.02	.03	.09
Cr_2O_3	---	---	---	---	---	---	---	---	---	---	---	---	---	---	.028	.02
MgO	1.2	1.3	.90	1.0	1.2	.64	.53	.39	.41	.55	.46	.38	.52	.44	.36	.28
CaO	32.9	45.0	34.7	45.4	46.0	34.7	46.5	47.3	44.9	43.9	43.2	43.6	46.0	44.1	44.88	43.19
Na_2O	.52	.34	.35	.13	.30	1.0	1.3	1.2	1.1	1.2	1.0	1.2	1.2	1.2	.97	1.19
K_2O	.44	.33	.44	.60	.12	.58	.18	.16	.20	.24	.18	.26	.18	.26	.27	.23
TiO_2	.13	.12	.13	.07	.03	.23	.10	.10	.09	.10	.08	.09	.08	.08	.07	.08
F	.88	.32	.56	.28	.69	2.70	3.64	3.81	3.59	3.51	3.52	3.42	3.54	3.59	3.77	3.58
Cl	---	---	---	---	---	---	---	---	---	---	---	---	---	---	.02	.02
SrO[1]	.09	.05	.03	.03	.06	.2	.3	.3	.5	.3	.3	.2	.2	.2	---	---
P_2O_5	6.7	2.2	3.6	1.4	4.4	21.4	28.2	29.0	28.2	27.2	27.8	27.9	28.2	28.4	27.85	26.92
CO_2	19.4	32.8	23.5	33.8	31.3	3.9	5.8	5.8	5.0	5.3	4.6	5.0	5.2	4.9	5.11	5.06
Total S as SO_3	.91	1.0	.54	.72	.62	1.2	2.3	1.8	1.7	1.3	1.3	1.6	1.5	1.5	1.97	1.74
H_2O	2.3	2.2	1.4	2.7	1.0	3.1	3.7	4.1	4.1	3.7	4.2	4.1	3.4	3.7	[2] 3.87	[2] 3.77
Total	98.87	100.70	98.71	101.24	101.87	101.85	102.85	102.18	102.49	101.89	102.16	101.36	102.17	101.59	[3] 101.97	[4] 102.22
Less O for F, Cl and S	.37	.13	.24	.12	.29	1.14	1.53	1.60	1.51	1.48	1.49	1.44	1.49	1.51	1.65	1.37
Corrected total	98.50	100.57	98.47	101.12	101.58	100.71	101.32	100.58	100.98	100.41	100.67	99.92	100.68	100.08	100.32	100.65

[1] Calculated from spectrographic analysis of Sr by multiplying percent Sr by 1.18.
[2] Includes organic carbon and nitrogen but not water driven off at 105° C.
[3] Includes 0.18 percent acid-insoluble sulfide.
[4] Includes 0.19 percent acid-insoluble sulfide.

NOTE.—Samples are listed below by number as follows:

1–11, auger hole 249:
1. Depth 23½–24 ft.
2. Depth 24–24½ ft.
3. Depth 24½–25 ft.
4. Depth 25–26 ft.
5. Depth 26½–27½ ft.
6. Depth 27½–28½ ft.
7. Depth 28½–29½ ft.
8. Depth 29½–30½ ft.
9. Depth 30½–31½ ft.
10. Depth 31½–32½ ft.
11. Depth 32½–24 ft.

12–18, auger hole 253:
12. Depth 18–20 ft.
13. Depth 20–21 ft.
14. Depth 21½–22½ ft.
15. Depth 22½–23 ft.
16. Depth 23–23½ ft.
17. Depth 23½–24 ft.
18. Depth 24–25 ft.
19. Auger hole 245; depth 29–30 ft.
20. Airport drainage ditch.
21. Carolina Giant Cement Co., Harleyville, S. C.
22. Upper Miocene coquina; McDowell tunnel, shaft No. 1, depth 9–16 ft.
23. Black phosphate rock; borrow pit, 1.3 miles south-southeast of Melgrove, S. C.
24. Phosphatic pebble, black surface; Lambs, S. C.
25. Phosphatic pebble, brown surface; Lambs, S. C.
26. Phosphatic internal mold of a pelecypod, white; Lambs, S. C.
27. Phosphatic pebble, tan surface; Lambs, S. C.
28. Tan phosphate rock; 0.6 mile southeast of the Farms, S. C.
29. Tan phosphate rock; 0.5 mile south-southeast of The Farms, S. C.
30. Tan phosphate rock; 1.1 miles south-southeast of Tenmile, S. C.
31. Tan phosphate rock; 0.7 mile north-northeast of Goodrich, S. C.
32. Phosphate rock; Lambs, S. C. (Jacob and others, analysis 1138).
33. Phosphate rock; Bulow mines, Johns Island, S. C. (Jacob and others, analysis 1139).

are ambiguous, subject to interpretation either as mixing of phosphate and carbonate or as substitution of P_2O_5 for CO_2, the diagram at least implies that the kind of phosphatic material in the Cooper marl is the same as that in the phosphate rock, namely a kind of calcium phosphate. The composition of this calcium phosphate is shown graphically in figure 11 in terms of compounds formed by CaO, CO_2, P_2O_5, and F.

In figure 11 the amounts of $Ca_3(PO_4)_2$, CaF_2, and carbonates in the phosphate rock and Cooper marl plot nearly along a straight line, the carbonates being calculated by adding calcite and dolomite, computed from the chemical analyses (see table 5). The proportion of $Ca_3(PO_4)_2$ to CaF_2 in the Cooper marl agrees closely with their proportion in the phosphate rock. This is not at all surprising; recent studies have shown that many marine phosphates are composed of carbonate-fluorapatite (Altschuler, Cisney, and Barlow, 1953) and therefore have a more or less fixed proportion of $Ca_3(PO_4)_2$ to CaF_2. But, significantly, this proportion is constant both with respect to the phosphate in the Cooper marl, concentrated mainly in the upper

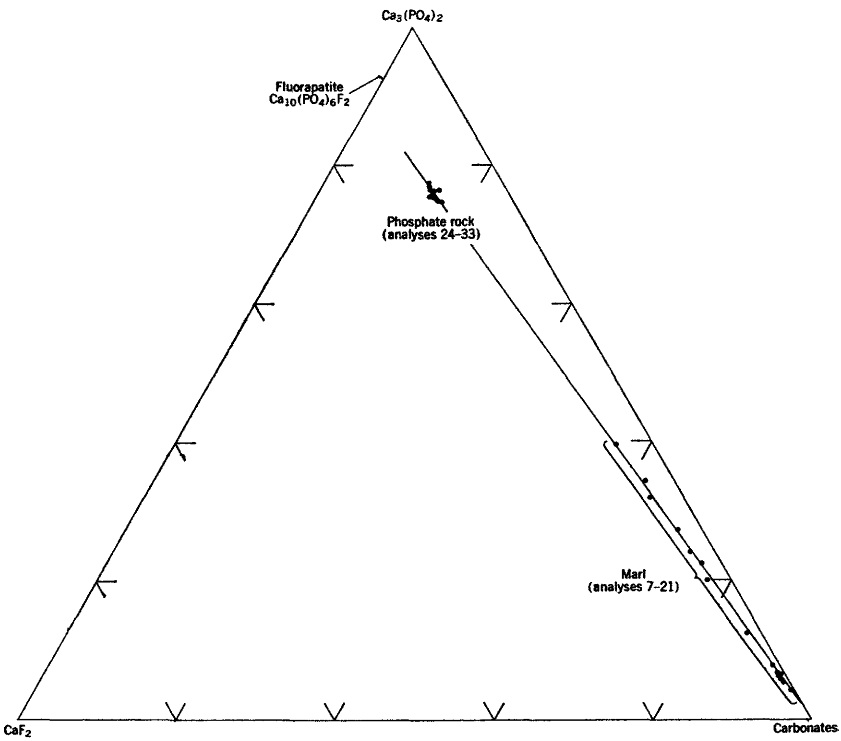

FIGURE 11.—Triangular diagram showing the relative amounts of calcium phosphate, calcium fluoride, and total carbonates in Cooper marl and phosphate rock. The relative amounts are computed from percentages listed in table 5.

TABLE 5.—*Percent of calcium phosphate, calcium fluoride, calcite, and dolomite calculated from percent of MgO, CaO, P_2O_5, CO_2 and F listed in table 4*

	1 [1]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
$Ca_3(PO_4)_2$	20.9	11.4	8.3	7.0	6.1	5.2	4.6	5.2	4.6	3.9	4.6	18.8	17.9	19.0	15.7	12.2	13.3
CaF_2	2.18	1.3	.82	.90	.62	.58	.47	.62	.51	.62	.47	2.38	1.9	2.14	1.7	1.8	1.5
Calcite [2]	4.5	5.0	9.6	7.5	22.2	39.2	51.3	50.0	59.0	68.4	61.4	36.3	30.9	23.4	36.0	40.9	39.0
Dolomite [CaO, MgO $(CO_2)_2$] [2]		26.3	37.0	42.5	25.6	14.7	9.9	9.0	4.2	1.8	3.5	1.1	1.3	3.1	4.0	5.9	5.2
MgO not accounted for	1.0	.9	1.2	.9	1.4	1.0	1.2	.8	1.2	1.2	1.5	.9	.9	.5	.7	.6	.9
CO_2 not accounted for																	
CaO not accounted for	.2																

	18	19	20	21 [1]	22	23 [1]	24 [1]	25	26	27	28 [3]	29 [3]	30	31 [3]	32	33 [3]
$Ca_3(PO_4)_2$	14.6	4.8	7.8	3.1	9.6	46.7	61.5	63.3	61.5	59.4	60.6	60.9	61.5	62.0	60.8	58.7
CaF_2	1.8	.66	1.2	.58	1.4	5.55	7.48	7.83	7.37	7.21	7.24	7.03	7.28	7.38	7.75	7.35
Calcite [2]	40.7	74.6	52.6	76.8	70.9	8.9	13.2	13.2	10.8	11.2	8.1	8.8	11.8	8.3	11.2	10.0
Dolomite [CaO, MgO $(CO_2)_2$] [2]	3.1		.74		.18				.55	.74	2.0	1.7		2.0	.37	1.3
MgO not accounted for	.5	1.3	.8	1.0	1.2	.6	.5	.4	.3	.4			.5		.3	
CO_2 not accounted for											.09	.4		.3		.04
CaO not accounted for				.3		.3	.3									

[1] Less CO_2 is available than is needed to combine with CaO remaining after forming $Ca_3(PO_4)_2$ and CaF_2. Accordingly, all the CO_2 was allotted to calcite. The percentage of CaO then remaining is listed.

[2] All the P_2O_5 was first allotted to $Ca_3(PO_4)_2$, and all the F to CaF_2. The CO_2 was then apportioned between calcite and dolomite according to the amount of CaO available, as follows: let x equal the number of calcite molecules and y the number of dolomite molecules; then $x+y$ equals the amount of available CO_2 and $x+y/2$ equals the amount of available CaO. Ordinarily, there is some surplus MgO after apportioning the CO_2.

[3] Less MgO is available than is needed to combine with CO_2 after forming calcite. Accordingly, all the MgO was first allotted to dolomite and the remaining CaO to calcite. The percentage of CO_2 then remaining is listed.

several feet as discrete amber-colored grains, and the phosphate rock, a product of chemical replacement. Apparently, the environments in which these phosphatic materials developed were similar. The large content of fluorine suggests that the environment was marine. Considering that analyses of the phosphate rock show several percent CO_2 (although the phosphate rock contains no modal carbonate), the phosphatic material is most likely carbonate-fluorapatite and similar to marine apatites found elsewhere.

Carbonate-fluorapatite, compared to ordinary fluorapatite, is characteristically deficient in P_2O_5, overfluorinated, and contains some carbonate ($CO_3^{=}$) according to Z. S. Altschuler (written communication). Carbonate-fluorapatite in the Bone Valley formation of Florida is from 3 to 6 percent deficient in P_2O_5, contains from 0.5 to 1 percent excess fluorine and about 3 percent carbonate. The formula for this mineral species can be expressed as $Ca_{10}(PO_4, CO_3)_6F_{2-3}$, where CO_3 substitutes for PO_4 (Altschuler, Jaffe, and Cuttitta, 1956). The phosphate rock of the Charleston area, as shown in figure 12, is

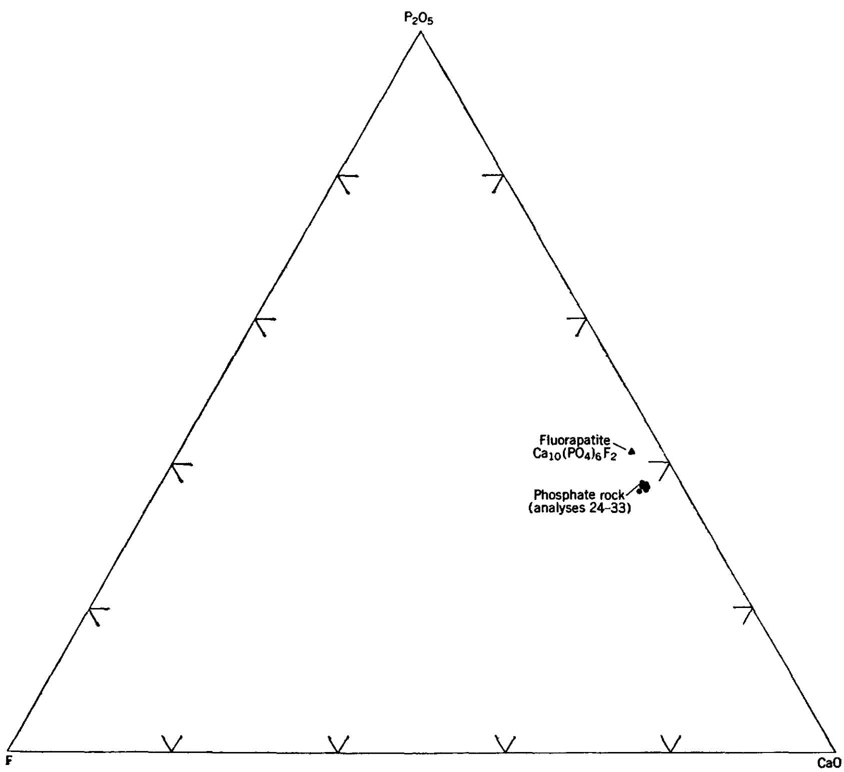

FIGURE 12.—Amounts of P_2O_5, F, and CaO in phosphate rock of the Charleston area compared to amounts in fluorapatite. Amounts calculated from percentages listed in table 4.

about 5 percent deficient in P_2O_5 and contains about 1 percent excess fluorine, compared to fluorapatite. (See also, fig. 11.) In these respects the phosphate rock chemically resembles the carbonate-fluorapatite in the Bone Valley formation. However, it contains about twice as much carbonate. (See table 4.) In the formula given above, amounts of PO_4 and CO_3 in the phosphate rock are apportioned approximately in the ratio of 5 to 1.

Other investigators have reported compositions of phosphate that differ from those of phosphate rock in the Charleston area. Sandy phosphate rock of the U.S.S.R., as reported by Bushinsky (1935, p. 91), is richer in carbonate and fluorine than the phosphate rock of Charleston. Both the Russian phosphate and that of the Charleston area contain more carbonate and fluorine than the phosphates grouped under the name "collophane" by Rogers (1922). The phosphate rock of the Charleston area apparently is most closely allied mineralogically with carbonate-fluorapatite reported from the marine phosphate deposits of French Morocco, Florida, and Idaho (Altschuler, Cisney, and Barlow, 1953).

The mode of formation of carbonate-fluorapatite is not well understood, but for the phosphate rock and Cooper marl of the Charleston area the mechanism could have been substitution of PO_4 for most of the CO_3 and enrichment in fluorine, thus replacing calcium carbonate with carbonate-fluorapatite.

Differences in some minor constituents of the phosphate rock and Cooper marl are less easily explained. The phosphate rock is 3 to 5 times richer in SrO than the Cooper marl. It contains more Na_2O and K_2O relative to Al_2O_3 than the Cooper marl: the phosphate rock averages 1.4 percent alkalies to 1.5 percent alumina; the corresponding amounts in Cooper marl are 1.1 and 2.5 percent. In Cooper marl the amounts of Na_2O and K_2O are nearly equal, but in the phosphate rock the amount of Na_2O is increased and the amount of K_2O is reduced. In places, the Cooper marl contains several percent of MgO, but the amount of MgO in the phosphate rock is small: it averages less than half the amount in samples of Cooper marl least rich in this constituent. The phosphate rock contains about 50 percent more total iron than the Cooper marl. Samples of Cooper marl relatively rich in P_2O_5 (6–8 percent) are correspondingly rich in equivalent uranium (0.006–0.008 percent). Samples poor in P_2O_5 (1–4 percent) are poor, also, in equivalent uranium (0.001–0.004 percent). In 148 samples of Cooper marl, analyzed for equivalent uranium, the average amount is 0.004 percent (range 0.001–0.008). In the phosphate rock, the average amount of equivalent uranium is 0.043 percent (range 0.025–0.063). The uranium probably is in the phosphate, because the amounts are directly proportional. Presumably, these minor differences between the phosphate rock and Cooper marl are due to exchanges and additions made at the time of phosphatization.

ORIGIN OF THE NODULAR PHOSPHATE ROCK

Earlier writers discussing the origin of the nodular phosphate rock in South Carolina were largely concerned with the environment in which a parent limy material became phosphatized. A summary of their theories is given by Rogers (1914, p. 203–209). The present discussion proposes no theory of origin, but deals with some properties of the phosphate rock that should be explained when more adequate data become available. The paleontologic, lithologic, and stratigraphic evidence is accepted as indicating that the nodular phosphate rock is phosphatized Cooper marl.

Small, amber-colored grains of phosphate are conspicuous in the Cooper marl, particularly in the upper part. Seen in thin section, many of them are phosphatic fillings and shell replacements of Foraminifera. Similar phosphatized Foraminifera are in the microcrystalline matrix of the phosphate rock and are presumed to have been inherited from the Cooper marl. Other phosphate grains of comparable size and appearance in the phosphate rock and Cooper marl are not obviously replacements of Foraminifera, but may represent analogous replacement of calcareous material. The remaining phosphate of the phosphate rock is distributed as grains of apatite comparable in size to carbonate grains in the Cooper marl.

Phosphatic internal molds of pelecypods that are mixed with the phosphate rock nodules in the lower part of the Ladson formation lithologically resemble the nodules and suggest that confinement within a shell may have aided phosphatization.

Removal of shells from the phosphate rock, leaving molds, poses a difficult problem in origin. Although limestone leached of shells in the upper several feet is rather common, cavities in the Cooper marl have nowhere been observed. If leached of shells, the soft marl would possibly compress into the openings. In fact, the phosphatic replacements of Foraminifera and low content of silica in the phosphate rock suggest that leaching of Cooper marl prior to phosphatization could not have been great. Probably the marl that was altered to phosphate rock was comparatively fresh.

Perhaps leaching of shells from the phosphate rock can be understood better by considering variations among shells in susceptibility to leaching and phosphatization. Aragonitic shells are more soluble than calcitic shells, but as shown in the following table the phosphate rock and Cooper marl have about the same number of aragonitic and calcitic pelecypod genera, although some of these genera have not

Comparison of aragonitic and calcitic pelecypod genera in the Cooper marl and phosphate rock

[Compiled by F. S. MacNeil]

	Cooper marl	Phosphate rock
Aragonitic genera:		
Antigona	×	×
Astarte	----------	×
Brachydontes	×	----------
Cardita	×	×
Cardium	----------	×
Crenella	×	----------
Nemocardium	×	----------
Panope	×	----------
Phacoides	----------	×
Venus	----------	×
Calcitic genera:[1]		
Amusium	×	×
Anomia	×	----------
Chlamys	×	----------
Gryphaeostrea	×	×
Ostrea	×	×
Pecten	×	×
Plicatula	----------	×

[1] Some of these genera have an internal aragonite layer. Their muscle attachments are commonly aragonite, also.

yet been found in both. There seems to have been no selective leaching of aragonitic pelecypods from Cooper marl prior to phosphatization. Probably the shells preserved in the phosphate rock as molds were mainly leached after the phosphate rock was formed, and leaching had no role in the conversion of marl to phosphate. Bushinsky (1935, p. 87) observed in the Russian phosphates that aragonitic shells were more easily changed to phosphate than calcitic shells, and that "fine-grained calcite crystals became phosphatized most easily, whereas the relatively coarse calcite crystals of the prisms of the shells of *Inoceramus* were the last to phosphatize." This suggests that, during phosphatization of the Cooper marl, Foraminifera and microcrystalline carbonate were converted to phosphate whereas larger, more impermeable shells remained unchanged. Later, these shells were removed by solution.

PRODUCTION AND RESERVES

Yearly production of phosphate rock in South Carolina is summarized in the following table, compiled from reports of the U.S. Geological Survey and the U.S. Bureau of Mines. A summary of the history of the phosphate industry in South Carolina is given by Rogers (1914, p. 216–218).

Phosphate rock, in long tons, produced in South Carolina

Year	Amount sold: Land rock (Pleistocene deposits)	Amount sold: River rock (Recent deposits)	Total	Amount mined [1]
Ending May 31:				
1867	6		6	
1868	12,262		12,262	
1869	31,958		31,958	
1870	63,252	1,989	65,241	
1871	56,533	17,655	74,188	
1872	36,258	22,502	58,760	
1873	33,426	45,777	79,203	
1874	51,624	57,716	109,340	
1875	54,821	67,969	122,790	
1876	50,566	81,912	132,478	
1877	36,431	126,569	163,000	
1878	112,622	97,700	210,322	
1879	100,779	98,586	199,365	
1880	125,601	65,162	190,763	
1881	142,193	124,541	266,732	
1882	191,305	140,772	332,077	
1883	219,202	159,178	378,380	
1884	250,297	181,482	431,779	
1885	225,913	169,490	395,403	
Ending Dec. 31:				
1885	149,400	128,389	277,789	
1886	253,484	177,065	430,549	
1887	261,658	218,900	480,558	
1888	290,689	157,878	448,567	
1889	329,543	212,102	541,645	
1890	353,757	110,241	463,998	
1891	344,978	130,528	475,506	
1892	243,652	150,575	394,228	
1893	308,435	194,129	502,564	
1894	307,305	142,803	450,108	
1895	270,560	161,415	431,975	
1896	267,072	135,351	402,423	
1897	267,380	90,900	358,280	
1898	298,610	101,274	399,884	
1899	223,949	132,701	356,650	
1900	266,186	62,987	329,173	
1901	225,189	95,992	321,181	
1902	245,243	68,122	313,365	
1903	233,540	25,000	258,540	
1904	258,806	12,000	270,806	
1905	234,676	35,549	270,225	
1906	190,180	33,495	223,675	
1907	228,354	28,867	257,221	
1908	192,263	33,232	225,495	
1909	201,254	6,700	207,954	
1910	[2] 179,659	(3)	179,659	
1911	169,156		169,156	
1912	131,490		131,490	
1913	109,333		109,333	
1914	106,919		106,919	
1915	83,460		83,460	
1916	53,047		53,047	39,035
1917	33,485		33,485	45,541
1918	37,040		37,040	33,673
1919	60,823		60,823	49,032
1920	44,141		44,141	42,709
1921				
1922	[4] 1,500		1,500	
1923–24				
1925	2,147		2,147	2,147
1926–37				
1938	100		100	100

[1] No records kept 1867–1915.
[2] Includes a small amount of river rock.
[3] Included in land rock.
[4] Sold from stocks of previous years.

An early estimate of the phosphate rock reserves in South Carolina was made by Moses (1883, p. 517):

> Although there are at least 500,000 acres of the lowlands and streams of South Carolina underlain by the phosphate beds, there are not more than 20,000 which it will pay to mine at present prices.

Production at that time ranged from 500 to 1,500 tons per acre, and averaged 700 tons. Technological improvements later increased both the yield per acre and the mineable acreage, owing to the ability to mine deeper, but F. B. Van Horn estimated reserves of only 3 million tons in 1909. In 1914, Rogers (p. 220) estimated reserves of 5 million tons, averaging 60 percent calcium phosphate. Mansfield (1917) later placed the amount of phosphate rock at 9 million tons. Subsequent production lowered this estimate to 8.8 million tons (Mansfield, 1925). The latest estimate of 8,798,000 tons (Jacob, 1938, p. 10) is based on the reserves originally calculated by Mansfield in 1917.

SOILS

Most soils in the Charleston area are classified by soil scientists as sandy, imperfectly drained, or hydromorphic associates of the group of Red-Yellow Podzolic soils. The term "associates" means contiguous soils. According to a definition framed in 1948 by a Committee on Great Soil Groups in the Division of Soil Survey, U. S. Department of Agriculture (Simonson, 1950, p. 316), Red-Yellow Podzolic soils are

> a group of well-developed, well-drained acid soils having thin organic (A_0) and organic-mineral (A_1) horizons over a light-colored bleached (A_2) horizon, over a red, yellowish-red or yellow, more clayey (B) horizon. Parent materials are all more or less siliceous. Coarse, reticulate streaks or mottles of red, yellow, brown, and light gray are characteristic of deep horizons of Red-Yellow Podzolic soils where parent materials are thick.

Other soils in the Charleston area are mainly classified by soil scientists as Half-bog soils that are believed to have developed under very poor drainage.

Several kinds of soils were recognized during the present study, although no attempt was made to classify them within the system used by the Soil Survey. The discussion that follows is intended to describe some aspects of weathering that are believed to be geologically significant and, accordingly, emphasizes the relation of the soils to geology. Soils recognized include: soil with red mottling, soil with brown hardpan, soil in loose sand, and soil in imperfectly drained sand.

DISTRIBUTION

Soils in the Charleston area are related to the parent materials. Red-mottled soil is developed in all exposed clayey parts of the

Ladson formation and is found as low as below tide. Soil with brown hardpan, lacking conspicuous red mottling, is developed in the Ladson formation where the material is dominantly sand. Soil in loose sand is limited to the sand on Tenmile Hill, to the well-drained sand ridges in the Pamlico formation, and to the terrace deposits along Goose Creek. Soil in imperfectly drained sand occurs in the Pamlico formation where the terrain is low.

TYPES OF SOILS

SOIL WITH RED MOTTLING

REPRESENTATIVE PROFILE

The most common soil in the Charleston area is distinguished by red mottling. Although the character of such soil changes somewhat with the terrain and kind of parent material, the profile description that follows represents soil in the Ladson formation where the parent material contains some clay, and where the terrain is relatively well drained and undisturbed by agriculture. (See plate 7.)

Generalized profile of soil with red mottling (see pl. 7)

	Thickness (feet)
Covering of leaves, pine needles, twigs, and leaf-mold less than half an inch thick.	
1. Sand, dark-gray (10 *YR* 3/2), very friable, massive	½
Contact sharp.	
2. Sand, yellowish-brown (10 *YR* 5/6), friable, massive	1½
Contact gradational.	
3. Sand, pale-yellow (10 *YR* 7/4), firm, massive	½
Contact abrupt, discontinuous.	
4. Sand, loamy, yellowish-brown (10 *YR* 5/8), rarely red (2.5*YR* 4/8), very firm; breaks into subangular clods about 1 in. in diameter; in places marked with indistinct mottles of red or yellow about half an inch across	1½
Contact gradational.	
5. Sand, loamy or clayey, very firm; mottled red and yellow where loamy; mottled red and gray where clayey; mottles vary from less than half an inch to more than 1 in across; size of mottles and amount of gray increase downward; color of mottles changes downward from red to yellow	4½
Contact sharp.	
6. Sand and clay, layered, friable; varies from light yellowish brown to gray depending upon proportion of sand to clay; coarse indistinct mottles of brown or red in upper 3 to 6 ft decrease in abundance downward	4½
Profile grades downward into layered parent material showing no effects of surface weathering.	

Most features of the mottled soil described above are widespread, but local factors modify the profile. Where disturbed by agriculture, the upper layers are mixed. Where the terrain is less well drained, the upper layers are thin. Where slopes descend from relatively flat areas, the mottled zone, unit 5, usually is near the surface; the brown

SOIL WITH RED MOTTLING EXPOSED NEAR THE SOUTHEAST CORNER OF A BORROW PIT ON U.S. HIGHWAY 52 SOUTH OF PETERS CREEK

The upper horizons of the soil are somewhat thinner than average. The numbers correspond to those in the generalized profile described on page 74. Divisions on the pole are 1 foot long.

DISCONTINUOUS BOUNDARY BETWEEN PALE-YELLOW SAND AND BROWN HARDPAN IN A SOIL WITH RED MOTTLING

Firm pale-yellow sand above very firm brown loamy sand (hardpan). The boundary between the two materials is sharp but discontinuous as shown by areas of hardpan surrounded by yellow sand. Divisions on the stake are 1 inch long.

SECTION OF RED MOTTLED ZONE IN A WEATHERING PROFILE DEVELOPED IN THE LADSON FORMATION

The top of the photograph is about 6 inches below the level where mottling begins. Divisions on the stake are 1 inch long.

HORIZONTAL SURFACE IN A RED MOTTLED ZONE

Zone is at base of section shown in plate 9. Gray streaks that outline polygons appear to be clay-filled cracks whose walls have been bleached. Divisions on the stake are 1 inch long.

hardpan, unit 4, pinches out. Less commonly, the slopes are underlain by brown hardpan without a mottled zone (fig. 13). (An interpretation of these opposing relations of hardpan to the mottled zone is given on pages 79–82.) Where poorly drained, the mottled soil differs considerably from the profile described above. The upper part is sandy, as elsewhere, but mottled sandy clay usually lies within 2 feet of the ground surface. Organic material is more abundant and extends deeper. Between the organic material and the sandy clay is a zone of nearly white sand, from 3 to 8 inches thick. Mottles in the sandy clay are very sharply defined in a gray matrix and are less red than in the better drained soils. Change in profile characteristics between areas differing in drainage quality is transitional.

CHARACTERISTICS OF THE PROFILE

The dark-gray surface layer of the mottled soils conforms closely to present topography. The yellowish-brown friable sand below similarly conforms, but locally pinches out (fig. 13). Potsherds in the yellowish-brown sand show that these upper parts of the soil developed recently. (The sherds are from pots of large diameter that were thick-walled, ¼ inch, poorly fired, unglazed, unpainted, and made from coarsely tempered clay. The interiors are smooth and commonly black. The exteriors are corrugated. Evidently, the potsherds are aboriginal.) Firm, pale-yellow sand, unit 3, beneath these layers conforms more closely to the lower part of the profile. The sand is virtually colorless and almost all quartz. Light-colored, siliceous horizons such as this in the red soils of the southeastern States have been interpreted by soil scientists as due to podzolization, a process believed to remove iron oxides and alumina and leave behind relatively immobile silica.[6] The light-colored sand is not entirely free of alumina, for some pale clay coats the grains of sand.

The hardpan, unit 4, is in the red-mottled soil wherever the parent materials are not dominantly clay and where they are moderately well drained. Sand characterizes the upper several feet of the weathering profile where the hardpan is formed. Pieces of the hardpan feel loamy when thoroughly moist, owing to fine-textured material between grains of sand. When dry, the hardpan is very difficult to crush in the hands, but it disintegrates in water, showing that the hardness is not due to a cement but probably to compaction.[7] The hardpan breaks into subangular clods, but has no inherent structure. The boundary of the hardpan with sand above is sharp but discontinuous; isolated areas of the hardpan are surrounded by pale-yellow sand, unit 3 (pl. 8). The change to red-mottled material below is

[6] For a discussion of processes leading to the development of a light-colored horizon in the upper part of red soils see Nikiforoff (1955, p. 53–56).

[7] For a discussion of this simple test, see Nikiforoff, Humbert, and Cady (1938).

gradual. In some places the lower part of the hardpan contains mottles of red that resemble the mottles below.

The hardpan is not common on the steepest slopes, although it follows closely lesser irregularities in terrain. It is part of the weathering profile in the Ladson formation in all areas where environmental conditions, enumerated above, are suitable for its development or preservation. The hardpan underlies surficial deposits in which no hardpan is found and, for this reason, is believed to have developed before these deposits were laid down. (See page 82.)

Mottling below the hardpan begins gradationally as faint areas of red less than half an inch across in brown, loamy sand. Distinctness of mottling increases with depth owing to loss of color in areas between mottles, but the redness decreases. In profile, the mottles are outlined by vertical and horizontal streaks of gray, clayey sand (pl. 9). Where the streaks first become prominent, the horizontal ones are spaced ½ to 1 inch apart; the vertical streaks are more widely spaced and somewhat more prominent. With increasing depth, the streaks become broader, more separated, and less regular; the mottles become larger, more yellow, and more diffused. Some vertical streaks branch at depth. The amount of gray increases downward. At the level where stratification can first be distinguished, taken to mark the base of the mottled zone 3 to 6 feet below its top, the soil is mostly gray.

The mottling pattern is shown by contrasts in both color and texture. Cores of mottles are characteristically deeply colored and free of clay, the edges more yellow and clayey. The gray areas are very clayey and contain medial seams of dark-gray clay, in places marked by impressions of thin rootlets. Such seams of clay are more conspicuous in the vertical streaks than in the horizontal streaks. Where the mottled zone has been exposed in excavations for several years, the mottles weather out as crudely formed hard balls, apparently cemented by iron oxide; when fresh, the mottles are soft.

Seen in plan, the mottled zone has a jointed pattern shown by gray streaks that intersect to form polygons. About 2 feet below the top of the mottled zone, the polygons are 4 to 8 inches across (pl. 10). Vertical streaks seen in profile are walls of blocks outlined by these polygons. Other gray areas seen in plan are roughly circular with a central core of dark-gray clay, commonly where the polygonal walls intersect.

SOIL WITH BROWN HARDPAN

Soil with brown hardpan, excepting soil in which a brown hardpan is underlain by a red-mottled zone, is developed in the Ladson formation where the deposits contain little clay. Because of differences from place to place, it is difficult to generalize about the characteristics of the hardpan. The three profiles described below are selected as representative.

Profile of soil with brown hardpan exposed in railroad cut 0.8 mile south of Tenmile

	Thickness (feet)
1. Sand, fine, dark-gray-brown (2.5 *Y* 4/6), loose; matted with grass roots	½
Contact gradational.	
2. Sand, fine, pale-yellow (2.5 *Y* 7/4), very friable; many fine grass roots	1
Contact gradational and discontinuous.	
3. Sand, fine, yellowish-brown (10 *YR* 5/6), very firm; faint medium-sized mottles of strong brown; few grass roots	1½
Contact gradational.	
4. Sand, fine, very pale yellow (2.5 *Y* 8/4), friable; distinct fine yellowish-brown mottles; rare flakes of white mica	1
Contact sharp and wavy.	
5. Sand, fine, light-yellowish-brown (2.5 *Y* 6/4), slightly firm; flakes of white mica	1½
Contact indefinite.	
6. Sand, fine, very pale yellow (2.5 *Y* 8/3), friable; flakes of white mica common; 1 ft exposed.	

Colors in the above profile are believed to be due to surface oxidation. Unit 6 is nearly colorless. The hardpan, unit 3, resembles hardpan that overlies red-mottled zones. Absence of mica in the upper part of the profile is believed to be due to destruction by weathering.

Profile with brown hardpan exposed in northwest wall of borrow pit 1.3 miles northwest of Lambs

	Thickness (feet)
1. Sand, fine, gray-brown (10 *YR* 5/2), very friable; fragments of carbonized wood	1
Contact sharp and wavy.	
2. Sand, fine, very pale brown (10 *YR* 7/4), friable; faint medium-sized mottles of light brown	1½
Contact sharp and wavy.	
3. Sand, fine, yellowish-brown (10 *YR* 5/8), very firm; very faint medium-sized mottles of strong brown	1
Contact gradational.	
4. Sand, fine, brownish-yellow (10 *YR* 6/8), very firm; faint medium-sized mottles of strong brown	3
Contact gradational and discontinuous.	
5. Sand, fine, dark brown (7.5 *YR* 5/8), very firm; faint medium-sized mottles of red and yellow; amount of red and degree of firmness decrease downward	3½
Contact indefinite.	
6. Sand, fine, yellow (10 *YR* 7/6), friable; streaked with brown; flakes of white mica	3
Contact sharp.	
7. Sand, fine, bedded, very pale yellow (2.5 *Y* 8/4); laminae of white mica abundant; crossbedding	3
Contact sharp.	
8. Laminated clay, mica, and sand; white (10 *YR* 8/1); 2½ ft exposed.	

Units 3, 4, and 5 in the above profile are the hardpan. Compared to hardpan at other places, this is two or three times thicker. Mottling in the lower part of this hardpan is not found where hardpan is thin. Absence of bedding in the upper 13 feet is believed to be due to soil-forming processes.

Profile with brown hardpan exposed in road cut on Summerville and Charleston Road, 0.1 mile northwest of Popperdam Creek

	Thickness (feet)
1. Sand, fine, gray-brown (2.5 *Y* 5/2), loose	½
Contact sharp and wavy.	
2. Sand, fine, brownish-yellow (10 *YR* 5/8), friable	1
Contact indefinite.	
3. Sand, fine, dark brown (7.5 *YR* 5/8), friable; faint medium-sized mottles of darker brown and lighter yellow	1
Contact gradational.	
4. Sand, fine, brownish-yellow (10 *YR* 6/8), firm; faint fine and medium-sized mottles of brown and yellow	1
Contact sharp and wavy.	
5. Sand, fine, dark brown (7.5 *YR* 5/8), very firm; distinct medium-sized mottles of brown	2
Contact indefinite.	
6. Sand, fine, yellow (10 *YR* 7/8), friable; distinct medium-sized mottles of brown and gray; sparse dark grains	1
Contact sharp.	
7. Sand, fine, yellowish-brown (10 *YR* 6/8), friable; very distinct coarse mottles of grayish yellow; 2½ ft exposed.	

Colors in the above profile are rather uniform from the base of the surface layer to a depth of 5.5 feet. The two lowest units are somewhat lighter colored. Unit 5 is the hardpan. Unit 4 may represent a kind of hardpan, also, but it is not as firm.

In detail, the soils with brown hardpan are not much alike. Thicknesses and kinds of material above and below the hardpan vary. Usually, the hardpan is overlain by somewhat lighter colored sand. Where the colors are similar, the top of the hardpan is distinguished by its firmness. The lower contact of the hardpan is gradational. Below the hardpan, preservation of bedding and of grains of mica and dark minerals indicate a decrease in weathering. Color near the surface can be attributed to the oxidized residues of these grains of mica and dark minerals preserved lower in the profile. Such residues usually tend to concentrate in the hardpan, as indicated by its dark brown color. That they do not form a cement is shown by disaggregation of the hardpan in water.

SOIL IN LOOSE SAND

The deposits of loose sand lack well-differentiated soil horizons and appear to be only slightly weathered. Because the loose sand is mostly underlain by soils with hardpan or red mottling, it has been considered by soil scientists as a horizon of these soils. But geologic mapping shows that the loose sand was deposited on the weathered Ladson formation and the soils formed by weathering of these deposits comprise a separate group. These soils include those developed in the sand on Tenmile Hill, the well-drained parts of the Pamlico formation, and the terrace deposits along Goose Creek.

Characteristics associated with weathering of the sand on Tenmile Hill and the Pamlico formation have already been described (see p. 55, 56, and 58), and the similarity of the weathering profile in terrace deposits along Goose Creek to a soil horizon 1 or 2 feet thick at the top of the Ladson formation was pointed out on page 61. Although these deposits of loose sand are highly permeable, well drained, and more or less dry, weathering is shown by a downward decrease in iron oxide stain, and by zones slightly more compacted and iron stained toward the top. In thick deposits, several such compacted zones may be seen. The compacted iron-stained material is somewhat more moist than sand above or below and seems to reflect the localization of vadose water. Yellow and pale-brown colors in the sand are believed to be due to weathering of iron-rich minerals such as mica, visible at depth where the deposits are white or gray.

SOIL IN IMPERFECTLY DRAINED SAND

Soils in sand, where water frequently stands at the surface after rains, are little modified by chemical decomposition but are dark (pl. 6). The darkness is dissipated by ignition with a blow torch, indicating combustion of organic material. Presumably, the damp environment favors plant growth but inhibits oxidation of products of organic decay. Dark organic residues extend downward several feet into sand where original bedding is preserved. If roots extended at deeply, bedding would be destroyed. Evidently, plants that contribute products of organic decay are shallow rooted—an observation supported by the paucity of roots in exposed profiles. The first section of Pamlico formation given on page 58 is a description of a soil in imperfectly drained sand. This soil grades laterally into a soil in loose sand where the land is well drained.

AGE OF THE SOILS

The soils in loose sand and in imperfectly drained sand merge and must, consequently, be about the same age. Because the deposits in which these soils are developed overlie brown hardpan and red mottled zones in the Ladson formation, these soils are the youngest features of weathering in the area.

Age relations of the soils with brown hardpan and with red nottling are more difficult to decipher, because the soils are developed on the same formation; but there is evidence that the red-mottled zones are older than the brown hardpan. Figure 13 shows that brown hardpan truncates red-mottled material and suggests that the hardpan did not form simultaneously with the red mottling. Although hardpan may normally have formed with the red-mottled zones, these relations seem to show that some hardpan developed later, and that the red-mottled zones are residual features of weathering. Some mottled zones are washed by tide water. Because the mottled zones represent oxidation and could have formed only while exposed to air, they must date from a time when sea level was lower.

The soils with brown hardpan are found near the tops of slopes. On flat areas back from the slopes are soils with red mottling below brown hardpan. Topographically, the sites are analogous to the one on the left of figure 13. Exposures are usually inadequate to trace the hardpan of the slopes continuously into hardpan on red-mottled zones in the flat areas, but testing with a soil auger suggests that hardpan of the slopes and flat areas merge. In the transition zone, the deposits a few feet deep become successively more clayey. Such a transition does not necessarily show that the hardpan is younger than the red mottling (kind of soil may be influenced by kind of parent material), but the relations shown in figure 13 are convincing evidence of age. Brown sandy hardpan at the left of the figure overlies clay. Although weathering might produce a sandy hardpan above clay, the change in texture should not be abrupt but should resemble the changes shown at the right of the figure, where sandy hardpan grades down into clay through a mottled zone in which the texture changes gradually to clay. The hardpan at the left of the figure seems to have formed in sandy slope wash deposited unconformably on the clay after red mottled material had been eroded.

Soils with brown hardpan resemble the upper parts of soils with red mottling. In turn, the soils in loose sand resemble the upper parts of soils with brown hardpan. By such analogies, it can be argued that the oldest weathering profiles are successively modified by later weathering (or deposition) and assume a polygenetic character. The kind of evidence needed to demonstrate the polygenetic character of Red-Yellow Podzolic soils is summarized by Nikiforoff (1955), and will not be discussed here. It suffices to say that the evidence is controversial. Mapping the geologic boundaries of deposits in which soils of the Charleston area are developed indicates several epochs of soil formation, but the mapping is no doubt too crude to give evidence on polygenesis of the soils. Locally, however, detailed examination of "unconformities" in the soil profiles indicates

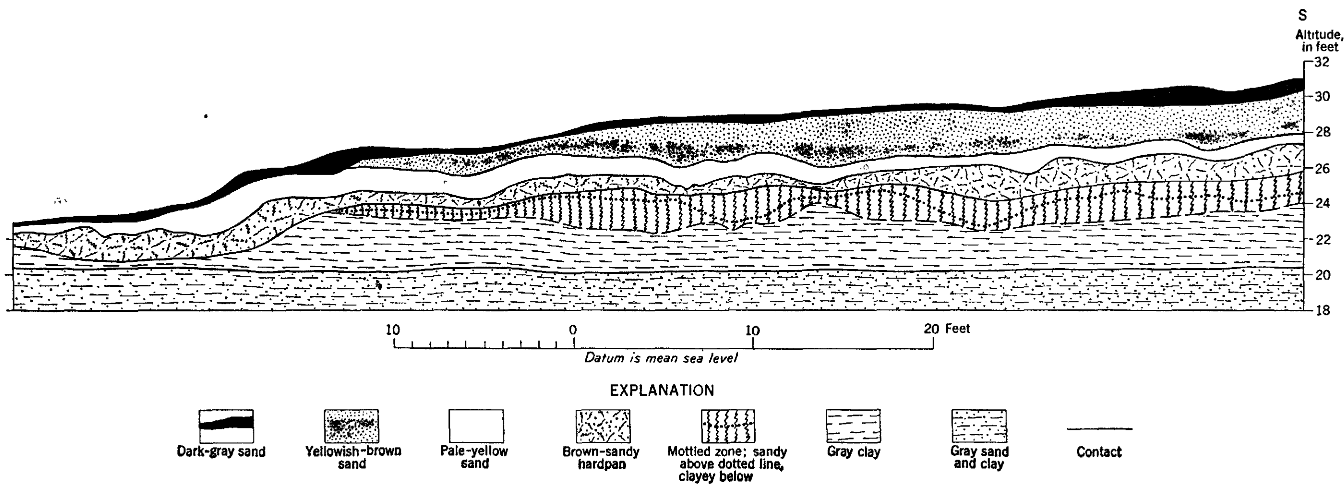

FIGURE 13.—Sketch of weathering profile in Ladson formation exposed in east wall of borrow pit on U. S. Highway 52 south of Peters Creek. Brown-sandy hardpan and soil horizons above conform more or less to present topography. A red-mottled zone pinches out where the land slopes down to Peters Creek on the north. The dotted line in the red-mottled zone marks an indistinct contact of sand above clay. About 20 feet farther south where the land is higher, this boundary lies near the base of the red-mottled zone and is horizontal and regular. The red-mottled zone is twice as thick 100 feet farther south. A dashed line drawn at the base of the red-mottled zone indicates a gradual change to clay in which stratification has not been effaced by weathering. This clay is sparsely mottled with horizontal streaks of yellowish red. Sand and clay at the base contain areas several inches across stained yellowish brown

interruptions in profile development—and, hence, polygenetic character. One such "unconformity" is that shown between brown hardpan and red mottling in figure 13 and discussed above. Another is in a borrow pit half a mile east of Saxon, where soil in loose sand of a terrace deposit along Goose Creek merges with the upper part of a profile with red mottling developed in the Ladson formation. If the soil horizons at these localities are unconformable, as they seem to be, then the successively older soils developed polygenetically.

GEOLOGIC HISTORY

Recorded geologic development of the South Carolina coastal plain began during the Cretaceous period when a wedge of sediment, thickening seaward, began to accumulate on crystalline rocks of an older era. Most of the sedimentary wedge had accumulated by the time the oldest sediment in the Charleston area was deposited. Thus, the geologic history of the Charleston area is recorded by relatively thin layers of sediment laid down during ebb and flow of the sea across older sediments that contain a much longer record of events. History read from rocks accessible in the Charleston area begins during the Oligocene epoch.

TERTIARY PERIOD

During the Oligocene the Charleston area was covered by about 200 feet of lime mud that compacted into the Cooper marl. The marl accumulated on slightly upturned edges of beds that were successively older toward Cape Fear, because of an earlier uplift which reached a maximum in that vicinity. Farther west and north, the marl was thinner and no doubt closer to the shore. Probably the marl accumulated on the continental shelf. From the remains of mollusks preserved in the Cooper marl, the ocean waters at this time were comparatively cool.

During much of the Miocene parts of areas now land probably were receiving no sediment or were being eroded. Differential movements of the earth's crust, influencing deposition and erosion, are suggested by preservation of a middle Miocene wedge of marine sand, clay, and limestone, named the Hawthorn formation, that thickens southward from the Charleston area, and by localized, thin, late Miocene beds of limestone, coquina, and marl, referred to as Duplin marl, most abundant north of the area. Early Miocene events are practically unknown, but the sea may have briefly covered the area. Mollusks preserved in these Miocene deposits resemble those found immediately north and south and indicate that the waters were neither much warmer nor cooler than today.

During the Pliocene the relations of land and sea were about as today, but for a time the sea covered a narrow belt along the present coast and left thin beds of shells mixed with sand—the Waccamaw formation. Fluctuations of sea level may have been greater than these shell deposits near the coast indicate, because marine mollusks which seem related to Pliocene forms are found farther inland 65 feet above present sea level and also nearer the coast 83 feet below present sea level. Whether these mollusks lived late in the Pliocene or early in the Pleistocene, they show a major change in relation of land and sea during a geologically short interval of time.

PLEISTOCENE EPOCH

Sometime during the Pleistocene the Charleston area began to be covered by marine sand and clay. Similar deposits may have been laid down during earlier epochs farther west, close to the seashore, but the record of such deposits is obscure. From the Pleistocene sand and clay, named the Ladson formation, it may be inferred that there was a regional change in sedimentation, possibly promoted by regimen changes in streams that brought larger amounts of sediment to the ocean. At the base of the Ladson formation is gravel, partly pieces of Cooper marl changed to phosphate rock. Transformation of marl to phosphate rock presumably took place while the marl was covered by phosphatic sea water, but the time of transformation is unknown. Layers of sand and clay accumulated to depths of at least 35 feet as the sea rose perhaps 100 feet above its present level.

With subsidence of the sea, the layers of sand and clay were eroded to form flat areas, possibly by differential erosion of layers contrasting slightly in texture. Soils with red mottling developed on the eroded terrain. The red-mottled soils were subsequently eroded locally, and brown sandy hardpan developed on red mottled material. Still later weathering appears to have modified the upper parts of soil profiles. Thus, the terrain and morphology of soils suggests a complex history of erosion and weathering. Deposition, erosion, and weathering of the Ladson formation may have progressed during a considerable part of the Pleistocene.

Deposits of loose sand laid down on the eroded and weathered Ladson formation during late Pleistocene time show minor changes in sea level and presumably the action of wind.

LOGS OF AUGER HOLES BORED IN THE LADSON QUADRANGLE

Log of auger hole 225, 0.3 mile S. 33° W. of Poppenheim Crossing, adjacent to shaft 2 of McDowell tunnel

[Altitude 29 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, clayey, firm, mottled gray and red; friable, dark-gray humus in upper foot	5
2. Clay with fine and medium-grained sand, very stiff, very pale gray (2.5 *Y* 8/2); becomes more sandy toward bottom	2½
3. Sand, fine, very pale yellow (5 *Y* 8/3)	3
4. Clay and fine sand, stiff, dark-gray (5 *Y* 4/1) to olive-gray (5 *GY* 6/2); lower half foot sandy and yellow green (5 *GY* 7/2)	8
Total thickness of fine-sand member	18½
Phosphate member:	
5. Sand, fine- and medium-grained, clayey, moderately stiff, pale-olive	1½
6. Clay and fine sand, stiff, olive-gray (5 *Y* 5/2)	7
7. Clay, brittle; upper half slightly sandy and yellowish green; lower half dark gray	6
8. Fine sand and clay, plastic, gray; calcareous	2
9. Clay with medium and fine sand, plastic, gray; calcareous; shell fragments; black grains of phosphate common (see colln. D206–T)	1½
Total thickness of phosphate member	18
Unconformity.	
Cooper marl:	
10. Marl, olive (5 *Y* 5/3); rare grains of phosphate; upper half foot soft; 1 ft penetrated.	

Log of auger hole 227, 1.4 miles S. 76° W. of Woodstock

[Altitude 55 feet]

	Thickness (feet)
Ladson formation:	
Medium-sand member:	
1. Sand, fine- and medium-grained, brownish-yellow (10 *YR* 6/6); gray humus in upper half foot; slightly clayey in lower half foot	3½
2. Sand, medium-grained, slightly clayey; gray with mottles of red (10 *R* 4/8) and yellow (10 *YR* 6/8); lower half more clayey	6½
3. Clay and medium-grained sand, very stiff, gray	2
Total thickness of medium-sand member	12

Log of auger hole 227, 1.4 miles S. 76° W. of Woodstock—Continued

	Thickness (feet)
Ladson formation—Continued	
Unconformity?	
Fine-sand member:	
4. Clay and fine sand, stiff, gray; lower half mostly sand	3
5. Fine sand and clay; coarse mottles of yellowish red and red	5½
6. Sand, fine, yellow (10 *YR* 6/8)	3
7. Clay, gray with very pale brown mottles in upper part	5
Total thickness of fine-sand member	16½
Phosphate member:	
8. Sand, medium-grained; mottled yellow and brown in upper part	5
9. Sand, medium- and fine-grained, yellowish-brown; sparse grains of phosphate	1½
10. Sand, medium-grained, slightly clayey, olive-gray (5 *Y* 4/2); rare dark-brown and tan grains of phosphate	2½
Total thickness of phosphate member	9

Unconformity.
Cooper marl:
11. Marl, olive (5 *Y* 5/2); shells; upper 2 ft soft; 2½ ft penetrated.

Log of auger hole 228, 0.8 mile S. 8° E. of Woodstock

[Altitude 25 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, friable to firm, yellowish-brown; grayish-brown humus in upper half foot	2
Phosphate member:	
2. Sand, medium-grained, mottles of yellowish brown and red; lower part slightly clayey	6½
3. Clay and fine sand, interlaminated; mottled yellow, red, and gray; lower part mostly clay	5
4. Sand, coarse, brownish-yellow (10 *YR* 6/6); subangular granules and pebbles of phosphate	4
Total thickness of phosphate member	15½

Unconformity.
Cooper marl:
5. Marl, olive (5 *Y* 5/3); lower part very firm; upper 2 ft soft; phosphate grains in upper 2½ ft; 3½ ft penetrated.

Log of auger hole 229, 1.6 miles N. 37° E. of Ashley Church

[Altitude 30 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, very fine, slightly clayey, very firm; mottled yellowish brown and red; dark-gray humus in upper half foot	4
2. Clay and very fine sand, stiff; mottled yellow and gray	3
3. Sand, fine, friable, grayish yellow	1
4. Sand and clay, fine, plastic, gray	6
Total thickness of fine-sand member	14
Phosphate member:	
5. Sand, fine and medium-grained, pale-brown and gray	5
6. Sand, coarse, clayey, gray; granules and pebbles of phosphate	1½
Total thickness of phosphate member	6½
Unconformity.	
Cooper marl:	
7. Marl, firm, pale-olive (5 *Y* 5/3); phosphate grains, mostly in upper part; 8 ft penetrated.	

Log of auger hole 230, 1.2 miles N. 54° W. of Ashley Church

[Altitude 23 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, brownish-yellow (10 *YR* 6/6); dark-grayish-brown humus in upper half foot	2½
2. Sand, fine, firm, clayey; mottles of yellow and red; lowest half foot very clayey	3½
Total thickness of fine-sand member	6
Phosphate member:	
3. Sand, medium-grained, firm, slightly clayey, mottles of brown in upper part	1½
4. Sand, medium- and coarse-grained, slightly clayey, grayish-yellow-green (5 *GY* 7/2); middle part mostly medium-grained sand; granules of phosphate in lower part	5
Total thickness of phosphate member	6½
Unconformity.	
Cooper marl:	
5. Marl, light-olive-brown (2.5 *Y* 5/4); phosphate grains; upper 2 ft soft; 3 ft penetrated.	

Log of auger hole 231, 0.8 mile S. 52° E. of Ashley Church

[Altitude 25 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, friable, brown (10 *YR* 5/3); dark-gray humus in upper part	2½
2. Sand, fine, slightly clayey, firm; gray with mottles of brownish yellow and red	4½
3. Sand, fine, and stiff clay; gray with mottles of brownish yellow	3½
Total thickness of fine-sand member	10½
Phosphate member:	
4. Sand, fine- and medium-grained, dark-gray; lower half clayey	6½
5. Clay and medium-grained sand, plastic, dark-gray (5 *Y* 4/1); pebbles of phosphate	2
Total thickness of phosphate member	8½
Unconformity.	
Cooper marl:	
6. Marl, firm, olive (5 *Y* 5/4); phosphate grains; upper part soft; 2½ ft penetrated.	

Log of auger hole 232, 0.8 mile N. 30° W. of Lambs

[Altitude 35 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, very fine, friable, brownish-yellow; dark-grayish-brown humus in upper half foot	3
2. Sand, fine, firm; mottled yellow, brown, and gray	2½
3. Sand, fine, slightly clayey, friable, reddish yellow (5 *YR* 5/8)	3
4. Sand, fine, friable, pale-yellow (2.5 *Y* 8/4) and gray; clay in lowest half foot	4
Total thickness of fine-sand member	12½
Phosphate member:	
5. Sand, medium-grained, yellowish-gray	8
6. Phosphate pebbles and nodules in matrix of yellowish-brown, calcareous sand and clay	3½
Thickness of phosphate member	11½
Unconformity.	
Cooper marl:	
7. Marl, olive (5 *Y* 5/3); shells; phosphate grains; upper 2 ft soft; 3 ft penetrated.	

Log of auger hole 233, 0.2 mile S. 30° E. of Lambs

[Altitude 29 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, very fine, friable, pale-yellow; brownish-gray humus in upper half foot	2½
2. Sand, fine, firm, brownish-yellow mottled with red (10 *R* 4/8)	3½
3. Clay, sandy, stiff; gray with coarse mottles of red and yellow in upper part, rich in mica in lower part	4½
Total thickness of fine-sand member	10½
Phosphate member:	
4. Sand, medium-grained, slightly clayey, plastic; light-gray with mottles of yellowish brown	½
5. Sand, fine, friable, yellow (10 *YR* 7/8) and gray	8
6. Clay, slightly sandy, very stiff, pale yellow and gray	2
7. Phosphate pebbles and nodules in matrix of grayish-brown, calcareous, phosphatic sand	1
Total thickness of phosphate member	11
Unconformity.	
Cooper marl:	
8. Marl, firm, olive (5 *Y* 5/3); phosphate grains; 4 ft penetrated.	

Log of auger hole 234, 1.9 miles S. 49° W. of Woodstock

[Altitude 30 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Clay, stiff, gray, and fine sand, upper part mottled brownish yellow (10 *YR* 6/6), lower part mottled yellow, red, and gray; humus zone at top	5
Phosphate member:	
2. Sand, medium-grained, clayey, stiff, gray to pale-greenish-gray (5 *GY* 7/2); coarse medium-sized mottles of dark brown; phosphate pebbles common at base	2½
3. Sand, medium- and fine-grained, clayey, stiff; mottled pale gray and pale greenish gray	1
4. Sand, fine, clayey, light-gray to olive-gray; phosphatic sand and pebbles in lower half	9½
Total thickness of phosphate member	13
Unconformity.	
Cooper marl:	
5. Marl, firm, olive-brown (2.5 *Y* 5/4); phosphate grains; shells; upper foot soft; 9 ft penetrated.	

Log of auger hole 235, 1.6 miles S. 51° W. of Ashley Phosphate

[Altitude 31 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, clayey; gray with mottles of yellowish red and brown; very dark gray humus in upper half foot	6½
2. Sand, fine, clayey, stiff, pale-yellowish-gray (2.5 *Y* 7/3); upper foot friable; mottles of red in lower part	4
3. Clay, fine sandy, stiff, gray	7
4. Sand, fine, clayey, plastic; light-olive-gray (5 *Y* 6/2) mottled with strong brown	1
Total thickness of fine-sand member	18½
Phosphate member:	
5. Sand, medium-grained, clayey, plastic, gray; grains and granules of phosphate	6½
6. Sand, coarse, slightly clayey, gray; phosphate granules	4
7. Sand, medium- and fine-grained, calcareous, olive-gray, phosphate grains	2½
Total thickness of phosphate member	13
Unconformity.	
Cooper marl at base.	

Log of auger hole 236, 0.2 mile S. 70° W. of Midland Park

[Altitude 40 feet]

	Thickness (feet)
Sand on Tenmile Hill:	
1. Sand, very fine, loose, yellow (2.5 *Y* 7/6) with faint mottles of brownish yellow; grayish-brown humus in upper half foot	4½
Unconformity.	
Ladson formation:	
Fine-sand member:	
2. Sand, fine, friable, grayish-brown mottled with reddish yellow in upper part	7½
3. Clay and fine sand, plastic, light-gray	1½
4. Sand, fine, loose, pale-yellowish-gray (2.5 *Y* 8/3)	½
5. Clay, slightly fine sandy, plastic, gray	4
Total thickness of fine-sand member	13½
Phosphate member:	
6. Clay and coarse to fine sand, plastic, gray	5½
7. Sand, fine, clayey, stiff, greenish gray (5 *G* 6/1), calcareous; phosphate grains in lower part	8½
Total thickness of phosphate member	14
Total thickness of Ladson formation	27½
Unconformity.	
Cooper marl at base.	

Log of auger hole 237, 0.5 mile N. 25° W. of Tenmile

[Altitude 32 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine and very fine, slightly clayey; strong brown mottled with red; grayish-brown humus in upper half foot	4
2. Sand, fine, friable; gray, mottled with red and yellow in upper part	8
3. Sand, fine, pale-gray to yellow; mica flakes common	7½
Total thickness of fine-sand member	19½
Phosphate member:	
4. Sand, medium-grained, gray	3½
5. Clay, brittle, pale-green (10 *G* 6/2); upper half foot sandy	4½
6. Phosphate pebbles in matrix of gray, calcareous sand and clay	2½
Total thickness of phosphate member	10½
Unconformity.	
Cooper marl:	
7. Marl, firm, pale-olive; phosphate grains; 1 ft penetrated.	

Log of auger hole 238, 0.7 mile N. 27° W. of Ahsley Phosphate

[Altitude 32 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, clayey, firm; mottled red (7.5 *R* 3/8), yellow, and gray; grayish-brown humus in upper half foot	3½
2. Clay and fine sand, stiff; gray with mottles of reddish yellow and brown	4
3. Sand, fine, pale yellow (2.5 *Y* 8/3)	3
4. Fine sand and clay, stiff; gray, mottled with yellowish brown in upper part	8½
5. Clay, slightly fine sandy, brittle to plastic, greenish gray	1
Total thickness of fine-sand member	20
Phosphate member:	
6. Clay and fine sand, stiff, grayish-brown to olive-yellow (5 *Y* 6/6); calcareous; pebbles and nodules of phosphate	3½
Unconformity.	
Cooper marl:	
7. Marl, firm, olive (2.5 *Y* 5/4); phosphate grains; upper part soft; 6 ft penetrated.	

Log of auger hole 240, 1.2 miles S. 83° W. of Otranto

[Altitude 44 feet]

	Thickness (feet)
Ladson formation:	
Medium-sand member:	
1. Sand, medium- and fine-grained, clayey, gray with mottles of yellowish brown and red; very dark gray humus in upper foot	4½
2. Sand, medium-grained, slightly clayey, firm, light-gray (8/0) mottled with red (10 *R* 4/8)	1
3. Sand, medium- and fine-grained, slightly clayey, plastic, yellowish-gray	4
Total thickness of medium-sand member	9½
Unconformity?	
Phosphate member:	
4. Sand, coarse to fine, clayey, plastic, yellowish-gray with mottles of brown	½
5. Clay, stiff, light-gray	1
6. Sand, medium- and coarse-grained, slightly clayey, plastic, pale-yellow (2.5 *Y* 7/4); phosphate pebbles in lower half	5½
Total thickness of phosphate member	7
Unconformity.	
Cooper marl:	
7. Marl, very firm, olive-brown (5 *Y* 5/4); phosphate grains; shells; upper foot soft; 4½ ft penetrated.	

Log of auguer hole 241, 1.4 miles S. 70° E. of Ladson

[Altitude 44 feet]

	Thickness (feet)
Ladson formation:	
Medium-sand member:	
1. Sand, medium- and fine-grained, slightly clayey, firm; mottled red and yellow; dark-grayish-brown humus in upper half foot	5½
2. Sand, medium- and fine-grained, clayey, stiff, light-gray, mottled with red (7.5 *R* 4/6)	2½
Total thickness of medium-sand member	8
Unconformity?	
Phosphate member:	
3. Sand, medium-grained, clayey, pastic, light gray with sparse mottles of red	2½
4. Clay, slightly fine sandy, brittle, very pale yellow (2.5 *Y* 8/2)	6
5. Sand, fine, slightly clayey, plastic, grayish-brown; calcareous; phosphate grains abundant	5
Total thickness of phosphate member	13½
Unconformity.	
Cooper marl:	
6. Marl, olive (5 *Y* 5/3); phosphate grains; upper foot soft, 3 ft penetrated.	

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Log of auger hole 242, 1 mile N. 58° W. of Ladson

The log of this hole is given in the description of the Ladson formation on page 37.

Log of auger drill hole 245, 1.5 miles N. 41° W. of Goose Creek store

[Altitude 38 feet]

	Thickness (feet)
Ladson formation:	
Medium-sand member:	
1. Sand, fine- and medium-grained, clayey, plastic; mottled yellow, brown, and gray; black humus in upper half foot	3
2. Sand, medium-grained, clayey, very firm; mottled yellow, red, and gray	2
Total thickness of medium-sand member	5
Unconformity?	
Phosphate member:	
3. Sand, medium- and coarse-grained, slightly clayey, firm, very pale yellowish gray (2.5 *Y* 8/2)	2
4. Sand, medium-grained, friable, slightly clayey, pale-yellow	5
5. Sand, coarse, yellow to olive-gray; abundant grains of phosphate	5
Total thickness of phosphate member	12
Unconformity.	
Cooper marl:	
6. Marl, firm, olive (5 *Y* 5/3); phosphate in upper part; upper 3 ft soft, 13 ft penetrated.	

Log of auger hole 246, 1.4 miles N. 54° E. of Goose Creek store

[Altitude 31 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, clayey, very firm; mottled yellow (2.5 *Y* 7/6), red (10 *R* 5/8), and gray; dark-gray humus in upper half foot	6
2. Sand, fine, clayey, friable; pale yellow, mottled with brown	2
Total thickness of fine-sand member	8
Phosphate member:	
3. Sand, medium-grained, and clay, interlaminated; brown to gray	1
4. Sand, fine to coarse, and stiff clay; light gray with mottles of brown	3
5. Sand, coarse, clayey, stiff, very light yellowish gray (2.5 *Y* 8/2)	3
6. Sand, coarse- and medium-grained, light-yellowish-gray; phosphate grains abundant in lower part	7½
Total thickness of phosphate member	14½
Unconformity.	
Cooper marl:	
7. Marl, olive (5 *Y* 5/3); shells; upper foot soft; 3½ ft penetrated.	

Log of auger hole 247, 0.9 mile N. 32° E. of Charleston Water Works

[Altitude 30 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, clayey, firm; mottled yellow, red, and gray; dark-grayish-brown humus in upper half foot	6
2. Sand, fine, slightly clayey, friable, gray with yellow and red mottles	3
3. Sand, fine, yellow (10 *YR* 7/8)	3½
4. Sand, fine, and clay, friable to stiff, dark brown; lower half foot mostly clay	5
Total thickness of fine-sand member	17½
Phosphate member:	
5. Sand, medium-grained, and clay, stiff, light-gray; shells	1
Unconformity.	
Cooper marl:	
6. Marl, very firm, olive (5 *Y* 4/3); phosphate grains; upper half soft, 7½ ft penetrated.	

Log of auger hole 248, 1 mile S. 6° E. of Otranto

[Altitude 28 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, clayey, very firm; mottled yellow (2.5 *Y* 8/6) and red (7.5 *R* 3/6); dark-grayish-brown humus in upper half foot	5
2. Sand, fine, slightly clayey, friable; mottled red and gray	2½
3. Sand, fine, and clay; upper part yellow; lower part gray	8½
4. Sand, fine, light-gray (7 *Y* 7/1)	2
5. Clay, stiff, greenish-gray (5 *GY* 6/1); upper half foot sandy	5
Total thickness of fine-sand member	23
Phosphate member:	
6. Clay with fine- and medium-grained sand, gray, plastic; calcareous; shells	5
7. Sand, fine to coarse, gray; calcareous; shells; nodules of phosphate	5
Total thickness of phosphate member	10
Unconformity.	
Cooper marl:	
8. Marl, firm, olive (5 *Y* 6/4); phosphate grains; 1 ft penetrated.	

Log of auger hole 249, 1 mile N. 78° W. of Charleston Water Works

[Altitude 36 feet]

	Thickness (feet)
Sand on Tenmile Hill:	
1. Sand, fine, loose, pale-yellow (2.5 *Y* 7/4) changing downward to brownish-yellow	3
Unconformity.	
Ladson formation:	
Fine-sand member:	
2. Sand, fine, slightly clayey, firm; mottled brown, red, and yellow	7
3. Sand, fine, yellow to gray; lower foot clayey	5½
Total thickness of fine-sand member	12½
Phosphate member:	
4. Sand, medium- and coarse-grained, slightly clayey, plastic, yellowish-gray	3½
5. Fine sand and clay, very stiff, yellow (5 *Y* 8/4)	2½
6. Sand, fine to coarse, gray to olive-yellow; phosphate grains and pebbles	2
Total thickness of phosphate member	8
Total thickness of Ladson formation	20½
Unconformity.	
Cooper marl:	
7. Marl, olive-brown (2.5 *Y* 4/3) changing downward to olive (5 *Y* 5/4); phosphate grains abundant in upper part; shells; upper part soft; 10½ ft penetrated.	

Log of auger hole 250, 1 mile N. 32° E. of The Farms

[Altitude 32 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, loose, yellow (10 *YR* 7/6); very dark grayish brown humus in upper foot	3
2. Sand, fine, slightly clayey, firm, mottled red and yellow	6
3. Sand, fine, friable, yellow with faint coarse mottles of yellowish red	2½
4. Sand, fine, very pale yellow (2.5 *Y* 8/6); abundant flakes of mica	6
Total thickness of fine-sand member	17½
Phosphate member:	
5. Sand, fine- and medium-grained, very pale yellow	4½
6. Clay with fine to coarse sand, plastic; calcareous; shells; fish teeth; phosphate nodules in lower part	3½
Total thickness of phosphate member	8
Unconformity.	
Cooper marl:	
7. Marl, olive (5 *Y* 4/3); phosphate grains; upper part soft; 5½ ft penetrated.	

Log of auger hole 251, 0.8 mile N. 29° E. of Goodrich

[Altitude 21 feet]

	Thickness (feet)
Pamlico formation:	
1. Sand, fine, loose, yellow (2.5 *Y* 7/6); black humus in upper half foot	2
Unconformity.	
Ladson formation:	
Fine-sand member:	
2. Sand, fine, slightly clayey, friable; yellow with mottles of red	6½
3. Sand, fine, loose, pale-yellow to pale-gray	1½
Total thickness of fine-sand member	8
Phosphate member:	
4. Sand, fine to coarse, slightly clayey, grayish-yellow; phosphate grains	3
5. Sand, fine, clayey, plastic, greenish gray (5 *GY* 5/1)	2½
6. Sand, coarse to fine, and clay, greenish gray; shells; phosphate nodules and pebbles	3
Total thickness of phosphate member	8½
Total thickness of Ladson formation	16½
Unconformity.	
Cooper marl:	
7. Marl, olive (5 *Y* 4/3); upper part soft; 5½ ft penetrated.	

Log of auger hole 253, 0.6 mile S. 40° W. of Ashley Marl Works

[Altitude 30 feet]

	Thickness (feet)
Ladson formation:	
Fine-sand member:	
1. Sand, fine, loose, light-yellowish-brown (10 *YR* 6/4) to gray; dark-grayish-brown humus in upper half foot	11½
2. Sand, fine, slightly clayey; very dark brown changing downward to light greenish gray (5 *GY* 7/1)	2½
3. Clay and fine sand, plastic, light-greenish-gray	1½
Total thickness of fine-sand member	15½
Phosphate member:	
4. Sand, medium- and coarse-grained, clayey, firm, greenish-gray; calcareous; shells; phosphate grains in lower part	2½
Unconformity.	
Cooper marl:	
5. Marl, firm, olive (5 *Y* 5/3); upper 2 ft soft; 7 ft penetrated.	

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